Effects of noise and reverberation on speech perception and listening comprehension of children and adults in a classroom-like setting

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Abstract

The effects of classroom noise and background speech on speech perception, measured by word-to-picture matching, and listening comprehension, measured by execution of oral instructions, were assessed in first- and third-grade children and adults in a classroom-like setting. For speech perception, in addition to noise, reverberation time (RT) was varied by conducting the experiment in two virtual classrooms with mean RT = 0.47 versus RT = 1.1 s. Children were more impaired than adults by background sounds in both speech perception and listening comprehension. Classroom noise evoked a reliable disruption in children´s speech perception even under conditions of short reverberation. RT had no effect on speech perception in silence, but evoked a severe increase in the impairments due to background sounds in all age groups. For listening comprehension, impairments due to background sounds were found in the children, stronger for first- than for third-graders, whereas adults were unaffected. Compared to classroom noise, background speech had a smaller effect on speech perception, but a stronger effect on listening comprehension, remaining significant when speech perception was controlled. This indicates that background speech affects higher-order cognitive processes involved in children´s comprehension. Children´s ratings of the sound-induced disturbance were low overall and uncorrelated to the actual disruption, indicating that the children did not consciously realize the detrimental effects. The present results confirm earlier findings on the substantial impact of noise and reverberation on children´s speech perception, and extend these to classroom-like environmental settings and listening demands closely resembling those faced by children at school.

Keywords: Children, classroom acoustics, listening comprehension, noise, reverberation, speech perception

DOI: 10.4103/1463-1741.70506

Introduction

The present study investigates the effects of reverberation and noise on speech perception and listening comprehension in children and adults in an everyday-like setting. In professional educational settings such as schools, preschool facilities and other learning environments, information is predominantly presented orally to the learner. Thus, listening is an important precondition for successful learning, and the acoustic conditions under which instruction takes place play a major role in learning facilitation. This is especially true for younger pupils, as the ability to recognize speech under adverse listening conditions does not reach adult levels until the teenage years. Consequently, the issue of classroom acoustics has gained much interest in recent years.[1-3]

The major determinant of room acoustics is reverberation time (RT). RT is the time in seconds required for sound pressure at a specific frequency to decay 60 dB after the sound source has stopped. Long RTs reduce the clarity of the speech and thereby intelligibility. This is because the speech signals reaching a listener are a mixture of direct energy and time-delayed reflections. In addition, when RTs are too long, undesired sounds (such as moving chairs or scraping feet) remain longer in the room and consequently, noise levels increase.

Current standards in the United Kingdom, Germany and the United States, as well as the World Health Organization (WHO) guideline values for schools[4] explicitly recommend that RTs do not exceed 0.6 seconds for classrooms with a volume of about 250 m^3, and that ambient noise levels in the empty rooms do not exceed 35 dB(A).[2,3,5] However, these guidelines are often neglected when schools are built or reconstructed, and teaching and learning often takes place in reverberant and noisy classrooms.[2,3,6-8]

Psychoacoustic studies have shown that children are more affected by unfavorable acoustic conditions than adults.[1,9-12]

Most of these studies were conducted in laboratory settings and focused on effects of noise and reverberation on speech perception, as assessed through identification of single words or syllables. In general, it was found that young children's performance in such tasks does not differ much from that of adults if the signals are presented in silence and without reverberation. In contrast, if the signals are distorted through noise and/or reverberation, performance is worse in children as compared to that of adults.

During school lessons, however, the listening tasks faced by the children are much more complex, as they involve not only identification, but also short-term storage and mental processing of the spoken information. There is evidence that noise and reverberation may affect such higher-order cognitive functions involved in comprehension. Studies with adults have shown that even under conditions of perfect intelligibility of the speech signals, background sounds and reverberation impair memory for spoken items,[13-16,46,47] listening comprehension,[17] and memory for spoken lectures.[48] Similar effects were reported for elementary school children.[18] These effects have been attributed to a reduction of the cognitive resources available for storage and processing of the information due to increased listening effort,[13,46] or to the background sounds specific interference with short-term memory representations ("Irrelevant Sound Effect" [16]). Thus, perfect speech intelligibility does not exclude noise-induced impairments in complex listening tasks, such as those faced by children during school lessons. Taking together these issues, it seems obvious that experimental research exploring the effects of noise and reverberation under conditions which closely resemble those given in actual classroom settings is needed to understand the impact of acoustic factors on school learning, and helps to assess the cost-benefit ratio of acoustic improvements in schools.

There is some evidence that children's performance in complex tasks is more impaired by speech noise when compared to non-speech sounds. This has been shown for listening tasks and for tasks involving storage and processing of visually presented items.[18] In the current study, the effects of background speech (female voice reading a newspaper article) and classroom noise without speech on speech perception and listening comprehension were investigated in two virtual classrooms in first- and third-grade children and adults. The virtual classrooms simulated the RTs of a real elementary school classroom before and after acoustic renovation. Thus, one of the virtual rooms had good and one had poor interior acoustics according to the German Industry Norm DIN 18041 (2004).[5] It was hypothesized that children are more affected than adults by adverse listening conditions, and that impairments in a complex listening task occur even under conditions of high speech intelligibility.

Experiments

Method

Tasks and materials

Tasks: The experimental tasks described below are modified versions of tasks used in prior studies in which the first author was involved.[1,18]

Speech perception was assessed by means of a word-to-picture matching task requiring discrimination between similar sounding words. Twelve lists of three similar-sounding common and concrete German nouns were created (e.g., *Fee* [fe:], *Reh* [re:], *See* [se:]). Each item was represented by a simple and easy-to-name picture. In each trial, three pictures representing the similar-sounding words were presented to the participants. Two seconds after onset of this slide, a spoken word corresponding to one of the three objects was presented. The participants had to mark the appropriate picture on the prepared answer sheets. Two parallel versions of the task were created which differed only in the order of the items. In each sound condition, 24 items were presented. Prior to the task, all pictures were shown to the participants and named by the experimenter.

Listening comprehension was assessed by means of execution of complex oral instructions. This is a task which is used in most of the standardized tests of language comprehension in Germany.[19,20] For the present experiments, a paper and pencil version of this kind of task was constructed. Complex oral instructions were presented to the participants (e.g., "Put a cross under the book that lies next to the chair"). The task was to carry out the instructions on prepared response sheets on which, for each instruction, a row with an arrangement of small black-and-white drawings, representing the target objects and distractor stimuli, was depicted. The answer sheets were available to the participants throughout the task. Participants were thus free to prepare execution of the instructions concurrent to their presentation. After offset of the instruction, 18 seconds were given to complete the entries on the response sheets.

Scoring was based on the number of elements correctly executed according to the given instruction. This was realized by means of an *a priori* constructed manual providing unequivocal scoring rules for each individual item.[20] For each age group, two parallel versions of this task with different, but formally similar instructions were constructed. Pilot studies ensured equal difficulty of the parallel test versions and equal task difficulty across the age groups. The latter resulted in longer and more complex instructions for adults as compared to children. Since the instructions were accompanied by background sounds, adults were also longer exposed to a higher "dose" of irrelevant sounds. However, as we expected stronger background noise effects for children, this works against our hypothesis.

Disturbance ratings: Noise-induced disturbance during task performance was rated in adults by means of a 5-point category scale. Participants had to complete the sentence "My performance in this task was […] by the background sound" with one of five response alternatives reaching from "not at all disturbed" to "most disturbed". For the children, a scale with smileys was constructed which differed in the form of the mouth.

Sounds

Speech signals: The words and instructions were read by a professional male speaker in a sound-attenuated laboratory and recorded with an artificial head system (Cortex MK2) with a sampling rate of 44.100 Hz and 16-Bit-resolution.

Background sounds: Performance was measured during silence and two different sound conditions: background speech, and classroom noise without speech. The background speech consisted of a Danish newspaper article read by a professional female Danish speaker. The record contained no reverberation and no remarkable changes in loudness and intonation. The classroom noise without speech contained typical classroom sounds such as moving chairs, scraping feet, coughing, leafing through papers, rattling with writing utensils and opening and closing school bags. The record was produced in a sound-attenuated laboratory room equipped with school furniture with assistance of 12 children and adults using an artificial head system (Cortex MK2).

Sound editing: The speech signals were mixed binaurally with the background sounds.

For the speech perception task, each word was mixed with a 3-second episode of the background sounds such that word onset was 1 second after onset of the background sound. For the sentence comprehension task, the background sounds started 1 second before onset of the instructions and endured until the end of the 18 seconds execution phase.

Experimental setup

Variation of reverberation times

The experiment was performed in a special laboratory room (volume 249 m^3) at the Hearing Research Centre of the University of Oldenburg. The room is equipped with an acoustic system which allows presentation of ambient sounds by means of eight loudspeakers, and variation of RTs by means of the "Variable Room Acoustics System" (VRAS) (LCS). VRAS is an electronic regenerative system for enhancing the natural acoustics of a room. It provides early as well as lateral and late (diffuse) acoustic energy enhancement. Reverberation (late/diffuse) enhancement increases envelopment and immerses the listeners in the performance. Twelve cardioid pattern microphones (AKG CK33) pick up the natural reverberant field of the room. With a special reflective algorithm, the sound is processed and the energy enhancements are distributed to 12 loudspeakers (Fohn Direct-1). Both microphones and speakers are hidden behind permeable ceiling material. To evenly pick up and distribute the sound, the speakers and microphones are spread in a 3 × 4 pattern in the reverberant field of a so called "action area" (6 × 8 m). This provides for a coupling of the entire room and preserves the global property of reverberation in the enhanced space. The tuning of the system included the adjustment of numerous parameters, such as the density of the reflections, the fraction of direct sound, the frequency response, and the delay ratio of the different channels, which define the RT, early decay time, clarity and other typical room acoustic parameters.

For the simulation of the virtual classrooms, the room acoustic parameters of a real, middle-sized classroom (volume 230 m^3) were measured before and after acoustic renovation and reconstructed with a set of tuning procedures. The RTs of the two virtual classrooms are depicted in Figure 1.

One of the virtual classrooms, in the following termed as "favorable room", had a mean RT of $T_{30\ (250\ \mathrm{Hz}–2\ \mathrm{kHz})} = 0.47$, representing optimal interior acoustics according to current standards (e.g., DIN 18041, 2004). The other virtual classroom, in the following termed as "unfavorable room", had a mean RT of $T_{30\ (250\ \mathrm{Hz}–2\ \mathrm{kHz})} = 1.10$, which is about twice as high as the values recommended in current guidelines. Note that classrooms with RTs of more than 1 second are not rare in elementary schools.[1,21,22] The values of the speech transmission index (STI) were also reconstructed. The STI values ranged in the favorable room from 0.57 to 0.67 (rated as "fair" to "good" according to ISO 9921), depending from the sender-receiver position in the room. In the favorable room, the STI values varied from 0.72 to 0.78, rated as "excellent" according to ISO 9921.

Sound presentation

Three rows, the first with four and the second and third with six working places, were arranged in the experimental

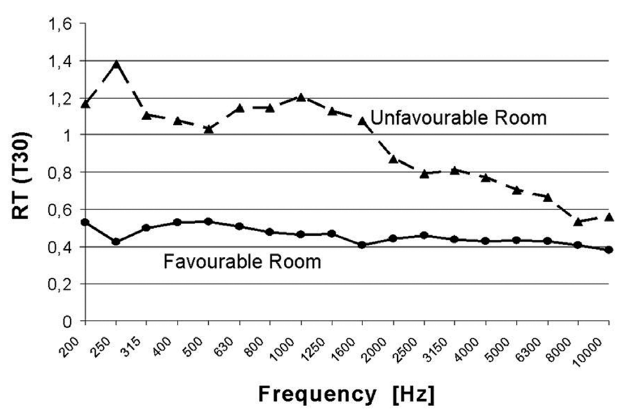

Figure 1: RTs ($T_{30\ (250\ \mathrm{Hz}–2\ \mathrm{kHz})}$) in the virtual classrooms. The settings are based on measurements in a classroom of an elementary school before and after the installation of sound-absorbing materials.

room. The speech signals were presented via a loudspeaker (Omnisource 4295, Brüel and Kjær) located in front of the room, with a height of 165 cm and a distance of 3, 6 and 9 m from the first, the second and the third seat rows, respectively. Signal level was set to 66 dB(A) at 1 m distance from the sound source, in order to simulate a teacher speaking with a raised voice.

Noise and signal levels were measured at each working place by means of a Brüel and Kjær sound level meter (2260 Investigator). Sound levels (Laeq, 20 seconds) and signal-to-noise ratios (SNRs), measured at the middle seat position in each row, are given in Table 1.

Just as in real classroom settings, there was a slight increase in noise level and a decrease in signal level with increasing seat row. There were no measurable differences in noise and signal levels between working places within a row of seats. As a result of reverberation, noise levels were about 3 dB higher in the unfavorable room. The level of the speech signal was only marginally affected by reverberation. Thus, SNRs were about 3 dB worse at each working place in the unfavorable room. In view of prior findings, the present range of SNRs can be counted as typical for elementary school classrooms.[2,6]

Table 1: Noise levels (L_{Aeq}, 20 seconds) and SNR with respect to background noise and tier in the experimental room

Room	Background speech				Classroom noise			
	Favorable		Unfavorable		Favorable		Unfavorable	
Seat row	Noise Level	SNR	Noise Level	SNR	Noise Level	SNR	Noise Level	SNR
First	53	3	56	0	52	4	56	0
Second	55	0	57	-3	54	1	57	-3
Third	55	-3	59	-6	55	-3	59	-6

Design and procedure

For speech perception, the effects of reverberation (favorable vs. unfavorable room) and noise were assessed in each of the three age groups. For listening comprehension, the effects of noise were assessed in each age group, but reverberation was not varied. The listening task was only performed in the favorable room because children's speech perception in noise in the unfavorable room was found to be so poor (see the section on Results) that potential effects on higher-order cognitive processes involved in comprehension would have been masked by difficulties to encode the information.

Reverberation was varied between subjects. The respective room settings were active during the whole experimental session. In the respective reverberation condition, each participant performed one block of each task in silence and one block in the presence of either background speech or classroom noise. In each age group, the order of blocks was counterbalanced across the participants. For each task, disturbance ratings were assessed immediately after the block of trials in noise was completed.

Paperboards were placed between adjacent seats in order to ensure that the participants could not see their neighbors' answer sheets. The presentation of the pictures and sounds was controlled by a notebook using standard presentation software. The graphics were presented on a screen in front of the room via a projector located outside the room.

Each task was carefully explained to the participants and practiced with examples.

Before a block with background sound was started, this sound was introduced to the participants for 30 seconds. Instruction was given to ignore the sound as irrelevant and to focus attention on the task. Each experimental trial started with an acoustic signal sounding like a gong, presented for 1100 ms.

Testing was performed in groups with 6–14 participants. Care was taken to ensure that in each of the sound groups (background speech vs. classroom noise), the children and adults were assigned to analogous seat positions such that noise and signal levels were kept constant across the age groups. In conditions where the number of participants differed with age, the proportion of participants assigned to the third seat row was lower in the children than in the adults. Consequently, the hypothesized age differences in the effects of the sound conditions are, if anything, underestimated.

When children performed the experiment, the conductor was assisted by two students who took care that the children used the correct answer sheet and entered their answer in the correct line. One block of trials took about 6–7 minutes to perform. The blocks were separated by a break. All the children managed to remain silent while performing the tasks.

Participants

Participants were native German speakers. All the participants had normal or corrected to normal vision and normal hearing.

Adults

There were 94 (26 male) student volunteers or employees from the University of Oldenburg, aged between 19 and 40 years (median = 23), who either received course credit or payment for participation. The participants were arbitrarily assigned to one of the four sound × reverberation combinations.

Children

The children were recruited from 10 elementary schools in Oldenburg. Each child received 5 Euros for participation for the class treasury. The children and their parents and teachers gave their agreement to this study.

First graders

A total of 108 first graders participated in the experiment: 56 children (25 males) with a median age of 7;0 (7 years, 0 months) (range 6;7–7;9), performed the speech perception and the listening task in the favorable room, 29 of them with classroom noise and 27 with background speech. Fifty-two children (25 males) with a median age of 7;0 (range 6;4–7;9) performed the speech perception task in the unfavorable room, 27 of them with classroom noise and 25 with background speech.

Third graders

A total of 149 third graders took part in the study. 102 children (40 males) with a median age of 8;9 (range 7;10–10;5) performed the speech perception task. These children were arbitrarily assigned to one of the four sound × reverberation combinations. Forty-seven children (21 males) with a median age of 9;0 (range 8;1–10;5) performed the listening comprehension task in the favorable room condition, 24 with classroom noise and 23 with background speech.

Results

Speech perception in noise and reverberation as a function of age

One of the first-grade children from the condition classroom noise/favorable room performed at chance level in the silent control condition of the task, indicating a misunderstanding of the instruction. The data from this participant were discarded from the analysis.

In a first step, the effects of Age, Reverberation and Seat row on performance in the silent control condition were analyzed by means of a three-factorial analysis of variance (ANOVA). The analysis yielded a significant main effect of Age [$F(2, 285) = 49.86$, MSE = 24.5, partial $\eta^2 = 0.26$; $P < 0.001$], with mean percent correct M = 92.13 (SD = 6.85), M = 96.04 (SD = 4.57) and M = 99.29 (SD = 1.9) for first graders, third graders and adults, respectively, a significant main effect of Seat row [$F(2, 285) = 3.99$, MSE = 24.5 partial $\eta^2 = 0.03$, $P < 0.05$] (despite only marginal differences in mean percent correct scores: M = 94.8, M = 95.7 and M = 96.6 for the first, second and third seat rows, respectively), but no effect of Reverberation and no interactions ($F < 1$ in all cases). Concerning the age effect, Bonferroni-corrected *post hoc* tests confirmed that the first graders performed worse than the third graders, who in turn scored lower than the adults ($P < 0.001$ in both cases). Thus, with the current signal level and quality, speech perception in silence was relatively high and unaffected by reverberation in each of the age groups.

As a measure of impairment evoked by noise in the two virtual rooms, difference scores were calculated for each participant by subtracting identification performance in noise from performance in the silent control condition. This measure was used as dependent variable. Separate 3-factorial ANOVAs were performed for each sound group (i.e., the group which performed the task with background speech and the group which performed the task with classroom noise) with Age, Reverberation and Seat row as between-subjects factors.

For background speech, the analysis revealed significant main effects on all factors: Reverberation [$F(1, 135) = 65.7$, MSE = 110.13, partial $\eta^2 = 0.33$, $P < 0.001$]; Seat row [$F(2, 135) = 32.33$, MSE = 110.13, partial $\eta^2 = 0.32$; $P < 0.001$] and Age [$F(2, 135) = 6.48$, MSE = 110.13, partial $\eta^2 = 0.09$, $P < 0.01$] and significant interactions between Age × Row and Row × Reverberation [$F(4, 135) = 2.47$, MSE = 110.13, partial $\eta^2 = 0.07$, $P < 0.05$, $F(2,135) = 3.79$, MSE = 110.13, partial $\eta^2 = 0.05$, $P < 0.05$]. Importantly, there was no Age × Reverberation interaction found [$F(2, 135) = 1.83$, $P < 0.16$]. The three-way interaction was also non-significant ($F < 1$). Means and standard errors of the difference scores with respect to age in the favorable and unfavorable room conditions are given in Figure 2 (for each seat row) and Figure 3a (pooled across seat rows).

As is evident from the figures, the magnitude of the disruption due to background speech was much more pronounced in the unfavorable as compared to the favorable room, and more pronounced in the children as compared to adults. The effect of seat row was more pronounced in the children as compared to adults, and more pronounced in the unfavorable as compared to the favorable room. The age differences in the impairment were further explored by separate analyses for each reverberation condition. These proved stronger impairment in the children when compared to adults in the unfavorable room [$F(2, 65) = 5.3$; $P < 0.01$], whereas in the favorable room, the groups did not differ [$F(2, 70) = 1.7$; $P < 0.19$].

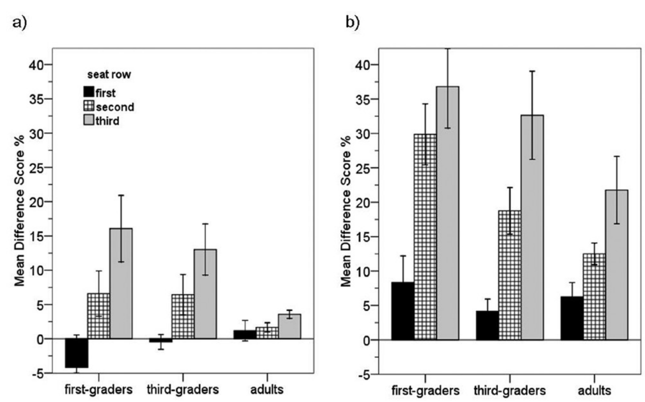

Figure 2: Percentage drop in speech perception performance in the presence of background speech (percent correctly identified words with competing speech subtracted from percent correctly identified words in silence) with respect to seat row and age. Error bars represent standard errors of the mean: (a) favorable room (b) unfavorable room

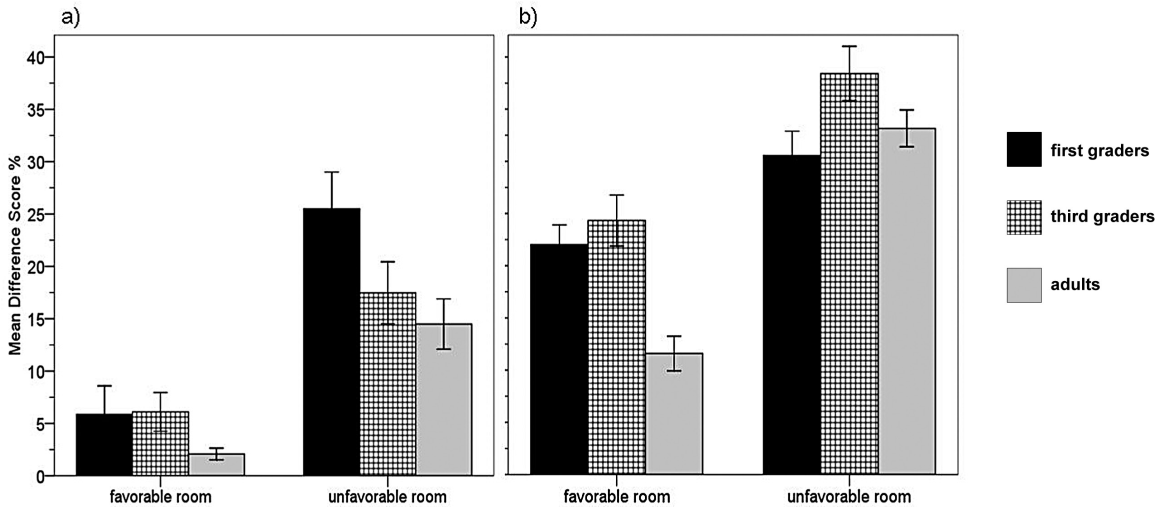

Figure 3: Percentage drop in speech perception performance in the presence of background speech (a) and classroom noise (b) with respect to age and reverberation (pooled across seat rows). Error bars represent standard errors of the mean

For classroom noise, the analysis revealed significant main effects for all factors, Reverberation [$F(1, 132) = 75.37$, MSE = 100.52, partial $\eta^2 = 0.36$, $P < 0.001$]; Seat row [$F(2, 132) = 10.07$, MSE = 100.52, partial $\eta^2 = 0.13$; $P < 0.001$] and Age [$F(2, 132) = 10.07$, MSE = 110.13, partial $\eta^2 = 0.13$, $P < 0.01$], as well as a significant interaction between Age and Reverberation [$F(2, 132) = 4.89$, MSE = 100.52, partial $\eta^2 = 0.07$ $P < 0.01$]. No other interactions were found to be significant. Means and standard errors with respect to age and reverberation are given in Figure 3b. *Post hoc* tests confirmed stronger impairments in both groups of children as compared to adults ($P < 0.01$). However, the age effect varied with reverberation. As Figure 3b indicates, the two-way interaction between Age and Reverberation results from the fact that the advantage of the adults in the favorable room is eliminated in the unfavorable room. Separate analysis for both room conditions confirmed that the disruption in both groups of children was more pronounced when compared to adults in the favorable room ($P < 0.001$ in both cases). In the unfavorable room, the magnitude of the disruption in the adults did not differ significantly from that found in the first and third graders.

In order to compare the magnitude of the disruption evoked by the two sounds, a three-way ANOVA was performed with the between-subject factors Age, Type of sound and Reverberation. This analysis yielded effects of Age and Reverberation in the same direction as in the earlier analyses. For the additional variable, Type of Sound, a main effect was found as well [$F(1, 291) = 117.7$, MSE = 139.47, partial $\eta^2 = 0.29$, $P < 0.001$]. Interactions were found for Type of sound × Age [$F(2, 291) = 3.81$, MSE = 139.47, partial $\eta^2 = 0.03$, $P < 0.05$] and between all three factors, [$F(2, 291) = 4.88$, MSE = 139.47, partial $\eta^2 = 0.03$, $P < 0.01$]. No other interactions were found to be significant, including Age × Reverberation ($F < 1$). Thus, performance was more disrupted by classroom noise as opposed to background speech, and the effect of reverberation did not differ with age and type of sound. As Figure 3 indicates, the three-way interaction was due to a reversal of the age effects in the disruption due to classroom noise versus background speech in the two reverberation conditions: In the favorable room, there was a marginal age difference in the background speech condition, but a strong age effect in the classroom noise condition. In the unfavorable room, a clear age effect emerged in background speech condition, whereas no clear developmental trend was evident with classroom noise. The two-way interaction between Type of sound and Age was due to the stronger effect of age in the background speech condition, although this was only evident in the unfavorable room.

The analyses described above proved a considerable increase in the noise-induced impairments with reverberation. As outlined earlier, as a result of reverberation, background sound levels were about 3 dB higher in the unfavorable as compared to the favorable room. In order to explore whether the effect of reverberation is solely caused by the increase in noise levels, the reverberation effect was re-analyzed with background sound level at the participants' seat position included as covariate. For both classroom noise and background speech, the effect of reverberation was eliminated when noise level was controlled ($P < 0.17$ and $P < 0.13$, respectively).

Listening comprehension in noise as a function of age

One first-grade child from the background speech group had severe difficulties with the task, resulting in extreme values in the distribution; the respective data were discarded from the analysis.

The number of elements correctly solved for each instruction was assessed for each participant by means of a scoring manual (see above). Inter-rater reliability, assessed via a random sample of 73 answer sheets scored by two independent raters, was $r = 0.98$.

A two-way ANOVA with Age and Seat row as between subjects factors on the data from the silent control condition proved a significant main effect of Age [$F(2, 140) = 4.58$, MSE = 184.59, partial $\eta^2 = 0.06$, $P < 0.05$], but no effect of Seat row [$F(2, 140) = 2.3$, $P < 0.1$] and no interaction [$F(4, 140) = 1.28$, $P < 0.28$]. Bonferroni-corrected *post hoc* tests revealed significant better performance in the third graders as compared to adults ($P < .05$). No other comparison reached significance. Mean percent correct scores were M = 72.6 (SD = 14.47), M = 78.7 (SD = 11.29) and M = 71.0 (SD = 15.19) in the first graders, third graders and adults, respectively. Thus, potential stronger effects of noise in the children cannot be attributed to differences in task difficulty.

As a measure of impairment, difference scores were calculated for each participant by subtracting accuracy in the noise conditions from accuracy in the silent control conditions. Means and standard errors with respect to noise and age are given in Figure 4.

Separate two-factorial ANOVAs were performed for each sound group (i.e., the group which performed the task with background speech and the group which performed the task with classroom noise) with Age and Seat row as between-subjects factors. For background speech, the ANOVA revealed main effects of Age [$F(2, 64) = 16.72$, MSE = 239.23, partial $\eta^2 = 0.34$, $P < 0.001$] and Seat row [$F(2, 64) = 4.45$, MSE = 239.23, partial $\eta^2 = 0.12$, $P < 0.05$], but no interaction. Mean difference scores were M = 24.65 (SD = 15.42), M = 17.29 (SD = 16.37) and M = –0.5 (SD = 17.37) in the first graders, third graders and adults, respectively. Paired *t*-tests in each age group on the data from the silent control and the background speech conditions proved significant decrements in the first graders [$t(25) = 8.15$, $P < 0.001$] and third graders [$t(22) = 5.1$, $P < 0.001$]. In the adults, listening comprehension was unaffected by background speech [$t(23) < 1$].

For classroom noise, the analysis revealed significant main effects of Age [$F(2, 67) = 7.79$, MSE = 219.54, partial $\eta^2 = 0.19$, $P < 0.001$] and Seat row [$F(2, 67) = 3.35$, MSE = 219.54, partial $\eta^2 = 0.09$, $P < 0.05$], but no interaction. Mean difference scores (pooled across seat row) were M = 19.12 (SD = 16.04), M = 9.56 (SD = 13.82) and M = 4.91 (SD = 15.99) in the first graders, third graders and adults, respectively. Paired *t*-tests in each age group on the data from the silent control and classroom noise conditions proved significant decrements due to classroom noise in the first graders [$t(28) = 6.42$, $P < 0.001$] and in the third graders [$t(23) = 3.39$, $P < 0.01$]. In the adults, the effect of classroom noise on listening comprehension was not significant [$t(22) = 1.47$, $P < 0.16$].

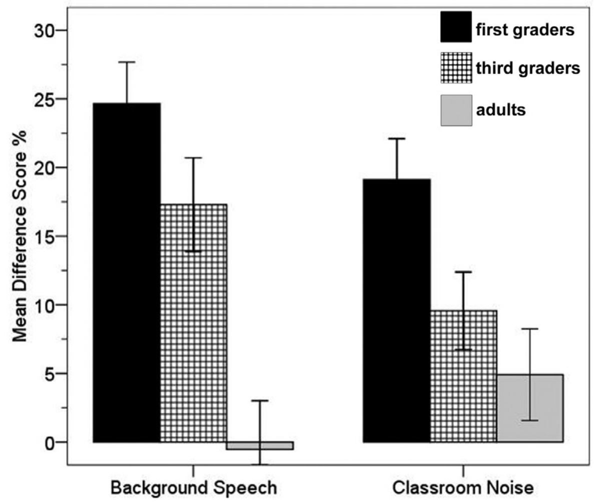

Figure 4: Percentage drop in listening comprehension in the presence of background speech and classroom noise with respect to age. The experiment was performed in the favorable room. Error bars represent standard errors of the mean

Thus, children's listening comprehension was significantly impaired by background speech and classroom noise, whereas adults were unaffected. The disruption found in the children was further explored by means of a three-factorial ANOVA with the between-subject factors Age (first vs. third graders), Type of sound and Seat row. The analysis revealed significant main effects on all factors [Age: $F(1, 90) = 7.45$, MSE = 206.48, partial $\eta^2 = 0.08$, $P < 0.01$; Type of sound: $F(1, 90) = 6.07$, MSE = 206.48, partial $\eta^2 = 0.06$, $P < 0.05$; Seat row: $F(2, 90) = 10.6$, MSE = 206.48, partial $\eta^2 = 0.19$, $P < 0.001$], but no interactions ($F < 1$ in all cases). First graders were more affected by the background sounds than third graders. Irrespective of age, background speech evoked a stronger disruption in listening comprehension when compared to classroom noise. This finding is important, since, as outlined above, speech perception was more impaired by classroom noise than by background speech. Thus, background speech and classroom noise seem to have differential effects on speech perception and listening comprehension in children. These potential interactions were explored further by including Type of task (speech perception vs. listening comprehension) as independent variable.

Differential effects of speech and classroom noise on speech perception and listening comprehension in children

The differential effects of classroom noise and background speech on listening comprehension and speech perception were confirmed by means of separate ANOVAs in the two groups of children. For the first graders, a three-way ANOVA was performed with Task (listening comprehension vs. speech perception) as a within subjects factor and Type of sound (classroom noise vs. background speech) and Seat row as between-subjects factors. This analysis revealed main effects of Task [$F(1, 48) = 11.40$, MSE = 121.57, partial $\eta^2 = 0.19$, $P < 0.001$] and Seat row [$F(2, 48) = 10.02$, MSE = 209.43, partial $\eta^2 = 0.30$, $P < 0.001$]. The main effect of Type of sound was not significant ($F = 2.12$), but there was a highly significant Task × Type of sound interaction [$F(1, 48) = 23.79$, MSE = 121.57, partial $\eta^2 = 0.33$, $P < 0.001$]. Speech perception was more impaired by classroom noise, whereas listening comprehension was more impaired by background speech. The other interactions were non-significant ($F < 1$ in all cases).

The same analysis was performed in the third graders, except that task was varied between subjects. The analysis proved a marginally significant main effect of Type of sound [$F(1, 87) = 3.81$, $P = 0.054$] and a significant effect of Seat row [$F(2, 87) = 12.75$, MSE = 142.19, partial $\eta^2 = 0.23$, $P < 0.001$], but no effect of Task ($F(1, 87) < 1$). Most important, there was a highly significant Task × Type of sound interaction [$F(1, 87) = 30.01$, MSE = 142.19, partial $\eta^2 = 0.26$, $P < 0.001$]. Listening comprehension was more impaired by background speech, whereas speech perception was more impaired by classroom noise. The crossover interactions are depicted in Figure 5.

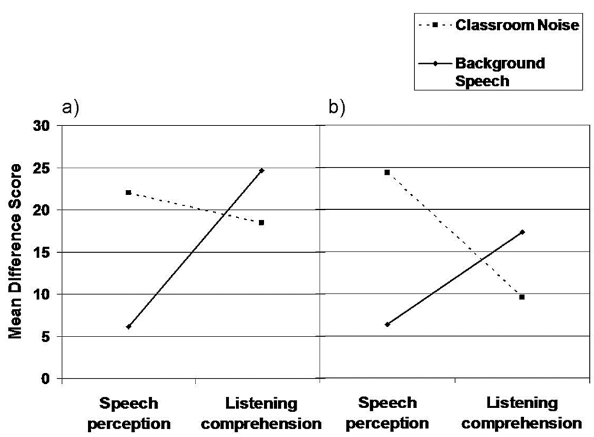

Figure 5: Differential effects of classroom noise and background speech on speech perception and listening comprehension (a) first graders (b) third graders

Are noise-induced impairments predictable by speech transmission index?

In order to explore whether the disruption of speech perception and listening comprehension evoked by the two sounds is predictable by *a priori* acoustic measurements, linear regression analyses were performed on the observed disruption (difference scores), with STI at the participants' seat position as predictor variable. For listening comprehension, the analysis was confined to children, as adults' performance in this task was unimpaired by both sounds. The regression coefficients are given in Table 2. For speech perception, STI explained 23, 23, and 66% of the variance (corrected *R*-squared) in the disruption evoked by classroom noise and 43, 34 and 46% of the variance in the disruption evoked by background speech in first graders, third graders and adults, respectively.

Thus, STI yields in fact a useful prediction of the impact of real-life noise on speech perception in a classroom-like setting in all age groups. For listening comprehension, STI explained 12 and 30% of the variance in the disruption evoked by background speech in first and third graders, respectively, and thus STI turned out to be a valuable predictor also for this condition. With classroom noise, however, STI failed to predict the disruption.

Disturbance ratings

For the speech perception task, separate two-way ANOVAs including the factors Type of sound and Reverberation on the disturbance ratings were performed for each age group. For the adults, the analysis yielded main effects of both factors Type of sound [$F(1, 90) = 5 .53$, MSE = 1.55, partial $\eta^2 = 0.06$, $P < 0.05$] and Reverberation [$F(1, 90) = 6.36$, MSE = 1.55, partial $\eta^2 = 0.07$, $P < 0.05$], but no interaction ($F < 1$). Mean disturbance ratings were higher for classroom noise than for background speech, and higher in the unfavorable than in the favorable room. Mean ratings were M = 1.83 (SD = 1.11) for classroom noise and M = 1.17 (SD = 1.31) for background speech in the favorable room and M = 2.42 (SD = 1.18) for classroom noise and M = 1.87 (SD = 1.36) for background

Table 2: Coefficients for linear regression predicting noise-induced impairments (difference scores) from STI at the participant´s seat location in the virtual classroom. a) speech perception b) listening comprehension

a)	Background speech					Classroom noise				
	B	SE	β	*P*	Corrected R-squared	B	SE	β	*P*	Corrected R-squared
First graders	-192.11	30.7	-.66	.001	.43	-91,5	21.89	-.5	.001	.23
Third graders	-127.96	24.08	-.59	.001	.34	-102.87	26.82	-.49	.001	.23
Adults	-105.33	16.49	-.69	.001	.46	-173.23	18.30	-.82	.001	.66

b)	Background speech					Classroom noise				
	B	SE	β	*P*	Corrected R-squared	B	SE	β	*P*	Corrected R-squared
First graders	-283.61	135.4	-.39	.05	.12	-221.24	137.65	-.29	n.s.	.05
Third graders	-417.8	128.4	-.58	.01	.30	-194.35	121.02	-.32	n.s.	.06

n.s.= Not significant

speech in the unfavorable room. For both the first and third graders, no significant main effects and no interactions were found (F < 1–2). Mean ratings of the children are given in Table 3. The mean disturbance ratings of the children were rather low, reaching from "not at all disturbed" (0) to "a bit disturbed" (1).

For the listening comprehension task, the disturbance ratings for classroom noise and background were compared through paired t-tests performed for each age group. For the adults, mean disturbance ratings were M = 2.13 (SD = 1.29) for classroom noise and M = 2.29 (SD = 1.12) for background speech. There was no significant difference between the means [$t(45) < 1$]. For the first graders, mean disturbance ratings were M = 1.31 (SD = 1.00) for classroom noise and M = 1.33 (SD = 0.96) for background speech. There was no significant difference between the means [$t(54) < 1$]. For the third graders, mean disturbance ratings were M = 1.71 (SD = 0.91) for classroom noise and M = 0.96 for background speech. Classroom noise was rated as more disturbing than background speech [$t(45) = 2.88$, $P < 0.01$]. The disturbance ratings were uncorrelated to the magnitude of the actual disruption in listening comprehension in both groups of children (first graders: $r = 0.05$, $P < 0.70$; third graders: $r = 0.11$, $P < 0.45$). Again, the findings indicate that the children did not consciously realize the noise-induced disruptions. Especially, they seemed to be unaware of the severe disruption evoked by background speech.

Table 3: Mean ratings (standard deviations in parentheses) of the disturbance in the speech perception task due to classroom noise and background speech with respect to reverberation in firstand third-graders

	Classroom noise		Background speech	
	Favorable	Unfavorable	Favorable	Unfavorable
First graders	0.89 (0.74)	0.67 (0.62)	0.74 (0.81)	1.0 (1.19)
Third graders	0.64 (0.57)	1.00 (0.74)	0.73 (0.69)	0.73 (0.67)

Figures in parentheses are standard deviations

General Discussion

In the present study, the effects of classroom noise and background speech on speech perception and listening comprehension were investigated in children and adults in a classroom-like setting. Speech perception was assessed by means of a word-to-picture matching task requiring discrimination between similar-sounding words. Listening comprehension was assessed by means of a paper-and-pencil task requiring the execution of complex oral instructions. For speech perception, the impact of reverberation also was explored. To achieve this aim, testing was done in two virtual classrooms, simulating the RTs of a real elementary school classroom before and after acoustic renovation. Mean RTs were 0.47 second in the favorable and 1.1 second in the unfavorable room condition. As a measure of impairment due to noise or due to the combination of noise and reverberation, difference scores were computed for each participant by subtracting performance in noise from performance in silence. For each of the four task × sound combinations, the difference scores differed significantly with age, confirming stronger impairment in the children when compared to adults.

For speech perception, reverberation had no effect when the task was performed in silence, but led to a severe increase in the disruption evoked by the background sounds. Background speech had a weaker effect on speech perception when compared to classroom noise. The age effect in the noise-induced impairments varied with type of sound and reverberation: in the favorable room, there was a marginal, non-significant age difference in the impairment evoked by background speech (6% drop in both groups of children and 2% in adults), but a strong age difference with classroom noise (22, 24, and 12% drop in first graders, third graders and adults, respectively). In the unfavorable room, a clear age effect was found in the background speech condition (25, 17, and 14% drop in the first graders, third graders and adults, respectively), whereas no clear developmental trend was evident with classroom noise. With the latter, the drop in performance exceeded 30% in each of the age groups. For background speech, the impact of the listeners' distance from the signal source on the sound-induced disruption was stronger in the unfavorable as compared to the favorable room, and stronger in the children when compared to adults.

For listening comprehension (measured in the favorable room), reliable impairments due to background speech and classroom noise were found in children. First graders were more impaired than third graders. Adults were unaffected by both background sounds. Further analyses of the children's data proved differential effects for the two sounds on speech perception and listening comprehension, as revealed by strong crossover interactions between task and type of sound. When compared to classroom noise, background speech had a weaker effect on speech perception, but a stronger effect on listening comprehension. Performance in the listening task deteriorated by 25 and by 17% in the presence of background speech in the first and third graders, respectively.

Before discussing these results in greater detail, we should remind that the noise and reverberation conditions used in the present study do not represent unrealistic listening situations for school children. Mean RTs exceeding 1 second are not rare in elementary school classrooms; average noise levels during the school lessons most often exceed 55 dB(A).[2,6,7,23] Shield and Dockrell[7] performed comprehensive measurements in classrooms of elementary schools in London and found average noise levels between 57 and 77 L_{Aeq}, depending on the specific classroom activity (e.g., silent individual work vs. group work with children moving around the classroom).

In the following discussion, the results concerning speech perception, listening comprehension and disturbance ratings will be addressed in succession, followed by a set of concluding remarks.

Speech perception

For speech perception, the most important results of the current study are the age effect in the disruption evoked by background sounds, and the severe increase in the sound-induced impairments when the task was performed in the unfavorable room. The former finding is in line with psychoacoustic studies demonstrating an increase in the detrimental effects of noise on speech perception with decreasing age (see Introduction). The current study verifies that this holds also for classroom-like settings.

A couple of mechanisms are responsible for young children's susceptibility to sound-induced disruption. Firstly, children are less able to use phonological long-term representations to reconstruct degraded speech signals. This is because their phoneme categories are less precise and thus less robust,[24-26] and their phonological word representations are more holistic and less segmented into phoneme units, which reduces the probability of successfully matching incomplete speech input with stored representations.[27] Secondly, children are less able than adults to focus attention on task-relevant information and resist interference from irrelevant sounds.[28-30] With respect to the auditory domain, there is evidence for poorer selective attention in children, indicated by higher susceptibility to informational masking in auditory signal detection tasks,[31,32] and more intrusions from the distractor message in dichotic listening tasks.[33] In a related account, Werner[34] proposed that children are less flexible in the usage of perceptual strategies for speech perception, resulting in difficulties to take advantage of the available cues in unfavorable listening conditions.

The second finding, the severe increase in noise-induced impairments in the unfavorable room, provides further evidence for the detrimental effects of prolonged reverberation on students‘ speech perception in classroom settings. In prior field studies,[1,35,36] students‘ word-in-noise identification scores were 10–37% worse in classrooms with long as compared to classrooms with short reverberation. In the current study, the impairment evoked by background sounds (pooled across age groups) increased from 5 to 19% for background speech and from 19 to 34% for classroom noise when the task was performed in the unfavorable room. Further analyses proved that the effect of reverberation was completely eliminated when background sound levels at the participants' seat positions were controlled (remind that noise levels were about 3 dB higher in the unfavorable as compared to the favorable room). No evidence for other mechanisms, such as distortion of the speech signals, was found. In line with this, speech perception in silence was unaffected by reverberation in all age groups. With respect to practical issues, however, this result should be interpreted with caution. The finding might not hold for classrooms with RTs still exceeding 1.1 seconds, or for speakers with a less clear and trained voice than that used in the present study. Furthermore, a certain level of background noise is unavoidable during school lessons, especially in elementary schools.[2] This is particularly true in view of the fact that frontal teaching methods are more and more replaced by contemporary teaching forms including student-centered activities such as group work. Thus, speech perception in silence is a relatively untypical task in actual classrooms. In the following section, we will focus on the effects of reverberation on speech perception under conditions of background noise.

Despite equal sound levels, background speech evoked a weaker disruption of speech perception as compared to classroom noise. In the favorable room, background speech evoked a minor impairment, which did not differ with age. This might be due to the fact that the amplitude variations of a single-talker speech noise create short gaps in the waveform, which help the listener to identify segments of the target voice.[37] Other factors, such as spectral differences between the target and the competing voice, may also play a role. However, when testing was performed in the unfavorable room, the disruption evoked by background speech increased considerably. This was particularly true for the first graders, who showed a 6 and 25% decrement with speech noise in the favorable and unfavorable conditions, respectively. Separate analyses in each age group proved that only for first graders, the difference between classroom noise and speech was eliminated in the unfavorable room, resulting from a disproportionate increase in the disruption evoked by speech noise. The first graders who sat in the second and third rows in the unfavorable room were most impaired by competing speech [Figure 2]. This indicates that young children are less able to take advantage of the temporal gaps inherent in speech when the acoustic conditions are more difficult.[34] Thus, we may conclude that young children who are sitting in the back rows in a reverberating classroom are at great risk of failing to follow the teachers instructions, or a group discussion, under conditions of competing speech. From a practical viewpoint, this means that group work with two or more concurrent discussions in a reverberating classroom is extremely difficult to handle for beginning school learners. The successful realization of such modern teaching forms requires optimal room acoustic conditions.

For classroom noise, a reliable impairment was found even under conditions of short reverberation. Children were more affected than adults. The advantage of the adults in the favorable room was eliminated in the unfavorable room. Thus, not even adults are capable to compensate for the speech perception impairment evoked by the combination of classroom noise and reverberation. Overall, the disruption found with classroom noise seems strong in view of prior findings reported by Jamieson *et al*.[38] In this study, the effects of classroom noise on speech perception, measured by word-to-picture matching, were investigated in children from kindergarten to grade 3, with more strictly controlled laboratory conditions using headphone presentation. In quiet and at 0 dB SNR, all the children performed at a comparable level, reaching more than 90% correct. At −6 dB, first graders' identification scores decreased by 18%, whereas performance in the third graders remained stable. In our study, in contrast, classroom noise evoked about 22% decrement in first and third graders at −3 to 4 dB SNR (i.e., in the favorable room, see Table 1), and more than 30% decrement with −6 to 0 dB SNR (i.e., in the unfavorable room). This confirms Jamieson's notion[38] [p. 516] that strictly controlled laboratory studies even underestimate the noise-induced disruption in children's speech perception in classroom settings.

The present results suggest that reducing reverberation is a necessary, but not a sufficient method to prevent negative effects of classroom noise. In addition, noise reduction can be achieved by adequate classroom furniture, and by arranging rules with the children such as wearing slippers instead of outdoor shoes during the lessons, avoiding metal paper-and-pencil cases, etc. In addition, in view of the significant impact of seat row, i.e., distance from the signal source, on the noise-induced impairments, teachers should assign children with poor learning abilities or specific developmental disorders to working places in front of the room, at the nearest distance from the teacher's place. These children are still more reliant on good acoustic conditions in order to follow the teacher's instructions than normally developing children.[1]

Listening comprehension

As outlined in the Introduction, the listening demands faced by children at school are much more complex than those involved in a word identification task. Therefore, a listening comprehension task was included in the current study. Due to the children's poor speech perception performance in the unfavorable room, the listening task was only conducted in the favorable room. Children's performance was severely impaired by background speech and classroom noise, stronger for first than for third graders, whereas adults were unaffected. Background speech evoked a stronger disruption than classroom noise. This contrasts the effects found for speech perception, which was impaired stronger by classroom noise.

This pattern of results indicates that the effects of classroom noise and background speech on children's listening comprehension result from different mechanisms. We propose that classroom noise affects comprehension through interference during encoding, i.e., energetic or informational masking. The smaller effect of classroom noise on listening comprehension when compared to speech perception may be due to the fact that comprehension of the instructions does not require perfect intelligibility of each syllable. Missing elements can be restored with the help of contextual cues. Obviously, the third graders are better able to solve this task than the first graders. In the former, the effect of classroom noise on listening is much smaller than its effect on perception [Figure 5].

In contrast to classroom noise, the effect of background speech on listening may result from interference with higher-order cognitive processes involved in children's listening comprehension. This account leads to the prediction that the difference in the effect of background speech on listening in children and adults should survive when speech perception in background speech is controlled, whereas the differential effect of classroom noise on listening performance in children and adults should be eliminated when speech perception is controlled. This prediction was confirmed in an ANOVA on the difference scores derived from the listening task in the first graders and adults (the third graders were not included, as speech perception and listening comprehension were assessed in different subgroups of children). For classroom noise, the age effect was eliminated when speech perception in classroom noise was included as covariate ($P < 0.11$). For background speech, in contrast, the age effect remained significant when speech perception in speech noise was controlled ($P < 0.01$).

Thus, we may conclude that the effect of background speech on children's listening performance cannot be attributed to poor speech perception. The finding coincides with a prior study demonstrating significant impairments of first graders' listening comprehension, measured by a similar task, due to background speech under conditions of perfect speech intelligibility.[18] How can this effect be explained? We attribute the disruptive effect of background speech on children's listening comprehension to the involvement of verbal short-term memory in this task. It has been shown that in children, listening comprehension is closely related to short-term memory.[39] In adults, in contrast, short-term memory plays a minor role in comprehension. This is presumably because in adults, comprehension usually proceeds on-line, whereas in children, semantic and syntactic analyses often "lag behind" the incoming discourse. In such situations, the temporary representation of the speech input held in short-term memory may significantly contribute to comprehension. In the framework of the "irrelevant sound effect", numerous studies with adults have shown that verbal short-term memory is highly susceptible to disruption by background speech,[16] and that this effect does not result from impaired encoding.[45] Current studies extended these findings to children.[18,30,40] Thus, background speech may impair children's listening performance through interference with the temporary record of the incoming speech in short-term memory. However, the significant impact of seat row, i.e., distance form the sound source, on the disruption indicates that other mechanisms, such as masking or difficulties in stream segregation, also contribute to the impairment found in the children. Taken together, the current results provide further evidence for negative effects of background speech on children's listening comprehension. This is an important finding from both a theoretical and a practical viewpoint, which clearly deserves further research.

Disturbance ratings

The children's ratings of the disturbance evoked by the background sounds in the speech perception task were surprisingly low, with mean ratings between "not at all disturbed" (0) to "a bit disturbed" (1). This is a surprising result in view of the reliable drop in children's speech perception performance due to classroom noise in both reverberation conditions, and due to background speech in the unfavorable room. Furthermore, the effects of reverberation and type of sound on the disruption of speech perception performance were reflected in the disturbance ratings of the adults, but not in those of the children. For listening comprehension, the children's ratings of perceived disturbance were unrelated to the actual impairment and did not reflect the differential effects of classroom noise and background speech on performance. Obviously, the children did not consciously realize the degree of disruption evoked by the background sounds. Prior studies have shown that elementary school children give reliable judgments of annoyance due to classroom noise, which correlate with noise levels[41,42] and reverberation.[1] Nevertheless, the children seem unable to estimate the impact of the noise on their own performance. In view of this discrepancy, it might be argued that our rating method was inadequate for children. However, the smiley scale is widely used in studies with young children and has proven reliable and valid results.[44] We propose that even though children are able to judge overall noise annoyance, they have difficulties to assess the degree of noise-induced disruption evoked in specific tasks. This finding clearly indicates that teachers and researchers cannot rely on the children's judgments when assessing the acoustic quality of classrooms.

Conclusions

The current study provides further evidence for the importance of adequate listening conditions in classrooms. In view of the magnitude of the observed impairments, current findings indicating chronic effects of noise and reverberation in classrooms on children's development are easily comprehensible. Clearly, children who, due to poor interior acoustics, often lose the content of the teachers' instructions, are at risk of poor academic achievement. In line with this, it has been shown that indoor noise levels in classrooms are significantly related to academic attainment with socioeconomic factors controlled.[43] A related study demonstrated poorer phonological processing abilities and less positive relationships to peers and teachers in children from reverberating classrooms when compared to children from classrooms with favorable acoustics.[1] It should be kept in mind that noise, in particular classroom noise and speech, is unavoidable during school lessons. The present results demonstrate that the effects of these sounds on children's speech perception depend heavily on the acoustic quality of the classrooms. Today, the knowledge on how to achieve optimal interior acoustics in classrooms is well established, and the considerable impact of acoustic conditions on children's learning is by now undisputable. The authorities responsible for the building of schools should now take care that this knowledge is efficiently transferred into practice. However, our results also demonstrate noise-induced impairments under conditions of good interior acoustics. Young children have severe difficulties to listen effectively in the presence of moderate intensity noise, whereas adults are unaffected. Teachers should be aware of such developmental effects and care for silence in learning episodes where listening is required.

Acknowledgments

This research was funded by German Research Foundation (DFG KL 1305/2-1). We thank the children, teachers and parents for their aid and cooperation in the current study. The authors wish to thank August Schick for helpful discussions and advice. Thanks also to Marco Deede, Lutz Fiedler, Julia Bastian and Niklas Grunwald for their help in organizing and running the experiments, and to Monique Rowles for proofreading the article.

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Source of Support: German Research Foundation (DFG KL 1305/2-1), **Conflict of Interest:** None declared.