Effects of Aircraft Noise on Reading and Quality of Life in Primary School Children in Germany: Results From the NORAH Study

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Abstract
A review of the literature shows that our knowledge concerning effects of chronic aircraft noise exposure on children is still limited and does not allow well-founded predictions for children living in specific noise-exposed areas. In this study, we investigated effects of aircraft noise on cognition and quality of life in 1,243 second graders from 29 schools around Frankfurt/Main Airport in Germany. Although exposure levels at schools were below 60 dB and thus considerably lower than in previous studies, multilevel analyses revealed that increasing exposure was linearly associated with less positive ratings of quality of life, increasing noise annoyance, and decreasing reading performance. A 20 dB increase in aircraft noise exposure was associated with a decrease in reading scores of one fifth of a standard deviation, corresponding to a reading delay of about 2 months. No effects were found for verbal precursors of reading acquisition. Teachers’ reports

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(N = 84) indicate that severe disruptions of classroom instruction due to aircraft noise may contribute to the effect on reading.

Keywords
aircraft noise, children, reading, phonological processing, quality of life

Although individual airplanes have become on average 75% less noisy over the last few decades, due to the growing amount of air traffic, the number of people exposed to aircraft noise is increasing. According to the European Commission, about 2.3 million EU citizens are currently exposed to aircraft noise levels exceeding 55 dB (Houthuijs, van Beek, Swart, & van Kempen, 2014). Numerous studies analyzed potential effects of aircraft noise exposure on a range of outcome variables, such as annoyance and quality of life (Babisch et al., 2009; Schreckenberg, Meis, Kahl, Peschel, & Eikmann, 2010), sleep disturbance (Basner, Samel, & Isermann, 2006), hypertension (Eriksson et al., 2007), cardiovascular disease (Davies & van Kamp, 2012), and cognitive performance in children. Concerning the latter, inconsistent results were reported with respect to effects on children’s attention (Haines, Stansfeld, Job, Berglund, & Head, 2001; Hygge, Evans, & Bullinger, 2002; Stansfeld et al., 2005; van Kempen et al., 2010) and memory (Haines et al., 2001; Matheson et al., 2010), whereas in the majority of studies, exposure to aircraft noise was consistently associated with lower reading performance (Green, Pasternack, & Shore, 1982; Haines et al., 2001; Hygge et al., 2002; Stansfeld et al., 2005; see for review, Clark & Sörqvist, 2012). Effects of aircraft noise on children’s quality of life have hitherto rarely been addressed. In the context of the Munich study, which will be outlined in detail below, a small but significant decline was observed in children’s ratings of quality of life 18 months after the opening of a new airport. No decline was found in the unexposed control group (Evans, Bullinger, & Hygge, 1998).

The current study was performed in the context of the NORAH (Noise-Related Annoyance, Cognition, and Health) project, a joint project of researchers from different disciplines designed to elucidate the effects of transportation noise on citizens of the metropolitan area of Rhine-Main around Frankfurt/Main airport in Germany. Here we report on the NORAH subproject that addressed potential effects of aircraft noise exposure on reading, reading-related phonological abilities, and quality of life in primary school children in the Rhine-Main region. We will start with a critical review of prior studies on this topic, and we will outline our motivation for conducting a further study and its incremental contribution.
This study was performed because our knowledge concerning effects of chronic aircraft noise exposure on children is still limited and does not allow well-founded predictions for children from specific noise-exposed areas such as Rhine-Main. This holds not only for effects on children’s quality of life, which have rarely been studied previously but, despite the existing literature, also for effects on reading for a number of reasons.

First, the majority of studies were performed in the 20th century, when individual airplanes were much noisier than nowadays, and average noise levels near airports were considerably higher. In fact, aircraft noise levels at the most exposed schools in the Rhine-Main region are comparable to levels at schools included as unexposed controls in prior studies. To the best of our knowledge, the current study is the first that addressed the effects of comparably moderate levels of aircraft noise on children.

Second, most previous studies compared children exposed to high noise levels with children exposed to low noise levels. These studies do not allow estimation of exposure–effect relationships, and thus yield no information on the level where the harmful effects begin, and on how the effects will change with increasing or decreasing exposure. Such knowledge is indispensable for judging the relevance of the noise effects and the costs and benefits of interventions in noise policy. Only three studies analyzed exposure–effect relationships, yielding inconsistent results. In two of them (Green et al., 1982; Stansfeld et al., 2005), increasing aircraft noise levels were significantly associated with decreasing reading scores, but in one, this association was eliminated when socioeconomic status (SES) was taken into account (Haines, Stansfeld, Head, & Job, 2002).

Third, a number of the earlier studies are difficult to interpret due to methodological limitations, each of which results in a potential overestimation of the noise effects. For example, cognitive abilities were usually measured in the children’s regular classrooms, but acute noise levels were not always controlled for. Thus, testing was done in noisy conditions for the chronically exposed and in quiet conditions for the non-exposed children (e.g., Seabi, Cockerst, Goldschagg, & Greyling, 2012). As acute noise may affect children’s cognitive performance (Klatte, Bergström, & Lachmann, 2013), this results in a confounding of effects of acute and chronic exposure. A further problem stems from incomplete control of SES. Aircraft noise has consistently been found to be associated with SES (Evans, 2004), which in turn is strongly related to children’s health, cognition, and academic achievement (R. H. Bradley & Corwyn, 2002), especially reading (Noble, Farah, & McCandliss, 2006). The association between SES and reading is mediated by a variety of individual and class-related factors, such as home literacy environment and parental involvement in school affairs (Aikens & Barbarin, 2008), migration
background and proficiency in the language of instruction (Lüdemann &
Schwerdt, 2013; Schnepf, 2007), and quality of schooling resulting from con-
textual effects of class composition (Sirin, 2005). School context effects may
contribute to individual differences in school achievement over and above
family context (Aikens & Barbarin, 2008; Schrader, Helmke, & Hosenfeld,
2008). However, noise studies have hitherto not included SES variables on
both class level and individual level, but have focused on either the class or the
individual level. When individual SES was used, assessment was usually
based on dichotomous variables (e.g., Haines et al., 2001; Seabi et al., 2012).
The variance in SES accounted for by these variables may not suffice to rule
out confounding of SES-induced and noise-induced effects on reading. In
addition, the hierarchical structure of the data (children in classes) was often
disregarded in the statistical analyses. This leads to a risk of overestimation of
effects due to alpha-level inflation (Hox, 1998).

The most influential studies concerning aircraft noise and children’s cog-
nition are the Munich longitudinal study (Hygge et al., 2002) and the RANCH
(Road-traffic and Aircraft Noise Exposure and Children’s Cognition and
Health) study (Stansfeld et al., 2005). The Munich study analyzed aircraft
noise effects on German children (N = 326, 8 to 12 years) in the context of a
naturally occurring quasi-experiment that was made possible by the reloca-
tion of the airport in Munich in 1992. Testing was performed in a sound-
attenuated mobile laboratory, thus eliminating potential effects of acute noise.
Prior to relocation (Wave 1), children exposed to high levels of aircraft noise
from the old airport performed worse on the most difficult reading test items
when compared with less exposed children in the same region. This group
difference disappeared after closure of the old airport (Waves 2 and 3). At the
new airport, there was a tendency (p < .074) for better performance in the
control children in Wave 3, but not in Waves 1 and 2. A similar pattern was
found for long-term memory.

Due to its quasi-experimental design, the Munich study is often cited as
strong evidence for a causal effect of aircraft noise on children’s cognition
(e.g., Clark & Stansfeld, 2007). We fully appreciate the relevance and the
sophisticated design of this study, but when judging the available evidence on
aircraft noise effects, we feel it is necessary to take into account some limita-
tions that are rarely discussed in the secondary literature. For example, long-
term memory was assessed by written recall of a text read the day before.
This is not the best measure of memory, as performance is affected by the
children’s reading and spelling abilities. With regard to the reading test, in the
control group at the old airport, no improvement in reading performance was
evident across the 24 months study period (Hygge et al., 2002; Figure 1),
presumably due to a floor effect (low error rates already in Wave 1). Thus, the
elimination of the group difference after relocation may not result from improved learning in the formerly exposed group, but from absence of learning in the control group. In addition, time of reading instruction (grade levels) was not controlled for, and a considerable number of children were excluded from the analyses of the reading scores without reporting the exclusion criteria. Later in the text (p. 472), Hygge et al. (2002) mention that the reduced number of cases results mainly from exclusion of participants who did not finish the difficult test items. Presumably, these children were especially poor readers, but no information is given concerning their distribution across the exposure groups. Furthermore, group comparability with respect to SES was verified for the entire sample, but not for the subsample of children that were actually included in the analyses. Finally, as in other studies, the clustered structure of the data was not considered in the analyses.

The cross-national RANCH study (Stansfeld et al., 2005) included children \((N = 2,844, 8 \text{ to } 12 \text{ years})\) living in the vicinity of huge international airports in the United Kingdom (London–Heathrow), the Netherlands (Amsterdam–Schiphol), and Spain (Madrid–Barajas). In RANCH, aircraft noise exposure was included as a continuous variable, and multilevel analyses were performed to account for the hierarchical nature of the data. Outdoor aircraft noise levels at the schools ranged from 30 to 77 dB \(L_{Aeq,07-23}\) (A-weighted average continuous equivalent sound pressure level from 07:00 to 23:00 hr). With individual SES controlled for using a combination of indicators, multilevel analyses revealed a linear exposure–effect relationship between aircraft noise at school and decreasing recognition memory and reading comprehension. The effect sizes did not differ significantly between countries. A 20 dB increase in aircraft noise was associated with a decrement in reading scores of one fifth (United Kingdom) to one eighth (Netherlands, Spain) of a standard deviation \((SD)\). No noise effects were found for long-term recall, working memory, and selective attention. Concerning noise annoyance, increasing aircraft noise was associated with increasing annoyance responses in children. The respective exposure–effect relationship was non-linear, with a steeper exposure-response gradient at aircraft noise levels above 60 dB.

With respect to potential mechanisms underlying the association between aircraft noise and reading, Stansfeld et al. (2005) discuss learned helplessness, teacher frustration, interruptions of classroom discourse, and general inattention to auditory and auditory-verbal stimuli, resulting from over-generalization of a strategy of tuning out unwanted sounds. Other researchers argued that the effect of aircraft noise on reading is mediated by effects on phonological precursors of reading acquisition (Evans & Maxwell, 1997; Klatte, Hellbrück, Seidel, & Leistner, 2010).
The important role of phonological processing abilities in learning to read is highlighted in developmental models of reading acquisition. According to Frith (1985), reading acquisition in alphabetic systems proceeds in three stages. In the logographic stage, the child is able to recognize a limited number of words by focusing on salient graphic features. In this stage, the child is not yet aware of the alphabetic principle (written words are composed of individual letters that represent speech sounds). In the alphabetic stage, the child acquires grapheme–phoneme associations, and becomes more and more adept at pronouncing unknown words through letter-by-letter decoding. Repeatedly reading the same words helps the child to gradually build up an orthographic lexicon that allows fast and direct access to the meaning of written words, without grapheme–phoneme conversion. Finally, the orthographic stage is reached when most words are recognized directly and automatically.

There is general agreement that the alphabetic stage is of particular importance for successful reading acquisition (Lachmann & van Leeuwen, 2014). Mastering the alphabetic stage requires intact phonological processing abilities, as these form the bases for grasping the alphabetic principle, and for acquisition and automatization of the grapheme–phoneme correspondences. Reading research identified four components of reading-related phonological abilities. These are speech perception, phonological short-term memory, phonological awareness (the ability to consciously access and manipulate the sound units of language), and rapid access to phonological representations in long-term memory (Melby-Lervåg, Lyster, & Hulme, 2012; Ziegler, Pech-Georgel, George, & Lorenzi, 2009). For speech perception, phonological short-term memory, and phonological awareness, laboratory studies have shown adverse effects of acute noise on children’s performance (Klatte, Meis, Sukowski, & Schick, 2007; Talarico et al., 2007). In addition, negative effects of chronic noise exposure on speech perception have been reported for children (Evans & Maxwell, 1997) and adults (Brattico et al., 2005). In view of this evidence, phonological abilities were included as outcome variables in the current study. In addition, comprehension and retention of oral information was included as a further predictor of reading acquisition (Catts, Adlof, & Weismer, 2006).

Due to differences in the consistency of letter-sound mappings, reading acquisition proceeds faster in German when compared with English (Seymour, Aro, & Erskine, 2003). As the acquisition stage is considered most vulnerable for negative effects of environmental noise (Maxwell & Evans, 2000), the children participating in the current study were younger when compared with prior studies. We included second graders because in German second-grade classes, the letter-sound mappings have usually been introduced, but children’s
orthographic lexicon is still limited, and reading is far from automatized (Lachmann & van Leeuwen, 2008).

In German metropolitan areas such as Rhine-Main, the proportion of children with a migration background is high and still increasing (Author Group Education Reports; Autorenguppe Bildungsberichterstattung, 2014). In the current sample, the majority of children (60%) had a migration background. Because migration background is strongly associated with lower reading achievement in European countries, especially Germany (see, for example, Entorf & Minoiu, 2005; Schwippert, Wendt, & Tarelli, 2012), one might expect that aircraft noise exposure is especially detrimental for migrant children, as it constitutes an additional obstacle for reading acquisition. However, contrary to this prediction, in a recent study conducted in the vicinity of Durban International Airport in South Africa (Seabi et al., 2012), a detrimental effect of aircraft noise at school on children’s reading was found only for children instructed in their first language, that is, English, whereas no effect was found for children with English as a second language. Irrespective of aircraft noise exposure, reading scores were much lower in the second-language learners when compared with the children with English as their first language. To learn more about potential differences in aircraft noise effects in subgroups of children, we performed analyses for both the whole sample, and for subsamples of migrant and non-migrant children.

Quality of life and annoyance due to aircraft noise were assessed through ratings provided by the children, parents, and class teachers. Schools were matched according to socioeconomic factors, and individual and class-level SES factors were controlled in the statistical analyses. Aircraft noise levels at school and at the participants’ home addresses were assessed by means of radar data for the time period of 12 months before data collection. Classroom insulation, reverberation, and exposure to road-traffic and railroad noise were also included.

We obtained approval for the study from the Hessian Ministry of Education, and from the Hessian Data Protection Official.

**Method**

**Recruitment of the School Sample**

Written information on the study and a questionnaire concerning socioeconomic factors and exposure to different noise sources were sent out to all 297 public primary schools in the Rhine-Main study region. For each school, aircraft noise exposure \(L_{\text{Aeq,06-22}}\) was calculated on the basis of aircraft noise contours. For estimation of students’ SES, the headmasters were asked to
indicate the percentage of students with a migration background, and to respond to the statement “Our school is located in a socially disadvantaged catchment area,” using a 5-point rating scale ranging from “absolutely true” to “absolutely false.” The headmasters of 160 schools, among them those of the most noise-exposed schools in the study region, returned the questionnaires. Analyses of the headmasters’ ratings confirmed that, in line with prior studies, aircraft noise exposure at school was significantly associated with lower SES and higher percentage of children with a migration background, \( r(154) = .26, p < .01 \) and \( r(145) = .36, p < .01 \), respectively.

From the 160 schools, 29 schools were selected for participation in the study. The most noise-exposed schools were selected first. The remaining schools were matched according to the headmasters’ reports concerning children’s SES and migration background. Schools in which the headmasters reported high annoyance due to road-traffic, railroad traffic, building sites, industry, or other noise sources were excluded.

**Participants**

In the selected schools, the parents of the second graders were informed about the study through parents’ evenings and written information in different languages. We received written parental consent for 1,309 children (77.3%) from 85 classes. Due to moves or illness at the time of testing, 1,243 children participated in the study. For reading and phonological abilities, complete data from the parent questionnaires and the test battery were available for 1,090 children (557 girls). For quality of life and noise annoyance, complete data were available for 1,058 children (545 girls) and 1,106 children (564 girls) respectively. In each of these subsamples, the children ranged in age from 7 to 10 years, with a mean age of 8 years and 4 months and a SD of 5 months, and 60% of the children had a migration background (at least one parent born outside Germany). The migrant children were from a number of different ethnic groups, for example, from Turkey, Russia, Poland, Serbia, Iran, and others. Length of residence at the current address (according to parents’ reports) was less than 1 year for 5%, 1 to 2 years for 11%, 3 to 4 years for 14%, and more than 4 years for 70% of the participants.

Teacher questionnaires were completed by 84 class teachers (77 women).

**Assessment of Noise Exposure**

Exposure levels at schools and at the children’s homes were assessed by the NORAH acoustic team under the guidance of one author (U.M.). Aircraft noise levels were calculated on the basis of radar data from the Flight Track
and Aircraft Noise Monitoring System (FANOMOS), provided by German Air Traffic Services ("Deutsche Flugsicherung GmbH," DFS). The FANOMOS data specify flight route, altitude, and model of aircraft for each individual flight. The calculations were performed according to standard, regularized algorithms specified in the 2007 version of the German Act for Protection against Aircraft Noise ("Gesetz zum Schutz gegen Fluglärm"; FluLärmG, 2007). Comparisons of calculated noise levels with levels from 21 aviation noise measurement stations around Frankfurt Airport confirmed the validity of the calculations (mean differences below 1 dB; see Möhler et al., 2014). Road-traffic and railway noise were calculated using a combination of information (e.g., traffic flow data, street types, proportion of heavy traffic, traffic census data, quantity of train runs, speed and lengths of the trains) provided by local authorities.

Average sound levels of aircraft, road-traffic, and railway noise were calculated for the time period of 12 months before data collection was conducted (May 2011 to April 2012). Calculations were performed for each individual child by linking the school and home addresses to the modeled noise levels computed for different times of day. For aircraft noise at school, we used the time period 8:00 a.m. to 2:00 p.m. on work days. Aircraft noise at home was calculated for daytime (06:00 a.m.-06:00 p.m.) and children’s night time (08:00 p.m.-06:00 a.m.). All noise estimates were calculated as A-weighted average continuous equivalent sound pressure levels ($L_{\text{Aeq}}$). Classroom insulation was estimated using a combination of variables (e.g., fenestration, glazing, wall thickness), according to German standards (VDI 2719, 1987). Classroom reverberation time was estimated by averaging the room impulse responses measured at four positions in the classroom. In one school, classroom reverberation could not be assessed due to a recent move into a new building. The building in which the children had been instructed in the year before the study had been demolished.

**Tasks and Materials**

**Reading.** We used a standardized reading comprehension test for primary school children instructed in German (Lenhard & Schneider, 2006). The test consists of three subtests measuring reading speed and accuracy on the level of single words, sentences, and short paragraphs, respectively. For word reading, the children have to select, out of four alternatives, the word matching a picture. For sentence reading, the children have to select, out of five alternatives, the word that fits into the sentence. For text reading, the children read a short text paragraph and several statements. They have to select the statement that is consistent with the content of the paragraph. Raw scores are
the number of items correctly completed in 3 min (words and sentences) and 7 min (paragraphs). For each subtest, the children’s raw scores were transformed into standard scores given in the test’s norm tables (T-scores, norm sample mean $M = 50$, $SD = 10$). In addition, a global reading score was computed for each child by averaging the $T$-scores across subtests.

**Non-verbal abilities.** A short form of the Colored Progressive Matrices was used (Bulheller & Häcker, 2002). In this test, incomplete visual patterns are presented to the children. The children have to select the missing piece from six alternatives.

**Story comprehension.** The subtest “Auditory Memory” from the German version of the “Intelligence and Developmental Scales” (IDS; Grob, Meyer, & Hagmann-von Arx, 2009) was modified for the current study and adapted for testing in groups. A short story was read to the children. Then, the children were asked questions concerning the story content. Each question was read out aloud by the experimenter along with three response alternatives. The response alternatives were illustrated by drawings shown on a screen in front of the classroom. The children had to mark the correct answer on their response sheets.

**Rapid retrieval of phonological representations from long-term memory.** Answer sheets printed with 96 pictures of common objects (e.g., bed, dog, tree, knife) were given to the children. The task was to cross out pictures representing words with the initial phoneme /b/, and to mark all pictures representing words with another initial sound with a circle. Raw scores are the number of items correctly marked in 2 min.

**Speech perception.** Speech perception was assessed by means of a word-to-picture matching task requiring identification of noise-masked words (Klatte, Lachmann, & Meis, 2010; Klatte et al., 2007). Word identification in noise provides a more sensitive indicator of the quality of phonological representations when compared to word identification in silence (Ziegler et al., 2009). Lists of three similar-sounding German nouns were created (e.g., *Fee* [fe:], *Reh* [re:], *See* [se:]). In each trial, three pictures representing the similar-sounding words were presented to the children. Two seconds after onset of this slide, a spoken word corresponding to one of the three pictures was presented in a multitalker speech noise with an S/N of about $-4$ dB. The children had to mark the appropriate picture on prepared answer sheets.
Verbal short-term memory. Same-different judgments were required for pairs of spoken pseudowords ranging in length from three to seven syllables. In each pair, the first item was produced by a female and the second by a male voice, thus avoiding decisions being based on purely auditory–sensory matches. Responses were marked on prepared response sheets on which each trial was represented by a smiling face (“same”) and a sad face (“different”).

Phonological awareness. The children had to decide which of three spoken CVC pseudowords differed from the others with respect to the initial sound (L. Bradley & Bryant, 1983). The position of the “odd” syllable in the sequence had to be marked on prepared response sheets.

Parent questionnaire. The parent questionnaire addressed SES, migration background, main language spoken at home, number of children’s books at home, and length of residence at the current address. SES was assessed as a multidimensional score including parents’ education, professional status, current occupation, and family income (Scheuch-Winkler Index; Lampert & Kroll, 2006).

Parents’ ratings of children’s quality of life. Parents’ reports of the children’s quality of life were assessed through items from the KINDL-R (Fragebogen zur Erfassung der gesundheitsbezogenen Lebensqualität bei Kindern und Jugendlichen, Ravens-Sieberer & Bullinger, 1998). The scale “Mental Well-Being” consisted of six items (e.g., “During the last 4 weeks, my child was grumpy and bad-tempered.”). The scale “Physical Well-Being” consisted of three items (e.g., “During the last 4 weeks, my child suffered from stomach ache or head ache.”) Answers were given using 5-point rating scales ranging from “never” to “almost always.” Scale reliability (Cronbach’s α) was .77 for physical and .76 for mental well-being.

Children’s noise annoyance and well-being at school. Children’s well-being at school was assessed through a five-item scale (e.g., “I feel fine in our school”; “I like learning new things at school”). Children’s annoyance due to aircraft noise at school was assessed through a four-item scale (e.g., “When learning at school, I am bothered by aircraft noise”). Scale reliability (Cronbach’s α) was .79 for well-being and .88 for annoyance.

The statements were read aloud by the experimenter. The children marked their response on answer sheets using age-appropriate pictorial rating scales, ranging from “absolutely false” to “absolutely true” (four points).
Teacher questionnaire. The teacher questionnaires addressed sociodemographic variables (age, gender, years of service), method and quantity of reading instruction, class size, parents’ involvement in school affairs, and annoyance due to noise at school. With regard to method and quantity of reading instruction, we adapted items from an international large-scale study on reading acquisition in primary schools (“Internationale Grundschule-Leseuntersuchung” [IGLU]; Bos et al., 2010). Parents’ involvement in school was assessed through an eight-item scale (e.g., “The parents are interested in their children’s achievement”; “The parents collaborate in school projects and parents’ evenings”). Answers were given using 4-point rating scales ranging from “absolutely true” to “absolutely false.” Scale reliability (Cronbach’s α) was .87. In addition, for children with a migration background, individual ratings of proficiency in the German language were obtained from the class teachers. Teachers’ noise annoyance was assessed through a global rating of annoyance due to the presence of aircraft noise during instruction ranging from “not at all annoyed” (1) to “severely annoyed” (5), and through additional items addressing concrete effects of aircraft noise on the quality of instruction (e.g., “Due to aircraft noise, I have to interrupt my talk/the discourse for a short time”).

Procedure

Data collection was performed at the end of school year, from April to June 2012. The tests were performed in the schools in groups of whole classes. The pictures were presented via a notebook and a data projector on a screen in front of the classroom. The speech materials were presented via wireless headphones to ensure perfect signal quality at each working place in the classroom, and thus eliminate acute effects of distance from the sound source, classroom reverberation, and noise from outside. The presentation of the pictures and sounds was controlled by means of standard presentation software (Microsoft PowerPoint 2010). Each task was carefully explained to the children and practiced with examples. The experimenter and two assistants ensured that all children followed the instructions. All in all, the testing session in the classroom took about three lessons (à 45 min).

Statistical Analyses

Preliminary analyses. Classroom reverberation times (RTs) ranged from 0.39 s to 1.2 s, with $M = 0.65$ and $SD = 0.23$. For 53 classrooms (66%), RTs were below 0.7 s and thus within the range of current standards (ANSI/ASA S12.60, 2010; DIN 18041, 2004). There are no generally accepted criteria for classifying longer RTs, but studies indicate harmful effects on speech perception with
classroom RTs exceeding 1 s (Klatte, Lachmann, & Meis, 2010; Ljung, Sörvqvist, Kjellberg, & Green, 2009). These were found in nine classrooms (11%). Classroom RTs were unrelated to aircraft noise levels at school ($r = -0.15; p < .19$) and to children’s reading scores on both class and individual level (class level: $r = -0.10; p < .37$; individual level: $r = .001, p < .99$). Thus, this variable was not included in the analyses. Including reverberation would have led to exclusion of the school in which, as outlined above, reverberation could not be measured because the school moved to a new location.

Methods and quantity of reading instruction according to teachers’ reports were also excluded from the analyses, as these variables proved unrelated to aircraft noise at school (all $ps > .32$), and to each of the four reading scores (all $ps > .5$).

**Multilevel analyses.** The impact of aircraft noise exposure on children’s abilities, quality of life, and annoyance was analyzed through multilevel analyses using Mplus 7 (Muthen & Muthen, 2014). Multilevel modeling is necessary in studies with a hierarchical structure of the data (children grouped within classes) to avoid misspecifications of parameters, for example, underestimation of standard errors (Hox, 2010). We used two-level random intercept models. Aircraft noise levels were included as continuous variables. Railroad and road-traffic noise levels were included as classed variables using 10 dB and 2.5 dB steps, respectively (10 dB steps were used for railroad noise, because more than one third of the children were unexposed to this kind of noise). The unadjusted model included only aircraft noise as a predictor variable.

For the cognitive outcome variables (reading ability, story comprehension, phonological abilities), the partially adjusted model included the Level 1 variables age, gender, non-verbal abilities, SES, migration background, number of children’s books at home, and German language proficiency. In addition, the partially adjusted model included the Level 2 (class level) variables percentage of children with a migration background in the class, mean SES, class size, and parental involvement. In case of reading scores as outcome variables, story comprehension, rapid access to phonological word representations, and phonological awareness were also included as Level 1 variables (speech perception and verbal short-term memory were not included, as regression analyses showed that they accounted for less than 0.5% of variance in reading over and above the other variables, which in combination explained 38% of the variance). For children’s well-being and annoyance due to aircraft noise at school, the partially adjusted model included the Level 1 variables age, gender, and SES. In all cases, the final (fully adjusted) model was further adjusted for the Level 2 variables classroom insulation, road-traffic noise, and railway noise at school.
Concerning parents’ ratings of children’s quality of life, aircraft noise at home was used as a predictor variable, and the fully adjusted model included age, gender, SES, and road-traffic and railroad noise at home.

**Calculation of exposure–effect curves.** Means shown in the exposure–effect curves are adjusted estimates based on the multilevel model for the respective outcome variable. The means were adjusted by the predictor estimates of both hierarchical levels and the respective intercept. We assigned the classes and individuals according to their aircraft noise exposure at school and at home to 5-dB bands of exposure (range \( \leq 40 \text{ dB} \) to \( \geq 55 \text{ dB} \)) and calculated the average scores of the adjusted outcome variables for each exposure band.

Confidence intervals for averages were calculated using bootstrapping, to reproduce the characteristics of the sample more precisely than by approximation to a theoretical distribution (Efron & Tibshirani, 1986). We estimated 95% confidence intervals for 5,000 generated samples. The resulting confidence intervals are not always symmetric with respect to the adjusted means, because estimation is based on the respective sample and not on a theoretical distribution.

After calculation of the exposure–effect curve, we examined whether a linear function provides an adequate description of the relation between aircraft noise exposure and the respective outcome variable. To this end, we compared fit indicators for one- and two-degree polynomials using the Matlab R2014 curve-fitting tool. Evaluation was based on the fit indicators “sum of squares error” (SSE), “root mean squared error” (RMSE), and the degrees of freedom “adjusted \( R^2 \).” For SSE and RMSE, a value closer to zero indicates a fit that is more useful for prediction. In contrast, for the adjusted \( R^2 \), a value closer to one indicates a better fit.

**Analyses of teachers’ annoyance ratings.** Based on the distribution of aircraft noise levels at school (\( L_{A eq,08-14} \)), the teachers (\( N = 84 \)) were subdivided into three exposure groups (low: 39 to 46 dB, \( n = 32 \); medium: 48 to 53 dB, \( n = 31 \); high: 55 to 59 dB, \( n = 21 \)). Group differences were analyzed via univariate analyses of variance for global annoyance ratings, and via analyses of response frequency distributions for items addressing concrete effects of aircraft noise on instruction.

**Results**

**Aircraft Noise Exposure**

Aircraft noise levels are given in Table 1. Aircraft noise levels at school were uncorrelated with children’s SES, \( r(1,090) = -0.027, p = .37 \). Thus, the matching of schools with respect to SES was successful.
Strong correlations were found between aircraft noise at school and at home ($r = .96$, $p < .001$; see Figure 1), and between daytime and nighttime aircraft noise exposure at home ($r = .95$, $p < .001$). Due to the strength of the correlations, it was not possible in the current study to disentangle effects of aircraft noise at school from effects of aircraft noise at home, or effects of daytime noise at home from effects of noise during the night.

**Table 1.** Aircraft Noise Exposure at School and at Home.

<table>
<thead>
<tr>
<th>Exposure at school: $L_{\text{Aeq},08-14}$ (dB)</th>
<th>$M$ ($SD$)</th>
<th>$Mdn$</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daytime exposure at home: $L_{\text{Aeq},06-18}$ (dB)</td>
<td>49.39 (6.17)</td>
<td>50.00</td>
<td>40.00-60.90</td>
</tr>
<tr>
<td>Nighttime exposure at home: $L_{\text{Aeq},20-06}$ (dB)</td>
<td>44.79 (5.99)</td>
<td>45.58</td>
<td>34.1-56.60</td>
</tr>
</tbody>
</table>

**Figure 1.** Association between aircraft noise exposure at school and aircraft noise exposure at home.
Effects of Aircraft Noise on Reading and Reading-Related Verbal Abilities

Unadjusted mean scores ($T$-scores) for word reading, sentence reading, text reading, and global reading for the whole sample, and for the subsamples of children with and without a migration background are given in Table 2. For all measures, $t$ tests confirmed lower performance in children with a migration background (see Table 2).

Multilevel analyses for the whole sample revealed significant associations between aircraft noise exposure at school and decreased reading scores after full adjustment. Detrimental effects of aircraft noise were found for the global reading score, and for the subtests word reading and text reading. Full multilevel model parameters are reported in Table 3 (global reading scores). Summary parameter estimates for word reading, sentence reading, and text reading are given in Table 4. A 10 dB increase of aircraft noise at school was associated with a decrease in children’s global reading and word reading scores by one tenth of a $SD$, that is, one point on the $T$-score scale. For text reading, a 10 dB increase of aircraft noise was associated with a decrease by one eighth of a $SD$ (1.2 $T$-scale points). For sentence reading, the effect of aircraft noise did not reach significance, neither in the unadjusted model nor in the adjusted models (see Table 4). Analyses of fit indicators (SSE, RMSE, and adjusted $R^2$) confirmed that linear curves exhibited a good fit to the data (see Table S1 in the online appendices). Thus, the modeling of linear relationships in the context of multilevel models was justified. The linear exposure–effect relationship for the global reading score is depicted in Figure 2.

The same analyses were performed in subgroups of children with and without a migration background. For children with a migration background, the association between aircraft noise and decreased reading scores did not reach significance (see Table 4), but there was a tendency for an adverse

---

**Table 2.** Unadjusted Mean Reading Scores ($T$-Scores) for the Whole Sample, and for Groups of Children With and Without a Migration Background.

<table>
<thead>
<tr>
<th></th>
<th>Whole sample ($N = 1,090$)</th>
<th>Migration background ($n = 651$)</th>
<th>No migration background ($n = 439$)</th>
<th>$t$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global reading score</td>
<td>46.98 (9.04)</td>
<td>46.05 (8.67)</td>
<td>48.35 (9.39)</td>
<td>4.08</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Word reading</td>
<td>47.24 (9.52)</td>
<td>46.66 (9.54)</td>
<td>48.09 (9.43)</td>
<td>2.43</td>
<td>.015</td>
</tr>
<tr>
<td>Sentence reading</td>
<td>46.35 (9.77)</td>
<td>45.37 (9.28)</td>
<td>47.80 (10.29)</td>
<td>3.97</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Text reading</td>
<td>47.35 (9.83)</td>
<td>46.13 (9.31)</td>
<td>49.17 (10.30)</td>
<td>4.97</td>
<td>&lt;.001</td>
</tr>
</tbody>
</table>

*Note.* Standard deviations in parentheses.
### Table 3. Multilevel Model Parameter Estimates for Aircraft Noise on Children’s Reading Abilities (Global Score), for the Unadjusted, Partially Adjusted, and Fully Adjusted Model.

<table>
<thead>
<tr>
<th></th>
<th>Unadjusted model</th>
<th>Partially adjusted model</th>
<th>Fully adjusted model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>b (SE)</td>
<td>b* (SE)</td>
<td>p (b) / p (b*)</td>
</tr>
<tr>
<td><strong>Intercept</strong></td>
<td>46.92 (0.384)</td>
<td>45.97 (0.543)</td>
<td>45.94 (0.534)</td>
</tr>
<tr>
<td><strong>Aircraft noise school (Level 2)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>−0.081 (0.064)</td>
<td>−0.190 (0.156)</td>
<td>0.103 / 0.113</td>
</tr>
<tr>
<td>Level 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Age</strong></td>
<td>−0.101 (0.041)</td>
<td>−0.060 (0.024)</td>
<td>0.013 / 0.014</td>
</tr>
<tr>
<td><strong>Gender</strong></td>
<td>0.085 (0.467)</td>
<td>0.005 (0.026)</td>
<td>0.855</td>
</tr>
<tr>
<td><strong>SES household</strong></td>
<td>0.121 (0.053)</td>
<td>0.066 (0.029)</td>
<td>0.022</td>
</tr>
<tr>
<td><strong>Migration background</strong></td>
<td>1.164 (0.614)</td>
<td>0.090 (0.034)</td>
<td>0.009</td>
</tr>
<tr>
<td><strong>Language proficiency</strong></td>
<td>1.686 (0.337)</td>
<td>0.146 (0.030)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td><strong>Number of children’s books</strong></td>
<td>0.663 (0.206)</td>
<td>0.097 (0.030)</td>
<td>.001</td>
</tr>
<tr>
<td><strong>Non-verbal abilities</strong></td>
<td>0.583 (0.218)</td>
<td>0.066 (0.025)</td>
<td>.007 / .008</td>
</tr>
<tr>
<td><strong>Story comprehension</strong></td>
<td>1.094 (0.191)</td>
<td>0.124 (0.022)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td><strong>Access to phonological representations</strong></td>
<td>3.116 (0.280)</td>
<td>0.355 (0.030)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td><strong>Phonological awareness</strong></td>
<td>2.018 (0.241)</td>
<td>0.227 (0.027)</td>
<td>&lt;.001</td>
</tr>
</tbody>
</table>

(continued)
Table 3. (continued)

<table>
<thead>
<tr>
<th></th>
<th>Unadjusted model</th>
<th>Partially adjusted model</th>
<th>Fully adjusted model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ICC = 0.081</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>b (SE)</td>
<td>b* (SE)</td>
<td>p (b / p (b*))</td>
</tr>
<tr>
<td>Level 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SES</td>
<td>-0.165 (0.210)</td>
<td>-0.217 (0.270)</td>
<td>0.431 / 0.422</td>
</tr>
<tr>
<td>Class migration background</td>
<td>-2.349 (2.205)</td>
<td>-0.295 (0.267)</td>
<td>-1.805 (2.136)</td>
</tr>
<tr>
<td>Class size</td>
<td>0.123 (0.108)</td>
<td>0.178 (0.152)</td>
<td>0.255 / 0.241</td>
</tr>
<tr>
<td>Parental involvement</td>
<td>0.219 (0.680)</td>
<td>0.062 (0.192)</td>
<td>0.747 / 0.746</td>
</tr>
<tr>
<td>Classroom insulation</td>
<td>0.009 (0.038)</td>
<td>0.037 (0.155)</td>
<td>0.809</td>
</tr>
<tr>
<td>Road-traffic noise at school</td>
<td>-0.270 (0.149)</td>
<td>-0.285 (0.157)</td>
<td>0.070</td>
</tr>
<tr>
<td>Railroad noise at school</td>
<td>0.320 (0.342)</td>
<td>0.138 (0.148)</td>
<td>0.349 / 0.351</td>
</tr>
<tr>
<td>R²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level 1 (within level)</td>
<td>.441</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level 2 (between level)</td>
<td>.036</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note. ICC = intraclass correlation; SE = standard error; b* = standardized regression coefficient; SES = socioeconomic status.
### Table 4. Multilevel Model Parameter Estimates for Effects of Aircraft Noise at School on Children’s Reading Scores for the Whole Sample, and Subsamples of Children With and Without a Migration Background.

**Whole sample (N = 1,090)**

<table>
<thead>
<tr>
<th></th>
<th>Unadjusted model</th>
<th>Partially adjusted model</th>
<th>Fully adjusted model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>b (SE) p (b)</td>
<td>b (SE) p (b)</td>
<td>b (SE) p (b)</td>
</tr>
<tr>
<td><strong>Word reading</strong></td>
<td>-0.086 (.071) .112</td>
<td>-0.120 (.062) .027</td>
<td>-0.105 (.064) .049</td>
</tr>
<tr>
<td></td>
<td>(0.071)</td>
<td>(0.062)</td>
<td>(0.064)</td>
</tr>
<tr>
<td><strong>Sentence reading</strong></td>
<td>-0.058 (.069) .201</td>
<td>-0.077 (.056) .086</td>
<td>-0.064 (.056) .125</td>
</tr>
<tr>
<td></td>
<td>(0.069)</td>
<td>(0.056)</td>
<td>(0.056)</td>
</tr>
<tr>
<td><strong>Text reading</strong></td>
<td>-0.097 (.064) .064</td>
<td>-0.109 (.045) .008</td>
<td>-0.118 (.045) .005</td>
</tr>
<tr>
<td></td>
<td>(0.064)</td>
<td>(0.045)</td>
<td>(0.045)</td>
</tr>
</tbody>
</table>

**Children with a migration background (n = 651)**

<table>
<thead>
<tr>
<th></th>
<th>Unadjusted model</th>
<th>Partially adjusted model</th>
<th>Fully adjusted model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>b (SE) p (b)</td>
<td>b (SE) p (b)</td>
<td>b (SE) p (b)</td>
</tr>
<tr>
<td><strong>Global score</strong></td>
<td>-0.036 (.069) .302</td>
<td>-0.061 (.059) .152</td>
<td>-0.057 (.062) .179</td>
</tr>
<tr>
<td></td>
<td>(0.069)</td>
<td>(0.059)</td>
<td>(0.062)</td>
</tr>
<tr>
<td><strong>Word reading</strong></td>
<td>-0.040 (.083) .313</td>
<td>-0.079 (.076) .151</td>
<td>-0.062 (.079) .218</td>
</tr>
<tr>
<td></td>
<td>(0.083)</td>
<td>(0.076)</td>
<td>(0.079)</td>
</tr>
<tr>
<td><strong>Sentence reading</strong></td>
<td>-0.010 (.073) .448</td>
<td>-0.030 (.064) .316</td>
<td>-0.021 (.065) .376</td>
</tr>
<tr>
<td></td>
<td>(0.073)</td>
<td>(0.064)</td>
<td>(0.065)</td>
</tr>
<tr>
<td><strong>Text reading</strong></td>
<td>-0.054 (.064) .200</td>
<td>-0.072 (.056) .099</td>
<td>-0.090 (.059) .065</td>
</tr>
<tr>
<td></td>
<td>(0.064)</td>
<td>(0.056)</td>
<td>(0.059)</td>
</tr>
</tbody>
</table>

(continued)
<table>
<thead>
<tr>
<th></th>
<th>Unadjusted model</th>
<th>Partially adjusted model&lt;sup&gt;d&lt;/sup&gt;</th>
<th>Fully adjusted model&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( b ) (( SE ))</td>
<td>( p ) (( b ))</td>
<td>( b ) (( SE ))</td>
</tr>
<tr>
<td>Global score</td>
<td>-0.151 (0.095)</td>
<td>.057</td>
<td>-0.153 (0.071)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-0.142 (0.075)</td>
</tr>
<tr>
<td>Word reading</td>
<td>-0.170 (0.098)</td>
<td>.041</td>
<td>-0.187 (0.081)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-0.172 (0.087)</td>
</tr>
<tr>
<td>Sentence reading</td>
<td>-0.133 (0.105)</td>
<td>.102</td>
<td>-0.132 (0.084)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-0.109 (0.088)</td>
</tr>
<tr>
<td>Text reading</td>
<td>-0.151 (0.097)</td>
<td>.060</td>
<td>-0.140 (0.068)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-0.144 (0.072)</td>
</tr>
</tbody>
</table>

<sup>a</sup>Adjusted for age, gender, SES, migration background, German language proficiency, number of children’s books, non-verbal abilities, story comprehension, phonological awareness, access to phonological representations, class socioeconomic status (SES), class size, percentage of children with a migration background, parental involvement in school affairs.

<sup>b</sup>Further adjusted for classroom insulation, road-traffic noise, and railroad noise at school.

<sup>c</sup>Adjusted for age, gender, SES, German language proficiency, number of children’s books, non-verbal abilities, story comprehension, phonological awareness, access to phonological representations, class SES, class size, percentage of children with a migration background, parental involvement in school affairs.

<sup>d</sup>Adjusted for age, gender, SES, number of children’s books, non-verbal abilities, story comprehension, phonological awareness, access to phonological representations, class SES, class size, percentage of children with a migration background, parental involvement in school affairs.
Effect of aircraft noise on text reading after full adjustment ($p < .065$). For children without a migration background, a 10 dB increase in aircraft noise exposure was associated with a decrease in reading performance by 1.4 points on the $T$-score scale (one seventh of a $SD$) for global reading and text reading, and by 1.7 points (one sixth of a $SD$) for word reading.

In the reading test used here, one tenth of a $SD$ corresponds to about 1 month of reading instruction. Thus, in terms of learning time, a 10 dB increase in aircraft noise is associated with a reading delay of about 1 month for the whole sample, and of about 1.5 months for the subsample of children without a migration background.

Multilevel analyses of story comprehension and phonological processing abilities, that is, phonological awareness, rapid access to phonological long-term representations, short-term memory, and speech perception as outcome variables yielded no significant effects of aircraft noise, neither in the partially nor in the fully adjusted models (all $p$s $\geq .08$). Summary multilevel model parameter estimates are provided in Table S2 (online appendices).

**Effects of Aircraft Noise on Children’s Quality of Life and Annoyance**

Unadjusted means for parents’ ratings of children’s physical and mental well-being were $M = 4.15$ ($SD = 0.75$) and $M = 3.79$ ($SD = 0.60$), respectively.
Thus, overall, the parents’ judgments of the children’s quality of life are pleasingly positive (maximum score 5). Children’s ratings of well-being at school (maximum score 4) were also positive overall, with average ratings $M = 3.27 (SD = 0.79)$. However, for each of these variables, multilevel analyses revealed significant associations between aircraft noise exposure and less positive ratings after full adjustment. Multilevel model parameters are given in Table 5 (physical and mental well-being) and Table 6 (well-being at school).

Inspection of fit indicators confirmed that linear exposure–effect curves exhibited a good fit to the data (see Table S1, online appendices). For physical well-being, mental well-being, and well-being at school, a 10 dB increase in aircraft noise levels was associated with a decrease of 0.12, 0.10, and 0.13 points on the rating scales, respectively. For each of the three scales, this

<table>
<thead>
<tr>
<th>Table 5. Multilevel Model Parameter Estimates for Effects of Aircraft Noise at Home on Parents’ Ratings of Children’s Quality of Life.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Physical well-being</td>
</tr>
<tr>
<td>Mental well-being</td>
</tr>
</tbody>
</table>

$^a$Adjusted for age, gender, and SES.
$^b$Adjusted for age, gender, SES, road-traffic noise, and railroad noise at home.

<table>
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<tbody>
<tr>
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<tr>
<td></td>
</tr>
<tr>
<td>Well-being at school</td>
</tr>
<tr>
<td>Annoyance due to aircraft noise at school</td>
</tr>
</tbody>
</table>

Note. SES = socioeconomic status.
$^a$Adjusted for age, gender, and SES.
$^b$Adjusted for age, gender, SES, classroom insulation, road-traffic noise, and railroad noise at school.
corresponds to a decrease of one sixth of a $SD$. The linear exposure–effect relationship for children’s mental well-being is depicted in Figure 3.

The unadjusted mean of children’s annoyance due to aircraft noise at school was $M = 1.75$ ($SD = 0.89$). Increasing aircraft noise was significantly associated with increasing annoyance responses in children (see Table 6). Again, there was no departure from linearity. A 10 dB increase in aircraft noise was associated with an increase of 0.5 points on the 4-point rating scale, corresponding to an increase of 0.6 $SD$.

**Teachers’ Noise Annoyance Responses**

The teachers in the three exposure groups (low: 39 to 46 dB $L_{Aeq,08-14}$; medium: 48 to 53 dB $L_{Aeq,08-14}$; high: 55 to 59 dB $L_{Aeq,08-14}$) did not differ in respect to age and years of teaching experience (both $F < 1$). Mean ratings of annoyance due to aircraft noise at school in teachers from low, medium, and highly exposed schools were $M = 1.26$ ($SD = 0.44$), $M = 2.68$ ($SD = 1.01$), and $M = 4.52$ ($SD = 0.75$), respectively. Analyses of variance confirmed significant differences between groups, $F(2, 80) = 111.55; p < .001$, $\eta_p^2 = .74$. Bonferroni-corrected post hoc tests revealed significant differences between the groups (low < medium < high, all $ps < .001$). Out of 21 teachers from the
highly exposed schools, 20 (95%) reported high or severe annoyance due to the presence of aircraft noise during instruction. The ratings were strongly correlated with aircraft noise levels at school, \( r(83) = .85; p < .001 \).

Inspections of single items addressing concrete effects of aircraft noise on instruction showed that, out of 21 teachers from highly exposed schools, 11 (52%) reported frequent interruptions of classroom discourse and observable distractions of the children due to aircraft noise, 18 (86%) reported keeping the windows closed even in warm weather due to aircraft noise, and 8 (38%) confirmed the statement “Due to the aircraft noise, I undertake fewer outdoor activities with the children.” In the less exposed groups, frequent interruptions of discourse, distractions of the children, or fewer outdoor activities due to aircraft noise were reported by just one out of 63 teachers (2%), and six teachers (10%) reported keeping the windows closed. For each item, the group differences in response frequencies were significant—interruptions of discourse: \( \chi^2(8, N = 84) = 56.47, p < .001 \); observable distractions of the children: \( \chi^2(8, N = 84) = 56.53, p < .001 \); keeping windows closed: \( \chi^2(6, N = 84) = 61.55, p < .001 \); fewer outdoor activities: \( \chi^2(6, N = 84) = 36.02, p < .001 \).

**Discussion**

In the current study, the effects of aircraft noise on reading, reading-related verbal abilities, and quality of life and annoyance were assessed in second graders living in the vicinity of Frankfurt/Main Airport in Germany. Noise exposure at school and at home was calculated on the basis of radar data for each individual child for a period of 12 months before data acquisition. In view of the reliable association between SES and both aircraft noise exposure and children’s academic achievement and health, special care was taken to avoid confounding of SES- and noise-induced effects. Schools were matched according to SES, and potentially confounding variables on both individual level and class level were assessed and included in the statistical analyses.

Multilevel analyses revealed linear exposure–effect associations between aircraft noise exposure and children’s reading, well-being at school, physical and mental well-being, and annoyance after full adjustment. When discussing these results, it has to be kept in mind that children’s aircraft noise exposure at school did not exceed 59 dB and was thus considerably lower when compared with prior studies. For example, in the RANCH study (Stansfeld et al., 2005), aircraft noise levels at school reached 77 dB (\( L_{\text{Aeq,06-23}} \)), and in the Munich study (Hygge et al., 2002) schools with aircraft noise levels of 59 dB (\( L_{\text{Aeq,24h}} \)) were included as “unexposed” controls (see Hygge et al., 2002, Table 1).

With regard to reading, a 20 dB increase in aircraft noise exposure was associated with a decrease in global reading scores of one fifth of a SD. In the
RANCH study, a 20 dB increase in exposure was associated with a decrease in reading performance of one fifth of a $SD$ in the United Kingdom, and by one eighth of a $SD$ in the Netherlands and Spain (Clark et al., 2006; Stansfeld et al., 2005). Thus, despite considerable differences in exposure levels, the effect found in the current study is similar to that found in RANCH.

The effect of aircraft noise on reading did not reach significance in the subsample of children with a migration background. This result is in line with a recent South African study, in which significant detrimental effects of aircraft noise at school on children’s reading were found in children with English as a first language, but not in children with English as a second language (Seabi et al., 2012). According to the authors, the differential effects might result from high noise exposure at home in the control group of second-language learners. For the current study, this account seems unlikely in view of the high correlation between noise exposure at school and at home. In our view, the non-significant effect for migrant children is best explained as a problem of statistical power, due to an accumulation of risk factors for reading acquisition in this group. In line with investigations on educational opportunities of migrant children in Germany (Schwippert et al., 2012), our study confirmed lower SES and a less stimulating home literacy environment (indicated by number of children’s books at home) in migrant children when compared with children without a migration background ($t$ tests, both $p < .001$). In addition, according to teachers’ ratings, 47% of the migrant children exhibited occasional difficulties in following instruction due to a lack of proficiency in the language of instruction. Severe language deficits were reported for 31% of the children. Due to these unfavorable conditions, the comparably small additional effect of aircraft noise on reading might be difficult to verify statistically. As shown in Table 4, for all reading scores, the association with aircraft noise was in the same direction for children with and without a migration background. For text reading, the analysis revealed a clear tendency for an adverse effect of aircraft noise in the migrant children ($p = .065$).

In terms of learning time, a 20 dB increase in aircraft noise was associated with a 2-months delay for the whole sample, and with a 3-months delay in the subsample of non-migrant children. Thus, in the current study, the most exposed children lag 2 to 3 months behind their least exposed peers. For evaluation of the noise effect, it might be helpful to consider the impact of other factors on reading. Simple group comparisons revealed a 6-month difference in reading development between children with low versus high SES (according to a standard classification of the unadjusted SES scores, see Lampert & Kroll, 2006), and an 8-month difference between children with few versus plenty of books at home. Even though these findings indicate that SES and home literacy have a much stronger impact on reading
when compared with aircraft noise, this does not mean that the noise effect is negligible. High noise exposure is usually associated with a range of other risk factors (Evans, 2004), which may interact in a hitherto unknown way. In addition, nothing is known concerning long-term effects. For the vast majority of our participants, exposure to aircraft noise will endure or even increase due to increasing air traffic. To the best of our knowledge, there is only one study addressing long-term effects of aircraft noise exposure during the primary grades. This study (Clark, Head, & Stansfeld, 2013) provides a 6-year follow-up of the U.K. sample of the RANCH study. No significant effects on reading performance in secondary school were found for aircraft noise in primary school, aircraft noise in secondary schools, and cumulative aircraft noise exposure in primary and secondary schools. However, as stated by the authors, this result is inconclusive due to severe attrition and, as a consequence, a lack of statistical power. Further longitudinal studies are needed to assess whether the adverse effects of aircraft noise are compensated, diminished, or further increased in the later grades. From a theoretical perspective, relatively small delays in acquiring basic reading functions may have harmful effects on later reading comprehension, because basic reading abilities provide the foundation for skilled word recognition (Frith, 1985; Share, 1995; Ziegler, Perry, & Zorzi, 2014).

In the current study, no effect of aircraft noise was found for auditory-verbal precursors of reading acquisition, that is, phonological processing and listening comprehension. Thus, we found no evidence for the assumption that the association between aircraft noise and reading is mediated by direct effects on verbal precursors of reading. However, we cannot completely rule out a mediating role of these functions for two reasons. First, even small impairments in phonological functions may have harmful effects on reading, and our paper-and-pencil group tests might not be sensitive enough to detect such tiny effects. Future studies addressing this question should include computerized individual testing. In RANCH, no effect of aircraft noise exposure on children’s selective attention was evident with a paper-and-pencil group test (Stansfeld et al., 2005), whereas with individual computerized testing, a significant detrimental effect of noise was found (van Kempen et al., 2010). Second, reading does not only require accurate operation of a range of basic functions, but also their adaptation and coordination (for review, see Lachmann, 2002). Thus, even if these functions operate efficiently in isolation, a deficit in the functional coordination will have harmful effects on reading.

In the current study, teachers from highly noise-exposed schools consistently reported severe disruptions of school lessons due to interruptions of discourse and noticeable distractions of the children due to aircraft noise.
The strong correlation between teachers’ ratings and aircraft noise levels at school underpin the validity and seriousness of the teachers’ judgments. These findings are in line with results from the RANCH project, where detrimental effects of aircraft noise and road-traffic noise on student communication, concentration, performance, and quality of work were reported by the teachers (Clark, Lopez Barrio, van Kamp, van Kempen, & Stansfeld, 2014). Such impairments are especially unfavorable for primary school children. The ability to control attention improves until the teenage years, and young children exhibit difficulties redirecting attention back to the task after interruptions (Pozuelos, Paz-Alonso, Castillo, & Rueda, 2014). In addition, young children are less able than older children and adults to understand speech in noisy conditions (Klatte, Lachmann, & Meis, 2010; Talarico et al., 2007). From the viewpoint of educational psychology, efficient utilization of lesson time is an important criterion for instructional quality (Schacter & Thum, 2004; Schrader et al., 2008). Teachers’ reports indicate that, under conditions of aircraft noise, part of the lesson time is lost. The reduction of instructional quality due to aircraft noise might contribute to the negative associations between aircraft noise and children’s reading found in the current and in prior studies. It should be kept in mind that disruptions of instruction due to aircraft noise are not confined to reading instruction, but are present throughout the teaching time. Thus, in addition to reading, future studies should include other domains of academic performance, such as spelling and math.

Aircraft noise was significantly associated with lower ratings of children’s mental and physical well-being and well-being at school. Because the ratings were pleasingly positive overall, and the effects of aircraft noise exposure were small, these findings might appear negligible. However, it has to be kept in mind that the children were only about 8 years old at the time of testing and, due to a lack of longitudinal studies, nothing is known about long-term effects under conditions of enduring or even increasing exposure.

Increasing aircraft noise was significantly associated with increasing annoyance responses in children. The significant correlation between children’s ratings and aircraft noise levels at school confirms that children as young as 8 years old are able to give valid judgments of environmental quality. About 40% of the children from the most exposed schools (≥55 dB) reported feeling disturbed by aircraft noise while learning at school. Regarding exposure–effect relationships for children’s annoyance, a curvilinear function was found in RANCH, with a steeper exposure-response gradient at aircraft levels above 60 dB. This finding is in line with the linear curve found in the current study, because in our sample exposure levels did not exceed 60 dB.
Both in the current study and in the RANCH study, aircraft noise exposure at school and at home were highly correlated. This results from the fact that children’s primary schools are generally located nearby their homes. Thus, as a rule, primary school children who are exposed to aircraft noise at school are also exposed to daytime and nighttime aircraft noise at home, that is, they have little opportunity to recover. Due to the high correlations, the question whether noise at school, noise at home, nighttime noise, or a combination of these variables is responsible for the detrimental effects on children’s reading and quality of life is difficult to answer empirically.

Limitations and Conclusions

In the current study, detrimental effects of aircraft noise exposure were found for children’s reading and quality of life with exposure levels not exceeding 60 dB $L_{Aeq}$. Special care was taken to rule out potential confounders such as SES and children’s proficiency in the language of instruction. Despite considerable differences in exposure levels, orthography, and age groups, the effect on reading found in the current study is comparable to that found in RANCH. This consistency provides strong evidence for a causal, linear association between aircraft noise exposure and decreasing reading performance in children.

As schools exposed to high levels of road-traffic noise, railroad noise, or other noise sources were excluded, we cannot draw any conclusions concerning effects of combined noise sources. In addition, air pollution was not considered in the current study. Even though a follow-up study in the U.K. RANCH (Clark et al., 2012) cohort yielded no evidence for detrimental or moderating effects of traffic-related air pollutants, further studies including a wider range of air pollution are needed. Furthermore, we did not analyze potential mediating effects of the quality of children’s home environments. In addition, as outlined above, this study is cross-sectional and does not provide any information concerning long-term effects under conditions of enduring or increasing exposure. Despite these limitations, this study provides further evidence for negative effects of aircraft noise on children’s development, and is thus of relevance for policies concerning noise and child health.

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