Listening effort for sentence comprehension in noisy classrooms: the mediating role of linguistic factors, inhibitory control, and noise sensitivity

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ABSTRACT

Children learn in classrooms in the presence of background noise, mostly produced by the children themselves. Even when the acoustic conditions are favorable (i.e., low noise levels), differences in individual performance and listening effort in complex academic tasks are observed. Personal characteristics such as linguistic and cognitive skills and sensitivity to noise have been reported as factors supporting students' performance. Moreover, the Framework for Understanding Effortful Listening (FUEL) postulates the additional, individual dimension of children's motivation should be considered when evaluating listening effort, besides task cognitive demands.

This study aims to explore the interplay of the above-mentioned individual factors for primary school children (N=120, grades 3 to 5) doing a sentence comprehension task in two-talkers background noise. Data on both accuracy and response time, as well as self-ratings of effort and motivation, were acquired. In addition, inhibitory control, linguistic competencies, and self-ratings of noise sensitivity were measured in quiet. Results first highlight the interplay of acoustic conditions and linguistic competencies in shaping the child's motivation in performing the task, and then show how the children's inhibitory control and noise sensitivity mediate behavioral and subjective effort. Thus, individual factors shall be taken into consideration when evaluating the effect of classroom acoustics on performance in academic tasks.

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1. INTRODUCTION

Children learn in classrooms in the presence of background noise. Several national and international standards were formulated in the last twenty years, aiming to define an acceptable level of background noise and guarantee a good speech reception. Unfortunately, the background noise the students are mostly exposed to is the one generated by the students themselves (i.e., other students chatting together) which can be hardly controlled through acoustic design strategies and has a high attention-capture potential, due to its informational content and presence of salient events. This type of noise may impair not only low-level auditory skills, such as speech identification and reception [1], but also more structured and cognitive-demanding tasks, such as reading, mathematics [2], and comprehension [3]. The latter in particular is a crucial ability for children, especially at the first levels of education, if they are to achieve academic success.

The consequences of learning in a challenging acoustic environment include reduced performance in the task at hand and increased listening effort, which is defined as the deliberate allocation of mental resources to overcome obstacles in goal pursuit when carrying out a task that involves listening [4]. Two dimensions contribute to the concept of listening effort: the cognitive demands during listening and the listener's motivation. The latter modulates the listening effort: the stronger the listener's motivation, the more willing she/he will be to put effort into the task, regardless of its demands. According to [5] the cognitive demands are related to four main aspects: (i) the acoustic conditions, (ii) the linguistic complexity of the speech material, (iii) the cognitive, and (iv) the linguistic abilities of the listeners.

Cognitive abilities, in particular, were found to mediate the effect of the acoustic condition on the listening effort [5], with listeners with lower cognitive abilities experiencing more effort in the same acoustic conditions and reaching an "overload" point of effort sooner than listeners with higher cognitive abilities, due to the fewer cognitive resources. With specific reference to children, von Lochow et al. [6] found an association between self-rating of effort in a passage comprehension task and high-level executive functions of the children. Children with better executive functioning experienced higher perceived effort by increasing the number of competing talkers in the background noise than children with poorer executive functioning. However, due to the general task selected for the study, it was not possible to pinpoint the exact measure of higher-level executive functions responsible for the association.

Another aspect that might influence children's perceived effort in noise is their noise sensitivity (self-rated by questionnaires). Individuals with high noise sensitivity are believed to have a lower perceptual threshold and might be particularly impaired by the presence of background noise. In recent studies in open-plan study environments, noise sensitivity was found to be related to the disturbance of students by the background noise [7] and to mediate the effect of noise in a writing task [8]. However, to date, no studies have explored the association for school-age children.

Therefore, considering the negative impact that listening effort and the resulting fatigue can have on the students' academic performance and their quality of life [9], it is crucial to understand both the acoustic conditions and the individual characteristics that might increase it. This study explored the mediating role of a linguistic factor (a basic literacy skill as the reading comprehension), a cognitive ability (one of the executive functions, the inhibitory control), and the self-reported noise sensitivity on the construct of listening effort. Two measures of effort (one behavioral, one subjective) were included in the study, as previous literature studies indicated that they might provide information about different dimensions of listening effort [10]. Consequently, they may be differently affected by the elicited individual characteristics. Moreover, the effort was evaluated over the two different subjective dimensions suggested by [5], asking the students to rate both the cognitive engagement when doing the task and the motivation to perform it in a good way.

2. MATERIALS AND METHODS

2.1. Participants

Children between the ages of 8 and 11 were recruited from eight primary school classes in Ferrara, Italy (equivalent to Year 4 to Year 6 in the UK). Data from five children were removed from the analysis, due to the presence of certified hearing disorders (*n*=1) or non-neurotypical development (*n*=5). The final sample of participants included 120 students (Year 4: n=28, M=8.25 years, SD=0.43 years, 15 female; Year 5: n=62, M=9.61 years, SD=0.49 years, 35 female; Year 6: n=30, M=10.9 years, SD=0.30 years, 14 female). Written informed consent was obtained from the children's parents.

2.2. Reading comprehension

Reading comprehension was assessed for the children, being one of the fundamental literacy skills for primary school students. A specifically created task was presented in quiet conditions on the same day as the experimental task. It consisted of four short narrative passages, differing in subject content, length (46-56 words), and syntactic complexity (simple, complex). After reading a passage on the tablet, the participants had to answer four multiple-choice questions about it (two factual questions, two inferential questions). Each question with a correct answer was scored as "one" whereas a wrong/missing answer was scored as "zero". Hence, the task had a maximum score of 16.
Based on the median score of the sample, participants were sorted into two groups ("low" and "high" literacy skills).

2.3. Inhibition

Inhibitory control of attention was assessed concerning the auditory domain, by presenting stimuli over headphones as a go/no-go task (adapted from [11]). Stimuli consisted of pure tones presented binaurally at 60 dB: the first stimulus (S1) was a pure tone at 1000 Hz presented for 100 ms, the second stimulus (S2) was obtained as a combination of two tones (tone at 1000 Hz presented for 100 ms – silence for 50 ms – tone at 800 Hz for 100 ms). S1 was presented on 70% of the trials and required response execution (button press response on the tablet – Go). S2 was presented on 30% of the trials and required inhibition of the response (not pressing the button – No Go). The inter-stimuli interval was set at 2000 ms.
There were two blocks, each consisting of 50 trials, preceded by a 10 trial practice block. Only presses to the Go tone with RT<2000 ms were considered correct, although all button presses were recorded to monitor omission and commission errors. For each trial, accuracy (correct/wrong answer) and speed of the response were recorded. The number of commission errors (over a maximum number of 30) was used as a measure of inhibition and used to sort the participants into two groups ("low" and "high" inhibition, based on the median split of the distribution).

2.4. Noise sensitivity

Noise sensitivity was assessed using the reduced Italian version of the Weinstein Noise Sensitivity Scale (WNSS [12]). The children had to indicate their agreement on five statements related to their sensitivity to noise. For each statement, the level of agreement could be chosen on a 5-point scale (from 1 "not at all" to 5 "very much"). The noise sensitivity questions were part of a broader questionnaire, implemented in Google Forms, and presented to the students one week after the experimental task in a quiet condition (ambient noise of the students' classroom).
To derive a single "Noise Sensitivity Scale" (NSS) score, the score of the last statement was flipped to match the direction of the others (i.e., higher scores imply a higher sensitivity to noise) and the average of the scores over the five statements was calculated. Participants were then sorted into two groups ("low" and "high" noise sensitivity) based on the median score of the sample.

2.5. Sentence comprehension task

The sentence comprehension task was designed to assess the children's ability to listen and comprehend a sentence in the presence of competing background noise.
For each listening condition, 15 sentences were aurally presented to the children using headphones. The sentences were split into three blocks, in which they were counterbalanced by syntactic complexity (low complexity: coordinate, passive objective relative, passive; high complexity: clitic,

relative objective). For each trial, participants listened to the playback of a sentence, with the noise starting around one second before the sentence offset and ending at the same time. At the audio offset, two images appeared on their tablet and they had to select the image that best matched the sentence content (Figure 1). It is worth noticing that in the image pair the action was always correct, whereas the order of the subject and the object was swapped. The image selection task was time-limited to 15 seconds.
Accuracy and RT (the time elapsed between the end of the audio playback and the moment an answer was selected) were recorded for each sentence.

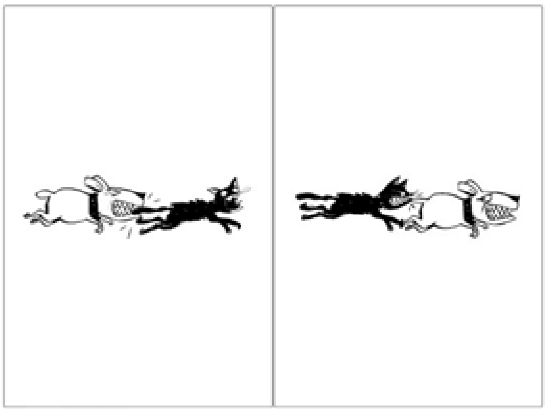

Figure 1 –Example of a set of images in the comprehension task. The target sentence was "Point to the cat that bites the dog".

2.4. Self-ratings of effort and motivation

Self-ratings of effort and motivation were collected following the completion of the experimental task in a given listening condition. The following questions were formulated:

- How hard did you have to work to understand the previous sentences?
- How important was it to you to perform well in the task?

Visual analog scales were used to collect the responses. Participants responded to the questions in the same order, using a slider bar with values ranging from 0 to 100 in increments of 1. The slider was initially positioned on the midpoint of the scale. Verbal anchors ("Not at all", "Extremely") were positioned at each endpoint of the slider bar.

2.5. Acoustic conditions

The sentence comprehension task was performed in two listening conditions, obtained by varying the presentation level of the same background noise, consisting of two competing talkers. To obtain the noise, two primary school girls were recorded individually in an anechoic chamber while reading aloud passages from different age-appropriate books. The individual recordings were normalized and convolved with the BRIRs simulated in a virtual classroom.
The classroom had a volume of 256 m^3, a reverberation time at the medium frequencies equal to 0.73 s, and was simulated in the room acoustic modeling program ODEON. In the virtual classroom, the receiver was positioned in the center of the area where students usually sit, and the competing talkers surrounded it, at nearly 1.5 m distance (front-right and back-left). A third speech source was simulated at the teacher position, close to the front of the classroom, in line with the receiver. The anechoic recordings of the two children and a female speaker reading the target material of the comprehension task were then convolved with the BRIRs in the virtual classroom.
For all the listening conditions of the experiment, the speech level was set to 60 dB(A). The background noise level was set to 59 and 51 dB(A), to obtain signal-to-noise ratios (SNR) equal to +1 and +9 dB. The SNRs were selected based on the findings in [13], measuring in classrooms an average SNR of 8 dB with a standard deviation of 6 dB. Therefore, both SNRs are deemed to represent

typical conditions in actual classrooms, with SNR=+1dB being at the more challenging end to increasing the involvement of cognitive resources.

2.6. Procedures and data analyses

A repeated-measures design was used in the study, with all children performing the comprehension task in the two listening conditions. Children took part in the experiment as a whole class, and the tasks were administered collectively in the classroom in which they usually have lessons. They completed the experimental task and the reading comprehension assessment in one session (testing time: 50 minutes), and the inhibition task and the noise sensitivity questionnaire in a second session, one week later. All tasks were completed using tablets and programmed using Gorilla (https://gorilla.sc/). Noise and signals were delivered via headphones (Sony MDR-ZX310).

Generalized linear mixed-effects models (GLMMs) were used for the statistical analysis, using the *R* software and the *lme4* package. First, models with SNR, syntactic complexity of the sentences, and level of literacy skills as fixed effects were created. The participant and item variables were included as random intercepts; moreover, the SNR was included as a random slope allowing for the possibility that the effect of the acoustic conditions could affect differently each participant. Then, further analyses were carried out to investigate whether there were any two-way interactions between the effect of noise (SNR) and individual characteristics (inhibition and noise sensitivity).

3. RESULTS

In the following sections, only the results for the outcomes of the experiment related to listening effort (response time, self-reports of effort, and motivation) will be presented.

3.1. Response time in sentence comprehension

Figure 2 shows the results for the response time, considering only the correct responses. The analysis showed that there were no significant main effects or interactions of the independent variables on the response time (all $p > 0.05$). However, when the individual characteristics of the children were included in the model, the presence of a significant main effect of the inhibitory control on the RT ($\chi^2(1) = 4.03$, $p = 0.044$) was found. The result suggests that students with a low inhibitory control have longer RTs than students with high inhibition (mean difference: 460 ms), independently of the listening conditions and the complexity of the task.

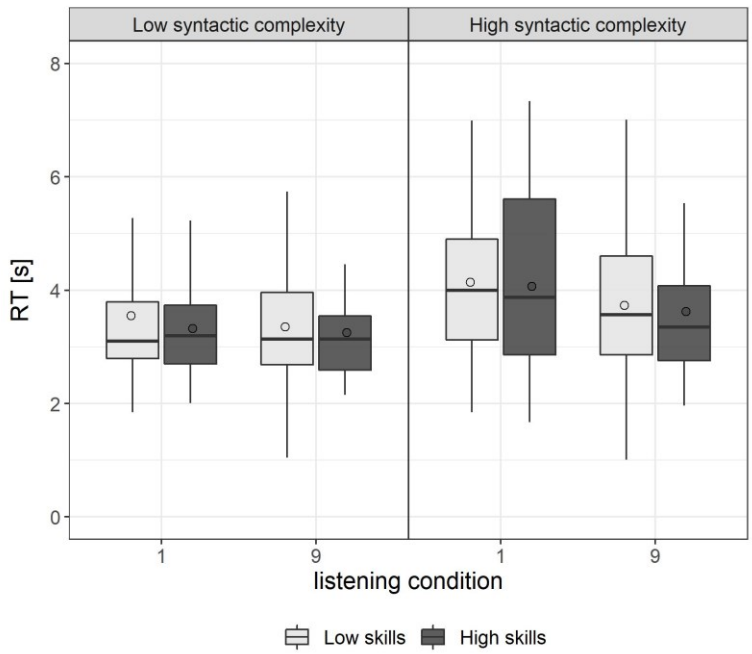

Figure 2 –Response time by listening condition (SNR= +1, +9 dB), sentence complexity and literacy skills of the students.

3.2. Self-ratings of effort

The analysis of the self-ratings of effort (Figure 3) indicated the absence of significant main effects or interactions of SNR and linguistic skills of the pupils on this measure. The second model, including noise sensitivity and inhibition, showed a significant main effect of the inhibitory control ($\chi^2(1)$ = 4.39, p =0.037) and a significant interaction between SNR and noise sensitivity ($\chi^2(1)$ = 4.92, p =0.027). The main effect indicated that students with a low inhibitory control rated the task as more effortful than the student with a high inhibitory control (mean difference: 12.5 points). The significant interaction suggested that students with a low noise sensitivity rated both listening conditions as equally effortful (no significant difference between the SNR), whereas the students with a high noise sensitivity rated the SNR1 condition as more effortful than the SNR9 condition (mean difference: 5.0 points).

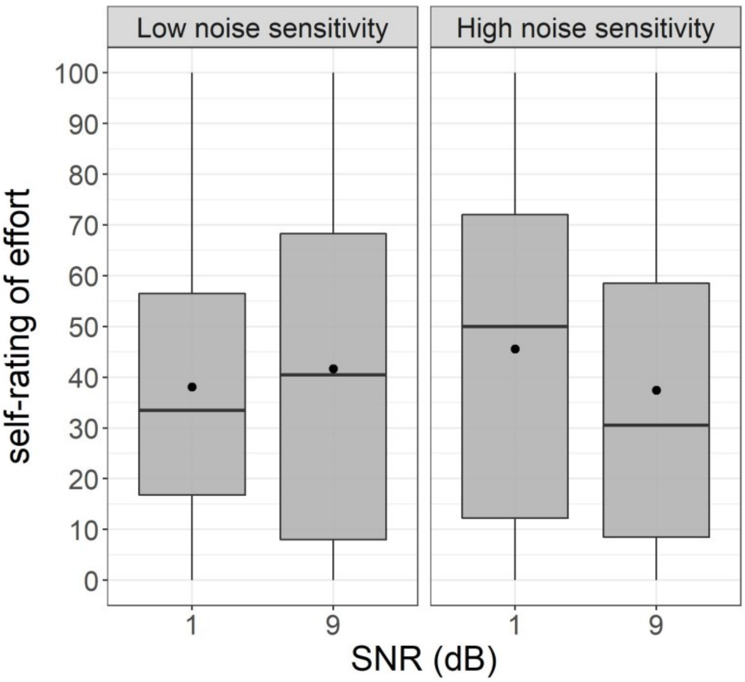

Figure 3 –Self-rating of listening effort by listening condition (SNR= +1, +9 dB), and self-reported noise sensitivity of the students. Higher values of self-rating indicate a greater perceived effort.

3.3. Self-ratings of motivation

The analysis of the self-ratings of motivation (Figure 4) indicated a significant interaction between the SNR and the literacy skills of the students ($\chi^2(1)$ = 8.58, p =0.003). The pairwise comparisons showed that students with higher literacy skills reported being significantly more motivated in doing the task in the SNR+9 than in the SNR+1 condition (p = 0.025, mean difference: 7 points). On the contrary, no difference in self-rated motivation was found for students with lower literacy skills. No other main effect nor interactions were significant ($p > 0.05$).

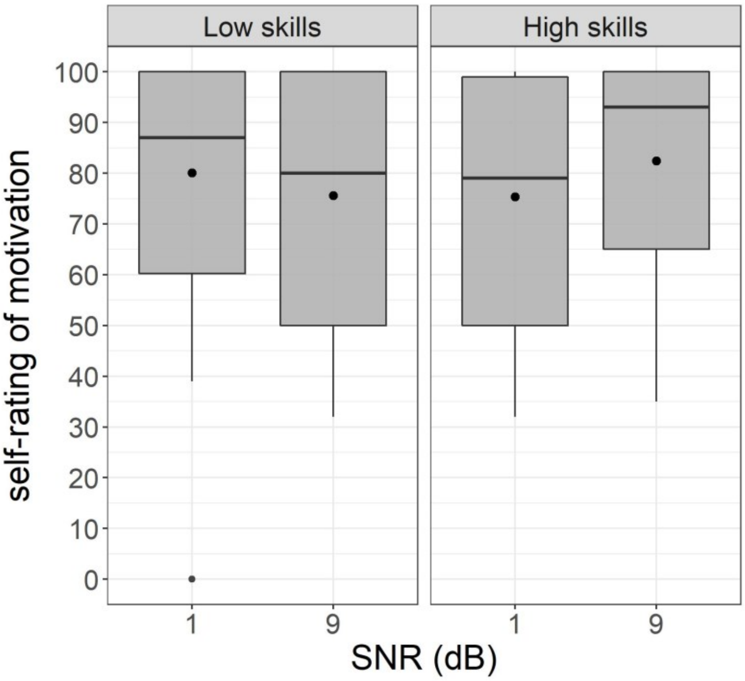

Figure 4 –Self-rating of motivation by listening condition (SNR= +1, +9 dB), and literacy skills (low/high) of the students. Higher values of self-rating indicate a greater motivation in completing the task.

4. DISCUSSION

The goal of this study was to measure auditory comprehension in noise for primary school children. Cognitive and linguistic factors, together with the individual characteristics of noise sensitivity were analyzed to determine their effect on the listening effort, measured both through the RT and self-rated through a VAS, and on the motivation to complete the task.

With reference to the effort caused by adverse listening conditions, by the variable cognitive demands of the task with inclusion of children's skills, the results of this study did not show any main effect of SNR effect in spite of the large difference used during the experiment. Previous studies showed instead that both RT and self-reports may demonstrate a benefit (i.e., faster RT and lower ratings) when even smaller SNR differences were used [14]. However, the difference in the cognitive demands of the task must be considered, being a low-level one in [14] (speech perception) and a high-level one in the present study. When the individual characteristics of the students were included in the analysis both measures of listening effort (RT and subjective data) were consistent in showing that inhibitory control was a statistically significant main effect, suggesting that this executive function might explain a remarkable part of the effort perceived by the children when performing a task in noise, whatever its sound level. As defined in [15], the inhibitory control of attention (also called *interference control at the perceptual level*) enables the listener to selectively attend to a stimulus, focusing attention on it and suppressing attention to other stimuli. It develops during childhood and continues to mature also during adolescence. The results of this study suggest that the individual inhibitory level might be predictive of the objective and subjective listening effort, or, in other words, that the ability to resist interference from noise goes along with the amount of cognitive resources allocated for doing the task (which builds the listening effort construct).

Moreover, only for the subjective listening effort, a significant interaction between SNR and self-reported noise sensitivity emerges from the analysis. Children who rated themselves as sensitive to noise also rated the SNR1 condition as being more effortful than the SNR9, suggesting that this individual characteristic might mediate the effect of noise on listening effort. Future studies should address this under-researched area, for which only results for adults are available.

From the FUEL model [4] it is clear that together with the cognitive demands of the task, also the individual's motivation affects listening effort. If a student has little motivation to understand the message of the teacher, a change in cognitive demands may result in little or no change in effort. Our elaboration did not employ motivation as an explanatory variable for listening effort: rather it aimed at a preliminary clarification of the relationship between children's skills and motivation during the deployment of the effort to reach the comprehension goal in noise. It was found that self-rated motivation is mediated by the literacy skills of the students so that children with a better mastering of reading comprehension (one of the foundation literacy skills for young learners) will be more motivated to maintain the effort and complete the listening task without disengaging when the listening conditions improve.

5. CONCLUSIONS

The main goal of this study was to explore the mediating role of the individual characteristics (cognitive and linguistic abilities, and noise sensitivity) on the listening effort of primary school children, with reference to a comprehension task. The results show that inhibitory control is a key cognitive ability that may explain part of the behavioral and self-reported effort of the children when doing the task. Self-rated noise sensitivity was found to mediate the effect of the listening condition on self-reported effort. Finally, the linguistic ability of reading comprehension was found to interact with the listening condition, significantly affecting the rating of motivation in completing the listening task.

Overall, the results of the study highlight the central role of the individual characteristics of the listeners in the construct of listening effort for school-age children. Future research should address which individual characteristics (and to what extent) are the most important for the construct, in order to develop an acoustic design approach for the learning spaces mostly centered on the students.

6. ACKNOWLEDGEMENTS

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