

Research Article

Noise and a Speaker's Impaired Voice Quality Disrupt Spoken Language Processing in School-Aged Children: Evidence From Performance and Response Time Measures

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Purpose: Our aim was to investigate isolated and combined effects of speech-shaped noise (SSN) and a speaker's impaired voice quality on spoken language processing in first-grade children.

Method: In individual examinations, 53 typically developing children aged 5–6 years performed a speech perception task (phoneme discrimination) and a listening comprehension task (sentence–picture matching). Speech stimuli were randomly presented in a 2 × 2 factorial design with the factors *noise* (no added noise vs. SSN at 0- dB SNR) and *voice quality* (normal voice vs. impaired voice). Outcome measures were task performance and response time (RT).

Results: SSN and impaired voice quality significantly lowered children's performance and increased RTs in

the speech perception task, particularly when combined. Regarding listening comprehension, a significant interaction between noise and voice quality indicated that children's performance was hindered by SSN when the speaker's voice was impaired but not when it was normal. RTs in this task were unaffected by noise or voice quality.

Conclusions: Results suggest that speech signal degradations caused by a speaker's impaired voice and background noise generate more processing errors and increased listening effort in young school-aged children. This finding is vital for classroom listening and highlights the importance of ensuring teachers' vocal health and adequate room acoustics.

Because of the trajectory of spoken language acquisition, children are highly vulnerable to adverse listening conditions (Elliott, 1979). Phonological awareness continuously improves during the first years of school (Anthony & Francis, 2005), which may partly explain why younger pupils in particular have difficulties understanding acoustically degraded speech (Astolfi et al., 2012; Johnson, 2000). Generally, children benefit from high-quality speech signals and quiet surroundings for effective listening, but such conditions are rare. In classrooms, for

example, noise levels frequently exceed official guidelines (Silva et al., 2016), and the prevalence of voice disorders in teachers is between 20% and 50% (Martins et al., 2014). Investigating school-aged children's ability to perceive and comprehend speech that is degraded by noise and impaired voice quality is therefore critical.

The complex system that allows us to understand and retain speech is known as spoken language processing (SLP; Medwetsky, 2011). We can broadly divide SLP into low-level speech perception and high-level listening comprehension. During speech perception, acoustic information is mapped onto linguistic representations (e.g., phonemes, syllables, or words; Holt & Lotto, 2010). This auditory–perceptual mapping is a prerequisite for listening comprehension. Following Klatte et al.'s (2010) use of the term, we define listening comprehension as the process whereby listeners integrate semantic, syntactic, and pragmatic information to construct the meaning of verbal messages.

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As a whole system, SLP is closely related to working memory. Among other theories (reviewed in Wingfield, 2016), this link has been described in the Ease of Language Understanding model (Rönnerberg et al., 2013), which provides a cross-modal explanation of how language is understood under different conditions. According to this model, impoverished speech signals may result in a mismatch between the perceptual input and a listener's phonological-lexical representations. To resolve this mismatch, the listener must deliberately allocate cognitive resources (i.e., explicit processing), which slows down processing because long-term memory must be consulted.

The effect of noise on school-aged children's SLP has repeatedly been demonstrated in listening tasks. For example, Jamieson et al. (2004) tested 5- to 8-year-old children's ability to discriminate among phonologically similar words at classroom-typical signal-to-noise ratios (SNRs), using a word-picture matching task presented in classroom noise. Decreasing SNRs significantly lowered task performance, particularly in younger children. Several further studies have shown noise-induced declines in speech perception (which focuses on low-level speech intelligibility; Bradley & Sato, 2008; Crandell & Smaldino, 1996; Klatte et al., 2010; Prodi et al., 2019), listening comprehension (which focuses on understanding longer utterances; Klatte et al., 2010; Nirme et al., 2019; Sullivan et al., 2015), and working memory (Osman & Sullivan, 2014; Sullivan et al., 2015). However, most of these studies examined children around the age of 8–10 years old. We believe it is important to investigate the effects of noise on pupils in the early school years (i.e., children aged 5–7 years) because the first grades are critical for language development (Anthony & Francis, 2005). Children's performance during this period may predict future academic performance, such as reading skills (Rabiner et al., 2016).

The effects of noise are influenced not only by SNRs but also by the source of noise (Astolfi et al., 2012; Klatte et al., 2010; Peng et al., 2016; Prodi & Visentin, 2015; Prodi, Visentin, Borella, et al., 2019). This may be explained by energetic and informational masking and spectrotemporal aspects. Energetic masking refers to physical interference by noise (i.e., poor intelligibility due to shared acoustic characteristics of the noise signal and the speech signal; Mattys et al., 2009), whereas informational masking refers to "...everything that reduces intelligibility once energetic masking has been accounted for" (Cooke et al., 2008, pp. 414–415). Under conditions of high energetic masking, small dips (or glimpses) in the noise signal may improve listeners' speech-in-noise processing (Cooke, 2006; Klatte et al., 2010). There is, for example, some indication that competing speech is more detrimental to children's listening comprehension, whereas steady-state noise has a stronger impact on speech perception (Klatte et al., 2010).

In addition to noise, children's SLP may be hampered when listening to a dysphonic speaker (i.e., a speaker with an impaired voice). Dysphonia is commonly used as a synonym for hoarseness and refers to a coarse or rough voice quality (Schwartz et al., 2009). While noise degrades

transmission (Mattys et al., 2012), impaired voice modulates the speech signal directly during speech production, thus at the source. Brännström, Kastberg, et al. (2018) suggested that the effect of impaired voice may be less problematic than the effect of noise. Morsomme et al. (2011) studied the effect of voice quality on phonological discrimination and passage comprehension in 8-year-old children. When listening to a voice that was moderately to severely impaired, children performed significantly worse than when listening to a normal voice. This aligns with past findings that revealed negative effects of impaired voice on children's acceptability judgments (Brännström, Kastberg, et al., 2018), passage comprehension (Chui & Ma, 2018; Rogerson & Dodd, 2005), and word recall (Morton & Watson, 2001).

Research suggests that the effects of voice quality may be mediated by source/degree of dysphonia and task demands. For example, more pronounced effects have been found when the impaired voice was mimicked (Chui & Ma, 2018; Morsomme et al., 2011; Rogerson & Dodd, 2005) rather than provoked by means of vocal loading tasks (Brännström, Kastberg, et al., 2018; Lyberg-Åhlander et al., 2015). In previous work, we pointed out that this probably relates to differences concerning dysphonia severity and perceptual voice characteristics (e.g., hyperfunction or breathiness; Schiller et al., 2019a). Regarding task demands, the impact of impaired voice appears to be more detrimental when the listening task creates a considerable processing load (Lyberg-Åhlander et al., 2015; Lyberg-Åhlander, Holm, et al., 2015). Processing load may increase not only due to linguistic factors but also due to acoustic interference (Rönnerberg et al., 2013); thus, listening to dysphonic speech in noisy conditions should be particularly challenging.

The combined effect of noise and impaired voice on children's SLP has rarely been investigated. Two studies (Brännström et al., 2018; von Lochow et al., 2018) assessed listening comprehension at different SNRs (i.e., no added noise, speech noise at +10 dB SNR, and speech noise at +5 dB SNR) and voice qualities (normal voice and mildly to moderately impaired voice) in children between the ages of 7 and 12 years. Neither study revealed a significant interaction between noise and voice quality or a main effect of voice quality on children's performance. Only noise triggered a decline in performance. Considering that separate effects of each factor have previously been observed, these results are counterintuitive. On the other hand, in line with a review by Lyberg-Åhlander, Brännström, and Sahlén (2015), both studies provided indications of a complex interplay between listening conditions, task demands, and children's executive functioning, which might have complicated the detection of significant effects. Clearly, this topic needs further investigation.

To better understand the listening effort required to listen to acoustically degraded speech, performance measures can be enriched with response time (RT) measures (McCreery & Stelmachowicz, 2013; McGarrigle et al., 2017; Visentin & Prodi, 2018). Listening effort refers to the

effort associated with “the deliberate allocation of mental resources to overcome obstacles in goal pursuit when carrying out a [listening] task” (Pichora-Fuller et al., 2016, p. 10S). Simply put, degraded listening conditions contribute to increased listening effort but only when the listener intends to listen. According to the Framework for Understanding Effortful Listening (Pichora-Fuller et al., 2016), listeners produce more errors and require longer processing times when their processing capacity is close to depletion. A recent study confirmed that collecting RTs in single-task paradigms (i.e., listening tasks that consist of one task only) is a useful technique for indirectly measuring listening effort in children at the age of 6 years and older (McGarrigle et al., 2019).

Indeed, McCreery and Stelmachowicz (2013) found that speech-shaped noise (SSN) and poor signal quality, induced by limiting the bandwidth, prolonged school-aged children’s RTs in a speech perception task. Likewise, in the study by Prodi, Visentin, Borella, et al. (2019), children responded significantly slower in a speech perception task and a listening comprehension task when speech was presented in classroom noise. In another study by Prodi et al. (2019), SSN increased 5- to 7-year-old children’s response latencies in a word–picture matching task. Two other studies found no detrimental effects of noise on children’s RTs (McGarrigle et al., 2017; Nakeva von Mentzer et al., 2018). Regarding voice quality, Sahlén et al. (2017) found that listening to an impaired voice increased RTs in girls but not boys in a listening comprehension task. The combined effect of noise and impaired voice on RTs has never been studied.

The goal of this study was to investigate isolated and combined effects of noise and a speaker’s impaired voice quality on speech perception and listening comprehension in first-grade children (5–6 years old). Speech perception primarily refers to the process of auditory–perceptual mapping. Listening comprehension focuses on the processing of meaning (i.e., content level of speech). Specifically, we sought to determine to what extent noise and impaired voice influenced children’s performance and RTs in a phonological discrimination task and a sentence–picture matching task. Four hypotheses were tested:

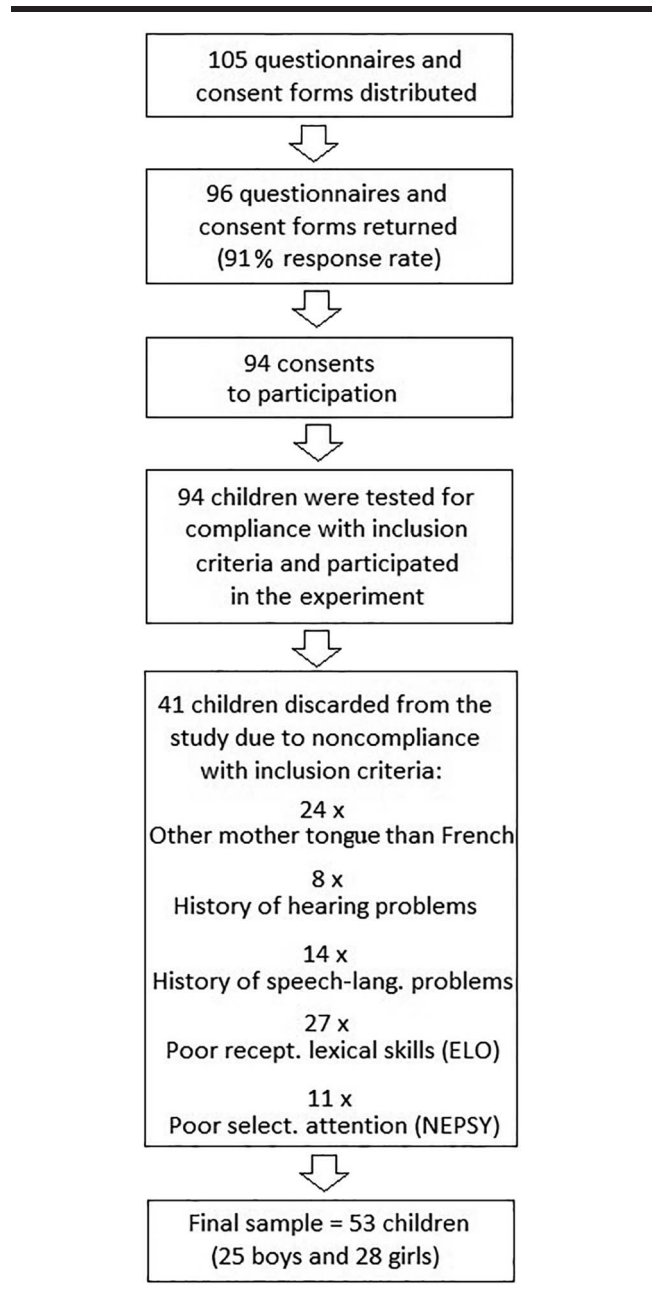
- H1: Noise or impaired voice quality reduces children’s performance and increases RTs in speech perception.
- H2: A combination of noise and impaired voice quality results in even poorer performance and longer RTs in speech perception than each factor alone.
- H3: Noise or impaired voice quality reduces children’s performance and increases RTs in listening comprehension.
- H4: A combination of noise and impaired voice quality results in even poorer performance and longer RTs in listening comprehension than each factor alone.

Method

Participants

Figure 1 depicts the participant recruitment and selection procedure. Out of 94 first-grade children who participated in the experiment, 53 children (28 girls) between 5 and 6 years old ($M = 6;4$ [years;months]) were eligible for inclusion in the statistical analysis. Participants were recruited from five randomly selected primary schools

Figure 1. Flowchart presenting the recruitment of participants and selection of the final sample. ELO = Épreuve du Langage Orale; NEPSY = NEuroPSychologique de L’Enfant.



within the French-speaking community of Belgium. During information sessions, the children were given consent forms and questionnaires for their parents. The questionnaires concerned the child's age, mother tongue, auditory development, and speech-language development.

We applied the following inclusion criteria: (a) between 5 and 6 years of age, (b) French native speaker, (c) normal auditory development, (d) normal speech-language development, (e) hearing thresholds ≤ 25 dB HL bilaterally at octave frequencies between 500 and 4000 Hz (audiometric screening), (f) score ≥ 25 th percentile (i.e., normal and above-normal performance) in a receptive lexical subtest (i.e., LexR subtest of the Évaluation du Langage Oral (ELO) [Oral Language Evaluation]; Khomsi, 2001), and (g) score ≥ 25 th percentile (i.e., normal and above-normal performance) in an auditory selective attention test (i.e., AA subtest of the Bilan NEuroPSychologique de L'Enfant 2 (NEPSY-II) [Developmental NEuroPSYchological Assessment]; Korkman et al., 2007).

Children's compliance with inclusion criteria (a) to (d) was determined based on parental report (questionnaire), whereas compliance with criteria (e) to (g) was assessed on the day of the experiment during individual examinations in a quiet room at school. These examinations consisted of the pure-tone audiometric screening (using a MADSEN Itera II audiometer with TDH-39 earphones), the receptive lexical test (ELO material), and the selective attention test (NEPSY-II material).

Ethics Statement

All participating children gave their oral informed consent. Written informed consent was obtained from their parents. The ethics committee of the Faculty of Psychology, Speech Therapy and Education Sciences (University of Liège, Belgium) approved the study (File No. 1617-54).

Speech Perception Task

Speech perception was assessed by means of a phonological discrimination task. For this purpose, we created a digitized version of the Épreuve Lilloise de Discrimination Phonologique (Macchi et al., 2012). List 1 of this test is designed for French-speaking children aged between 5 years and 6;6 and contains 36 spoken pseudoword pairs (i.e., words that follow phonotactic rules but have no meaning, which controls for semantic priming effects). Speech items demonstrate either structural oppositions (e.g., kaʃifugR/ – /kaʃifugR/) or phonemic oppositions (e.g., /zil/ – /zij/) and their length ranges between one and three syllables. The children's task is to decide whether the two pseudowords in each pair are identical or different.

In our version of the task, children discriminated between the pseudowords by touching a screen (see Appendix A for a picture of the experimental setup). The task was presented on a laptop with an integrated touch screen (Dell Latitude 5480). We used the experimental software OpenSesame (Mathôt et al., 2012). Children were instructed to

discriminate between pseudowords by touching the correct response symbol on the screen (i.e., symbols denoting the options "same" vs. "different"). Speech stimuli were played via earphones (AKG K 271 MK II) in a randomized order. Performance was measured in terms of a binary outcome variable (1 = correct response, 0 = incorrect response). RTs were automatically collected in OpenSesame and comprised the time from stimulus offset to the moment the touch response was registered. This means that, irrespective of the listening condition, RTs were measured in quiet surroundings. The permitted RT was unlimited. Response symbols remained visible on the screen until the response was registered.

Listening Comprehension Task

Listening comprehension was assessed with a sentence-picture matching task from the ELO material (Khomsi, 2001). Again, a digitized version of the task was created for this study. Designed for children aged 5–10 years, the ELO sentence-picture matching task contains 32 sentences (21 of which are recommended for the use with 6-year-olds), which vary in length and syntactic complexity. Each sentence is presented orally with a set of four pictures (one target picture and three morphosyntactic or semantic distractors). The children's task is to match each sentence to the corresponding picture.

For the purpose of this study, the 21 ELO sentences were presented via earphones and pictures were presented on a computer screen (see Appendix B for a picture of the experimental setup). Presentation material and software were the same as for the speech perception task. Children were instructed to listen to each sentence and select the matching picture on the screen. Sentences were presented in a randomized order, and performance and RT measures were collected in the same way as for the speech perception task.

Listening Conditions and Stimuli Preparation

Speech stimuli (i.e., pseudoword pairs and sentences) were prepared according to four listening conditions: (C1) normal voice in quiet, (C2) impaired voice in quiet, (C3) normal voice in noise, and (C4) impaired voice in noise. For speech-in-quiet conditions (C1 and C2), we achieved highly favorable SNRs ranging between +31 dB and +33 dB (a certain amount of noise is introduced automatically during the recording procedure). For speech-in-noise conditions (C3 and C4), we applied a 0 dB SNR to simulate typical classroom conditions (Crandell & Smaldino, 1996; Howard et al., 2010).

We recorded the speech stimuli in accordance with the recommendations of Barsties and De Bodt (2015). The speaker was a 51-year-old female speech-language therapist. During a single recording session, she recorded all stimuli in her normal voice and an imitated dysphonic voice. These speech files are available in the NOrmophonic and DYsphonic Speech samples database (Schiller et al., 2019b).

A previous study validated both voice qualities using perceptual and acoustic evaluations (Schiller et al., 2019a). For the perceptual evaluation, five speech-language therapists listened to part of the speech samples and rated them on the parameters of the GRBAS scale (i.e., overall Grade, Roughness, Breathiness, Asthenia, and Strain; Hirano, 1981), as well as their authenticity and consistency. They perceived the normal voice as nonpathological (i.e., all GRBAS parameters rated 0), authentic, and consistent. The imitated dysphonic voice was perceived as rough and asthenic, and moderately to severely dysphonic (median GRBAS scores: Grade = 3, Roughness = 3, Breathiness = 2, Asthenia = 3, Strain = 1), with acceptable authenticity and consistency. Interrater reliability was moderate ($K = 0.52$). For the acoustic evaluation, we calculated the Acoustic Voice Quality Index (Maryn et al., 2010), which is based on a sustained vowel /a/ concatenated with connected speech, as an objective measure of dysphonia. Its score ranges from 0 (*normal voice*) to 10 (*severe dysphonia*). Moreover, we extracted jitter, shimmer, and harmonics-to-noise ratios (HNRs) from a sustained vowel /a/. The results were in line with the perceptual evaluations. The normal voice yielded a non-pathological Acoustic Voice Quality Index score of 2.53. Perturbation measures were also low. The imitated dysphonic voice yielded an Acoustic Voice Quality Index score of 6.89, indicating a moderate-to-severe voice pathology, and high perturbation measures (jitter = 2.8%, shimmer = 9.2%, HNR = 10.8). In summary, our voice evaluation suggested that (a) the speaker's normal voice was non-pathological, and (b) she succeeded in imitating a moderate-to-severe dysphonia.

Before the speech-in-noise conditions were created, all auditory stimuli were equalized to a mean level (root-mean-square) of 65 dB, using Praat (Version 6.0.29; Boersma & Weenink, 2017). Speech stimuli were then merged with SSN to create an SNR of 0 dB. We used the Speech Transmission Index for Public Address Systems signal (DIN EN IEC 60268-16; Deutsches Institut für Normung e.V. [German Institute for Standardization], 2019), an amplitude-modulated SSN covering several octave bands in the frequency range of speech (125 Hz to 8 kHz). Houtgast et al. (2002) developed this signal as a test signal for the Speech Transmission Index. The quasistationary characteristics of the Speech Transmission Index for Public Address Systems signal preclude the risk of erratic noise events masking certain phonemes more than others. At the same time, the signal approximates the spectral and temporal characteristics of speech, which is favorable because competing speech is a common type of interference in classroom listening. Speech-in-noise conditions (C3 and C4) were prepared such that the noise and speech signal always started and ended simultaneously. No noise was played between the items.

The long-term average spectra of the two voice qualities and the noise signal are presented in Figure 2. Two important aspects should be mentioned: First, the normal voice shows more spectral components than the impaired voice in frequency regions up to about 2000 Hz, which are critical for speech intelligibility (Ardoint & Lorenzi, 2010;

Ishikawa et al., 2020). Compared to SSN, the normal voice is more intense up to frequencies of about 1000 Hz (covering the fundamental frequency and the range of the first formant), which may contribute to vowel disambiguation. Second, the impaired voice generally shows more spectral components in higher frequency regions, with a peak between 3300 and 4100 Hz. This suggests a higher proportion of noise components (i.e., components potentially degrading speech intelligibility), which aligns with the low HNR (i.e., 10.8 vs. 25 in the normal voice).

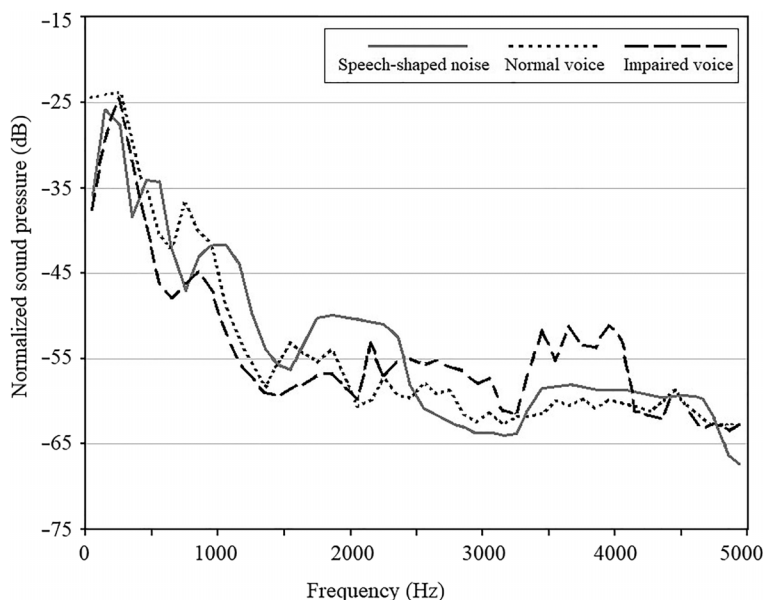
Procedure

Prior to the experiment, we ran a pilot study to evaluate the appropriateness and clarity of our material and experimental procedure. Five 5- and 6-year-old children were tested in quiet rooms in their homes. The pilot test confirmed that the study design was suitable, the instructions were comprehensible, and the 0 dB SNR was appropriate. Several children were not familiar with the touch screen, so we incorporated a short practice phase in the procedure for the main experiment.

The main experiment was conducted in separate rooms at each of the participating schools. Noise levels were measured with a PCE-353 sound level meter (PCE Holding GmbH) and ranged between 35 and 43 dB(A). A potential effect of ambient noise on the results cannot be fully ruled out, as the earphones used to present the auditory stimuli were not noise attenuating. Children were assessed individually. Each assessment lasted about 20 min. In a fully crossed design, all children performed both listening tasks: speech perception and listening comprehension. Stimuli were presented randomly according to the four listening conditions. For example, a child might listen to one item in a normal voice in quiet and the next item in an impaired voice in noise. We used OpenSesame software (Mathôt et al., 2012) to randomize sequence allocation based on participant number. The examiners were three second-year speech-language therapy students who were supervised by the first author (I. S.) to ensure standardized test administration.

During the experiment, we first seated the children in front of the laptop and taught them how to use the touch screen. Based on a sample speech signal, children were encouraged to set a comfortable intensity level. The experimenter then asked, "Is this level comfortable for you or is it too loud or too quiet?" and allowed time for further adjustments if necessary. Afterward, the experimenter launched the experiment, which started with the listening comprehension task followed by the speech perception task. Our rationale for this predefined order was that the task instructions for the listening comprehension task were less abstract, which helped children to become familiar with the response method. Each task began with a few practice trials (listening comprehension: $n = 3$; speech perception: $n = 4$). The practice trials used different material from the tasks and were later discarded from the statistical analyses. The children were instructed to listen carefully to each

Figure 2. Long-term average spectra of the normal voice, impaired voice, and speech-shaped noise. Signals were normalized to a mean level (root-mean-square) of 65 dB.



item and then to respond as accurately as possible by selecting the corresponding symbol (speech perception task) or picture (listening comprehension task). They received no instructions about how quickly they should respond and were unaware that RTs were collected. Considering the children's young age, we did not want to create any pressure regarding response speed. When a child touched the screen, it went black. The examiner launched the next item after verifying that the child was still attending to the task. Between the two tasks, the children were allowed a short break of about 1 or 2 min.

Statistical Analysis

Data were analyzed using R software (Version 3.3.2; R Core Team, 2019). Response variables were task performance and RT. Performance was assessed in terms of children's probability of correct responses. RT (in ms) comprised the time from stimulus offset to screen touch. Only RTs from correct trials fed into the statistical models, following the lead of earlier studies (Balota et al., 2013; McCreery & Stelmachowicz, 2013; Zhang et al., 2012). The rationale was that RTs from incorrect trials are difficult to interpret as errors may have different causes. RTs of less than 200 ms ($n = 30$) were considered unrealistically short (potentially representing fast guesses) and removed (Balota et al., 2013; Whelan, 2008; Zhang et al., 2012). We also removed RTs that were not immediately registered ($n = 21$). These RTs were removed based on the experimental record (i.e., the experimenter noted when a child touched the screen twice, which occurred if the first touch response was too soft). Overall, performance data include 3,021 trials and RT data came from 2,005 of these trials (i.e., 66%).

The relationship between these response variables was investigated with Spearman correlations.

Statistical modeling involved generalized linear mixed-effect models (GLMMs) using the `glmer` function of the `lme4` package (Version 1.1-15; Bates et al., 2015). Unlike classical analyses of variance (ANOVAs), GLMMs allow individual predictions rather than averaging data over items or participants (Baayen & Milin, 2010). With respect to the binary outcome variable task performance, we chose GLMMs because they have been claimed to generate more reliable results for categorical variables than ANOVAs (Jaeger, 2008). Regarding RTs, our data were positively skewed, which is a typical result (Whelan, 2008). They also contained missing values. We opted for GLMMs as they do not require prior data transformation to yield normal distributions (Lo & Andrews, 2015) and are powerful in dealing with missing data (Quené & Van Den Bergh, 2004).

To assess task performance, we fitted the GLMMs with a binomial distribution and a logit link function. Similar to Visentin and Prodi (2018), we modeled RTs with a gamma distribution and log link function. For each of the two tasks, we fitted one GLMM for task performance and one for RT. Noise (no added noise vs. SSN at 0 dB SNR), voice quality (normal voice vs. impaired voice), and the Noise \times Voice Quality interaction were treated as fixed factors. The models controlled for random effects of participant, item, and trial by means of random intercepts. School and gender were two further factors we initially considered but then dropped because they did not significantly improve the models.

Models were established by increasing their complexity in a stepwise process. Each new model was compared to the previous simpler model (e.g., Noise \times Voice Quality vs.

Noise + Voice Quality) by means of the Akaike Information Criterion (Akaike, 1974) using R's ANOVA function. When listening comprehension performance was modeled, the interaction term improved the model fit and was therefore kept as a fixed factor. The other three final models that predicted performance and RTs for speech perception and RTs for listening comprehension included noise and voice quality as separate fixed effects. We assumed an $\alpha = .05$ significance level. For significant effects, we performed pairwise comparisons using the lsmeans package (Lenth, 2016), adjusting for multiple comparisons by means of Tukey's honest significant difference test.

Results

In the following sections, we present the effects of noise and voice quality on performance and RT measures according to task. Regarding RTs, we generally found that children took significantly more time when responding incorrectly than when responding correctly, $\chi^2(1) = 117$, $p < .001$. For speech perception, mean RTs were 1,895 ms ($SE = 75$) for incorrect trials and 1,730 ms ($SE = 65$) for correct trials; for listening comprehension, the means were 4,153 ms ($SE = 281$) and 3,513 ms ($SE = 232$), respectively. The RT results discussed below concern only data from correct trials.

Effects of Noise and Impaired Voice on Speech Perception

Performance and RT measures for each condition of the speech perception task are presented in Figures 3 and 4, respectively. Figure 3 shows that performance was best in the control condition (C1: $M = .89$, $SE = .02$, range = 0.33–1), decreased in the impaired voice condition (C2: $M = .83$, $SE = .04$, range = 0.11–1) and the SSN condition (C3: $M = .72$, $SE = .05$, range = 0.22–1), and dropped close to chance level when the two factors were combined (C4: $M = .60$, $SE = .06$, range = 0.22–0.89). Likewise, Figure 4 shows that RTs were shortest in the control condition (C1: $M = 1,630$ ms, $SE = 98$, range = 986–3,708 ms), increased in the impaired voice (C2: $M = 1,737$ ms, $SE = 105$, range = 1,014–3,775 ms) and SSN conditions (C3: $M = 1,792$ ms, $SE = 108$, range = 1,095–3,911 ms), and were longest when the two factors were combined (C4: $M = 1,910$ ms, $SE = 116$, range = 985–5,569 ms).

Table 1 presents the GLMM results for the speech perception task. Both noise and voice quality significantly affected children's performance and RTs irrespective of gender. Compared to the control condition (C1), post hoc Tukey's honest significant difference pairwise comparisons showed that either impaired voice (C2) or SSN (C3) significantly reduced children's speech perception performance (C1–C2: $z = -4.5$, $p < .001$; C1–C3: $z = -9.16$, $p < .001$) and lengthened their RTs (C1–C2: $z = 3.52$, $p = .002$; C1–C3: $z = 5.14$, $p < .001$). Moreover, the combination of noise and impaired voice (C4) was significantly more disruptive than either factor alone, both in terms of performance

(C2–C4: $z = -9.16$, $p < .001$; C3–C4: $z = -4.5$, $p < .001$) and in terms of RTs (C2–C4: $z = 3.52$, $p = .002$ and C3–C4: $z = 5.14$, $p < .001$). Most of the remaining comparisons between conditions were also significant (performance: C1–C4: $z = -9.48$, $p < .001$; C2–C3: $z = -3.57$, $p = .002$; RT: C1–C4: $z = 6.1$, $p < .001$; and C2–C3: $z = 1.19$, $p = .632$). Speech perception performance did not correlate with RT ($r_s = -.08$, $p = .244$). The absence of a correlation between the task performance and RT variables indicated that there was no speed–accuracy trade-off, which would have occurred if fast responders made more errors than slow ones (Ratcliff et al., 2004).

Effects of Noise and Impaired Voice on Listening Comprehension

Figure 5 presents performance measures, and Figure 6 shows RT measures for each condition of the listening comprehension task. As illustrated in Figure 5, children's performance under the normal voice in quiet condition (C1) was equal to their performance with a normal voice in noise (C3: $M = .60$, $SD = .06$, range = 0–1). When listening to the impaired voice, however, children performed better in quiet (C2) than in noise (C2: $M = .66$, $SD = .05$, range = 0.2–1; C4: $M = .50$, $SD = .06$, range = 0–1). Figure 6 shows that RTs were relatively equal across all conditions (C1: $M = 3,415$ ms, $SE = 316$, range = 1,284–9,032 ms; C2: $M = 3,408$ ms, $SE = 314$, range = 1,084–8,347 ms; C3: $M = 3,509$ ms, $SE = 323$, range = 863–24,264 ms; C4: $M = 3,501$ ms, $SE = 324$, range = 1,196–23,186 ms).

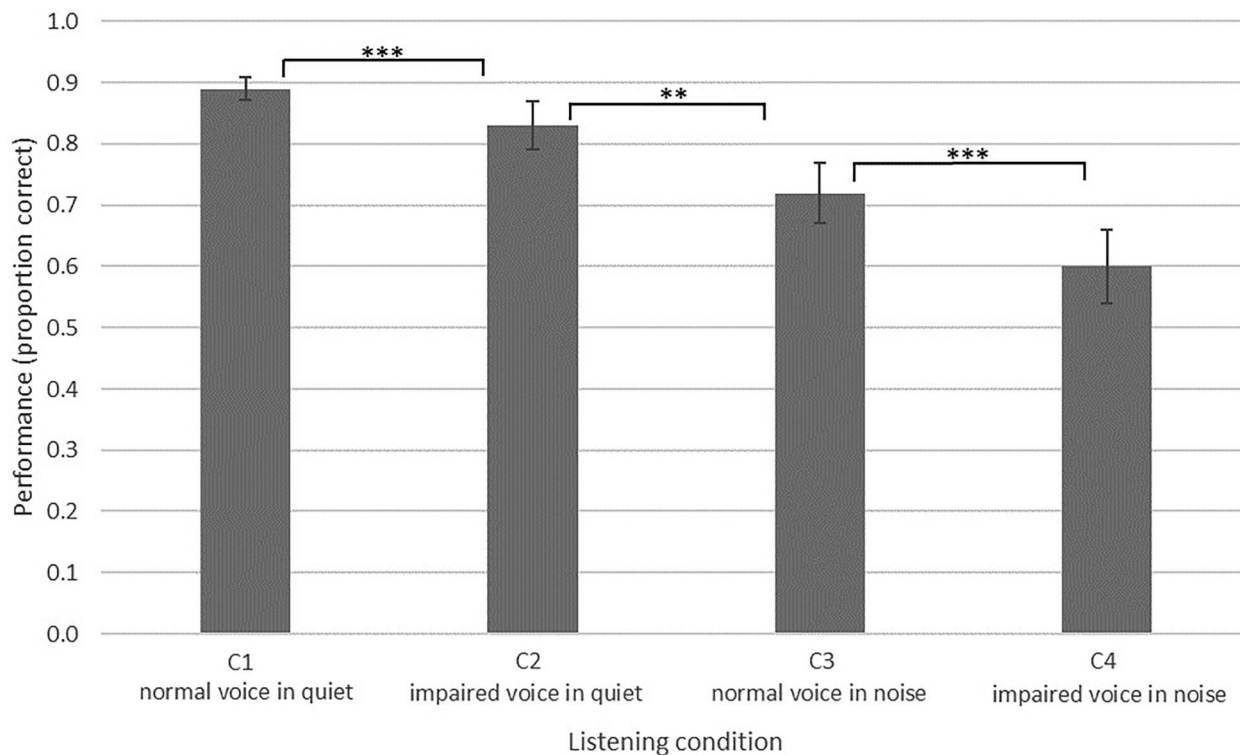
Table 2 presents the GLMM results for the listening comprehension task. Again, results were unaffected by children's gender. There was a significant interaction between noise and voice quality on children's task performance, indicating that SSN only impeded performance when the speaker's voice was impaired. Post hoc comparisons confirmed that the performance difference between the two impaired-voice conditions was significant (C2–C4: $z = -3.38$, $p < .01$), whereas there was no performance difference between the two normal voice conditions (C1–C3: $z = 0.17$, $p = 1$), and none of the other pairwise comparisons was significant. Neither noise nor voice quality significantly affected RTs. Finally, performance and RTs were not correlated ($r_s = .024$, $p = .73$), again suggesting that there was no speed–accuracy trade-off.

Discussion

Effects of Noise and Impaired Voice on Speech Perception

In this study, we explored the effects of noise and a speaker's impaired voice on first-grade children's speech perception and listening comprehension. The results of the speech perception task showed that each factor generated a decrease in performance and an increase in RT. This was in line with H1 (i.e., noise or impaired voice quality

Figure 3. Mean speech perception performance as a function of listening condition. Performance measured as probability of correct responses. Error bars represent standard errors (SE). ** $p < .01$. *** $p < .001$.



reduces children’s performance and increases RTs in speech perception).

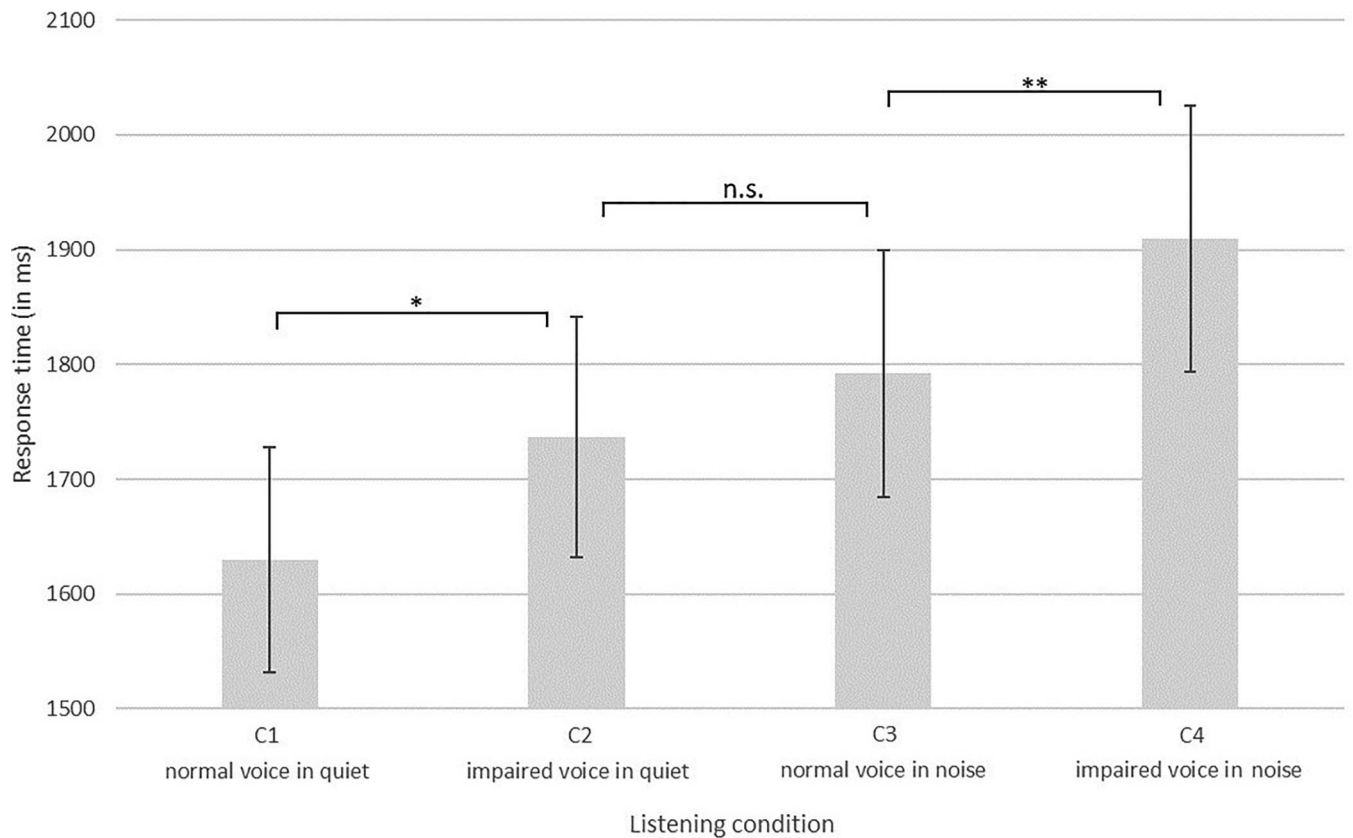
Regarding the effect of noise on speech perception performance, the results were generally in compliance with the findings of Jamieson et al. (2004) and Klatte et al. (2010), who assessed speech-in-noise perception in 5- to 8-year-olds. Their noise sources were classroom noise (Jamieson et al., 2004; Klatte et al., 2010) and speech noise (Klatte et al., 2010). A comparison with age-matched children from these studies supported the hypothesis that noise effects vary with noise source, task complexity, and SNR; in our study, SSN at 0 dB SNR lowered phoneme discrimination performance by ~20% compared to the control condition. Klatte et al. (2010) found a similar effect size for classroom noise (~22%) but a lower effect size for speech noise (~6%) in a word–picture matching task presented at comparable SNRs. In Jamieson et al.’s (2004) study, classroom noise did not affect word–picture matching until an SNR of –6 dB. To better predict the effects of different noise sources on children’s speech perception, more studies should be conducted, in which several types of noise are contrasted (e.g., Peng et al., 2016). Nevertheless, interstudy comparisons are hampered due to methodological differences.

Our results showed a significant increase in RTs of ~170 ms in noise at 0 dB SNR compared to quiet. This supports earlier findings by McCreery and Stelmachowicz (2013); Prodi, Visentin, Borella, et al. (2019); and Prodi,

Visentin, Peretti, et al. (2019), who administered speech perception tasks to children aged 6–12 years, 11–13 years, and 5–7 years, respectively. For example, McCreery and Stelmachowicz (2013) measured an RT increase of ~90 ms in noise when SNRs dropped from +9 dB to +3 dB SNR. For Prodi, Visentin, Borella, et al. (2019), classroom noise (but not traffic noise) presented at ~0 dB SNR resulted in an RT increase of ~130 ms compared to no additional noise. However, McGarrigle et al. (2017) found no effects of noise on children’s RTs. In Nakeva von Mentzer et al.’s (2018) study, children actually responded faster in noisy conditions than in quiet conditions. Possible reasons for these unexpected findings might be floor/ceiling effects (McGarrigle et al., 2017) and an unbalanced test order (Nakeva von Mentzer et al., 2018). We controlled these factors by using an existing task with available reference data and by ensuring a randomized sequence. Our results indicate that noise may slow down children’s SLP even when auditory–perceptual mapping is successful (recall that we only analyzed RTs from correct trials). Concurring with the cognitive mechanisms described in the Ease of Language Understanding model (Rönnberg et al., 2013) and the Framework for Understanding Effortful Listening (Pichora-Fuller et al., 2016), we interpreted this RT increase as an indication of listening effort resulting from excessive processing costs.

Our study provides the first evidence of the negative effect of impaired voice on phonological discrimination in

Figure 4. Mean response time in speech perception task as a function of listening condition. Error bars represent standard errors. * $p < .05$, and ** $p < .01$. n.s. = not significant.



5- to 6-year-old children. Listening to an impaired voice lowered performance by ~11% and increased RTs by ~100 ms. The disruptive effect of impaired voice concurs with the findings of Morsomme et al. (2011), although their listeners were older (8 years) and the results involved only performance measures. We assume that the negative effect of impaired voice is due to imprecise phoneme realizations, an example being the devoicing of voiced phonemes (Schoentgen, 2006). In line with this assumption, a recent study showed that dysphonia reduces vowel intelligibility (Ishikawa et al., 2020). As opposed to when listening to a normal voice, children seem to have required more processing time to discriminate such nonprototypical phoneme

candidates (e.g., when discriminating the pseudowords /tɔ̃kl/ and /tɔ̃gl/).

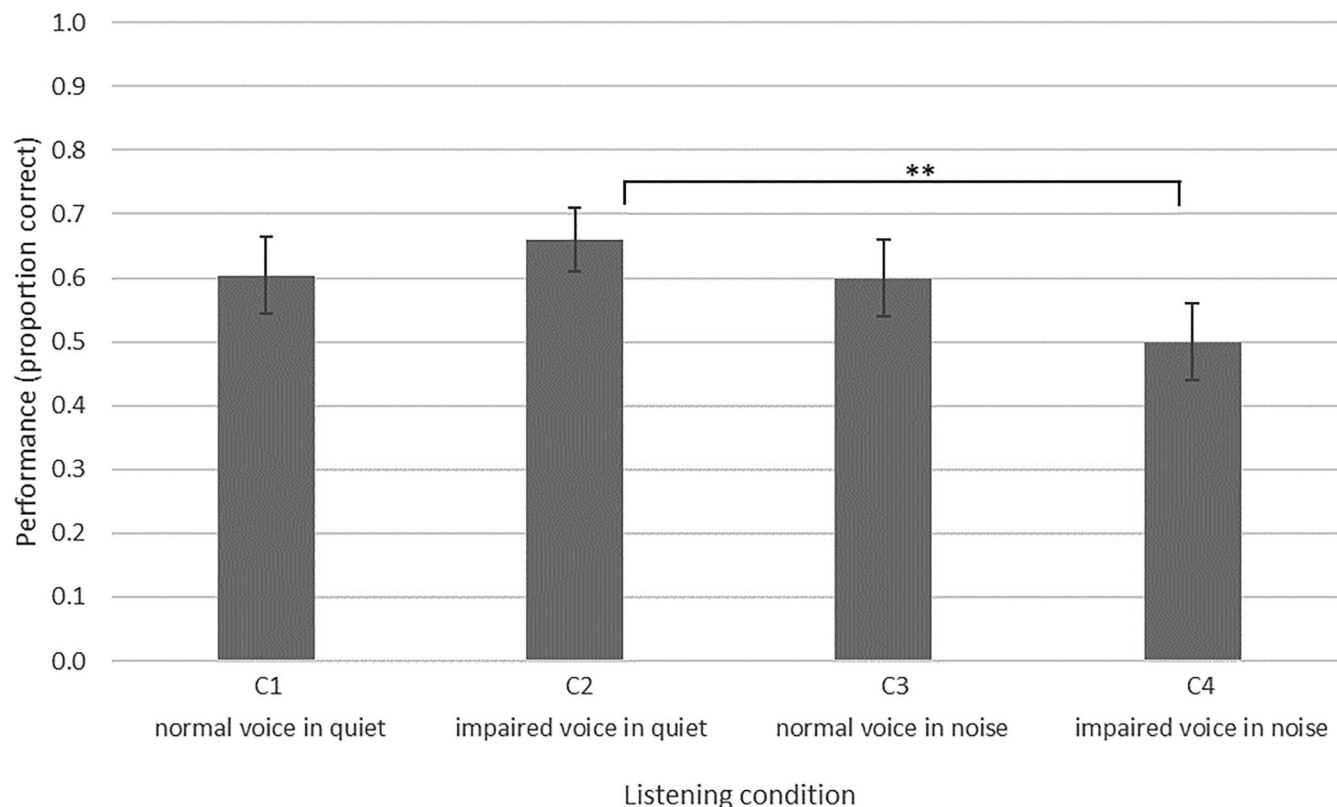
In line with H2 (i.e., a combination of noise and impaired voice quality results in even poorer performance and longer RTs in speech perception than each factor alone), the combination of noise and impaired voice had more detrimental effects on children’s performance and RTs than each factor in isolation. When listening to an impaired voice in noise, children’s performance decreased by ~33% and RTs increased by ~270 ms compared to the control condition. In the absence of any contextual cues, the speech perception task required children to rely solely on auditory-perceptual mapping. This was no longer possible as

Table 1. GLMM results for the speech perception task in terms of performance and response time.

Fixed factor	Performance				Response time			
	β	95% CI	z	p	β	95% CI	t	p
Noise (SSN vs. no added noise)	-1.16	[-1.40, -0.91]	-9.16	< .001	0.1	[0.06, 0.13]	5.14	< .001
Voice quality (impaired vs. normal)	-0.55	[-0.78, -0.31]	-4.5	< .001	0.06	[0.03, 0.1]	3.52	< .001

Note. Performance measured as the probability of correct responses. Response times for correct trials measured in milliseconds. GLMM = generalized linear mixed-effect models; β = fixed effect coefficient; CI = confidence interval; SSN = speech-shaped noise.

Figure 5. Mean listening comprehension performance as a function of listening condition. Performance measured as probability of correct responses. Error bars represent standard errors (SE). $**p < .01$.



intelligibility became too low to restore missing phonemes. Importantly, the effect of noise did not simply outweigh the effect of impaired voice but added to it. In the present study, we applied an imitated, moderately to severely dysphonic voice. It would be interesting to investigate whether the results would change if the degree of dysphonia was lower.

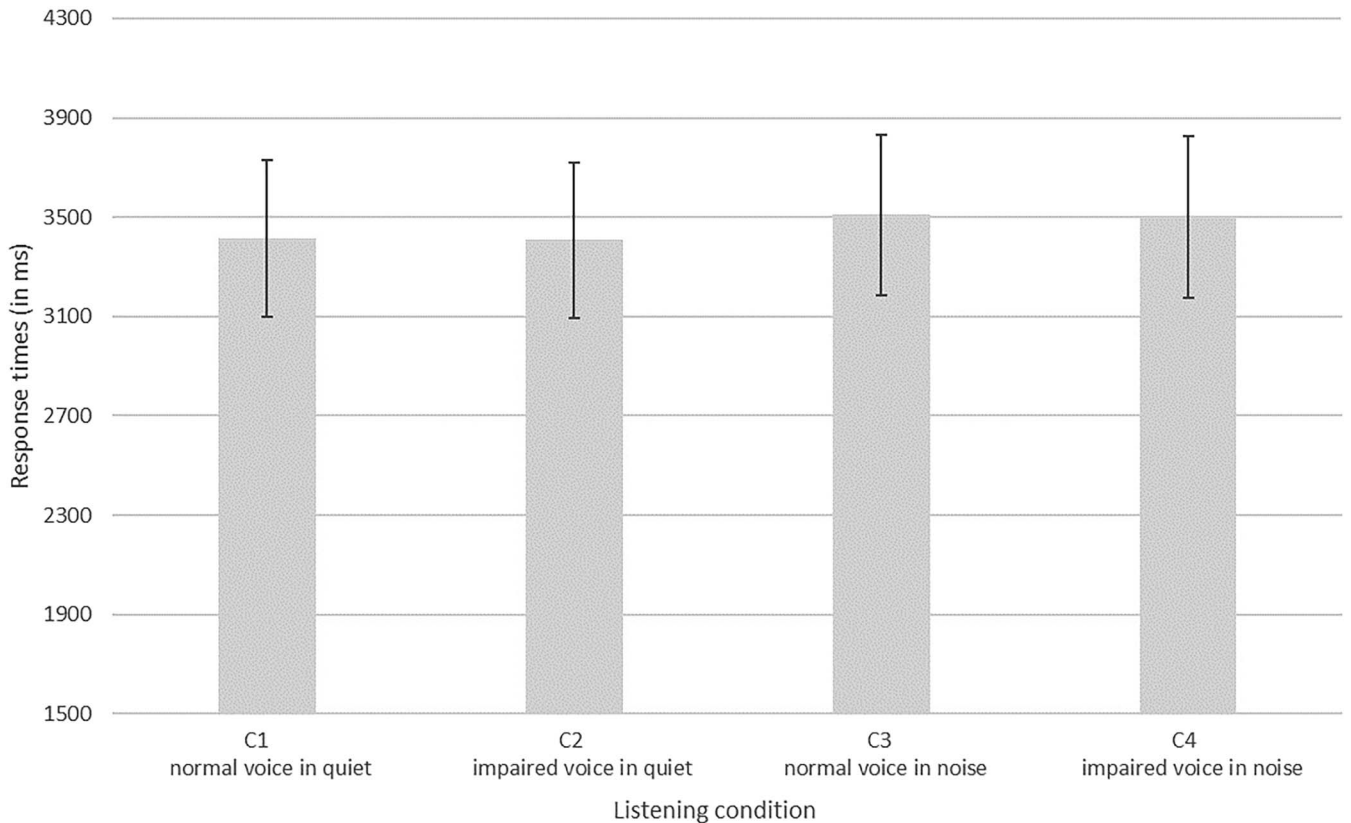
Effects of Noise and Impaired Voice on Listening Comprehension

Contrary to H3 (i.e., noise or impaired voice quality reduces children's performance and increases RTs in listening comprehension) and previous studies (Chui & Ma, 2018; Klatt et al., 2010; Morsomme et al., 2011; Osman & Sullivan, 2014; Prodi, Visentin, Borella, et al., 2019; Rogerson & Dodd, 2005; Sullivan et al., 2015), we found that noise and impaired voice quality did not have separate effects on children's performance or RTs in the listening comprehension task. One reason might be that this task offered syntactic and semantic contextual cues the children could use to compensate for reduced intelligibility. Considering that comprehension performance collapsed when the two factors were combined, the benefit of contextual cues seems to have diminished as listening conditions became too adverse. In addition, the strong variance in performance

and RT data suggests that the lack of main effects of either noise or impaired voice could also relate to item heterogeneity (i.e., variations in sentence length and syntactic complexity). Although our GLMMs controlled for the effect of item, the fact that working memory demands varied between the sentences is not ideal. Consider, for example, that children's speech-in-noise listening performance has been shown to correlate with their working memory loading (Sullivan et al., 2015). In line with this, impaired voice appears to be most disruptive at an intermediate degree of task difficulty, whereas the effects diminish as the task becomes either too simple or too complex (Lyberg-Åhlander, Brännström, & Sahlén, 2015). Analyzing performance and RT data for each individual sentence might therefore have revealed more detailed information regarding this factor, but it was beyond the scope of the present study.

Our results partially confirmed H4 (i.e., a combination of noise and impaired voice quality results in even poorer performance and longer RTs in listening comprehension than each factor alone). The central result was the significant interaction effect between noise and voice quality on children's performance (but not RTs). When the speaker's voice was normal, performance was unaffected by noise. However, when the speaker's voice was impaired, noise decreased performance by ~23%. Analyses of the long-term average spectra (see Figure 2) indicated that the

Figure 6. Mean response time in listening comprehension as a function of listening condition. Error bars represent standard errors (SE).



spectral properties of the speech signals might have contributed to this finding. For example, the normal voice was characterized by more spectral components in frequency regions up to about 2000 Hz (regions that are important for speech intelligibility). As shown by Schiller et al. (2019a), the normal voice was also more favorable in terms of HNR (i.e., 25 dB vs. 10.8 dB). These factors suggest that the impaired voice was more susceptible to energetic masking by noise than the normal voice. Although our results did not entirely concur with H4, they demonstrate that a combination of noise at a typical classroom level (Howard et al., 2010) and a speaker's impaired voice may severely affect children's listening comprehension. We speculate that this

effect is twofold: (a) Speech intelligibility declines with the increasing spectral overlap of speech and noise signals, and (b) listening becomes more effortful as more cognitive capacity is taken up by the processing of the speaker's atypical voice quality or the inhibition of irrelevant noise.

In contrast to this study, the two previous studies that investigated the combined effects of noise and impaired voice on children's listening comprehension found neither an additive effect nor a significant interaction (Brännström, von Lochow, et al., 2018; von Lochow et al., 2018). Let us consider some possible reasons: first, we applied a 0 dB SNR, which likely resulted in a higher ratio of masked speech segments than the more favorable SNRs applied by

Table 2. GLMM results for the listening comprehension task in terms of performance and response time.

Fixed factor	Performance				Response time			
	β	95% CI	<i>z</i>	<i>p</i>	β	95% CI	<i>t</i>	<i>p</i>
Noise (SSN vs. no added noise)	-.03	[-0.4, -0.34]	-0.17	.863	0.03	[-0.05, 0.1]	0.72	.47
Voice quality (impaired vs. normal)	-.23	[-0.14, -0.60]	-1.21	.226	0.0	[-0.07, 0.07]	-0.05	.957
Noise \times Voice Quality	-.60	[-1.13, 0.09]	-2.28	.023	—	—	—	—

Note. Performance measured as the probability of correct responses. Response times for correct trials measured in milliseconds. GLMM = generalized linear mixed-effect models; β = fixed effect coefficient, CI = confidence interval; SSN = speech-shaped noise.

von Lochow et al. (2018; i.e., +5 dB) and Brännström, von Lochow, et al. (2018; i.e., +10 dB). Second, we used SSN, whereas the other two studies used actual speech noise (i.e., noise coming from one or more speakers, inducing different proportions of energetic and informational masking; Mattys et al., 2009). Third, we used an imitated impaired voice with a moderate-to-severe degree of dysphonia, whereas the other two studies used provoked impaired voices with a mild-to-moderate degree of dysphonia. Although previous studies have suggested that even mild voice impairments may affect performance (Chui & Ma, 2018; Rogerson & Dodd, 2005), it is still possible that our impaired voice was more disturbing. Finally, von Lochow et al. (2018) and Brännström, von Lochow, et al. (2018) tested children with a mean age of 8 and 10 years, respectively, who might have possessed more advanced SLP skills to cope with adverse listening conditions than our 5- and 6-year-old participants. This concurs with the assumption that children become less affected by masking and more proficient at using contextual cues in noisy situations as they get older (Elliott, 1979).

Overall Considerations

In this study, both noise and impaired voice were found to hamper children's processing of spoken language. However, how can we distinguish between their effects on the speech signal and on SLP? Regarding effects on the speech signal, this is relatively straightforward: Impaired voice modulates the speech signal during production. Acoustically, it is characterized by correlates such as increased noise components or F0 and amplitude irregularities (Schoentgen, 2006). Noise interferes with the speech signal during its transmission by creating overlapping acoustic information (Cooke et al., 2008; Mattys et al., 2009). Regarding effects on children's SLP, the differentiation is less clear-cut. As our results indicated, both factors may reduce intelligibility—impaired voice by distorting speech (e.g., devoicing of voiced phonemes) and noise by masking it—and may increase listening effort. An important difference concerns the quantification of exposure; noise interference can be quantified by means of SNR. To measure the degree of dysphonia, researchers rely on subjective ratings or acoustic analyses. We therefore question the claim that noise may be more disturbing than impaired voice (Brännström, Kastberg, et al., 2018). Although the findings from the speech perception task would support this claim, we argue that drawing such a comparison is problematic since noise and impaired voice do not share a common metric. In the future, it may be interesting to explore whether SNR and HNR can be related in a way that allows the comparison of interfering noise and “phonation noise” (i.e., noise caused by dysphonia).

Limitations

There are some limitations on this study that should be considered. First, adhering to the common practice in speech-in-noise perception studies (Crandell et al., 1996;

Klatte et al., 2010; McGarrigle et al., 2017; Peng et al., 2016), the speech recordings were made in quiet conditions. While this approach ensures a high recording quality, it does not account for the fact that speakers adapt their voice use in noisy situations—the Lombard effect (Lombard, 1911). Such vocal adjustments may improve speech intelligibility (Garnier & Henrich, 2014), and it is therefore possible that our speech-in-noise conditions posed a greater listening challenge than if Lombard speech had been used (e.g., Brännström, von Lochow, et al., 2018; von Lochow et al., 2018).

Second, we prepared the auditory stimuli such that speech and noise started and ended simultaneously in each speech-in-noise condition. The rationale was to keep the length of the items stable across the four different listening conditions, randomized across participants. We concede that this method has the risk that noise onsets may potentially affect children's performance. Introducing a lead time (i.e., launching noise prior to the speech signal) could avoid this problem and might therefore be the preferred method. For example, Visentin and Prodi (2018) and Brännström, von Lochow, et al. (2018) launched noise signals 1,000 ms before the start of the speech signal.

Third, in line with some previous studies (Prodi, Visentin, Peretti, et al., 2019; Visentin & Prodi, 2018), we defined RT as the time between the offset of the auditory stimulus and the point when the child touched the screen. However, RTs to speech stimuli may vary with a listener's motivation (Lyberg-Åhlander, Brännström, & Sahlén, 2015), and motivation is likely affected by item length and complexity. To better account for this aspect, it would have been interesting to also measure RTs from the onset of the auditory stimulus and relate them to the RTs reported here.

Conclusions

This study shows that listening to speech in noise and/or to a speaker's impaired voice may disrupt children's ability to process spoken language. SSN and impaired voice impeded 5- and 6-year-old children's performance and lengthened their RTs in a speech perception task, particularly when combined. It seems that, even when no processing errors are made, adverse listening conditions still slow down children's phoneme perception. The results of the listening comprehension task revealed that children's speech-in-noise performance declined significantly when the speaker's voice was impaired but not when it was normal. Taken together, our findings suggest that a combination of noise and impaired voice may be especially detrimental for SLP in school-aged children, which has crucial implications for the educational context. Children would probably need to explicitly employ processing capacity to understand a dysphonic teacher in a noisy classroom. This may be particularly difficult for children with language or hearing impairments, or nonnative speakers. Another important discovery was that noise and impaired voice affected SLP at quite an early stage. Disruptions during speech perception are likely to carry over to higher order SLP, potentially

affecting auditory working memory, syntactic parsing, and semantic processing. Future experiments in more realistic settings and with different noise sources are needed to confirm the ecological validity of our findings.

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Appendix A

Experimental Setup for the Speech Perception Task

Children listened to pairs of pseudowords and responded by means of screen touch. For each pair, they were instructed to decide whether the two pseudowords sounded the same (→ select identical planets) or slightly different (→ select different planets).



Appendix B

Experimental Setup for the Listening Comprehension Task

Children listened to sentences and selected the corresponding picture by means of screen touch. In this example, the sentence was "L'oiseau a fait son nid" [The bird built its nest].

