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Primary school children's verbal working memory performances in classrooms with different acoustic conditions

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ABSTRACT

Verbal working memory plays a crucial role in supporting the learning process over the school years. In this study, we investigated the role of the acoustic conditions of school classrooms, specifically reverberation time and babble noise, on second-graders' verbal working memory. A sample of twenty-five second-graders was administered a validated verbal working memory task in two different acoustic conditions, with a time frame of 1 month: *Poor acoustic quality* (long reverberation time [Long RT] and babble) versus *Adequate acoustic quality* (short reverberation time [Short RT] and babble). Results showed that the same children were able to remember fewer words and less accurately on the task in a classroom with longer reverberation time and babble compared to one with shorter reverberation time and babble. Moreover, children omitted more words in the recall task in the *Poor acoustic quality* condition than in the *Adequate acoustic quality* condition. The results suggested that primary school children's verbal working memory processing is sensitive to variations in the classroom acoustic conditions. These findings offer a research contribution about the importance of adopting a contextual view on cognitive development and insights for the implementation of school interventions in terms of metacognitive work on learning to listen and classroom design.

1. Introduction

In recent years, the relation between the acoustic quality of the school environment and the cognitive and learning process has received increasing attention, both nationally (e.g., Secchi et al., 2018) and internationally (e.g., Connolly et al., 2019). This field of research responds to the need to adopt a contextual view on cognitive development to highlight the effects of the characteristics of physical spaces on development and wellbeing, as suggested by the literature (Barrett et al., 2015). Focusing specifically on primary school and young children's cognitive functioning, this study aims to contribute to our understanding of the effect of background classroom speech, delivered with a multi-talker babble noise, on second graders' working memory performances when working in different school classrooms' reverberation levels. Babble noise was recorded in a classroom previously examined and represents a typical unintelligible chatter produced by pupils of a school. Working memory is a complex and dynamic process aimed at maintain a limited amount of information in an active and accessible state while simultaneously dealing with and processing new incoming

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information (Baddeley, 2007; Conway et al., 2008). Since the early years of life, the working memory plays an essential role for multimodal integration of information (e.g., verbal, semantic, symbolic types) (Morra, 2008; Morra & Panesi, 2017). The most acknowledged models in literature (e.g., Baddeley, 1986, 1996; Baddeley & Hitch, 1974; Baddeley & Logie, 1999) describe the system of working memory as including a limited-capacity central executive, a phonological loop involved in the temporary retain of verbal information (Baddeley, 1986), and a visual-spatial sketchpad functioning as a workspace for temporary storage of visual and spatial information (Logie, 1995). The central executive has the essential role of orchestrating the phonological loop and the visual-spatial sketchpad using a limited amount of cognitive resources (Baddeley, 1996). In this study we focused on the verbal dimension of working memory represented by the phonological loop functioning. The involvement of verbal working memory in higher-order complex cognitive activities, such as reading (decoding and comprehension) (Argyropoulos et al., 2017; Oakhill et al., 2003), mathematical ability (Van de Weijer-Bergsma et al., 2015), problem-solving (Fyfe et al., 2015), vocabulary and language acquisition (Martin & Ellis, 2012), is acknowledged in the literature. Verbal working memory plays a key role in supporting children's classroom activities. A concrete example of an everyday classroom activity that strongly relies on working memory is taking in mind lengthy instructions verbally described by the teachers to be applied by children when collaborating in a small group or when performing a task (e.g., writing a story with defined story plot or characters), and taking note with simultaneous processing and storage of lessons provided by the teacher (see also, Tracy, 2006). In the present study a specific focus on 2nd-graders was based on the assumption that an adequate functioning of verbal working memory, to store and manipulate verbal information in working memory, is foundational for progress in acquiring complex knowledge and skills in areas such as literacy (e.g., sentence listening while writing, story listening while processing comprehension) and mathematics (e.g., memory for mathematical formula instruction while processing a calculation). A minor distraction is likely to result in complete loss of the stored information, and so in a failed performance which risks compromising literacy and mathematics achievement in a long-term perspective. Among the various external (e.g., van Kempen et al., 2010; Belojevic et al., 2012; Haines et al., 2002) and internal (e.g., Maxwell & Evans, 2000; Shield & Dockrell, 2008; Klatte et al., 2010a) factors of school noise, Reverberation Time (RT) is a significant parameter to estimate the school indoor environmental acoustic quality. The phenomenon of reverberation originates when a sound is reflected from surfaces (i.e., materials or structures) resulting in echo signals that are reflected for a certain amount of time (e.g., Knecht et al., 2002). Reverberation is typically measured as the time required by the sound pressure level to decrease by 60 dB after the sound source has ceased to operate (T60). High levels of reverberation amplify speeches and sounds, resulting in a risk factor for effortful cognitive processing for children (Jianxin & Jiang, 2018), especially in the case of chronic noise exposure in classrooms (World Health Organization [WHO], 2020). Prior studies have shown that a high level of reverberation affects speech comprehension in high school pupils (Connolly et al., 2019), as well as in children and adults (Kjellberg, 2004; Klatte et al., 2010a), decoding (i.e., accuracy and speed) and writing processing in elementary school children (Dockrell & Shield, 2006), and logical-mathematical processing in children (Klatte et al., 2013). What is more, previous studies found that children exposed to high levels of reverberation in school environments reach lower scores on standardized tests (Klatte et al., 2013; Kristiansen et al., 2011; Shield et al., 2010) and undesirable behavioral outcomes (Avsar & Gönüllü, 2010), with longitudinal negative repercussions on emotional well-being (Bottalico & Astolfi, 2012; Kristiansen et al., 2011). In reviewing the literature, it emerges that the effects of reverberation of school classrooms are particularly urgent to be investigated in relation to cognitive processes such as verbal working memory that are at the basis of school activities and achievements. Specifically, children in the early years of primary school may be particularly sensitive to the acoustic quality conditions of classroom environments. Young children's verbal working memory functioning is still in development. The environmental features of the most significant life contexts in which the child spends a great amount of time may have an impact on the child's verbal working memory functioning, especially in primary school which is characterized by a strongly participatory approach. Both curricular and extracurricular activities at school promote interpersonal interactions and children's participation in school activities, lessons, and group activities. The presence of babbling and chatting in classrooms characterized by high reverberation constitutes a risk factor for the correct transmission of auditory-verbal information that, in turn, compromises the verbal working memory processes. The Italian reference standard for reverberation is UNI 11532–2:2020, which is mandatory according to the Ministerial Decree 11/10/2017 (minimum environmental criteria). The decree applies the most up-to-date international regulatory framework on the acoustic quality of school environments. The standard indicates the acceptable thresholds of reverberation time, clarity C50, and Speech Transmission Index for classrooms of different types and functions (music rooms, classrooms for lectures, classrooms for group lessons, including classrooms with students with hearing impairment). Despite this, noise exposure in Italian schools is a problem that remains unresolved, and classroom acoustical comfort is still inadequate due to high levels of noise and reverberation time (Minichilli et al., 2018; Secchi et al., 2016).

1.1. Working memory and classroom acoustic quality: which relation?

Studies mentioned above have indicated the significant role of effortful working memory processing for learning, language-related activities, and scholastic performance. However, few studies are focused on the effect that a poor classroom acoustic condition has on young children's verbal working memory. Among the few findings, some authors (e.g., Osman & Sullivan, 2014; Sullivan et al., 2015) have shown that the presence of babble noise impacts auditory working memory performance in school-age children (8 −10-year--olds). Indeed, the presence of babble noise interferes with working memory processes, particularly with the phonological loop processing, resulting in a lower working memory capacity (Jianxin & Jiang, 2018). The detrimental effect of noise also affects children's verbal stimuli elaboration, comprehension, and speech discrimination (Lewis et al., 2014; Shield & Dockrell, 2003). In the literature, some effects might explain these results. According to Marsh and colleagues (2009), the automatic processing of speech items before being subjected to attentional processes may interfere with the rehearsal of the to-be-remembered items (*interference by the process*). Furthermore, unexpected changes in speech may divert attention away from the task (*deviation effect*; Sörqvist, 2010). Young children may be particularly vulnerable to the effects of high levels of reverberation. Cognitive demands for adequate codification, monitoring, and elaboration highly increase when they try to compensate for lacking or mismatching speech information by background noise or by reverberation (Hurtig et al., 2016). In addition, the processes responsible for the performance, still immature in children (Vuontela et al., 2003), are likely to be a further disadvantageous aspect in young children. For this reason, the effects of classroom noise on verbal working memory acquire particular relevance if investigated in the early years of primary school, when not yet automatized processes (e.g., read and spell) could require a high demand of cognitive resources (e.g., working memory), that in turn could be reduced by inadequate classroom acoustic conditions (e.g., Jianxin & Jiang, 2018).

1.2. Rationale

The literature suggests that children's working memory is affected by classroom acoustic quality, including babble noise, and there is also evidence that reverberation levels are related to negative outcomes on test scores. However, the effect of reverberation in school classrooms on children's verbal working memory performance needs to be clarified. Thus, the present study tries to fill this gap in research by uncovering the mechanism by which reverberation levels may lead to negative outcomes in working memory performances. Specifically, this study contributes to advancing our knowledge in several directions. First, this study focused on the scarcely investigated population of second graders of primary school, while most of this kind of research has been conducted on adults (e.g., Bistafa & Bradley, 2000; Klatte et al., 2010b).

Second, this study is carried out in an ecological school setting (i.e., classrooms). In contrast, most of the research evidence on the detrimental effect of poor conditions on performance has been provided in studies using laboratory conditions (i.e., computer simulations) or simulations. By using a simulated classroom environment, Valente et al. (2012) reported significantly degraded performance in discourse comprehension in school-age children when increasing background noise and reverberation. Also, the result that this impairment was less evident in sentence recognition requiring to repeat material quickly after hearing it without long-term comprehension in unfavorable environments highlights the need to better understand the impact of acoustical environment on cognitive processes and abilities to learn and understand in the classroom in younger children by conducting studies with a greater degree of ecological validity. To further respect the participatory life of school activities in primary school, in this study the impact of background classroom speech delivered with a multi-talker babble noise in the presence of different reverberation levels on working memory performances in primary school children was investigated.

Third, this study focused on verbal working memory that, although its crucial recognized role for effective learning achievement, has been poorly investigated in relation to school acoustic quality.

This study was conducted in the Italian context where the classroom acoustic quality is poorly investigated in relation to children's learning and school attainments. As in other countries, in Italy, the primary education level is compulsory for children starting around the age of six. Primary education years are a central stage for learning to read, write, and calculate. Children spend a considerable amount of time of their life in classrooms composed of an average of twenty-two children following the same school journey.

1.3. Aims and hypotheses

This study aims to verify whether second graders' verbal working memory task scores change when the verbal working memory task is performed in different acoustic quality conditions (*poor "Long RT and babble"* versus *adequate "Short RT and babble"*).

Following the literature, we expected children's verbal working memory to be compromised by unfavorable acoustic quality resulting in lower verbal working memory task scores change when the verbal working memory task is performed in the *Poor* acoustic quality condition than when performed in the *Adequate* acoustic quality condition. In fact, children performing the verbal working memory task in a classroom with high reverberation might spend the majority of cognitive resources to correctly discriminate and process unclear or masked verbal stimuli. The same children performing the verbal working memory task in a classroom with low reverberation might devote their cognitive resources to simultaneously manage multiple tasks (e.g., discriminating verbal stimuli while manipulating other material) and to figure out the correct solution (e.g., recalling words heard).

2. Method

2.1. Participants

The initial sample was composed of thirty children in the second grade of primary school. Four participants did not complete the task in its entirety in one of the two conditions, and one did not adhere to the task instructions performing both components of the dual-task together, thus were excluded from further analysis. A total of 25 typically-developing children (*M-age* = 7 years and 6 months; female = 9 and male = 16) were thus included in the final sample. This is a convenience sample (McBurney & White, 2009) recruited for a pilot study (school year 2018/19) from one primary school located in the central part of Italy in an urban, middle-class, generally well-to-do environment. Each child was tested twice during the school year (months of April and June). All participants attended the second year of primary education. This research was conducted after agreement with the school head and following privacy requirements (Legislative Decree DL-196/2003). Ethical standards for research were guaranteed by adhering to the World Medical Association guidelines for conducting research, described in the most recent version of the Declaration of Helsinki. In addition, the study was approved by the Ethics Committee of the authors' University of [city and country], and informed consent was obtained from parents. Teachers and children were informed that the purpose of the research was to investigate how children's work in different acoustic conditions (adequate vs. not correct) not to test their competencies. We did not specify that the target was on working memory. Furthermore, they were informed that children's performance would not be evaluated with grades for school purposes. Children were asked to do the best they could, so that they would make an effort but without the anxiety of the grade in the school report. All participating children were offered the opportunity to withdraw at any point during the testing. In attachment to informed consent, a parental survey to explore children's background information (e.g., education, socio-economic status) was used. The parents' levels of education were evaluated on a scale starting from elementary school diploma to a university degree. Most parents have a high school diploma (41.2 % among mothers; 29.4 % among fathers) or a university degree (52. 9% among mothers; 35.3% among fathers). A lower percentage of parents have another qualification above a high school diploma (11.8 % among fathers) or a middle school certificate (5.9 % among mothers; 23.5 % among fathers). As regards the socio-economic status, most parents were employers or freelance professionals (29.4 % among mothers; 23.5 % among fathers), self-employed workers (17.6 % among mothers; 23.5 % among fathers), or administrative employees (17.6 % among mothers; 11.8 % among fathers). A lower percentage of parents were specialized workers (5.9 % among mothers; 11.8 % among fathers), unemployed (5.9 % among mothers), school teachers (11.8 % among mothers, 5.9 % among fathers), university teachers (5.9 % among fathers), soldiers (5.9 % among fathers), office workers (5.9 % among mothers, 5.9 % among fathers), or educators (5.9 % among mothers, 5.9 % among fathers).

2.2. Procedure

The study was conducted in a school previously identified to show significant contrasts in reverberation times (RT) in two classrooms of the same school building. The reverberation time levels were chosen as a parameter to evaluate the classroom acoustic quality like previous studies in the literature (Shield et al., 2015). The optimal value recommended by the Italian standard UNI 11532–2:2020 for the two classrooms, which are characterized by a volume of about 190 m3, is 0.56 (s). One of the two classrooms identified for this study showed a poor acoustic quality with "Long RT" - the Reverberation Time in the octave frequency bands 500–2000 Hz was variable between 1.4 and 1.2 (s); thus, it was higher than the recommended index level. The other classroom showed an adequate acoustic quality with "Short RT" - the Reverberation Time in the octave frequency bands 500–2000 Hz was about 0.3 (s). This acoustic comfort was obtained thanks to a sound-absorbing system applied in this classroom. This sound-absorbing system was composed of wall panels and hanging panels, adaptable to classrooms of different sizes and different shapes. It was specifically developed by the research team of the Department of Architecture and the Department of Industrial Engineering in the University of [city and country] that collaborated with the Psychological Unit for this research.

To address the purpose of the study, the initial sample of children ($n = 25$) was randomly divided into two groups and assigned to different acoustic conditions twice. In the first research session in the month of April, one group of children ($n = 13$) performed the verbal working memory task in a classroom with poor acoustic quality (Long RT), while the other group ($n = 12$) in a classroom with adequate acoustic quality (Short RT). In the second research session in the month of June, the two groups performed the same verbal working memory task again but in the other acoustic condition (i.e., the group in the Long RT in April passed to the Short RT in June and vice versa). The two classrooms were matched for size, wall color, decorations, etc. Children participate at the same time of day (in the morning from 9 till 12 am) in both classrooms. The same two teachers were present during administration. Children maintained the same position in the classroom in the two research sessions. In each of the acoustic conditions, a sound source reproduced a typical background babble noise that simulated the "classroom babble". The emission level of the sound source was the same in the two classrooms but, as a consequence of the different Reverberation Time, in the "Long RT" classroom the equivalent A weighted Sound Pressure Level, L_{Aeq}, in the center of the room, was 59.5 dBA, while in the "Short RT" classroom it was 49.0 dBA. Children were not allowed to speak during the verbal working memory task, following the administration procedure described in the test manual. At the end of the two research sessions, each child had completed the task in two classrooms with different acoustic quality levels, *Poor* versus *Adequate*.

For each research session, the same test procedure and test items were used for both testing sessions. Specifically, each child performed the validated Listening Span Test (LST; Palladino, 2005) individually in a group session with their peers, in the presence of the same teacher (one for each testing session), the same researcher/examiner who administered the task (Ph.D. in Psychology), and the same researcher to control the sound pressure level produced by the voice and by the babble noise and the background noise level.

In each experiment, children completed two different test sessions, experiencing one noise condition in the first test session and a different noise condition in the second test session. The order of the noise conditions was counterbalanced across the group, with half of the participants in each year group performing the test in the *Poor acoustic quality* (long reverberation time [Long RT] and babble) condition first and half performing the test in the *Adequate acoustic quality* (short reverberation time [Short RT] and babble) condition first. In addition, children completed the two different test sessions separated by four school weeks (one month) to avoid familiarity with the test.

3. Measures

Listening Span Test (LST; Palladino, 2005).

To test verbal working memory, a simplified version of Daneman and Carpenter's (1980) *Listening Span Test* for children from second to fifth grade (Palladino, 2005) was used. Based on the test manual, a series of phrasal statements were verbally provided to children by the researcher. The stability of the researcher's voice level was monitored throughout the research session. The researcher gave verbal instructions, trained the children to the task with some examples, as described in the manual, and responded to their questions. Each sentence was provided by the researchers at a rate of approximately 1 s per word, followed by an interval of approximately 3 s for the child's answer concerning the judge of the truthfulness/falsity of the sentence heard. In practice, each child wrote down 'true' or 'false' for each sentence heard and, after the end of the complete series of sentences, each child wrote down the final words recalled by the heard sentences. For example, the child's correct performance (*) for the level 2-sentences read by the researcher would be:

1. The hen is an animal covered in fur (* false)
2. Fairy tales are fictional stories (* true)

* Fur, fictional.

All items were presented verbally by the researcher following items in a fixed order as provided by the test. The task is characterized by an increasing level of difficulty due to the growing number of sentences in each level (from "level 2: sequence A with two sentences and level 2: sequence B with two sentences" till "level 5: sequence A with five sentences and level 5: sequence B with five sentences"). The complete set of items/sentences in the test (excluded the examples) was made of 28 items. In this study, the administration was performed until level 4 - sequence A (14 items), given that participants went to the level 4 - sequence A encountering evident difficulties.

Based on the test guidelines (Palladino, 2005), children's responses were codified to obtain the following indexes.

The index Evaluations was obtained by assigning 1 point for each statement heard correctly judged for its truthfulness or falsity by the child. Taking the example provided before, the scoring would be 1 for false/0 for true (statement 1) and 1 for true/0 for false (statement 2).

The index Words recalled was obtained by assigning 1 point for each correct word recalled by the child. Taking the example provided before, the scoring would be 1 for the last word correctly recalled "fur" (statement 1) and 1 for the last word correctly recalled "fictional" (statement 2).

The index Span indicates the sequence of words of maximum length correctly remembered and written down by the child. Taking the example provided before, the scoring would be 2 if the child correctly recalled both last words ("fur" and "fictional") of the two statements.

The index Intrusions was obtained by counting each word recalled and written down by the child that was not in the last position in the sentence uttered by the researcher. Taking the example provided before, the scoring would be 1 if the child reported the word "animal" which was present in the statement 1, but not in the last position.

The index Inventions was obtained by counting each word written down by the child with semantic or phonological similarity to the last word but not present in the sentence uttered by the researcher. Taking the example provided before, the scoring would be 1 if the child reported "bird" as a word with semantic similarity with "hen" (statement 1).

The index Inversions was obtained by counting each word recalled and written down by the child but not in the exact sequence of presentation as in the sentence uttered by the researcher, such as "fictional, fur" instead of "fur, fictional" in the example provided before.

In addition, we calculated the number of omitted answers for both the evaluation and the word recall tasks.

Table 1
Means (M), standard deviations (SDs), skewness, kurtosis, and Shapiro-Wilk tests of the indexes of the Listening Span Test (LST).

Variables	Classroom acoustic conditions						
	Poor [Long RT]						
	N	Min-Max	M (SD)	skewness	kurtosis	Shapiro-Wilk W	p-value
Intrusions	25	0–6	0.56 (1.33)	3.24	12.03	0.49	**0.000**
Inversions	25	0–1	0.12 (0.33)	2.49	4.56	0.38	**0.000**
Inventions	25	0–1	0.16 (0.37)	1.98	2.06	0.45	**0.000**
Evaluations	25	5–14	12.44 (2.24)	-2.01	4.16	0.71	**0.000**
Omitted evaluations	25	0–4	0.76 (1.13)	1.46	1.53	0.72	**0.000**
Recalled words	25	0–12	6.60 (3.04)	0.00	-0.37	0.98	0.769
Omitted words	25	2–14	6.68 (3.00)	0.48	-0.03	0.96	0.414
Span	25	0–4	1.88 (0.83)	0.24	1.15	0.87	**0.003**
	Adequate [Short RT]						
	N	Min-Max	M(SD)	skewness	kurtosis	Shapiro-Wilk W	p-value
Intrusions	25	0–2	0.28 (0.54)	1.86	2.94	0.57	**0.000**
Inversions	25	0–2	0.08 (0.40)	5.00	25.0	0.20	**0.000**
Inventions	25	0–2	0.12 (0.44)	3.88	15.34	0.31	**0.000**
Evaluations	25	5–14	12.52 (2.18)	-2.04	4.85	0.71	**0.000**
Omitted evaluations	25	0–8	1.16 (2.01)	2.16	4.79	0.66	**0.000**
Recalled words	25	3–14	8.52 (3.07)	-0.05	-1.17	0.95	0.164
Omitted words	25	0–10	4.84 (2.85)	0.07	-1.12	0.95	0.221
Span	25	1–4	2.40 (0.76)	-0.24	-0.31	0.85	**0.002**

Note. $n = 25$. The bold numbers are significant p-values.

4. Data analysis

The Shapiro-Wilk test was used to determine the normality of the distribution. To examine whether second graders' verbal working memory performances change in different acoustic conditions, statistical comparisons of scores obtained by the same children in the two classrooms with different acoustic quality levels (*Poor* versus *Adequate*) were performed. The normal and non-normal distributed variables were respectively assessed by paired-samples T-test or Wilcoxon signed-rank test. To control the effect of the order of assignment of the subjects to the two conditions, we conducted a Two-Way Mixed ANOVA for the variables that showed a significant difference between the two conditions. ANOVA is considered quite robust against violations of the normality assumption. The independent variables were the acoustic quality condition (*Poor* versus *Adequate*) and the order in which the subjects performed the test in the two conditions. The first was a repeated measures factor (within-subjects factor) indicating the two administrations of the test. The latter was a between-subjects factor at two levels, since half of the participants performed the test first in the classroom with poor acoustic quality and then in the one with adequate acoustic quality, while the other half did the opposite. A p-value less than 0.05 was considered statistically significant. Effect sizes of 0.2, 0.5, and 0.8 were considered small, medium, and large in magnitude, respectively. Statistical analysis was performed using the SPSS software package, version 26.

5. Results

The results of descriptive analysis are presented in Table 1.

The results of statistical comparisons of verbal working memory performances obtained by the same children in the two classrooms with different acoustic conditions (poor vs. adequate) are reported in Table 2.

As can be seen, children's verbal working memory performances significantly change in relation to two classrooms with different acoustic conditions (see Fig. 1). Specifically, the *Span* was significantly higher in the classroom with adequate acoustic conditions ($M = 2.40$; $M\ dn = 2$) than in the classroom with poor acoustic conditions ($M = 1.88$; $M\ dn = 2$). A Wilcoxon signed-rank test indicated that this difference was statistically significant, $T = 122$, $Z = -2.31$, $p = .021$, $r = -0.33$.

Furthermore, for the index *Recalled words*, children's performances were lower (M = 6.60, SD = 3.04) in the classroom with poor acoustic conditions as compared to those obtained by the same children in the classroom with adequate acoustic conditions (M = 8.53, SD = 3.07). This difference, − 1.92, 95% CI [− 3.64, − 0.20], was statistically significant, $t(24) = -2.30$, $p = .030$, *Cohen's* $d = -0.46$.

Finally, the number of *Omitted words* was higher in the classroom with poor acoustic conditions ($M = 6.68$, $SD = 3.00$) than in the classroom with adequate acoustic conditions (M = 4.84, SD = 2.85). This difference, 1.84, 95% CI [0.09, − 3.59], was statistically significant, $t(24) = 2.17$, $p = .040$, *Cohen's* $d = 0.43$.

No statistically significant differences between the two conditions were observed in the other variables taken into account (see Table 2).

A Two-Way Mixed ANOVA was conducted to investigate the impact of condition and order in which the subjects performed the test in the two conditions as well as their interaction effects on the indexes *Span*, *Recalled word*, and *Omitted words*. Regarding the *Span*, there was a significant main effect of acoustic condition, $F(1,23) = 4.31$, $p = .049$, $\eta^2 = .16$. However, there was not a significant main effect of order, $F(1,23) = 0.40$, $p = .532$, with participants belonging to the two groups showing similar average *Span* scores (respectively, M = 2.08 and M = 2.21). Moreover, there was not a significant interaction between condition and order, $F(1,23) = 1.12$, $p = .301$, indicating that the differences in *Span* scores were not dependent on the order in which the subjects performed the test in the two conditions.

A significant main effect of acoustic condition, $F(1,23) = 5.19$, $p = .032$, $\eta^2 = .18$, was also found on *Recalled words*. However, there was not a significant main effect of order, $F(1,23) = 1.61$, $p = .218$, with participants belonging to the two groups showing similar average *Recalled words* scores (respectively, M = 6.77 and M = 8.42) nor a significant interaction between condition and order, $F(1,23) = 3.79$, $p = .064$. Therefore, the differences in *Recalled words* scores in the two conditions were not dependent on the order of assignment of the subjects to the two conditions.

Table 2
Means (medians) comparisons (paired-samples t-test or Wilcoxon signed-rank test and related effect size) across the two different classroom acoustic conditions for verbal working memory performances.

Variables	Classroom acoustic conditions						
	Poor [Long RT]		Adequate [Short RT]				
	M (M dn)	SD	M (M dn)	SD	Statistic	*p*	Effect size
Intrusions	0.56 (0)	1.32	0.28 (0)	0.54	-0.81	0.417	–
Inversions	0.12 (0)	0.33	0.08 (0)	0.40	-0.38	0.705	–
Inventions	0.16 (0)	0.37	0.12 (0)	0.44	-0.33	0.739	–
Evaluations	12.44 (13)	2.24	12.52 (13)	2.18	-0.06	0.954	–
Omitted evaluations	0.76 (0)	1.13	1.16 (0)	3.04	-0.99	0.320	–
Recalled words	6.60 (6)	3.04	8.52 (8)	3.07	-2.30	**0.030**	-0.46
Omitted words	6.68 (6)	3.00	4.84 (6)	2.85	2.17	**0.040**	0.43
Span	1.88 (2)	0.83	2.40 (2)	0.76	-2.31	**0.021**	-0.33

Note. $n = 25$. The bold numbers are significant p-values.

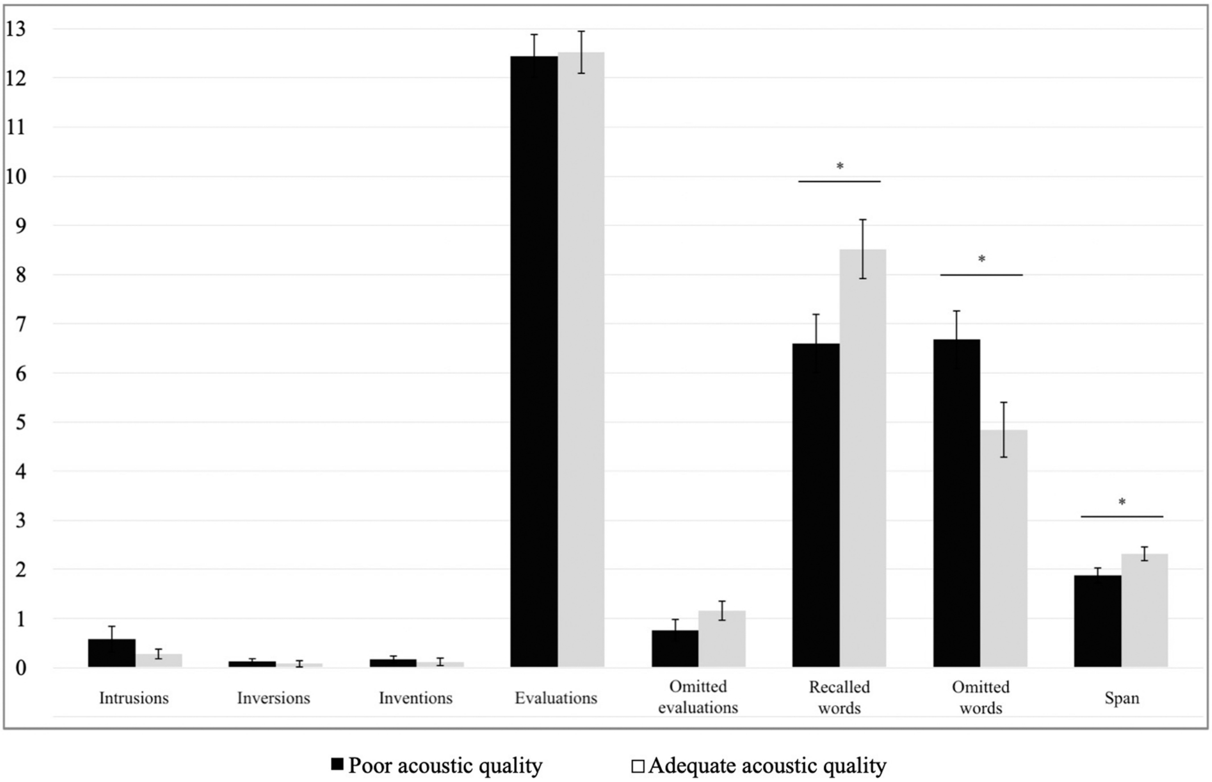

Fig. 1. Mean scores of *Recalled words*, *Omitted words* and *Span* indexes as a function of the acoustic condition. Error bars indicate standard errors of the means. *Note*. $*p < 0.05$.

Lastly, regarding *Omitted words*, there was a significant main effect of acoustic condition, $F(1,23) = 4.52$, $p = .044$, $\eta^2 = .16$. However, there was not a significant main effect of order, $F(1,23) = 0.730$, $p = .402$, with participants belonging to the two groups showing similar average *Omitted words* scores (respectively, M = 6.42 and M = 5.04). Furthermore, there was not a significant interaction between condition and order, $F(1,23) = 3.18$, $p = .088$, indicating that the differences in *Omitted words* scores were not dependent on the order in which the subjects performed the test in the two conditions.

6. Discussion

In this study, we investigated whether second graders' verbal working memory task scores change when the verbal working memory task is performed in different acoustic quality conditions (*poor "Long RT and babble"* versus *adequate "Short RT and babble"*). This study was carried out in the ecological school setting of primary school classrooms with second graders. The results give insight into whether the variations of indoor acoustic comfort (measured as reverberation time index), that were found to affect several learning-related activities in prior laboratory research, can influence verbal working memory in young children whose basic school processes (e.g., reading and spelling) are still not automated or fully controlled.

Our results demonstrated that second graders' verbal working memory task scores were significantly lower when children performed the verbal working memory task in the classroom with poor acoustic quality (*"Long RT and babble"*) than when the same children performed the task in the classroom with adequate acoustic quality (*"Short RT and babble"*). In line with previous studies (e.g., Osman & Sullivan, 2014; Sullivan et al., 2015), our findings confirmed that unfavorable levels of noise impact cognitive processing and contributed to advancing our understanding of the link between noise in school environments and verbal working memory performances in young children. Specifically, our results showed that the task scores for the indexes *Span* and *Words recalled* were significantly compromised by the poor acoustic quality of the classroom. The results obtained by comparing the same children's verbal working memory task scores obtained by the two different acoustic conditions (*"Long RT and babble"* versus *"Short RT and babble"*) showed a decrease in the word sequence of maximum length correctly remembered (index of *Span*) and of the correct words recalled (*Words recalled*) when children were performing the verbal working memory task in the classroom with *"Long RT and babble"*. According to the theory of Sörqvist (2010), unexpected changes in speech may divert attention away from the task (*deviation effect*). Following this line of reasoning, unclear or masked speech information that arises from the high level of reverberation in addition to the classroom babble might divert young children's attention away from the verbal working memory task resulting in poor performances.

Moreover, our findings showed that the number of words omitted was significantly higher in the *Poor acoustic quality* condition than in the *Adequate acoustic quality* condition, while children's scores at the *Evaluations, Intrusions,* and *Inversions* indexes were similar in the two acoustic conditions. This result indicates that the performance impairment consisted mainly of a reduced number of responses while the error rate remained stable. We could advance several interpretations of this selective environmental interference effect on some aspects of verbal performance, but not others. Firstly, based on our results, young children in presence of unfavorable levels of noise (Poor acoustic quality condition) likely devote a consistent portion of cognitive resources to making appropriate judgments (scores at Evaluations) with an inevitable loss of cognitive resources to be devoted to the remembering of the last two words in the sentences uttered by the researcher as required by the task. The unfavorable levels of noise stress the central executive system of working memory, which has limited cognitive resources, with a consequent detrimental effect on the adequate functioning of the phonological loop. A further line of interpretation about the high number of omissions in the unfavorable acoustic conditions can be linked to the fact that the child might prefer or choose to omit words when not sure instead of tending to make inventions. Finally, it could be that children consider making appropriate judgments of the statements as the primary task to address the large proportion of their cognitive resources also because of their scarce abilities to self-regulate their activities and resources to achieve all the tasks.

7. Limitations and future research

A limitation of the current study is the small sample size. This study constitutes a preliminary research work that opens the way to further investigation with a larger sample to verify whether these findings are replicated in other studies. Also, a larger sample will allow to verify the effect of other variables, such as gender and abilities, on verbal working memory performances under different acoustic conditions. In the present study, in fact, it was not possible to control the effect of other variables, such as gender, on performance, due to the unbalanced and restricted numbers of males and females in our sample. Furthermore, our sample includes children with no special educational needs and a high socio-economic level. In future studies, it would be interesting to consider children with special educational needs and with different socio-economic backgrounds to investigate the moderating role of these variables in the relation between noise and learning. In terms of assessment, given the use of a single working memory task, it remains to be cleared whether the found effects are specific to verbal working memory, general to working memory, or even would generalize to many other cognitive domains. Future research could examine and clarify the presence of specific effects. Also, further research could help in establishing the longitudinal impact of chronic exposure to unfavorable levels of noise in classrooms on a range of children's cognitive and language performances. For this purpose, it would be useful to replicate this study following two larger cohorts of children across primary school years, one cohort of children attending school in classrooms with Long RT and a cohort of children attending school in classrooms with Short RT. Such an investigation could include the administration of school tasks in multiple domains (e.g., reading, numeracy, writing) and children's performances at national standardized tests (e.g., INVALSI tests - National Institute for the Evaluation of the Education and Training System). In future studies, it could be important to conduct a study on teachers' perception of the acoustic quality of the classroom, as an important indicator of their job satisfaction and a potential variable influencing teaching and children's performances.

8. Conclusions and implications

In summary, this study showed that a poor auditory condition in the classroom negatively affects the efficiency of verbal working memory performances in second graders of primary school. Working memory is implicated in learning and particularly poorly functioning in children with specific learning disorders. Verbal working memory is crucial for learning and school attainment, given its strong involvement in several learning activities requiring the child a multimodal integration of information (e.g., auditory, semantic, symbolic). At the theoretical level, our findings inform that reverberation has a negative impact on performance, preventing children's concentration while performing the dual task. Our results suggest that it is important to further investigate children's cognitive processes and development in interaction with the features (e.g., classroom noise) of significant contexts for children's development, such as schools. The relation between environmental features and verbal working memory efficiency highlights the potential to design acoustic solutions for classrooms that can sustain acoustic comfort in school environments by integrating metacognitive work on learning to listen (e.g., Wang, 2016). In the design of a solution for acoustic correction, the consideration of spatial aspects, together with the possibility of easily applying adequate technical solutions (e.g., wall panels) and the choice of versatile and aesthetically pleasing architectural solutions should be sustained (see, Laurìa et al., 2020). In addition, teachers and parents could sustain children to develop awareness about the importance of listening and about the conditions (personal factors such as motivation), as well as some strategies (metacognitive, cognitive, and socio-affective) that could facilitate listening.

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Competing interests

The authors have declared that no competing interests exist.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.cogdev.2022.101256.

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