PROCEEDINGS of the
23rd International Congress on Acoustics

9 to 13 September 2019 in Aachen, Germany

Speech comprehension and intelligibility in noise in 11 to 13 years old children: what is the relationship?

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ABSTRACT

In classrooms, the correct reception of what the teacher says is a necessary condition for learning, but it is not sufficient to ensure that the content of the message is understood. Notwithstanding this, usually a direct positive correlation between the performance in speech reception and sentence comprehension (SC) is assumed. In fact, this idea is the ground for the use of speech intelligibility (SI) in the design of learning spaces. In this study, the relationship between SC and SI is investigated in three listening conditions, with reference to 159 school-age children, aged 11 to 13 years old, with normal hearing. Participants completed two tasks designed and validated to measure SI and SC, which were presented in three conditions: quiet, classroom noise and road traffic noise. The tasks were presented to groups of children within their classrooms, via tablet and loudspeakers, within a one-hour session. For each task, results in quiet were compared to the results in noise, assessing the specific effect of each masker; furthermore, the presence of an interaction between noise type and task type was investigated to gain insight on the relation between the two tasks.

Keywords: classroom acoustics, sentence comprehension, intelligibility

1. INTRODUCTION

For children in classrooms, the ability of hearing what the teacher says is critical for success in academic activities. However, the correct reception of the spoken message it is not sufficient to ensure that the content of the message is understood (1). Currently, all the standards in classroom acoustics are conceived to guarantee speech intelligibility (SI) only. The standards provide limits in terms of acoustical indicators, which are designed to account for the separate and/or joint effects of noise and room reverberation on speech reception. Unfortunately, SI is at the surface of the levels of representation involved in verbal processing (2), and it is mainly informative on the correct reception of the acoustic-phonetic cues of the message. Even though a variety of test have developed to evaluate SI, relying on progressively more cognitive demanding material (from isolated words, to unpredictable sentences), they are not able to capture the higher level language processing required in communication during lessons. Indeed, the latter relies on messages with variable syntactical forms, lexical, semantic and contextual information, and the listeners are expected not only to understand the content, but also to make inferences based on their previous knowledge.

In order to improve assessments based only on SI, a viable alternative is the usage of sentence comprehension (SC). This task provides information on levels of language processing beyond speech reception, since auditory, syntactic, contextual and semantic information can be manipulated in a

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simple and scalable manner (3). The comparison of the two tasks (SI and SC) have not been systematically examined, whereas some results are available for the comparison of SI and some more complex tasks of listening comprehension (4, 5). Overall, literature results point toward a poor relation between performance in speech intelligibility and comprehension tasks. The relation should be more closely investigated aiming at providing effective tools for the control of noise and reverberation in the classroom.

Reasons for the specific impact of noise and reverberation on the outcomes of verbal tasks in classrooms have also been formulated. In particular, it was found that the interference of noise on speech depends not only on the noise level, but also on its spectro-temporal characteristics. The changing state character of an unintelligible speech-like masker affects high level cognitive processing in both children and adults, due to the interference with the to-be-remembered material (6).

Furthermore, most of the available results related to speech processing of children in the classroom are based on their task performance, whereas only a few take into consideration their listening effort by using the behavioral measure of response time (7-9). Considering listening effort beside performance would allow depicting a more comprehensive view of both perceptual and cognitive processing that children implement to cope with listening in noisy classrooms.

The present study investigates SI and SC in real reverberating classrooms, using standardized test. Middle-school students were presented with the tasks in a closed-set format, by using portable devices (tablets). Three listening conditions were presented: quiet, traffic noise, classroom noise. Two outcome measures were considered (task performance and response time), and used to develop a comprehensive view of the speech processing phenomenon.

2. METHODS

2.1 Participants

A total of 159 students participated in the study, from nine classes (three for each grade) of two middle-schools located in Ferrara (Italy): 53 11-year-olds (33%), 49 12-year-olds (31%) and 57 13-year-olds (36%).

2.2 Experimental design

Participants completed the two tasks in the three listening conditions in one session, during the morning school-hours. An assessment of the students' reading comprehension in quiet was carried out in a separate session, one week after the experiment. The order of the tasks and the order of the listening conditions within each task was balanced across the classes of each age group. The three test lists used for each task were pseudo-randomized, in order to avoid the matching of the same test list with the same listening condition.

2.3 Laboratory classrooms

The experimental session took place in two laboratory classrooms, one for each school. Both classroom were box-shaped and had a similar volume of 155 m^3. In order to make the acoustic conditions of the two classrooms as similar as possible, one of the two spaces was equipped with sound absorbing polyester fiber blankets. The temporary acoustic treatment ensured that the difference in the reverberation time of the two classrooms was smaller than the just-noticeable difference defined in the ISO 3382 standard (10).

During the test sessions, the classrooms were setup as for regular lessons (desks and chairs arranged in regular lines and facing the teacher's desk). A Gras 44AB mouth simulator was placed close to the teacher's desk, at a height of 1.5 m, and used for the playback of the speech signals. Furthermore, a Look Line D203 omnidirectional source placed on the floor, close to one of the room corners, and used for the playback of the background noises.

2.4 Speech intelligibility task

Speech intelligibility was assessed by using the Matrix Sentence Test in the Italian language (11, ITAMatrix). In each trial a five-word sentence was orally presented. The sentence had a fixed syntactic structure but no semantical predictability (e.g., "Mary draw five little boxes"); it was pseudo-randomly generated from a 10x5 base-word matrix. After the sentence playback, the base-word matrix was presented to the participants; their task was to select the words they heard in serial order. Each trial was time-limited to 15 s.

Participants were presented with a total of 48 sentences (16 for each listening conditions); the three listening conditions were presented in a blocked fashion. For each sentence, speech intelligibility (percentage of correct words identified within the sentence) and response times (RTs) were recorded. The latter quantity was defined as the time elapsed between the audio offset and the selection of the first word on the tablet.

2.5 Sentence comprehension task

Sentence comprehension was evaluated by using the COMPRENDO test (12). The test consists of meaningful sentences in the Italian language, which differ in their syntactic complexity (e.g., "The mother is chasing the child" or "The child looks at the cat and the mother pets the dog"). The sentences were recorded by an adult, native Italian female speaker in a silent room. Afterwards, the sentences were digitally filtered to match the long-term spectrum of the female speaker of the ITAMatrix.

During the experiment, the sentences were orally presented to the participants. After the audio offset, a set of four images appeared on the tablet and the participants were asked to select the image that properly described the sentence they just heard. Each trial was time-limited to 12 s. Sixteen sentences were presented for each listening condition, and for each trial accuracy and response time were recorded.

2.6 Listening conditions

The tasks were presented in three listening conditions: quiet, road traffic noise and classroom noise. In all conditions the speech signal was fixed to a level of 63 dB(A), measured at 1 m in front of the mouth simulator; this correspond to a talker speaking with a vocal effort intermediate between "normal" and "raised" (13).

In the quiet condition the tasks were presented in the ambient noise of the classrooms, primarily made up by noises coming from the adjacent classrooms. In the traffic condition, recordings of a busy road in conditions of dense traffic were played back. The classroom noise consisted an unintelligible fluctuating masker mixed with sound events typical of a working classroom (pen drops, turning over of book pages…). The fluctuating masker was obtained by processing Italian phrases, spoken by a native female speaker, according to the established ICRA procedure (14).

The background noises were played back at a level of 60 dB(A), measured at the audience position. The noise level was chosen to be intermediate between the maximum and the minimum levels (70 and 50 dB(A), respectively) measured in working secondary-school classrooms (15).

The objective description of the listening conditions during the experiment was achieved by measuring the reverberation time and the long-term levels of the ambient noise, the speech signal, and the added background noises (reproduced as during the tests) at the end of the experiment, within the occupied classroom. The listening conditions are summarized in Table 1. It is worth noticing that the difference between the listening conditions in the two classrooms are always smaller than the JND for all the acoustic parameters. Then, the two classrooms can be considered as almost equivalent from the point of view of acoustical perception, and their results will be considered together henceforth.

Table 1 – Listening conditions in the two classrooms during the experiment (occupied conditions): reverberation time T_{mid} (average across the 500–2000 Hz octave bands), A-weighted sound pressure level, sound-to-noise ratio (SNR).

Acoustic parameter	classroom A	classroom B
T_{mid} [s]	0.68	0.69
speech signal level dB(A)	60.4	59.5
SNR – quiet (dB)	17.1	19.0
SNR – traffic (dB)	-0.5	-0.4
SNR – classroom noise (dB)	-0.1	0.6

2.7 Procedures

The participants were collectively presented with the test session. They were divided in groups

composed by the whole class, which took turns in the laboratory classroom.

Upon entering the classroom, each child was given a tablet and randomly assigned to a seating position. Afterwards the participants were briefly informed on the study aim, and started the test session. Prior to each task, verbal instructions were given to the participants, which were also familiarized with the task and the data collection system by presenting a set of four trials in quiet.

In the noisy listening conditions, the noise playback started approximately one second before the sentence and ended simultaneously to the signal. Each experimental trial was time-limited, and only when all participants had responded or reached the time out, the next sentence was played back automatically.

The whole experiment was managed by using a wireless test bench (9), based on a server application which simultaneously controlled the audio playback, the presentation of the base-matrix/images on the tablets and the data collection.

2.8 Data analysis

Statistical analyses were performed using generalized mixed-effects models (GLMMs), selected to deal with the repeated-measures design and the lack of normality in the distribution of the dependent variables.

The software *R* was used for the analysis (packages: *lme4*, *lsmeans*), with a significance level of 0.05. A GLMM with a binomial distribution was used to analyze the accuracy data (SI or percentage correct), whereas a Gamma distribution with a log-link function was selected for the RTs. The variable participant was included as a random intercept and the within-subject factor listening condition was included in the random effects as a random slope. Furthermore, the score in the reading comprehension task was entered in the models as a covariate. When appropriate, planned pairwise comparisons were performed, correcting for the test multiplicity using a Bonferroni procedure.

Prior to data analysis, missing data points due to technical errors or out-of-times were removed from the databases (7.1% for the SI task, 1.4% for the SC task).

3. RESULTS

3.1 Effects of listening condition of task performance

Two GLMMs were set up, one for each task, with performance as the dependent variable; listening condition was included as a fixed factor. Figure 1 displays the performance as a function of listening condition, for the two tasks.

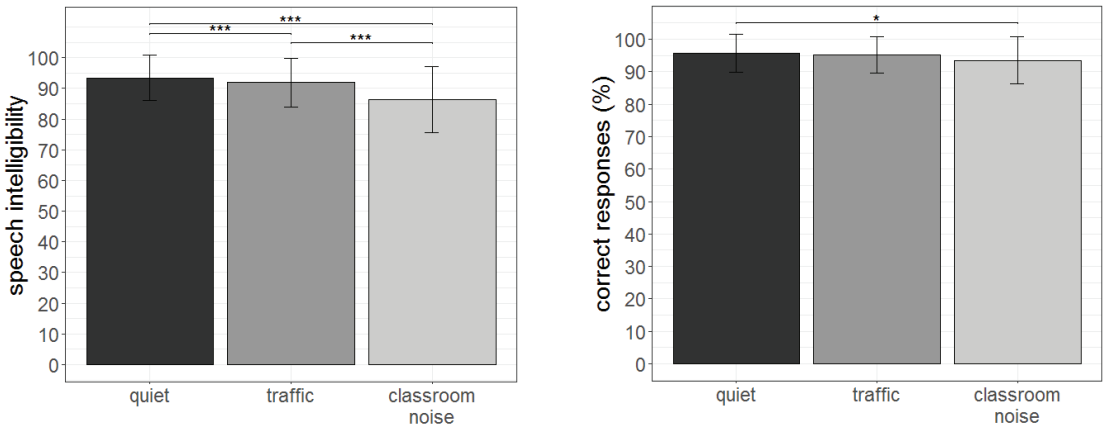

Figure 1 – Mean performance (SD) as a function of the listening condition for the two tasks: speech intelligibility (left panel), sentence comprehension (right panel). *$p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

For the speech intelligibility task, analysis revealed a significant main effect of listening condition ($\chi^2(2)=189.23$, $p<0.001$). Post hoc tests indicated that performance significantly decreased in noisy compared to quiet condition, and in classroom noise compared to traffic ($p<0.001$ for all comparisons). The performance decrease in traffic compared to quiet was equal to 1.6%; in classroom noise performance decreased of an additional 5.5%.

For the sentence comprehension task the effect of listening condition was significant as well

($\chi^2(2)=8.30$, $p=0.016$). Post hoc pairwise comparisons revealed that the probability of a correct response was significantly higher in quiet compared to classroom noise ($p=0.016$); the task performance decreased in classroom noise versus quiet by 2.2%.

3.2 Effects of listening condition of response time

Two GLMMs were set up, one for each task, with RT as the dependent variable; listening condition was included as a fixed factor. Figure 2 displays the RT as a function of listening condition, for the two tasks.

For the speech intelligibility task, analysis revealed a significant main effect of listening condition ($\chi^2(2)=22.63$, $p<0.001$). Post hoc tests indicated that RTs significantly slowed down in classroom noise compared to quiet and traffic ($p<0.001$ and $p=0.002$, respectively). The mean ratio (ratio of the mean RT in classroom noise to RT in another condition) was 0.92 with reference to quiet and 0.95 with reference to traffic.

For the sentence comprehension task the effect of listening condition was significant as well ($\chi^2(2)=30.60$, $p<0.001$). Post hoc pairwise comparisons revealed that RTs significantly slowed down in classroom noise compared to quiet and traffic ($p<0.001$ for both comparisons); no significant difference was found in the RTs of the two noisy conditions. The mean ratio was 0.92 with reference to quiet, and 0.93 with reference to the traffic condition.

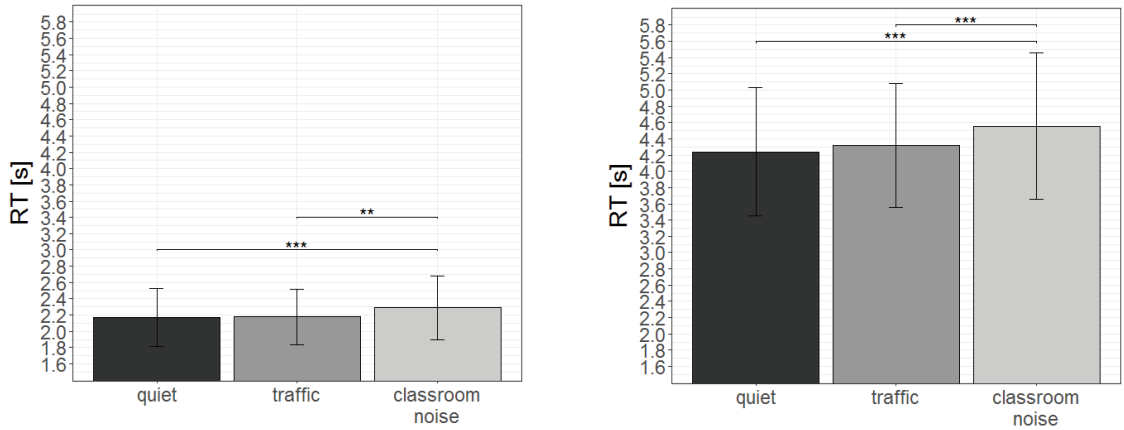

Figure 2 – Mean response times (SD) as a function of the listening condition for the two tasks: speech intelligibility (left panel), sentence comprehension (right panel). *$p < 0.05$; ** $p < 0.01$; *** $p <0.001$

3.3 Comparison of the effect of noise on the two tasks

In order to compare directly the effects of noisy conditions on performance and RTs of the two task, the relative change in noise compared to quiet was considered.

The change in performance was quantified by the ratio of the task performance in noise to the task performance in quiet. Therefore, the quiet condition has a value equal to the unity for all participants-task combinations, and smaller values denote decreased performance compared with the quiet condition. Concerning RTs, the normalization was defined by the ratio of the median RT in noise to the median RT in quiet, for each task. For this variable, values greater than one reveal increased listening effort compared with quiet. The normalized results are presented in Figure 3, as a function of the noisy listening conditions.

The statistical analysis was carried out with two LMMs (one for each dependent variable). The models included listening condition (traffic and classroom; as quiet was one by definition it was not included in the model), task (speech intelligibility, sentence comprehension), and their two-way interaction as fixed factors. The score in the reading comprehension task was added to the models as a covariate; a random intercept (participant) and two random slopes (the within-participant variables listening condition and task) were also specified.

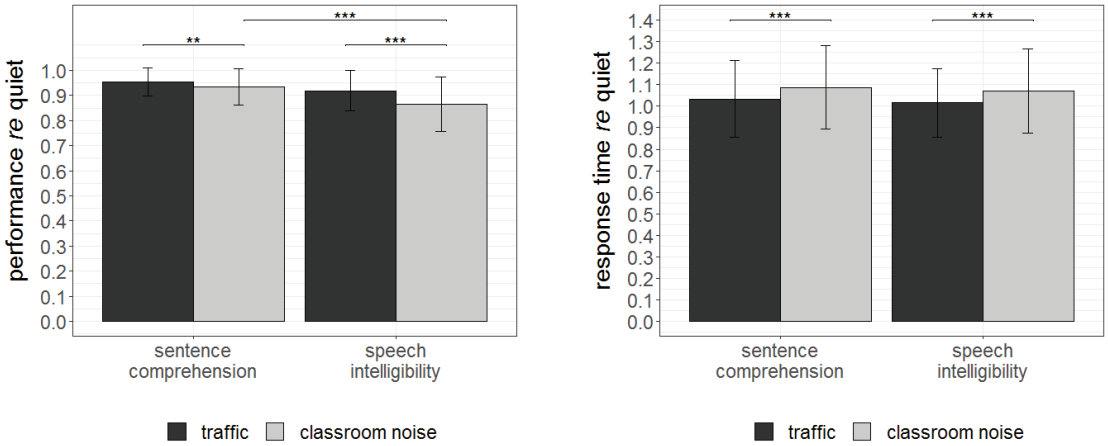

Figure 3 – Accuracy scores (left) and response times (right) relative to the quiet condition, as a function of the task and the noise type. *$p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Concerning the normalized performance, analysis indicated a significant effect of listening condition ($\chi^2(2)=59.33$, $p<0.001$) and task ($\chi^2(1)=18.18$, $p<0.001$), and a significant interaction between the two factors as well ($\chi^2(2)=23.93$, $p<0.001$). The pairwise comparisons between the tasks for each listening condition revealed a significant difference between the tasks only in classroom noise ($p<0.001$); no difference was found in traffic. When the effect of listening condition was considered for each task, the pairwise comparisons revealed that in both tasks the performance decrease was greater in classroom noise versus traffic (speech comprehension: $p=0.007$; sentence comprehension: $p<0.001$).

Concerning the normalized response times, the analysis indicated a significant main effect of listening condition ($\chi^2(1)=29.34$, $p<0.001$), with higher normalized results in the classroom noise condition compared to traffic. The main effect of task and the two-way interaction were not significant.

4. DISCUSSION

4.1 Effects of listening condition

For both tasks and dependent variables, a significant main effect of listening condition was found, indicating that the addition of a background noise at a level typical of a working classroom generally decreased the pupils' performance and slowed down the RTs compared to quiet.

When considering performance in the SI task, all listening conditions could be distinguished: classroom noise disrupted intelligibility significantly more than traffic, which in turn was more impairing than quiet. Differently, in the SC task, only a significant decrease in classroom noise versus quiet was be found, whereas performance in traffic was not significantly different from performance in quiet. This finding could be related to a ceiling effect observed in the accuracy of the task, with results higher than 95% for all listening conditions. The effect can be traced back to the additional cues that the pictorial representation of the actions provided and that supported the listeners in coping with the task. As expected, the classroom noise impaired performance in the two tasks more than traffic, due to its changing-state nature. In addition to this domain-specific interference, the effect of the classroom noise may also be related to a capture of attention. In fact, salient sound events (as the pen dropping, chair scratching events mixed to the ICRA signal) additionally impair the performance by capturing the listener's attention (16).

Concerning the effects of listening conditions on RTs, it was found that in both tasks the response latencies were longer in classroom noise compared with both quiet and traffic. In this study RTs was considered as a proxy of listening effort, with slower RTs indicating increased effort. The longer latencies in classroom noise, mirroring the performance decrease, indicated that more use of cognitive resources is needed for processing the auditory information in degraded listening conditions; this results in fewer resources available for the task and in turn in a poorer performance.

Differently, the absence of significant differences between the other two listening conditions

suggests that the 11-13 years children were able to cope successfully with the traffic noise, which did not impair listening effort in comparison with quiet. The finding is in line with previous studies that used response time as a proxy for listening effort for primary school students (9, 17) and indicated that even when background noises have the same SNR with respect to the teacher's voice, the difference in their spectral content may lead to an additional cognitive load.

4.2 Speech intelligibility *versus* sentence comprehension

This work addressed the relation between SI and SC using a standardized audiological test for SI and a standardized test battery for SC. The tools were designed to respond to cognitive mechanisms that do not match. In the SC tasks listeners are required to create a global picture of the sentence meaning by integrating lexical, semantic and syntactic information. Differently, the SI task requires to recognize and to recall all the words of the sentence, without any support from the context or from the fixed syntactic structure. Therefore, the absolute results of the two tasks were not directly compared and instead changes relative to quiet were considered.

Concerning performance, the analysis indicated a significant interaction between noise and task, suggesting that classroom noise had a greater impact on SI compared to SC. The finding is in line with previous studies, suggesting that the two tasks are differently impacted by the background noise level (4) and by the spectro-temporal characteristics of the masker (5). Overall, the findings suggest that directly transposing the results obtained in SI (in quiet or in noise) to SC might not be meaningful and thus acoustical conditions that guarantee optimal intelligibility might not be equally adequate for speech comprehension.

Concerning RTs, no significant interaction was found between noise and task thus suggesting that the increase of listening effort due to the presence of classroom noise did not depend on the type of task. However, further analyses are needed to get a deeper insight on the relation, which for instance may be influenced by developmental effects (e.g., age of the students).

Even though research on the topic is still scarce, the current results seem to suggest that the link between the SI and the SC tasks cannot be captured by a simple relationship, which is instead strongly influenced by the specific characteristics of the tasks themselves. For instance, it was found that the visual, closed-set format of the SC task selected greatly supported the listeners in solving the task and made SC comparatively easier than SI. The near-ceiling results prevented a direct comparison of SC and SI performance, so that it was not possible to draw a meaningful relationship between the two tasks. However, given the interactions pointed out by the analysis on the normalized quantities, it is believed that a more extensive investigation of the relationship would be of interest.

5. CONCLUSIONS

In this study, speech intelligibility and sentence comprehension in 11 to 13-year-olds were investigated under three listening conditions (quiet, traffic, classroom noise), aiming at better understanding the effects of background noise, and the relationship between the two tasks. The following results were found:

(1) A background noise with changing state characteristics was detrimental to the performance of 11 to 13-year-olds in both tasks; the effect was also mirrored by listening effort, as witnessed by a slowing down of the RTs. Differently, the children were able to cope successfully with the traffic noise, which did not impair listening effort in comparison with quiet.

(2) Classroom noise impaired more SI than SC but a clear relationship between the two tasks could not be derived, since several factors, such as the character of the noise and task details appear to modulate the relation between the two tasks. Further investigations are warranted to explore the relation over a wider range of SNR and noise types.

ACKNOWLEDGEMENTS

The authors would like to thank the schools, the children and the teachers who took part in the study. In addition, the authors acknowledge Hörtech GmbH, Oldenburg (D), for providing the speech recordings of the Matrix Sentence Test in the Italian language, and Cristiana Erbi, who administered and scored the reading comprehension test.

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