

Children's auditory perception and cognitive processing skills in adverse listening  
situations

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**Abstract**

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Children are reported to have substantial difficulty in complex everyday environments (e.g., classroom). In typical classrooms, children are asked to perform learning activities that often require attention to more than one concurrent task in the presence of task-irrelevant background noise. Demands on auditory and cognitive processes affect how well children understand spoken language in the classroom. This three-manuscript dissertation sought to examine the effects of auditory distraction on working memory and auditory comprehension performance in school-age children with normal hearing. Experiment I examined whether children with normal hearing demonstrate poorer working memory performance in four-talker babble at 0 and -5 dB signal-to-noise ratios (SNR). Experiment II evaluated how the relationship between children's working memory and auditory comprehension performance changes in classroom noise at -5 dB

SNR compared to quiet. Experiment III expanded on previous findings by systematically increasing difficulty of cognitive tasks and level of four-talker babble. Together these studies demonstrate that when auditory perception is difficult, higher-level cognitive processing is compromised. The results are consistent with the view that listening in adverse situations draws on a child's limited pool of cognitive resources that would otherwise be available for speech comprehension and for encoding information in memory. The results also confirm the need for complex listening tasks and situations to adequately estimate children's speech-in-noise difficulties.

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## Dissertation Outline

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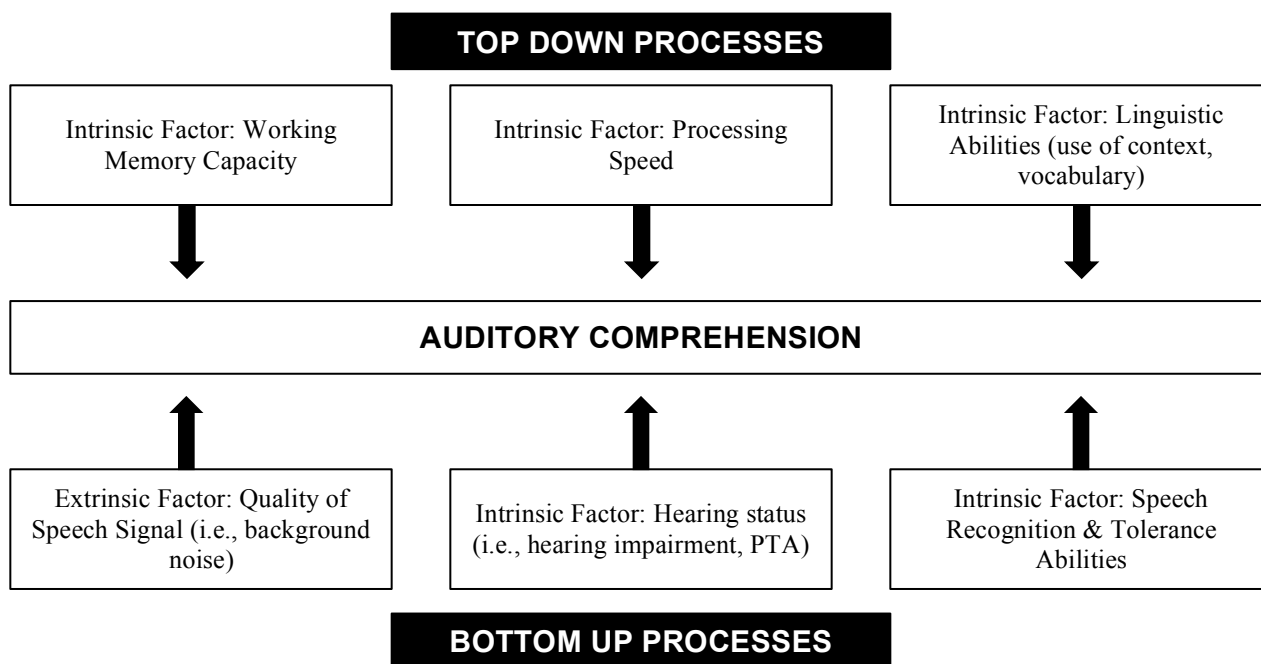
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## GENERAL INTRODUCTION

For adults and children with normal hearing, understanding speech is an effortless and often overlooked task under optimal conditions. However, the ability to successfully understand speech in adverse listening situations (e.g., classroom) requires effort and relies on a dynamic interplay between sensory and cognitive based processes. Sensory or bottom-up processes refer to the perception of auditory input, such as the identification of acoustic sounds, recognition of word-order, recognition of word patterns, and recognition of intonation cues (Pichora-Fuller, Schneider, & Daneman, 1995). Schneider (2011) suggests speech communication is more than perception of sound; although perception is the foundation, it also requires comprehension of meaning. Higher-order or top-down processes, such as working memory, are needed for interpretation of sounds into meaningful units in the context of prior knowledge (Boothroyd 1997; Conway, Pisoni, & Kronenberger, 2009).

For example, to participate effectively in a classroom discussion, children need to do more than simply recognize and repeat speech. They have to keep track of who said what, extract the meaning of each utterance, store it in memory for future use, integrate the incoming information with what each conversational participant has said in the past, and draw on the child's own knowledge of the topic under consideration to extract general themes and formulate responses. In other words, to acquire and use the information contained in spoken language requires the smooth and rapid functioning of an integrated system of perceptual and cognitive processes (Figure 1).

Figure 1. Contributions of top-down and bottom-up processes to auditory comprehension.



In reference to Figure 1, listeners are influenced by many intrinsic and extrinsic variables that can enhance or impede effective speech understanding. Zekveld (2008) described intrinsic factors as those that come from the listener; and, extrinsic factors as those that come from the environment. Intrinsic (individual) factors influencing a child's auditory comprehension include: age, the status of the child's sensory processing (auditory and visual), attention span, grammatical and lexical knowledge, working memory, cognition, past experiences, and mental and physical state. Extrinsic factors influencing auditory comprehension include background noise, visual information (i.e., being able to see the face of the speaker), passage complexity, talker's voice, and overall quality of speech transmission.

Aging-adult literature has expansively surveyed the effects of intrinsic (e.g., old age, working memory span) and extrinsic variables (e.g., background noise) on speech understanding. Less is known about the effects of background noise on comprehension and its relationship to working memory in the pediatric population. The main objective of this dissertation was to examine the effects of background noise at levels typical for classrooms on complex listening tasks: working memory and auditory comprehension. Experiment I examined whether children with normal hearing demonstrate poorer working memory performance in four-talker babble at 0 and -5 dB signal-to-noise ratios (SNR). Experiment II evaluated how the relationship between children's working memory and auditory comprehension performance changes in classroom noise at -5 dB SNR compared to quiet. Experiment III expanded on previous findings by systematically increasing difficulty of cognitive tasks and level of four-talker babble.

## **Chapter 1**

# **CHILDREN'S AUDITORY WORKING MEMORY PERFORMANCE IN DEGRADED LISTENING CONDITIONS**

## Research Article

# Children's Auditory Working Memory Performance in Degraded Listening Conditions

Homira Osman<sup>a</sup> and Jessica R. Sullivan<sup>a</sup>

**Purpose:** The objectives of this study were to determine (a) whether school-age children with typical hearing demonstrate poorer auditory working memory performance in multitalker babble at degraded signal-to-noise ratios than in quiet; and (b) whether the amount of cognitive demand of the task contributed to differences in performance in noise. It was hypothesized that stressing the working memory system with the presence of noise would impede working memory processes in real time and result in poorer working memory performance in degraded conditions.

**Method:** Twenty children with typical hearing between 8 and 10 years old were tested using 4 auditory working memory tasks (Forward Digit Recall, Backward Digit Recall, Listening Recall Primary, and Listening Recall Secondary). Stimuli were from the standardized Working Memory Test Battery for Children. Each task was administered in quiet and in 4-talker babble noise at 0 dB and -5 dB signal-to-noise ratios.

**Results:** Children's auditory working memory performance was systematically decreased in the presence of multitalker babble noise compared with quiet. Differences between low-complexity and high-complexity tasks were observed, with children performing more poorly on tasks with greater storage and processing demands. There was no interaction between noise and complexity of task. All tasks were negatively impacted similarly by the addition of noise.

**Conclusions:** Auditory working memory performance was negatively impacted by the presence of multitalker babble noise. Regardless of complexity of task, noise had a similar effect on performance. These findings suggest that the addition of noise inhibits auditory working memory processes in real time for school-age children.

**Key Words:** children, auditory working memory, hearing, cognition, noise, perception

Children experience listening environments filled with background noise on a daily basis, particularly in the classroom. Although the adultlike development of the sensory-peripheral auditory system in children allows simple auditory tasks, such as listening in quiet, to be performed with ease (see Werner & Leibold, 2004), more complex listening tasks such as listening in noise are effortful and difficult, even in typically developing children with typical hearing. Degraded environments are unfavorable to listening and understanding and can lead to communication deficits (Picard & Bradley, 2001). Children require more favorable signal-to-noise ratios (SNRs) than adults and are particularly vulnerable to the negative effects of noise (Elliott et al., 1979; Hall, Grose, Buss, & Dev, 2002; Nittroter & Boothroyd, 1990). One explanation for this difference is the development of language and emerging higher order cognitive processes.

Competing noise may increase demand for cognitive processes during perceptual tasks. This increase in cognitive load may come at the cost of using cognitive processing resources that could be available for other tasks, such as auditory working memory. The objective of the present study was to determine whether school-age children's auditory working memory was impacted by the presence of multitalker babble.

## *Relationship Between Sensory and Neurocognitive Processes*

The ability to successfully listen and understand speech in noisy environments involves both sensory- and cognitive-based processes. Sensory or bottom-up processes refer to the perception of auditory input, specifically the identification of acoustic sounds (Pichora-Fuller, Schneider, & Daneman, 1995). Higher order or top-down processes, such as attention and working memory, are needed for interpretation of sounds into meaningful units in the context of prior knowledge (Boothroyd, 1997; Conway, Pisoni, & Kronenberger, 2009). Sensory and neurocognitive processes

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are integrated and interdependent in complex perceptual tasks, such as speech perception in noise (Anderson & Kraus, 2010; Anderson, Parbery-Clark, Yi, & Kraus, 2011). Individuals allocate more cognitive resources to understanding speech in noise, where top-down processing is explicit and more cognitively demanding than quiet (Lunner, Rudner, & Rönnerberg, 2009; Rönnerberg, Rudner, Foo, & Lunner, 2008; Wightman & Kistler, 2005; Zekveld, Kramer, & Festen, 2011). Rönnerberg and colleagues (2008) suggest that, under high degradation conditions, explicit processing resources are invoked due to a mismatch between phonological information extracted from the distorted speech signal and the phonological information represented in long-term memory. Thus, the better one's cognitive abilities, particularly working memory, the better and more automatic his or her ability to communicate in noise (Parbery-Clark, Skoe, Lam, & Kraus, 2009).

Working memory is conceptualized as a capacity-limited system that is responsible for encoding, storing, processing, and rehearsal of information (Baddeley, 2000, 2003; Baddeley & Larsen, 2007). In the multicomponent and modality-specific view of working memory put forth by Baddeley (2000), auditory working memory (AWM) involves the phonological loop (passive temporary storage of verbal information) and central executive (active memory system that controls and regulates processing activities and attention). A substantial body of evidence indicates that auditory working memory is positively related to language development, speech perception, reading comprehension, and scholastic achievement (Cleary, Pisoni, & Geers, 2001; Daneman, Nemeth, Stainton, & Huelsmann, 1995; Gathercole & Baddeley, 1993; Just & Carpenter, 1992; Pickering & Gathercole, 2001; Pisoni & Cleary, 2004). The acquisition of language and long-term learning of the sound patterns of new words is considerably affected by poor working memory skills (Baddeley, Gathercole, & Papagno, 1998; Gathercole & Pickering, 2000; Gathercole, Willis, Emslie, & Baddeley, 1992). Furthermore, of children whose AWM abilities fall in the bottom tenth percentile, more than 80% have significant difficulties in reading or mathematics (Gathercole & Alloway, 2008). Not only do AWM abilities predict children's success in school, Daneman and Merikle (1996) clearly note that AWM is a good predictor of communicative success.

### *Auditory Working Memory in Noise*

Background noise, especially speech babble, contributes to inefficient processing of the working memory system. Salamé and Baddeley (1982) described impaired recall performance in the presence of irrelevant auditory stimuli as the "irrelevant speech effect." The irrelevant speech effect is a well-established effect in the cognitive adult literature (see Neath, 2000), where it is concluded that speech babble gains automatic entry into the auditory store of memory (i.e., phonological loop). Auditory to-be-remembered items also enter the phonological loop, through subvocal rehearsal. With competing representations of both irrelevant auditory

and to-be-remembered auditory items in the phonological loop, errors become more likely, resulting in decreased recall performance (Salamé & Baddeley, 1982).

Murphy, Craik, Li, and Schneider (2000) assessed working memory in typically hearing young and older adults using a serial recall of word pairs in the presence of speech babble. The presence of the babble noise significantly affected performance for both age groups (Murphy et al., 2000). Audibility was not an explanation for the findings because the participants could repeat back individual items accurately in the presence of speech babble at the same level. Pichora-Fuller et al. (1995) compared working memory performance at varying levels of noise in older and younger adults. The older adults group performed significantly worse in 0 dB SNR compared to +5 dB SNR. This suggests a greater share of resources were used for processing in the degraded 0 dB SNR listening condition, leaving fewer resources available for successfully recalling sentence-final words.

In a series of adult studies, Pichora-Fuller and colleagues (Pichora-Fuller, 2003; Pichora-Fuller et al., 1995; Pichora-Fuller & Singh, 2006) found that unfavorable SNRs required listeners to rely more on working memory. This suggests that the extraction of sensory information in noise requires greater allocation of top-down resources, leaving fewer resources for processing and storing of other information for later recall (Pichora-Fuller et al., 1995; Sarampalis, Kalluri, Edwards, & Hafter, 2009; Wingfield, Tun, & McCoy, 2005). In other words, working memory resources are used to allow the listener to decode the signal in noise and support auditory processing (Pichora-Fuller et al., 1995; Rönnerberg et al., 2008). Lunner et al. (2009) suggested that the increased demand of noise may result in slower processing, greater number of task errors, and loss of information from temporary storage.

Studies on the relationship between auditory working memory and noise in the pediatric population are sparse. However, understanding speech in degraded conditions is well established as important for school-age children. Not only are children vulnerable to the negative effects of noise and require a greater SNR than adults (Fallon, Trehub, & Schneider, 2000; Hall et al., 2002), they also encounter everyday environments (i.e., classrooms) that are not favorable for communication and learning (Bradley & Sato, 2008; Picard & Bradley, 2001). Recommended noise levels and reverberation times for classrooms are often exceeded (American National Standards Institute, 2002; Crandell & Smaldino, 2000; Krishnan & Gandour, 2009). Crandell (1993) identified commonly reported classroom SNRs as +6, +3, 0, -3, and -6 dB. Such degraded listening conditions contribute to an increased risk for academic difficulties (Green, Pasternak, & Shore, 1982; Shield & Dockrell, 2003; Sperling, Zhong-Lin, Manis, & Seidenberg, 2005). The combined importance of auditory working memory for language learning and deleterious effects of degraded listening conditions emphasizes the need for assessing the role of noise on AWM in school-age children.

In a recent study, Stiles, McGregor, and Bentler (2012) studied 6- to 9-year-old children with typical hearing and

with mild to moderately severe sensorineural hearing loss on auditory and visuospatial working memory tasks. Working memory tasks were administered in quiet and at +15 dB SNR to assess whether size of receptive vocabularies and deficits in working memory were related. Stiles et al. (2012) found no effect of background random noise (low-pass air conditioner) on auditory and visuospatial tasks at +15 dB SNR in both groups. It is presumed the type of noise used may not have been as taxing as background speech babble. However, Pichora-Fuller (2006) indicated that listening is more challenging when the background noise is competing speech than when it is random white noise with adults.

Therefore, we sought to understand (a) whether children with typical hearing demonstrate poorer AWM performance in speech babble noise at commonly experienced SNRs than in quiet; and (b) whether the amount of cognitive demand of the task contributes to differences in performance in noise. It was hypothesized that stressing the working memory system with the presence of noise would impede working memory processes in real time and result in poorer working memory performance in degraded conditions. In addition, it was hypothesized that working memory measures of low complexity would be less affected by noise than measures of high complexity.

## Method

### Participants

Twenty children between 8 and 10 years old ( $M = 9;2$  [years;months]; 9 boys, 11 girls) were recruited from the University of Washington Communication Studies Participant Pool. This age range was selected because working memory and attentional processes are the most similar during these developmental ages. Each child and parent voluntarily signed written assent and consent forms approved by the University of Washington Institutional Review Board and were offered compensation upon completion of the study. All children had hearing thresholds  $\leq 20$  dB HL bilaterally at octave frequencies between 0.25 and 8 kHz, as determined by a hearing screening administered prior to testing. Participants were monolingual English speakers with no known neurological disorders, no history of recurring otitis media, and normal cognition and language development as determined

by parent interview. To ensure that all participants had age-appropriate receptive vocabulary, the Peabody Picture Vocabulary Test—Fourth Edition (PPVT-IV, Form A; Dunn & Dunn, 2006) was administered. All participants had a standardized score no lower than one standard deviation below the published norm mean for their respective ages.

### Measures of Working Memory

Three subtests from the Working Memory Test Battery for Children (WMTB-C; Pickering & Gathercole, 2001) were administered in two conditions (quiet and noise), as shown in Table 1. These measures were selected to tap into the ongoing storage and processing functions of AWM, specifically the central executive and phonological loop subcomponents of working memory (Pickering & Gathercole, 2001).

*Forward Digit Recall.* The Forward Digit Recall test (FWt) involved the presentation of spoken sequences of digits that the child was asked to recall in correct serial order. Digits were presented in sequences at 1-s intervals. Following a practice session, a maximum of six lists were presented in a span procedure. Sequence length was increased by one if the child recalled six lists at that length correctly. Testing began with three-digit sequences (i.e., 5-1-3) and continued until three lists of a particular length were recalled incorrectly. Within any given sequence, no digits were repeated. The number of lists correctly recalled was scored. Responses to each sequence were scored 0 or 1. No credit was given for any correctly recalled sequences after three errors were made in a particular list. The mean test-retest reliability coefficient of this measure is .81 (Gathercole, Pickering, Ambridge, & Wearing, 2004).

*Backward Digit Recall.* The Backward Digit Recall test (BWt) is identical to the Forward Digit Recall test except that the child was asked to recall the sequence of digits in reverse order. For example, the sequence 5-1-3 presented at a rate of one digit per second would be correctly recalled as 3-1-5. Unlike the Forward Digit Recall test, testing began with two-digit sequences. Practice trials were given with two-digit and three-digit sequences to ensure that each participant understood the concept of “backward.” The Backward Digit Recall test shares the span procedure and scoring outlined

**Table 1.** Description and examples of each working memory task administered.

Type of working memory	Method	Task	Examples of stimuli	Correct response
Phonological loop	Digit span	Forward Digit Recall	8, 5, 2 9, 7, 3, 1	8, 5, 2 9, 7, 3, 1
		Backward Digit Recall	8, 5, 2 9, 7, 3, 1	2, 5, 8 1, 3, 7, 9
Central executive	Listening span	Listening Recall Primary	Fish have fur.	False
		Listening Recall Secondary	Oranges live in water. Fish have fur. Oranges live in water.	False Fur Water

for the Forward Digit Recall test. The mean test–retest reliability coefficient of this measure is .62 (Gathercole et al., 2004).

**Listening Recall.** The Listening Recall test is based on a procedure originally developed for adults (Daneman & Carpenter, 1980). For the Listening Recall test (Lt), the child was asked to listen to a series of short sentences, judge the veracity of each sentence by responding “true” or “false,” and recall the final word of each of the sentences in sequence. Sequences began with a single sentence and increased by a single sentence following the span procedure outlined for FWt and BWt. In comparison to the aforementioned digit recall tests, where the child encoded and immediately recalled information, the Listening Recall test required additional processing while information was maintained. Therefore, scoring for this measure was modified; the judgment of veracity of sentences was scored as the primary task (Ltp), and repetition of the last word of each sentence (Lts) was scored as the secondary task. The mean test–retest reliability coefficient is .61 (Gathercole et al., 2004).

### Procedure

The complete test protocol was administered in a single test session. All auditory working memory tasks were completed in a double-walled sound booth. The speech was presented at 0° azimuth from the front loudspeaker while noise was presented at 180° azimuth from the rear loudspeaker. The child was seated 1.5 m from the front speaker. A young, adult, English-speaking female speaker presented the speech stimuli at a fixed level of 65 dB SPL, as measured at the location of the participant’s head with a Quest Sound-Pro 3M sound level meter. Each working memory subtest was administered in three conditions: quiet and in the presence of competing four-talker babble noise at 0 dB and –5 dB SNRs. The speech signal was held constant at a level of 65 dB SPL and the SNR was adjusted by varying the noise level. The four-talker babble consisted of one male and three female speakers and was supplied with the QuickSIN Speech-in-Noise test (Version 1.3, Etymotic Research). Four-talker babble and the select SNRs were chosen because they are representative of everyday situations encountered by children and the long-term spectrum of the multitalker babble resembles the long-term average speech spectrum (Crandell, 1993). Listening conditions and working memory tasks were counterbalanced across participants.

### Results

A within-group experimental study design was selected to meet the aims of this study. Statistical analyses were performed using NCSS software, Version 8. To analyze the effects of listening condition (quiet, 0 dB SNR, –5 dB SNR) and task (FWt, BWt, Ltp, Lts), a balanced two-way analysis of variance (ANOVA) was selected with scores (number of trials correct) on each task as the dependent variable. Because of their known relationship to working memory, the analyses included age and receptive vocabulary (PPVT age-equivalent)

as covariates (Gathercole et al., 2004). A  $p$  value of less than .05 was statistically significant.

Table 2 presents mean values and standard deviations of each auditory working memory task as a function of listening condition. To normalize scores across tasks, we derived  $z$  scores from the mean scores and standard deviations. The scores in the quiet condition are consistent with published normative means by age and are similar to scores reported in previous studies (Gathercole et al., 2004; Stiles et al., 2012).

There were significant main effects for listening conditions,  $F(2, 60) = 2, p < .0001$ , and task,  $F(2, 45) = 3, p < .0001$ . Age was found to be a significant covariate,  $F(1, 60) = 20.44, p < .0001$ , with younger children demonstrating better auditory working memory performance than older children.

Figure 1 illustrates the average performance ( $\pm 1 SE$ ) for each task as a function of listening condition. Within each panel of Figure 1, listening conditions are arranged in order of decreasing SNR (quiet, 0 dB SNR, –5 dB SNR) to demonstrate the degradation and difficulty experienced.

Post hoc analyses using a Tukey-Kramer Multiple Comparison Test indicated significant differences across listening conditions. Listening in degraded SNRs contributed to poorer performance than in quiet (quiet > 0 dB SNR > –5 dB SNR). Significant differences were also found between any two tasks (performance on FWt > BWt > Ltp > Lts). There was no interaction between SNR and task. This suggests that noise impacts auditory working memory performance similarly across tasks (Figure 2).

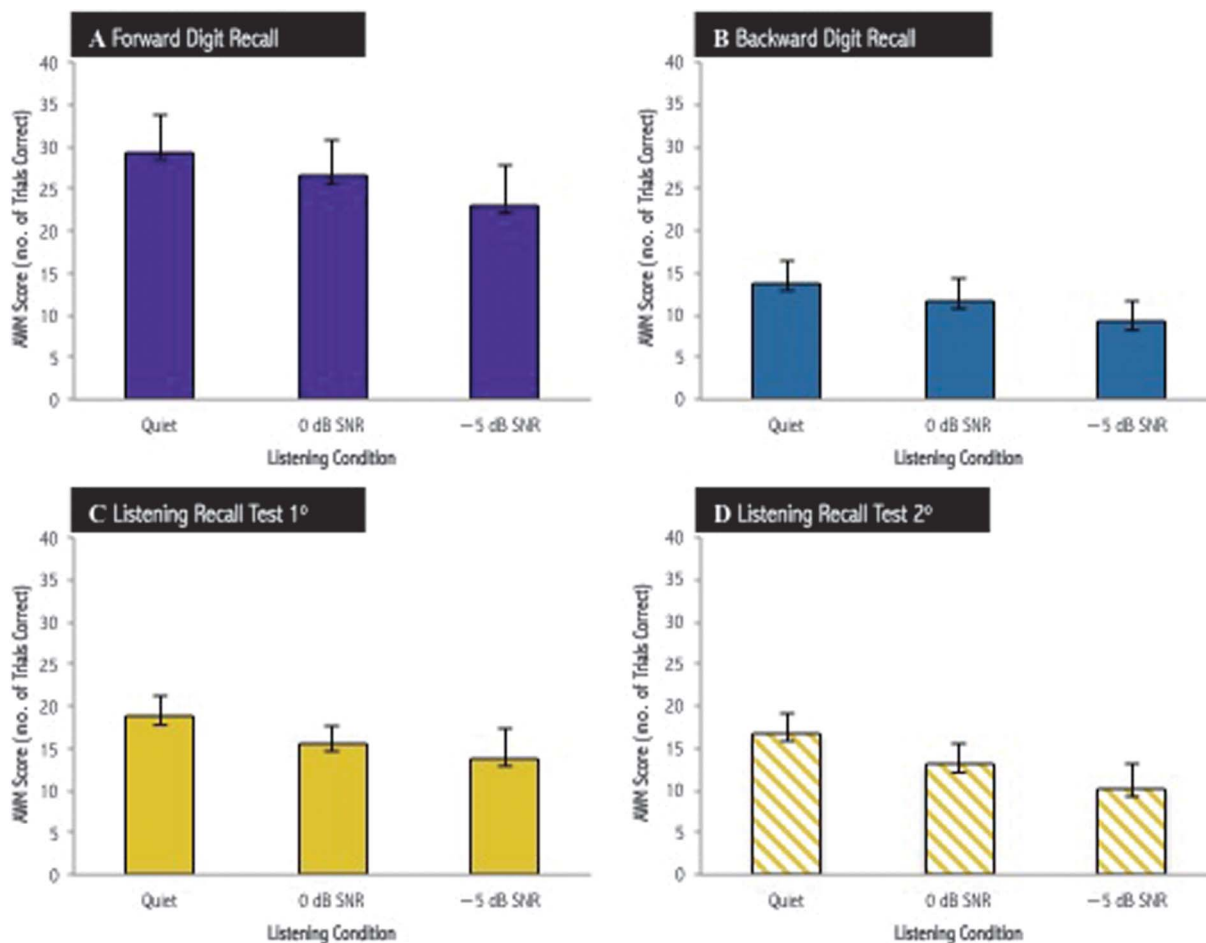
Overall, working memory performance decreased as listening conditions became more degraded. Performance was highest for all tasks in quiet but decreased significantly when noise was added. Regardless of complexity, each task was affected by noise in a similar manner; performance decreased by approximately 10% at –5 dB SNR compared with quiet for all tasks.

**Table 2.** Scores for auditory working memory tasks as a function of listening condition.

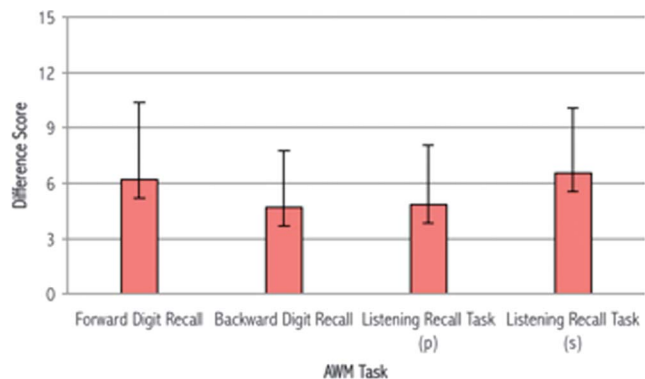
Task and condition	<i>M</i>	<i>SD</i>	<i>z</i>
Forward Digit Recall			
Quiet	29.4	4.27	0.60
0 dB SNR	26.5	4.17	0.03
–5 dB SNR	23.5	6.39	–0.64
Backward Digit Recall			
Quiet	13.9	2.63	0.72
0 dB SNR	11.7	2.62	0.02
–5 dB SNR	9.20	2.57	0.74
Listening Recall Primary			
Quiet	18.8	2.53	0.79
0 dB SNR	15.7	2.10	0.13
–5 dB SNR	13.9	3.39	0.66
Listening Recall Secondary			
Quiet	16.8	2.35	0.92
0 dB SNR	13.1	2.40	0.08
–5 dB SNR	10.25	2.97	0.84

Note. SNR = signal-to-noise ratio.

**Figure 1.** Average performance ( $\pm 1$  SE) for each task is plotted as a function of listening condition. AWM = auditory working memory.



**Figure 2.** Average difference score (between quiet and -5 dB SNR) for each task. p = primary; s = secondary. Error bars represent SE.



## Discussion

### Effect of Noise

The present study set out to examine the effect of noise on AWM in children with typical hearing. It was hypothesized that the presence of multitalker babble noise would result in reduced AWM performance. This hypothesis was previously supported in adult listeners by findings of Pichora-Fuller et al. (1995, 2006), Rönnberg et al. (2008), and Murphy et al. (2000), who reported reduced AWM in noise. The results of the present study provide validation of this hypothesis in the pediatric population by showing a systematic decrease in AWM performance in the presence of multitalker babble noise.

The design of this study allowed for description of the immediate effect of multitalker babble noise than was possible with previous pediatric studies. For example, Pisoni and Cleary (2003), Strait, Hornickel, and Kraus (2011), and Strait and Kraus (2011) used a correlational design to determine the relationship between performance on a speech-in-noise task and children's working memory performance. Although

a moderate to strong correlation between digit span scores and speech recognition in noise among children who wear cochlear implants has been revealed (Pisoni & Geers, 1998), this approach does not allow for comparison of AWM across SNRs. When an experimental study was employed by Stiles et al. (2012), no effect of noise at a favorable +15 dB SNR on auditory and visuospatial working memory in school-age children was found. However, the expected outcome was reduced working memory performance in the presence of background noise. The authors explained the null effect to be a result of their use of low-pass random broadband noise with an air conditioner running as their primary noise source. Other adult studies, which have used multitalker speech babble, have shown a negative effect of noise on AWM (Andrade, 2001; Murphy, Craik, Li, & Schneider, 2000). Perhaps the semantic information present in multitalker babble noise imposes greater cognitive demand and contributes to poorer performance. Speech is a more distracting stimulus because it shares more features, such as phonological code, with the AWM stimuli, and thus interferes more than random white noise, which has no phonological code (Elliott, 2002). Furthermore, classroom noise is associated with reduced performance on everyday academic tasks (Hétu, Truchon-Gagnon, & Bilodeau, 1990). This suggests that the distracting effects of multitalker babble noise are greater than random white noise. Using multitalker speech babble and keeping methods similar to previous adult studies (e.g., Pichora-Fuller, 2006; Pichora-Fuller et al., 1995), a significant reduction in real-time performance on all four AWM tasks was found at 0 dB SNR and -5 dB SNR in this study.

### *Effect of Cognitive Processing*

Each task required the child to both store and process information simultaneously but at varying levels of difficulty. In general, as processing became more involved, performance was systematically decreased. Of the three tasks, Forward Digit Recall yielded the highest scores because of ease of task and its heavy reliance on storage processes. Backward Digit Recall had an increased processing demand, recalling the numbers in reverse order, which resulted in poorer performance. This suggests that when given the same stimuli (i.e., numbers), the level of processing involved directly relates to performance. The Listening Recall task, a high cognitive task, yielded the poorest scores and was subjectively reported as the most challenging posttesting. This task involved processing the meaning of the sentences to judge whether it was true or false and remembering the final words. In particular, the secondary component of the Listening Recall task, in which the child was asked to recall the list of last words in increasing set sizes, generated the lowest scores. This suggests that any task that calls for additional processing resources is subject to poorer scores and compromises recall. This pattern of performance on low and high cognitive tasks was similar across listening conditions.

With regard to noise, we initially hypothesized that as complexity of task increased, so would the effect of noise.

Instead, we found no interaction between noise and complexity of task. A significant reduction of approximately 6% in scores was observed between quiet and 0 dB SNR for each task. An approximate 10% reduction in scores was found between quiet and the most degraded listening condition, -5 dB SNR, for each task. This demonstrates that even the addition of a small amount of multitalker speech babble noise can suppress an intact AWM system for children.

In terms of processing models for speech, cognitive resources were reallocated from immediate processing and storage to decoding of auditory information in the degraded 0 and -5 dB SNR listening conditions (Lunner et al., 2009; Pichora-Fuller, 2003; Pichora-Fuller et al., 1995; Pichora-Fuller & Souza, 2003; Rönnberg et al., 2008; Rudner, Foo, Rönnberg, & Lunner, 2009; Wingfield et al., 2005). The addition of multitalker noise not only resulted in a shift of cognitive resources and reduced working memory, but also noise placed an increased reliance on top-down functions for successful processing. Although cognitive efficiency is expected to improve throughout childhood (Kail, 1991), maximal efficiency is not evident under degraded listening conditions. Therefore, it can be implied that school-age children in noisy settings may have reduced working memory and increased listening or processing effort (Lunner et al., 2009; Zekveld et al., 2011).

It is worth noting that an effect of complexity or predictability of task on working memory performance in noise has been repeatedly identified in adult studies (e.g., Conway et al., 2005; Pichora-Fuller et al., 1995; Tun & Wingfield, 1999). For example, Pichora-Fuller and colleagues (1995) found significant differences between recall of low and high context last words in noise. The effect of context was pronounced at the most adverse SNR (0 dB), in which the scores on high context words were better than on low context words. In quiet and at positive SNRs, no difference in working memory on low and high context stimuli was observed. Adults derive benefit from contextual cues when they identify words in noisy backgrounds (Dubno, Ahlstrom, & Horwitz, 2000; Pichora-Fuller et al., 1995). This supports the processing model, which suggests there is a greater reliance on top-down processes when listening in noise becomes more challenging. When limited information from context is attained and a task is administered in noise, more allocation of resources is required, leaving fewer resources for working memory (Pichora-Fuller et al., 1995).

In the present study, however, no benefit of context or complexity was found. The effect of noise was similar for low (recall of numbers) and high (recall of novel sentences) complexity stimuli. It appears that the addition of noise has a systematic effect on auditory working memory performance regardless of complexity of task. This suggests that noise adds a substantial processing demand that supersedes any cognitive load of task alone. We speculate our finding may result from a number of reasons outlined below.

One possible reason is that children lack experience in noise to be able to use context and complexity to their benefit. Adults have more practice and experience using their knowledge to help with processing of a degraded signal in

noise, or, in other words, to “fill in the gaps.” Adults expend fewer resources for processing familiar stimuli in noise and instead allocate their top-down resources to recall and storage of information in noise (Pichora-Fuller, 2006; Pichora-Fuller et al., 1995). Although children also benefit from semantic and syntactic cues in some situations (e.g., Cole, 1981; Cole & Perfetti, 1980; Liu, Bates, Powell, & Wulfeck, 1997; Tyler & Marslen-Wilson, 1981), there are indications that high levels of background noise interfere with the optimal use of such cues (Elliott et al., 1979; Nitttrouer & Boothroyd, 1990). Elliott (1982) found that children with typical hearing (ages 11–17 years) performed poorer at 0 and –5 SNRs on high predictability sentences than adults. It should also be noted that although the language demands of the Listening Recall task were well within the capability of all of the children, as shown by their high degree of accuracy in the quiet condition and their PPVT scores, the inclusion of these stimuli may have been more taxing in noise. Thus, the protracted developmental course for acquiring auditory world knowledge, experience needed to process speech as meaningful and to use context (Elliott, Hammer, & Evan, 1987; Kuhl, 2004), and the coinciding development of cognitive processing abilities (Gathercole, 2007; Jusczyk & Luce, 2002; Locke, 1993) could have contributed to the negative effect of noise on auditory working memory in children observed in this study.

In addition, the use of more taxing distractors, four-talker speech babble and adverse listening conditions (0 dB and –5 dB SNR), may have contributed to the effect of noise on all tasks. In the past, random noise and highly favorable SNRs (i.e., +15 dB SNR) were used with children (Stiles et al., 2012). To allow for comparison and further understanding of the role of noise on AWM, future studies should include a Listening Recall task with low and high context sentence stimuli (Humes & Floyd, 2005) and select levels of noise that are representative of real-world environments for school-age children (Crandell, 1993).

## Future Directions

We therefore summarize that the presence of speech babble noise negatively impacts AWM in children with typical hearing. The addition of noise inhibits auditory working memory processes in real time. These results indicate that a compromised working memory system in noise may contribute to a child’s failure to cope with simultaneous processing and storage demands of everyday activities and implies negative consequences in speech understanding, language learning, and, ultimately, academic success. This underlines the importance of accommodations (i.e., soundfield FM systems), management of noise for all children, especially those with other deficits (i.e., hearing loss), and the development of effective strategies for children to cope with noisy situations in which they may experience working memory deficits.

To adequately provide evidence for such implications, future studies should focus on clarifying and determining the role of noise on AWM in school-age children. In this

study, an approximate 10% decrease was found across working memory tasks in noise. It is unknown how this decrease in performance manifests itself in everyday activities. The next step in this line of research is to use ornate measures tapping into functional performance, such as listening comprehension—the highest auditory skill—to assess the effect of noise on children with typical hearing and hearing impairment. In addition, further research should aim to provide information on the conditions that break down the working memory system. Assessing visuospatial working memory in noise will help to determine whether all memory types are affected by noise in a similar manner. The relationship between cognitive processes and speech perception in noise should also be explored. Such studies will be important in understanding whether and how interventions focusing on working memory are appropriate for school-age children.

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## **Chapter 2**

THE EFFECT OF NOISE ON THE RELATIONSHIP BETWEEN AUDITORY  
WORKING MEMORY AND COMPREHENSION IN SCHOOL-AGE CHILDREN

## Research Article

# The Effect of Noise on the Relationship Between Auditory Working Memory and Comprehension in School-Age Children

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**Purpose:** The objectives of the current study were to examine the effect of noise (−5 dB SNR) on auditory comprehension and to examine its relationship with working memory. It was hypothesized that noise has a negative impact on information processing, auditory working memory, and comprehension.

**Method:** Children with normal hearing between the ages of 8 and 10 years were administered working memory and comprehension tasks in quiet and noise. The comprehension measure comprised 5 domains: main idea, details, reasoning, vocabulary, and understanding messages.

**Results:** Performance on auditory working memory and comprehension tasks were significantly poorer in noise

than in quiet. The reasoning, details, understanding, and vocabulary subtests were particularly affected in noise ( $p < .05$ ). The relationship between auditory working memory and comprehension was stronger in noise than in quiet, suggesting an increased contribution of working memory.

**Conclusions:** These data suggest that school-age children's auditory working memory and comprehension are negatively affected by noise. Performance on comprehension tasks in noise is strongly related to demands placed on working memory, supporting the theory that degrading listening conditions draws resources away from the primary task.

Children have difficulty understanding speech in noisy and reverberant environments, thus requiring more favorable signal-to-noise ratios (SNRs) to achieve adultlike performance (Crandell & Smaldino, 2000; Crukley & Scollie, 2012; Elliott et al., 1979; Finitzo-Hieber & Tillman, 1978; Nitttrouer & Boothroyd, 1990). The ability to comprehend complex verbal information in adverse listening environments is vital for children to achieve academic success. Until recently, the majority of studies have focused on the effect of noise on lower level auditory-perception skills, such as discrimination and recognition (Elliott et al., 1979; Finitzo-Hieber & Tillman, 1978; Gustafson & Pittman, 2010). Emerging evidence suggests, however, that unfavorable listening conditions have a negative effect on higher auditory perception and cognitive processes such as working memory (Osman & Sullivan, 2014; Stiles, McGregor, & Bentler, 2012; Valente, Plevinsky, Franco, Heinrichs-Graham, & Lewis, 2012). Working memory is a

capacity-limited system that temporarily stores and processes information (Baddeley, 2000). Because some theoretical approaches suggest working memory may be domain specific, we will refer to it as *auditory working memory* in this article because all tasks were auditory only (Siegel & Ryan, 1989). The fact that working memory is a capacity-limited system is important because, if the demands on encoding and processing are increased, then the amount of storage is reduced. Several studies have indicated that auditory working memory is positively related to the development of speech perception, language, reading comprehension, and academic achievement (e.g., Cleary, Pisoni, & Geers, 2001; Gathercole & Baddeley, 1993; Pickering & Gathercole, 2001; Pisoni & Cleary, 2003). However, the role that working memory plays in the components of auditory comprehension in noise is unclear. The current study evaluated the effect of noise at an adverse SNR on auditory comprehension and examined its relationship with working memory.

Despite the adultlike development of the sensory peripheral auditory system, children have difficulty with more complex listening tasks, such as speech recognition in noise and auditory comprehension. One explanation for this difficulty is the protracted development of higher-order cognitive processes, such as auditory working memory, which may contribute to deficits in speech understanding in noise.

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As children mature, their working memory capacities increase and may be used more to aid in complex listening tasks (e.g., speech understanding in noise; Hitch, Halliday, Schaafstal, & Schraagen, 1988; Siegel & Ryan, 1989). According to Siegel and Ryan (1989), working memory can be reduced by intrinsic and extrinsic factors. Intrinsic (e.g., attention, hearing loss) and/or extrinsic factors (e.g., noise, linguistic complexity) reduce the amount of resources available for encoding, storage, and processing. Extrinsic factors, in particular, have a negative effect on a child's comprehension in school settings (Swain, Friehe, & Harrington, 2004).

Several researchers recently have investigated the effect of noise on working memory in children at the recommended and reported classroom noise levels (American Speech-Language-Hearing Association, 2005; American National Standards Institute, 2010). In one study, Stiles et al. (2012) did not find an effect of noise at a recommended favorable SNR (+15 dB SNR) on auditory and visuospatial tasks of working memory. However, they did find a relationship between vocabulary and working memory for children with and without hearing loss: Children with better working memory had larger vocabularies. In a second study, Osman and Sullivan (2014) found that working memory performance systematically decreased in the presence of multitalker babble noise at unfavorable SNRs (0 and -5 dB SNR) in children with normal hearing. There was an approximate 10% decrease in performance between quiet and noise conditions on forward digit recall, backward digit recall, and listening span. It is possible that the reduction in encoding and processing to auditory working memory could affect the speech recognition and comprehension in noise abilities of children.

Auditory comprehension is the most important and complex skill within the hierarchy of auditory perception proposed by Erber (1975). Auditory comprehension is a complex process that involves accessing prior knowledge along with phonological and grammatical information to make inferences about the meaning of a message. There are several models of the hierarchy of comprehension skills (e.g., Bloom's taxonomy) that describe how the levels of comprehension skills build upon one another. Most researchers and clinicians agree that comprehension skills range from recalling the facts (main idea), to making an inference (understanding), to evaluation of facts (reasoning). Children in U.S. classrooms, on average, spend 65% of the school day engaged in listening activities that require all of these skills in a variety of formats throughout the school day (Palmer, 1997). Therefore, comprehension is necessary for children to achieve academic success and develop age-appropriate literacy skills.

Few studies have investigated the effect of noise on auditory comprehension. However, emerging evidence indicates that noise can have a negative impact on children's auditory comprehension in simulated classroom settings. For example, Klatte, Lachmann, and Meis (2010) investigated the effects of running speech and classroom noise on auditory comprehension, measured by execution of oral instructions in school-age children and adults. Running

speech and classroom noise resulted in a significant decline in children's auditory comprehension. Valente et al. (2012) investigated the effects of background noise and reverberation on sentence recognition and story comprehension on school-age children and adults. Increasing background noise and reverberation negatively affected performance on story comprehension compared to minimal effects of noise in measures of sentence recognition. Regardless of differences in SNR, both studies demonstrated a negative effect of noise on auditory comprehension in simulated classroom settings.

Because comprehension is critical to classroom learning, and classroom environments often have poor acoustics (Knecht, Nelson, Whitelaw, & Feth, 2002), a more thorough understanding of comprehension in noise is warranted. Some authors define the five components of comprehension of an auditory message as (a) listening for the main idea, (b) identifying the facts and details, (c) making inferences and reasoning, (d) defining vocabulary, and (e) extracting and understanding the most relevant messages (Bowers, Huisling, & LoGiudice, 2006). Schafer et al. (2013) found that, in an extremely adverse listening condition (-5 dB SNR), spatially separated classroom noise negatively affected the five domains differently in children with normal hearing. The identifying-the-details, reasoning, and understanding-messages domains were most affected by noise. One explanation could be that these domains require more cognitive resources (e.g., working memory), and the noise makes it even harder to draw upon them. Another explanation could be that the children's poor auditory comprehension was the consequence of noise masking certain aspects of the passage, making it inaudible.

The present study aimed to replicate previous findings on the effects of background noise on auditory working memory and comprehension, examine the relationship between auditory working memory and comprehension in quiet and in noise, and compare effects of noise (i.e., noise-quiet) on auditory working memory and comprehension. We believe that the negative effect of noise will be replicated on both auditory working memory and comprehension tasks. Perhaps children who have better working memory capacity will also demonstrate better auditory comprehension in noise performance. In our previous study (Osman & Sullivan, 2014), we found a 10% reduction in working memory performance, but we do not know how working memory affects an individual's comprehension abilities across domains. We hypothesize that those complex comprehension domains (i.e., reasoning and understanding) that require more processing and cognitive resources will be more strongly correlated to auditory working memory. On the basis of previous findings by Schafer et al. (2013), we predicted that on the comprehension task, understanding an auditory passage and using reasoning skills to infer from an auditory passage would be most affected by noise. We also expected that these domains would be more strongly correlated to working memory than to main idea. Because the main idea is reinforced throughout the story with context cues and vocabulary, children may rely

on that information more so than on working memory. On the basis of previous research, we predicted that vocabulary will be strongly correlated with working memory (Stiles et al., 2012). We also predicted that, because the ability to use working memory to encode, store, and process information is compromised by extrinsic factors, the relationship with comprehension would be stronger in the noise condition because of the increased cognitive demand.

## Method

### Participants

Twenty children with normal hearing ages 8–10 years (mean age 9;0 [years;months],  $SD = 0.76$ ; nine boys and 11 girls) were recruited from the University of Washington Communication Studies P30 Participant Pool. All participants passed a hearing screening bilaterally at octave frequencies between 0.25 and 8 kHz at 20 dB HL. Participants were monolingual English speakers, right handed, and had normal cognition and language development as determined by parent interview. Furthermore, parents reported no known neurological disorders or history of recurring otitis media. Clinical Evaluation of Language Fundamentals—Fourth Edition (Semel, Wiig, & Secord, 2003) receptive language subtests (semantic relationship and understanding paragraphs) were administered to determine the baseline auditory comprehension level for each participant, which was within 1  $SD$  of the normed mean scores.

### Measures of Working Memory and Comprehension

The backward digit recall and listening recall subsets of the Working Memory Test Battery for Children (Pickering & Gathercole, 2001) were administered in two conditions (quiet and noise). The backward digit recall subtest and listening recall subtest were selected because of the access to the central executive and phonological loop subcomponents of working memory (Pickering & Gathercole, 2001). The backward digit recall subtest asked the child to recall a sequence of digits in reverse order. For example, the sequence 6-4-3 presented at a rate of 1 digit per second would be correctly recalled as 3-4-6. Testing began with two-digit sequences. Within any given sequence, no digits were repeated. The number of lists correctly recalled was scored, and responses to each sequence were scored 0 or 1. The mean test–retest reliability coefficient of this measure is .62 (Gathercole et al, 2004). The listening recall subtest is based on a procedure originally developed for adults (Daneman & Carpenter, 1980). For the listening recall subtest the child was asked to listen to a series of short sentences, judge the veracity of each sentence by responding “true” or “false,” and recall the final word of each of the sentences in sequence. Sequences began with a single sentence and increased by a single sentence following the span procedure. The mean test–retest reliability coefficient for the listening recall subtest is .61 (Gathercole, Pickering, Ambridge, & Wearing, 2004).

### Measures of Auditory Comprehension

The original Listening Comprehension Test 2 (Bowers et al., 2006) consists of 25 stories of varying length (two to eight sentences), which are presented live voice by the examiner, and three to four comprehension questions associated with each story. In the modified version, only eight passages, increasing in length from two to seven sentences, were utilized and were recorded by an English-speaking female talker. The eight passages were followed by two or four questions recorded by the same female speaker that corresponded to one of the aforementioned five subtests: main idea, details, reasoning, vocabulary, and understanding messages (see Table 1). In total, each child was asked 14 questions per listening condition. For each listening condition (i.e., quiet and noise) easy, medium and hard passages were administered with a corresponding question across the following domains: main idea, details, reasoning, and vocabulary. The understanding messages subtest was the only subtest that consisted of two questions per passage and was administered once for each condition. Difficulty of the passage was determined on the basis of the length of the passage and linguistic complexity.

### Procedure

In order to replicate previous studies, procedures used for working memory tasks were similar to those used by Osman and Sullivan (2014). The working memory tasks were presented monitored-live voice by a young adult female speaker. The speech was presented at 60 dBA at 0° azimuth, as measured at the location of the child’s head (Schafer & Thibodeau, 2006). The multiclassroom noise was presented at 65 dBA from 180° azimuth. In order to ensure that each participant understood the concept of “backwards,” practice trials were given with two-digit and three-digit sequences.

We modified the presentation setup from the Schafer et al. (2013) study. In the present study, the speech and multiclassroom noises were presented at 0° azimuth (–5 SNR), and the passages were presented via CD player. The participants were seated 1.5 m from the front speaker for all tasks. As illustrated in Figure 1, the long-term average spectrum of the story passages and background noise was similar. The order of the comprehension and working memory tasks were counterbalanced across participants, and the passages were counterbalanced across conditions and participants. Answers to questions were scored correct or incorrect and received either a 1 or 0, respectively.

## Results

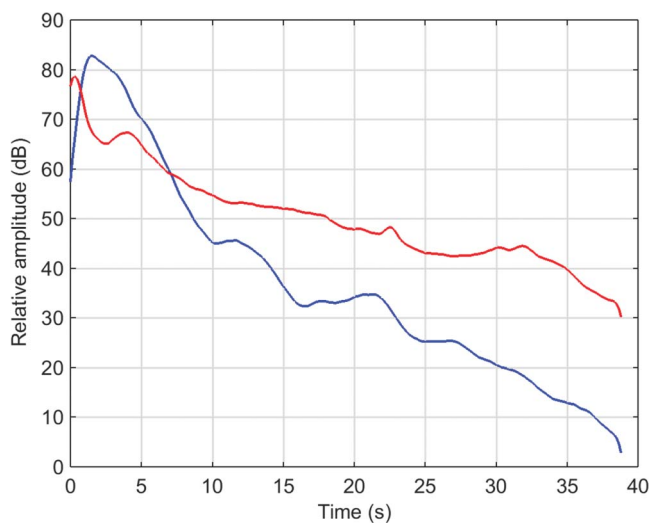
The following sections provide (a) a statistical analysis of quiet and noise conditions for the auditory working memory task, (b) a statistical analysis of quiet and noise conditions for the auditory-comprehension task, (c) correlations between the two test measures in quiet and in noise, and (d) a correlation analysis to determine the effect of

**Table 1.** Sample passage, questions, and target responses from the Listening Comprehension Test 2.

Passage	Main idea	Details	Reasoning	Vocabulary	Understanding
<i>I'm glad our class is sitting in the front rows. We will see everything. My sister has a big part. She gets to wear four costumes. She's been practicing for weeks. The curtain is going up!</i>	Q: What am I talking about?  <b>Target response:</b> Any reference to a play, performance, show, program, recital	Q: Where is this student's class sitting?  <b>Target response:</b> Any reference to in front, near the stage	Q: What do you think the sister did to practice her role?  <b>Target response:</b> Any reference to studied, memorized, repeated, rehearsed, read her lines/part/script, kept looking at it, going over it	Q: What does practicing mean?  <b>Target response:</b> Any reference to rehearsing, doing something repeatedly, studying	
<i>There's a flash flood warning in the Rosemont area this afternoon. Be ready to evacuate if necessary.</i>					Q: What are you supposed to do if you live in the Rosemont area? <b>Target response:</b> Any reference to evacuating Q: Why are you supposed to be ready to evacuate? <b>Target response:</b> Any reference to flooding, getting trapped, drowning

noise on each domain of comprehension as it relates to auditory working memory. The purpose of the analyses described in the first two sections was to replicate findings on previous studies (Osman & Sullivan, 2014; Schafer et al., 2013), whereas remaining statistical analyses were conducted to examine relationships among conditions and tasks.

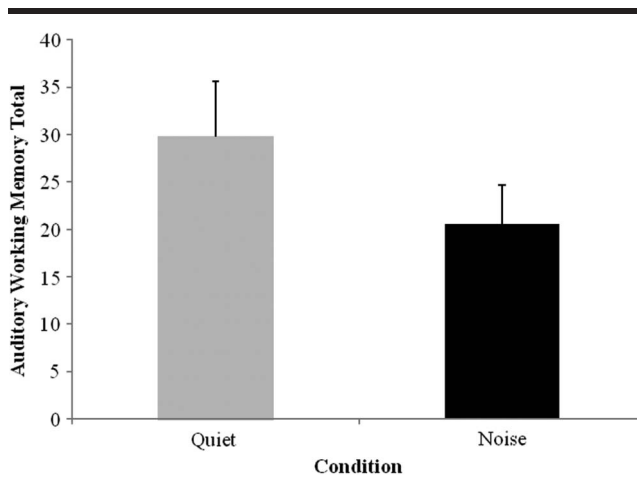
**Figure 1.** Long-term average spectrum of passages (blue) and classroom noise (red).



### *Auditory Working Memory: Quiet Versus Noise*

Average total scores in quiet and noise across the two auditory working memory tasks are shown in Figure 2. A one-factor repeated-measures analysis of variance (RM ANOVA) was conducted to determine whether the average difference between the quiet and noise conditions was significant. The analysis revealed a significant main effect of condition,  $F(1, 40) = 132.4, p < .001$ , with the noise condition resulting in significantly poorer performance on auditory working memory task.

**Figure 2.** Mean auditory working total score in quiet and noise.



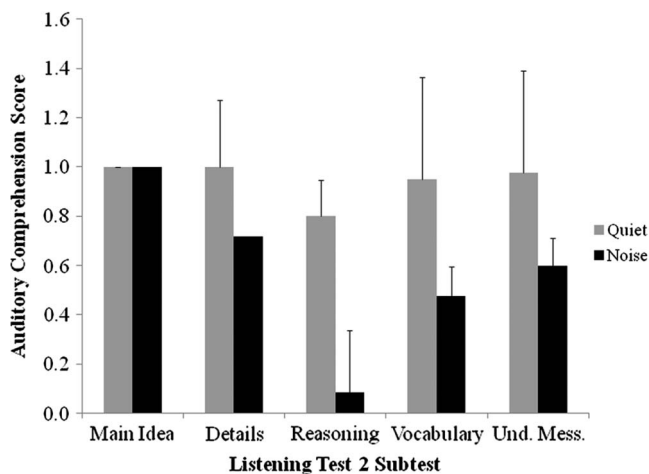
### Auditory Comprehension: Quiet Versus Noise

Average scores in quiet and noise across the five subtests of the Listening Comprehension Test 2 (Bowers et al., 2006) are displayed in Figure 3. A two-factor RM ANOVA with the independent variables of listening condition and subtest revealed a significant main effect of condition,  $F(1, 200) = 146.1, p < .000001$ ; a significant main effect of subtest,  $F(4, 200) = 34.8, p < .001$ ; and a significant interaction effect between condition and subtest,  $F(4, 200) = 16.8, p < .001$ . Post hoc comparisons with the Tukey–Kramer Multiple Comparisons Test (Tukey, 1953; Kramer, 1956) revealed that comprehension performance in the noise conditions significantly worse than in the quiet condition ( $p < .05$ ). Post hoc comparisons across the subtests suggested that performance on the reasoning subtest was significantly poorer ( $p < .05$ ) than scores in all remaining conditions, and performance on the vocabulary subtest was significantly poorer than scores on the details and main idea subtests. The main idea subtest resulted in the best performance, and main idea scores were significantly better ( $p < .05$ ) than scores on the reasoning, vocabulary, details, and understanding messages subtests. The post hoc analysis of the significant two-way Condition  $\times$  Subtest interaction revealed that the reasoning subtest in noise resulted in significantly poorer performance ( $p < .05$ ) than all remaining conditions in quiet and noise. In addition, performance on the vocabulary subtest in noise was significantly poorer ( $p < .05$ ) than in all remaining conditions. Finally, the main idea subtests in quiet and in noise were not significantly different from each other and resulted in significantly better performance than all remaining subtests in noise.

### Relationships Between Auditory Working Memory and Listening Comprehension

To examine potential relationships between auditory working memory and listening comprehension, Pearson

**Figure 3.** Mean comprehension subtests in quiet and noise. Und. Mess. = understanding messages.



correlation analyses were conducted between the total auditory working memory score and the total listening comprehension score in quiet and in noise. Figure 4 illustrates a moderate or strong correlation between auditory working memory and the listening comprehension in quiet ( $r = .50, p = .05$ ) and in noise ( $r = .75, p = .05$ ), respectively. In other words, the relationship between working memory and comprehension became stronger when the participants were tested in noise.

To examine a potential relationship between the working memory tasks and the subtests of the Listening Comprehension Test 2 across conditions, a correlation matrix was calculated (see Table 2). In the quiet condition, there was only one significant relationship between the comprehension subtests and the working memory tasks. Reasoning was significantly correlated with listening recall in quiet,  $r = .50, p = .05$ , whereas in the noise conditions significant correlations between working memory and two of the comprehension subtests, vocabulary and understanding messages, were found. Only the vocabulary subtest in noise was significantly related to all working memory tasks across conditions. In addition, a significant relationship was found between understanding messages in noise and backward digit recall in quiet,  $r = .62, p = .05$ , and listening recall in quiet,  $r = .58, p = .05$ . This finding suggests that working memory plays a role in more complex comprehension tasks, such as reasoning and understanding in noise. It also suggests that vocabulary size will aid working memory in any condition, especially in noise.

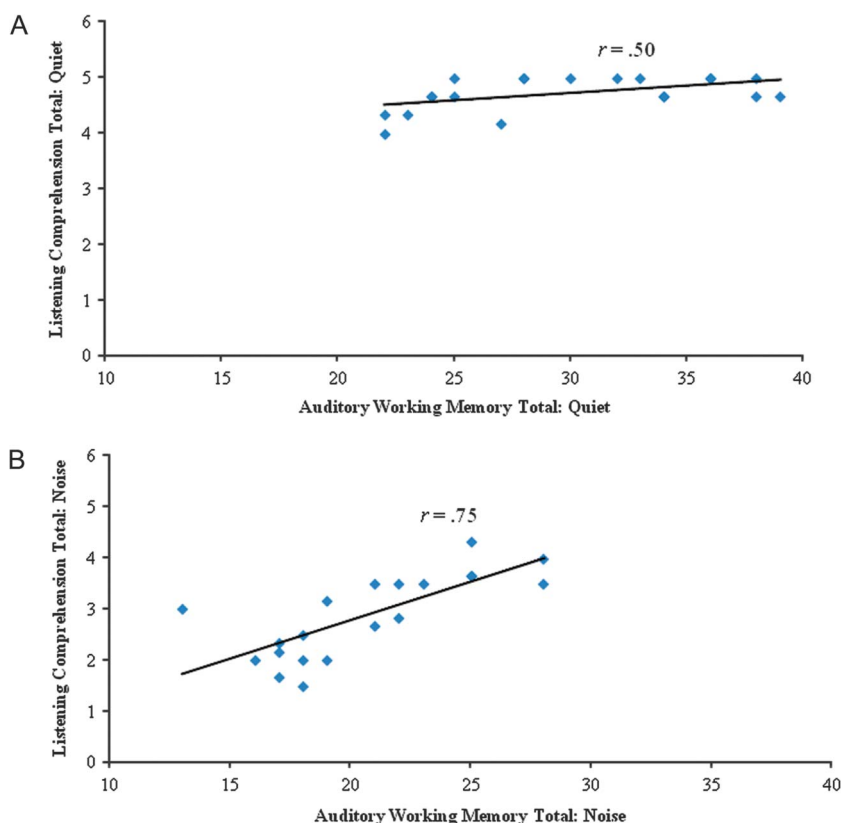
### Comparison of Noise Effects (Quiet Score – Noise Score) on Auditory Working Memory and Listening Comprehension

In order to compare the effects of noise on the measures, difference scores were calculated between quiet and noise conditions on the auditory working memory and listening comprehension total scores. Difference scores were calculated by subtracting the scores in noise from the scores in quiet to determine the effect of noise on the respective test type. A one-factor ANOVA was then used to determine whether one measure resulted in significantly different performance and, according to the analysis, auditory working memory was significantly more affected by background noise than was comprehension,  $F(1, 40) = 81.9, p < .001$ .

### Discussion

This study confirms previous findings that noise has a significant impact on auditory working memory and listening comprehension, and it provides several new insights into relationships between aspects of working memory and comprehension in children. The correlation analyses tested our hypothesis related to the effect of noise on working memory and comprehension.

More specifically, to replicate our previous work, children with normal hearing were tested on two subsets of the Working Memory Test Battery for Children and a

**Figure 4.** Correlation of auditory working memory and comprehension in quiet and noise.

modified version of Listening Comprehension Test 2 in quiet and noise. Results in the present study replicated previous findings related to the negative effect of noise on auditory working memory (Osman & Sullivan, 2014) and comprehension (Schafer et al., 2013) performance. The results indicated that auditory working memory and comprehension scores were significantly worse in noise relative to the quiet condition. We were able to replicate the systematic decrease in auditory working memory performance

**Table 2.** Correlation matrix of backward digit recall and listening comprehension subtests across conditions.

Condition	BW Quiet	BW Noise	LRT Quiet	LRT Noise
Main idea quiet				
Details quiet				
Reasoning quiet	0.27	0.06	0.50*	0.09
Vocabulary quiet	0.39	0.30	0.35	0.11
Und. mess. quiet	0.17	0.13	0.01	0.11
Main idea noise				
Details noise	-0.007	-0.002	0.27	0.19
Reasoning noise	0.36	0.39	0.33	0.20
Vocabulary noise	0.71*	0.71*	0.70*	0.64*
Und. mess. noise	0.62*	0.52	0.58*	0.40

Note. BW = backward digit recall; LRT = listening recall test; Und. mess = understanding messages.

\* $p < .05$ .

from quiet to noise on both the backward digit recall and listening recall tasks from Osman and Sullivan (2014). There was no interaction between noise and complexity of task in either study: The effect of noise was similar across working memory tasks. However, the effect of noise did vary across comprehension domains both in the study by Schafer et al. (2013) and in the present study. Further analysis of the five comprehension subtests found that noise had a significant negative effect on details, vocabulary, reasoning, and understanding messages. We had initially hypothesized that more involved or higher-order comprehension tasks, such as reasoning and understanding messages, would be more affected by noise because they require more cognitive resources. These findings were consistent with the results of Schafer et al.'s investigation, in which details, reasoning, and understanding messages were affected by the presence of noise. The significantly poorer performance in noise compared to quiet on the vocabulary, details, reasoning, and understanding messages subtests may be attributed to several factors, including working memory, as well as reduced audibility of the stimuli in noise, developmental aspects of hearing in noise, developmental effects for the tasks, or limited knowledge of vocabulary in passages (Schafer et al., 2013).

When the correlation analyses were examined, the primary finding was that the working memory total score was positively correlated with comprehension scores in quiet

and noise. Put simply, children with better total working memory had better performance on the comprehension task. A moderate relationship between comprehension and working memory in quiet suggests an active role of working memory when encoding and processing demands are minimal and/or there are fewer distractions. However, a strong relationship in noise reflects a possible increase in processing demand and/or effect of the adverse listening condition on working memory that requires more activation. Therefore, children with higher working memory scores were able to perform better on the comprehension task in noise. This finding suggests that children with larger working memory capacities are better able to compensate when extrinsic factors such as noise are present.

An important consideration in this discussion is the variability found across correlation coefficients (see Table 2), which represent the degree to which working memory contributes to the various comprehension domains. Consistent with Osman and Sullivan's (2014) results, working memory performance was decreased by approximately 10% in the presence of noise on backward digit recall and listening recall task. However, there was not an even distribution of this reduction across comprehension domains. It was anticipated that more complex comprehension tasks, such as vocabulary, understanding, and reasoning, would account for the 10% reduction in working memory. This was only partially supported by our findings; only vocabulary and understanding in noise had some significant relationship to working memory. The correlation matrix revealed that vocabulary accounted for the greatest amount of variance on working memory tasks across conditions. This finding is consistent with Stiles et al. (2012) and supports our hypothesis. One interpretation is that children with larger vocabularies have more cognitive resources to draw upon and can use working memory more effectively in adverse listening conditions. However, it is important to note that the small sample size and relatively low reliability of the auditory working memory tasks could have contributed to some of the variability across the matrix.

It is not immediately obvious why only the reasoning subtest did not have any significant relationship with working memory in noise. Although reasoning was significantly affected by noise, it had a weak relationship in noise with the working memory measures in quiet and noise. One possible explanation is that reasoning is a comprehension skill, which builds upon other tasks (e.g., understanding and vocabulary) and draws upon other cognitive resources. Therefore, the contribution of working memory is not increased. As a result, children may draw upon other cognitive resources in addition to working memory to complete a reasoning task accurately. With respect to developmental effect of the tasks, the reasoning subtest was particularly difficult because it required children to generate new information in the form of inferences and conclusions on the basis of what they heard in the story. However, understanding messages in noise had moderate relationships with backward digit recall in quiet, listening recall in quiet, and backward digit recall in noise.

We believe any negative performance on the details subtest was related to lack of audibility, not working memory. This was confirmed with the correlation matrix analyses, which indicated that the details subtest had no relationship with the working memory task in quiet and noise. It is possible that the inability to successfully recall details in noise was due to masking of the targeted fact in the passage, suggesting that poor audibility and/or attention could be attributed to reduced performance on the detail subtest in noise.

As expected, we did not find a significant relationship between working memory and the main idea subtest. Children had similar performance on the main idea subtest in quiet and noise, suggesting that potentially easier or lower-level tasks can still be performed well in adverse listening conditions. There is a strong likelihood that children performed best in the main idea category because, throughout the passage, they were given several opportunities to hear the topic of the passage. Even though children were not given the passage topics prior to testing, there is a strong likelihood that children performed best in the main idea category because, throughout the passage, they were given several opportunities to hear the topic of the passage. This result is consistent with the finding that children require increased amounts of acoustic-phonetic information and context to identify words and understand passages as well as adults (Cole & Perfetti, 1980).

On the basis of the results of the present study, it would appear that there are several factors involved in poor auditory comprehension in noise. In lower-level comprehension tasks, such as details, children are affected by noise when there are fewer opportunities to hear the information. However, when given a variety of information on a topic, children are able to identify the main idea even under adverse listening conditions. In both cases, audibility and task complexity are key factors in performing the comprehension task in noise. In terms of more complex comprehension tasks, there appears to be a stronger relationship with working memory (see Table 2). Because the vocabulary and understanding messages subtests show a significant relationship with auditory working memory, the theory that working memory contributes more to tasks that are more complex is supported. Framed within the context of encoding and processing of information, the results, we believe, indicate that when either task complexity and/or external distracter increase demands (noise), working memory and comprehension performances are reduced (Pichora-Fuller, Schneider, & Daneman, 1995; Towse & Hitch, 1995; Towse, Hitch, & Horton, 2007). However, the lack of relationship between working memory and reasoning suggests that more work is needed to fully explain this finding and its clinical relevance.

## Conclusion

There is a relationship between auditory working memory and comprehension, especially in quiet and in noise conditions. Children perform more poorly on working

memory and comprehension tasks in the presence of noise relative to quiet. Although it has been previously hypothesized that the reduction in performance in noise is related to a lack of audibility, the data in this study indicate that other factors, such as vocabulary size and working memory capacity, may contribute to poor auditory comprehension in noise. Further research is needed to determine how this translates into classroom performance.

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### **Chapter 3**

#### **THE INTERACTION BETWEEN TASK DIFFICULTY AND NOISE LEVEL ON CHILDREN'S AUDITORY-COGNITIVE PERFORMANCE**

# The Interaction Between Task Difficulty and Noise Level on Children's Auditory-Cognitive Performance

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## ABSTRACT

**PURPOSE:** To evaluate the effects of task difficulty and intensity level of four-talker masker on children's working memory (WM) and auditory comprehension performance.

**METHODS:** Thirty children with normal hearing (ages 8-10) were assessed on WM and comprehension tasks. Low-difficulty (backward digit recall) and high-difficulty (letter-number sequencing) WM tasks were directly compared in quiet and four-talker babble at +15, +5, 0, and -5 dB signal-to-noise ratios (SNR). In the same listening conditions, comprehension of spoken passages was evaluated with questions targeting listening for the main idea, identifying details, defining vocabulary, and inferring information.

**RESULTS:** Performance on WM and auditory comprehension tasks were negatively affected by increasing levels of four-talker babble. However, the effect of four-talker babble was not uniform at each SNR and for each task. An interaction between task difficulty and SNR determined the degree of disruption. Similarly, comprehension subtests that required manipulating information were particularly affected at more negative SNRs.

**CONCLUSIONS:** Children's auditory-cognitive performance is highly sensitive to processing load. The extent that children engage cognitive resources depends on demands of task difficulty and level of four-talker babble. The combined costs of performing a difficult task in adverse acoustical conditions are greater than the sum of the individual costs.

## INTRODUCTION

There are currently no clinical audiologic metrics to assess the full range of auditory and cognitive demands placed on a child in the classroom. The main focus of pediatric audiologic evaluations is to provide information on a child's hearing sensitivity by detection of pulsed pure tones and speech recognition of isolated words or short sentences in quiet. However, children spend much of their lives functioning in noisy environments (e.g., classroom) (Crukley, Scollie, & Parsa, 2011). Numerous studies indicate typical classroom signal-to-noise ratios (SNR) range from -7 to +5 dB, which are levels known to support word recognition scores of no greater than 60% correct for children (Nittrouer & Boothroyd, 1990; Arnold & Canning, 1999; Crandell & Smaldino, 2000; Picard & Bradley, 2001). This is problematic because the majority of learning tasks involve complex listening processes such as short-term storage and mental processing of verbal information (Palmer, 1997). High demands on these listening processes in acoustically compromised environments negatively affect how children comprehend speech and can impact communicative, psychosocial, and academic performance (Maxwell & Evans, 2000; Shield & Dockrell, 2003; Stelmachowicz, et al., 2002; Rosenberg, 2010). To accurately assess the speech-in-noise challenges children face, performance must be examined using complex listening tasks that demand cognitive processing presented at SNRs that are typical for mainstream classroom environments.

### *Complex Listening Tasks*

Most studies have examined children's speech understanding in noise with tasks that required identification of phonemes (Leibold & Buss, 2013), words in isolation (Caldwell

& Nittrouer, 2013) or words in sentences (Lewis et al., 2010). Speech understanding thereby refers to a listener's ability to recognize and repeat target stimuli (Humes & Dubno, 2010). In the classroom, instruction is primarily presented through spoken information and a student's understanding extends beyond the identification level. Children are expected to demonstrate comprehension by answering questions, following instructions, generating new ideas or engaging in discussions (Flexer, 2004). While identification tasks demonstrate children's susceptibility to masking effects of noise, the associated effects on comprehension and other higher-level cognitive skills might be underestimated (Klatte et al., 2010a; Prodi et al., 2010; Prodi et al. 2013). For example, Klatte and colleagues (2007) directly compared 6- to 7-year old children's performance on word identification, verbal short-term memory and sentence-comprehension tasks in competing speech at +5 dB SNR. Verbal short-term memory and sentence-comprehension performance were substantially disrupted by competing speech, but word-identification was unaffected. The decline in performance on tasks requiring higher-level processing of speech in background noise has been generally attributed to greater demands on cognitive resources (Jerger, 2007; Schneider & Pichora-Fuller, 2000; Pichora-Fuller, 2003).

The cognitive resources devoted to processing and storing speech to short-term memory has been described as finite (Kahneman, 1973). A greater need for cognitive resources to encode and process speech means a decrease in availability of resources for storage and subsequent recall (Lunner et al., 2009). The quality of the auditory input and the requirements of the listening task can each impose a significant demand for cognitive

resources (Souza et al., 2015; Heinrich et al., 2015). For instance, in order to maintain speech understanding at a reasonably high accuracy level in background noise, cognitive resources are directed towards parsing the auditory scene and recovering the degraded speech signals (Schneider, 2011). Background noise may also tax a listener to rely on contextual cues, prior knowledge, and explicit cognitive processes such as working memory to support listening; this is especially true if a primary task is more involved (Ronnberg et al., 2013). The increase in cognitive load leaves fewer resources for simultaneous processing and storage of primary task-relevant information that a listener needs to engage in and can come at a cost of performance and listening effort (Pichora-Fuller, Schneider, & Daneman, 1995). Although the evidence for the cognitive resource allocation hypothesis is from studies of adults experiencing age-related cognitive decline (e.g., Tun et al., 2009; Pichora-Fuller et al., 1995; Murphy et al., 2000; Mishra et al., 2013), children are also susceptible to resource limitations. Children have limited flexibility in perceptual strategies, less access to linguistic knowledge, and are still developing cognitive skills required to support the demands of listening in background noise (refer to Klatt et al., 2013 for review). Children also disengage from a task more rapidly than adults when the cognitive load for a task exceeds their capacity, which further contributes to speech-in-noise difficulties (Johnson et al., 2014).

The degree of challenge a child experiences with degraded auditory input is related to their capacity to process and store simultaneous information – working memory (Baddeley, 2000; Sorqvist & Ronnberg, 2014). For example, Osman & Sullivan (2014) evaluated the effects of multi-talker babble at 0 and -5 dB SNR on forward-digit,

backward-digit, and listening-span performance in a group of 8- to 10-year old children with normal hearing. As the listening condition became worse, a systematic decline in performance on each working memory task was observed. This finding is consistent with the cognitive resource allocation hypothesis in that a trade-off between concurrent processing and maintenance of information was observed. As more processing resources were devoted towards decoding of target stimuli in multi-talker babble compared to quiet, fewer resources were available for manipulation, storage, and successful retrieval of information. Other studies have also demonstrated a negative effect of background noise on children's memory for speech (i.e., irrelevant sound effect; Elliott, 2002, Klatte et al., 2010b).

In reference to Caleffe-Scheck's (2005) organizational framework of auditory skills, if background noise has a deleterious effect on a child's ability to remember varying lengths of auditory information in a specific order, then it is reasonable to assume more difficult tasks requiring extraction, manipulation, interpretation, and storage of verbal information (i.e. comprehension) are prone to further disruption. In fact, there is an emerging body of evidence that suggests children have difficulty comprehending complex messages in background noise. For example, background noise was more disruptive for following directions (Klatte et al., 2010a) and answering factual questions (Valente et al., 2012; Lewis et al., 2015) than for mere recognition of sentences. While these studies confirmed the discrepancy in the effect of background noise on identification and comprehension tasks, recent studies have shown differential effects of background noise across multi-faceted aspects of comprehension (Schafer et al., 2013;

Sullivan et al, 2015a). Sullivan and colleagues (2015a) found that 8- to 10-year old children with normal hearing had more difficulty answering questions about spoken passages presented in classroom noise at -5 dB SNR than in a quiet condition. Specifically, children were less able to determine the most pertinent information, store details in memory for later recall, define vocabulary, and integrate information with prior knowledge in the presence of noise. The aspects of comprehension, which was organized in a hierarchal manner based on depth of processing involved, determined the magnitude of effect of classroom noise (Kintsch, 1988; Kintsch and van Dijk, 1978). Sullivan et al. (2015a) also noted a strong relationship between working memory and auditory comprehension in noise. This supports the idea that children draw upon explicit cognitive processes to understand information contained in discourse (Akeroyd, 2008; Daneman & Merikle, 1996; Gathercole & Baddeley, 1993; Just & Carpenter, 1992). This relationship also emphasizes that complex listening tasks that tap into processing, manipulation, and storage processes of verbal information can effectively predict the effects of background noise on comprehension.

### *Complex Auditory Environments*

Similar to task difficulty, the properties of an auditory environment can add to the complexity of listening. Auditory and cognitive demands posed by background noise are known to depend on the type of interfering sounds and the SNR at which those sounds occur (Heinrich et al., 2015; Howard et al., 2010). Children's difficulties on complex listening tasks in noise have been mostly studied using a single relatively favorable SNR. For instance, Stiles et al. (2012) examined working memory performance in a group of 6-

to 9-year old children with and without hearing loss under a highly favorable acoustic condition: low-pass broadband noise at +15 dB SNR. No effect of noise on working memory was found and was explained in part by the minimal disruptiveness of non-speech babble on children's cognitive processes. Choi et al., (2014) evaluated 7- to 14-year old children's ability to recall words and digits in speech-shaped noise at +8 dB SNR. Children were unaffected by noise at this level when only words or digits were presented, but decrements in recall of 3- and 5-digits were observed when the digits were followed by monosyllabic words. In a simulated classroom experiment, sentence-recognition and passage comprehension was assessed at +10 dB SNR (Valente et al., 2012). Sentence recognition performance was at or near ceiling for all participants, but poorer scores on the comprehension task were noted for children compared to adults. When the SNR was adjusted to +7 dB in a second experiment, children's performance on the comprehension tasks was further compromised. Considering classrooms are rarely at or near the American National Standards Institute ([ANSI], 2002) recommendation of +15 and more often at 0 dB SNR (Arnold & Canning, 1999), performance at low SNRs might be more sensitive to children's speech in noise difficulties on such classroom-relevant tasks.

Substantial declines in elementary school-age children's working memory and comprehension performance have been found at low SNRs such as 0 and -5 dB SNR in four-talker babble (Osman & Sullivan, 2014) and classroom noise (Sullivan & Osman, 2015a; Schafer et al., 2013) compared to quiet. Differences in task performance between quiet and low SNRs may be interpreted as reflecting the greatest amount of demand

imposed by background noise. Only a few studies to date have examined children's performance on complex tasks across a range of SNRs (e.g., Klatte et al., 2010a; Howard et al., 2010). In one study, Klatte and colleagues (2010a) examined children and adults' word-to-picture identification and listening comprehension performance in the presence of single-talker masker and classroom noise. For each noise type, intensity levels and reverberation times were adjusted to simulate an unfavorable and favorable room. The SNRs for the favorable and unfavorable room were approximately 3 dB apart. Howard et al. (2010) assessed children's listening effort using a dual-task paradigm in quiet and at +4, 0, and -4 dB SNR. Declines in secondary task performance were noted across listening condition, but especially at more negative SNRs. The authors concluded that greater listening effort was required and fewer cognitive resources were available when multi-tasking was involved and as the listening condition became unfavorable.

### *Current Study*

Although there is relatively sparse literature regarding the effects of noise on difficult listening tasks, previous work has demonstrated negative effects of background noise levels that are typical of classrooms. However, extant literature is complicated by use of: a range of tasks which vary in difficulty; different types of maskers; and a limited range of SNRs. Mackersie and colleagues (2001) have advised that evaluating performance across a wide range of SNRs provides a more thorough estimate of functional performance. To predict children's listening abilities in the classroom, research is needed to examine how working memory and comprehension are affected when listening in complex auditory environments. Therefore, in the present study we sought systematically

investigate the effects of four-talker babble across a range of classroom-relevant SNRs on classroom-relevant tasks. We were interested in identifying the cognitive load prompted by an independent task competing with four-talker babble for limited processing resources. Specifically, we aimed to answer: (1) whether four-talker babble affects performance on low- and high-working memory tasks to the same degree at each SNR; (2) whether four-talker babble affects performance on comprehension sub-tests to the same degree at each SNR; (3) whether the demands of task difficulty and level of four-talker babble have an additive effect on performance. We hypothesize that performance will decrease as the quality of the speech signal is degraded by four-talker babble and as more processing is required by task.

## METHOD

### *Participants*

Thirty children, ages 8 to 9 ( $M= 8;8$  [years;months],  $SD= 0.53$ ), participated in the current study. Equal numbers of males and females were recruited from the Communication Studies Participant P30 database at the University of Washington. Inclusionary criteria for this study were defined as: monolingual English speakers, right-handedness, and normal age-appropriate receptive language development. According to parent report, participants had no known neurological disorders, history of recurring otitis media, and previous experience or familiarity with the experimental tasks. None of the children had any reported history of speech, language, learning or cognitive problems. Information on each child's classroom acoustic environment and class size was also noted (Table 1). The parent or guardian of each child read and signed a statement of

informed consent approved by the Human Subjects Review Committee at the University of Washington. Each child also gave formal assent to participate in the study.

[Insert Table 1]

### *Screening Measures*

In a soundproof booth, each child's hearing sensitivity was measured using a Grason-Stadler Instruments GSI-61 audiometer calibrated to ANSI specifications (ANSI, 2004). Pure-tone air conduction thresholds were measured under TDH-50 headphones at octave frequencies from 250 Hz to 8000 Hz in both ears. All participants had clinically-normal hearing at each frequency in both ears (15 dB HL or less; American National Standards Institute [ANSI], 2004) (Table 2). Most comfortable level (MCLs) and background noise level (BNLs) were also measured for each participant, in accordance to the pediatric-specific protocol outlined in Moore, Gordon-Hickey, and Jones (2011) and found to be consistent with published 8 year-old data (e.g., Freyaldenhoven & Fisher Smiley, 2006).

[Insert Table 2]

Children were screened for baseline auditory comprehension skills using the Clinical Evaluation of Language Fundamentals-Fourth Edition (CELF-4; Semel, Wiig, & Secord, 2003). The Understanding Spoken Paragraphs and Semantic Relationships subtests were administered to determine the baseline auditory comprehension level for each participant. In the Understanding Spoken Paragraphs subtest each child's ability to (a) sustain attention and focus while listening to spoken paragraphs, (b) create meaning from oral

narratives and text, (c) answer questions about the content of the information given, and (d) use critical thinking strategies for interpreting beyond the given information. The Semantic Relationships test was used to evaluate the child's ability to interpret sentences that (a) make comparisons, (b) identify location or direction, (c) specify time relationships, and (d) include serial order. Both screening measures assessed skills necessary for the completion of the experimental tasks. All participants had scores within 1 standard deviation (SD) of the normed mean scores. Receptive vocabulary was also measured for each participant using the Peabody Picture Vocabulary Test, Fourth Edition (PPVT-4; Form A, Dunn & Dunn, 2006). Each participant was presented with a set of words and asked to indicate the picture that matches the word spoken by either saying the number corresponding to the picture or by pointing to it. The set of words was determined by the child's age and continued until the child committed eight or more errors in a set, establishing the ceiling set. All of the children in the study were within 1 SD of the normal range for their age [standard score,  $M= 128.77$ ,  $SD= 8.87$ ; age-equivalent score,  $M= 12.38$ ,  $SD= 1.57$ ].

#### *Experimental Task Stimuli*

Three complex listening tasks were used: backward digit recall, letter-number sequencing, and auditory comprehension. The authors *a priori* designated the backward digit recall task as a *low*-difficulty task and the letter number sequencing task as a *high*-difficulty task (Stierwalt et al., 2006).

The backward digit recall was obtained from the Working Memory Test Battery for Children (WMTB-C; Pickering & Gathercole, 2001). This is a standardized working memory task used to assess the storage and processing functions of auditory working memory. Digits were presented using clear speech in sequences at 1-second intervals via monitored live voice. Participants were asked to respond by recalling the numbers in reverse order, from which they were presented. Three practice trials were given to ensure that each participant understood the concept of “backwards.” Following a practice session, each child was given six trials per list-length set. Testing began with three-digit sequences (*i.e.*, 5-1-3). Sequence length was increased by one if the child recalled a set of six correctly. Testing stopped if the child repeated three trials within a set incorrectly. Within any given sequence, no digits were repeated. Responses to each sequence were scored either 0 or 1. No credit was given for any correctly recalled sequences after three errors were made in a particular list.

The letter-number sequencing task was obtained from the Wechsler Intelligence Scale for Children (WISC-V; Wechsler, 2014). This is a standardized working memory task used to assess each child’s ability to maintain and manipulate information in conscious awareness. A series of letters and numbers were presented and participants were asked to recite numbers first in ascending order followed by letters in alphabetical order. Participants were given four practice trials in order to familiarize them with the task. For example, if 8-B-2 was spoken, then the child was expected to respond with 2-8-B. After successful completion of practice trials, sequences of letters and numbers (starting with 2-item sequences) were presented in blocks of increasing items. Testing was discontinued

once the participant made 6 errors in a block. Rhyming letters and numbers were not included.

Auditory comprehension was assessed using a modified version of the Listening Comprehension Test 2<sup>TM</sup> (Bowers et al., 2006). This measure was used to assess each child's ability to recall details, make judgments, and comprehend auditory information. Ten passages of equivalent complexity, 89.6 to 92.8, as measured by the Flesh-Kincaid readability level were selected. For each passage, four associated questions were asked that addressed a particular listening behavior: *main idea*, *details*, *reasoning*, and *vocabulary*. The *main idea* question focused on the identifying the primary topic of the passage. The *details* question required the child recall of one or more details presented within the passage. The *reasoning* question required the child to answer or infer answers from the information provided in the passage. The *vocabulary* question asked the child to define a specific word in the passage. A more detailed description is in Sullivan, Osman, and Schafer (2015), as the procedure and test materials are consistent with that study.

### *Experimental Design and Procedure*

The experiment was a within-subjects factorial design. The within-subjects factors were listening condition (quiet, +15, +5, 0, -5 dB SNR) and task (backward digit recall, letter-number sequencing, auditory comprehension). All three experimental tasks were completed in a double-walled sound booth in a single 1-hour session. Five-minute rest periods were given between tasks to reduce possible fatigue effects. To minimize order

effects, the task order and the listening condition order were determined by a counterbalanced design.

For the experimental tasks, the spoken stimuli and auditory distraction was routed through a CD player (HHB DualBurn CDR-882) and presented at 0 degrees azimuth from the front power speaker (Fostex PMO.5 MKII). The child was seated 1.5 meters from the front speaker throughout the session. A young English-speaking adult female speaker presented the tasks via monitored live voice at a fixed level of 60 dBA, as measured at the location of the participant's head with a Quest SoundPro 3M sound level meter. This level was consistent with most comfortable listening levels obtained for each child (Table 2) and ensured good audibility of the spoken stimuli across all listening conditions. The stimuli for the auditory distraction conditions involved digitally recorded competing speech, supplied from the Quick Speech-in-Noise (QuickSIN) test (Version 1.3, Etymotic Research). The competing speech consisted of one male and three female English-speaking talkers simultaneously producing readings of different passages. Occasional words in the four-talker babble were intelligible. The long-term spectrum of this noise resembled the long-term average speech spectrum (as in Sullivan, Osman, Schafer, 2015a). Four-talker babble was selected because of its informational masking properties and its ecological validity (represents everyday situations children contend with on a daily basis). The former is especially important for the current study because informational masking may result from increased cognitive load, competing attention, misattribution of components of the babble to the target speech stimuli, and/or linguistic interference (Cooke et al., 2005). The level of the four-talker babble was adjusted to

create the different listening conditions: +15 dB SNR (45 dBA), +5 dB SNR (55 dBA), 0 dB SNR (60 dBA), -5 dB SNR (65 dBA).

To determine if proceeding to the next set of items was appropriate (i.e., span procedure), scoring for each task was completed online during the tasks. Each child was given a 15-s response window to initiate a response. After the session, a secondary blind rater reviewed 40% of the recordings. In the examination of reliability for scoring of tasks, inter-rater reliability agreement was calculated as 98.6%.

## RESULTS

The following sections provide descriptive statistics and inferential analyses for the auditory working memory and auditory comprehension tasks.

### *Working Memory Performance Data*

To examine distribution characteristics according to task difficulty, means and standard deviations were calculated for each task across listening conditions (Table 3). Scores were indicated as total number of trials correct. For a direct comparison of the effect of varying levels of 4-talker babble on the two auditory working memory tasks, the average proportion differences from quiet were also computed. On average, performance decreased by a proportion of 38.59 (6.33 trials) from quiet to -5 dB SNR, the most degraded listening condition, for the backward digit recall. The difference for the letter number sequencing task was 44.23 (8.27 trials). The average performance for each task across the five listening conditions is plotted in Figure 1.

[Insert Table 3]

Statistical analyses were performed using SPSS software, Version 21. To analyze the effects of listening condition (quiet, +15, +5, 0, -5 dB SNR) and cognitive load of task (low: backward digit recall, high: letter number sequencing), a 5 x 2 factorial repeated measures analysis of variance (RM-ANOVA) was performed. The dependent variable was the number of correct trials across all blocks reported by the child. The results of the RM-ANOVA revealed two significant main effects and one interaction. There was a main effect of listening condition (Sphericity Assumed,  $F(4,22) = 228.906, p < 0.001$ ) and a main effect of task ( $F(2,22) = 128.053, p < 0.001$ ). Large effect sizes were observed for the main effects ( $\eta^2$  .941 listening condition, .197 task) and interaction ( $\eta^2$  .474). The main effects were moderated by the interaction between listening condition and task ( $F(4, 44) = 10.895, p < 0.01$ ). Performance decreased significantly both when the task became more difficult (or manipulation load increases) and when SNR became more negative. Post-hoc Bonferroni-correctly paired-samples t-tests showed that all conditions differed significantly ( $p < 0.001$ ) from one another for each task, with the exception that no difference was noted between 0 and -5 dB SNR for the backward digit recall task.

[Insert Figure 1]

#### *Auditory Comprehension Data*

Average scores in the five listening conditions across the subtests of the Listening Test<sup>2</sup> are displayed in Figure 2. A two-factor RM ANOVA with the independent variables of

listening condition and subtest revealed a significant main effect of condition,  $F(1, 200) = 146.1, p < 0.001$ , significant main effect of subtest,  $F(4, 200) = 34.8, p < 0.001$ , and significant interaction effect between listening condition and subtest,  $F(4, 200) = 16.8, p < 0.001$ . Post-hoc comparisons with the Tukey-Kramer Multiple Comparisons Test revealed that comprehension performance in the noise conditions was significantly worse than in the quiet condition ( $p < 0.01$ ). Post-hoc comparisons across the subtests suggested that performance in the reasoning subtest was significantly poorer ( $p < .05$ ) than scores in all other conditions, and the details subtest was significantly poorer than the vocabulary and main idea subtests. The main idea subtest resulted in no change across SNR and therefore, it served as a control condition. The reasoning subtest experienced the greatest decrease in performance across SNR (decrease in performance of 70%), followed by the details subtest (decrease in proportion of 50%).

[Insert Figure 2]

## DISCUSSION

The present study was designed to assess the effects of task difficulty and level of four-talker babble on complex listening task performance in children with normal hearing. Our results can be summarized as follows: children were less accurate in their performance (a) when the working memory tasks were presented with four-talker babble regardless of level compared to quiet (b) when the comprehension task was presented with four-talker babble regardless of level compared to quiet and (c) when the cognitive load was increased by task difficulty and by the presence of high levels of four-talker babble. The

pattern of our findings is consistent with theoretical approaches of cognitive resource allocation that include variables of cognitive load and effort.

#### A. Effect of four-talker babble on working memory task performance

As expected, mean performance was worse for both working memory tasks as the SNR became more negative. This is consistent with previous studies that indicate when an auditory interference (i.e., background noise) is added to a primary listening task, a reduction in accuracy, ease, and speed of information processing is typically observed (e.g., Johnston, Wagstaff, & Griffith, 1972). The initial straightforward reason commonly offered to explain such findings is that background noise compromises the overall intelligibility of the target speech signal. However, studies have demonstrated that even in conditions where excellent identification of target speech signals in noise is noted, there can be significant decrements in adults' performance on auditory memory tasks (i.e., Luce et al., 1983; Heinrich, Schneider, & Craik, 2008; Pichora-Fuller et al., 1995; Wingfield, Tun & McCoy, 2005; Rabbitt, 1968; 1991). For example, Rabbitt (1968) showed that remembering digits presented in noise was reduced in a group of normal hearing adults, even when the level of noise allowed for near-perfect identification of the individual digits. Similarly, Murphy and colleagues (2000) found that low- and moderate-levels of 12-talker babble adversely affected young and older adults' performance on a paired-associate memory task by up to 50%. However, 12-talker babble at those levels had only a marginal effect of 9% on word identification accuracy compared to scores obtained in quiet. The current study verifies that declines in performance accuracy on working memory tasks are evident in highly favorable listening conditions (i.e., +15 dB

SNR) and occur irrespective of the level of the four-talker babble for school-aged children. While overall intelligibility does not explain our negative effects of four-talker babble at all levels on working memory performance, it is possible that other processes account for such deficits.

One possible model that can account for the findings of the current study is the feature model (Nairne, 1990; Neath, 2000; Surprenant & Neath, 1996). This model suggests that the addition of competing babble degrades the physical representation of the target speech signal in the encoding phase to such an extent that surviving memory traces exist in a degraded/blurry form. Prior to successful manipulation and recall, the traces must be interpreted by matching to stored representations. It is possible that this contributes to our findings because children are less able to use stored phonological knowledge to successfully match degraded speech input with stored representations (Klatte et al., 2010a; Metsala, 1997; Eisenberg et al., 2000; Hazan & Barrett, 2000). Since our target stimuli for the working memory tasks were constrained to overlearned alphabet and numerical items as the set of possibilities, it is not likely that the incorrect interpretation of degraded physical trace alone would account for the substantial declines in working memory performance across all SNRs. However, whether degraded items were initially encoded out of order cannot be ruled out.

A cognitive resource allocation perspective may explain our findings more favorably. Kahneman (1973) suggested individuals have a limited pool of cognitive resources from which resources are allocated to tasks. If tasks are performed concurrently and rely on

access to the same resources, then fewer resources will be available for each task and thus limit task performance (Francis & Nusbaum, 2009). In the current study, it is possible additional resources were deployed: (1) to hear the speech signal in the presence of four-talker babble; (2) to segregate the target stimuli from the four-talker babble; (3) to ignore the irrelevant information presented in the four-talker babble. First, additional perceptual effort may have been needed to accurately identify target items in the varying levels of four-talker babble, which may have come at the cost of cognitive resources needed for further elaborative processing, storage, and recall required by the backward digit recall and letter-number sequencing tasks (McCoy et al., 2005). McCreery and Stelmachowicz (2013) reported increased verbal processing times and decreased non-word recall for a group of 6- to 10-year old children with normal hearing when audibility was reduced, even when identification remained intact. This suggests that school-aged children must expend more time and effort to decode degraded stimuli than in conditions where the stimulus has intact acoustic-phonetic representations (McCreery & Stelmachowicz, 2011; 2013).

It has also been argued that competing babble adversely affects working memory performance due to demands of auditory stream segregation (Heinrich et al., 2008). Cognitive resources may be used to segregate the input into two distinct streams, leaving fewer resources for encoding, rehearsal and integration of information necessary for making judgments within a particular auditory stream (Koelewijn et al., 2014). Brungart et al., (2013) reported that segregating target information from an irrelevant speech masker may require the allocation of additional cognitive resources that are not required

with speech spectrum noise. In a series of five experiments using a serial-position paradigm, Heinrich and colleagues (2008) demonstrated a significant effect of 12-talker babble on serial word recall when it was presented in a continual manner (500 ms before and 500 ms after the end of the word pair). However, when the 12-talker babble was presented only between word pairs or only during word pair presentation, no effect of 12-talker babble was shown. The four-talker babble we used was presented preceding-, during-, and after- the presentation of the target digit and alphabet items. Thus, it is possible that cognitive resources were directed towards stream segregation and the extraction of target items from the continual four-talker babble. In addition, our two streams of information (target items and irrelevant four-talker babble) were from the same speaker at 0 degrees azimuth: this likely made it more difficult for a child to segregate, encode, process, and manipulate information (Sullivan et al., 2015b; Garadat & Litovsky, 2005; Litovsky, 2005).

Finally, the inclusion of four-talker babble may have imposed additional demands on phonemic, semantic, or syntactic systems during working memory task performance (Hasher & Zacks, 1979). In a recent study, Francis et al., (2016) found listening to speech in the presence of a speech masker introduces additional processing demands compared to understanding computer-synthesized degraded speech. When speech-specific information is available from a masker, a competitive aspect for processing resources is introduced (Zekveld et al., 2014; Rabbitt, 1991; Tun et al., 2002; Sarampalis et al., 2009). This is especially the case when the competing babble has relatively low number of talkers (Hall et al., 2002; Freyman et al., 2004), when talkers are of the same gender as

the target talker (Brungart, 2001), and when the same language as target talker is used by the target and competing talkers (Van Engen & Bradlow, 2007). Our competing babble comprised of one male and three female English-speaking adult talkers. Use of this four-talker babble likely elicited activity at different linguistic levels, including phonemic, phonological, syntactic, prosodic, and semantic, which interfered with children's perception, subsequent processing and recall of the target items. This babble may have also been distracting because it included an "odd sex" talker (one male among females) (Brungart et al., 2001). These explanations reconcile the difference in the effect of noise at +15 dB SNR reported by Stiles et al., (2012) and this study. That is, the lack of informational masking in the low-pass random broadband noise used in the former study may not have been disruptive enough to require reallocation of working memory resources during children's performance of digit and Corsi span tasks.

#### **B. Effect of four-talker babble on auditory comprehension task performance**

As discussed above, additional cognitive resources were likely required in four-talker babble, which came at a cost in performance on the comprehension task. Composite auditory comprehension performance decreased systematically as a function of SNR. However, the effects of four-talker babble on each subtest were not uniform across SNR. The amount of task-requirements and the associated linguistic and semantic, demands varied between subtests of the comprehension task, even though the perceptual demands related to the listening condition were kept the same. Each subtest varied in depth of processing and engaged a different amount of cognitive resources. For example, the reasoning subtest of the comprehension task assessed a child's ability to make semantic

links and inferences, which involved relating information to existing knowledge stored in semantic long-term memory. Whereas, the main idea subtest simply assessed a child's ability to relay the gist of the passage. If a child missed a detail, their ability to recall the main idea of a passage was unaffected due to saliency and redundancy of information. However, if a child missed a detail, their ability to recall, make judgments, relate information with existing knowledge, or integrate across the passage was affected considerably, especially at high levels of four-talker babble. This might be a result of the inadequate processing time available to decipher prior details as information is presented continually. It could also be that as initial details in a passage are being processed to extract meaning, the later-presented information may be lost due to decay in storage (Broadbent, 1958). Both explanations underline the necessity for more cognitive resources for certain subtests that rely on integration of serial information. The unique combination of the cognitive resources required for each subtest and by the four-talker babble possibly contributed to the non-uniform decrements in performance across listening condition. Thus, the pattern of our findings is most qualified by the interaction between demands of task and SNR.

### C. Interaction between levels of four-talker babble and task difficulty

Increasing levels of four-talker babble adversely affected children's performance on working memory and auditory comprehension tasks. However, performance did not change by the same degree with the same levels of increasing four-talker babble across tasks. The magnitude of disruption caused by four-talker babble seems to be a function of the degree of processing required by each task or subtest. The nature of the interactions

observed in this study also suggests that the effects of four-talker babble are modulated by task difficulty, which fully aligns with the interference-by-process account of auditory distraction. Declines in performance are assumed to occur when the non-deliberate processing of the auditory distraction competes for the same cognitive processes deployed by the primary task, increasing the overall processing load for performing the task (Hughes et al., 2007; 2013). The amount of cognitive resources required by the task determines the effect of the auditory distraction rather than the level of the auditory distraction alone. When there was a high level of auditory distraction but the task was relatively easy, a light burden on available resources was placed and the disruptive effect of auditory distraction was small. When the level of the auditory distraction was kept the same but the task was more difficult, the disruptive effect of auditory distraction was relatively larger. Although our working memory tasks involved a closed set of highly over-learned forms with low-lexical mismatch probability, the categorization/order sequencing aspect and a much larger set of possibilities (26 alphabetical letters and 8 numerical digits) increased the processing demands and manipulation load for the letter-number sequencing task. For example, a 44% drop in performance on the letter-number sequencing task compared to a 39% drop for the backward digit recall task was observed at -5 dB SNR from the quiet condition.

In a similar manner, performance on comprehension was affected by four-talker babble to a greater extent with increased subtest difficulty and as SNR decreased. Performance was the poorest on the most demanding subtest, reasoning, and was progressively better for subtests of less difficulty. This finding was most obvious at -5 dB SNR: a 75% difference

between the reasoning and main idea subtest scores was noted, consistent with Sullivan et al. 2015a. The gap between performance scores on the reasoning and main idea subtests narrowed as SNR improved, such that only a 5% difference between the most- and least-difficult subtest was indicated at +5 dB SNR and virtually no difference in subtest-specific performance was found in quiet. This suggests that high level of performance is achievable when children are able to devote their cognitive resources toward the demands of the task without competition from four-talker babble. When there is competition from four-talker babble, the residual cognitive resources available for other task-necessary processing is limited, compromising successful performance on more difficult tasks (Mishra et al., 2014).

Together our findings indicate that children's auditory-cognitive performance is highly sensitive to cognitive processing load. The extent to which children engage cognitive resources depends on the combined demands of SNR and task difficulty (Best et al., 2010; Koelwijn et al., 2014). This is corroborated by pupil dilation studies (e.g., Granholm et al., 1996; Zekveld & Kramer, 2014; Koelewijn et al. 2014), which indicate pupil dilation is the largest in high processing load conditions and smaller in low load conditions. Ultimately, the addition of more complex tasks and unfavorable levels of noise tax the auditory and cognitive systems to a huge degree.

## FUTURE DIRECTIONS

From an ecological point of view, a study with SNRs representative of current classrooms, listening tasks that reflect learning activities, and use of a speech masker as an auditory interference encountered by elementary-aged school children is valuable. However, a

simulated-classroom and a real-time virtual acoustical modeling technique where manipulating the level of background noise, reverberation characteristics, number and direction of multiple target talkers may have better mimicked an occupied classroom environment and may prove to be more insightful (Valente et al., 2012; Klatte et al., 2010). The findings of the current study represent a homogenous relatively high functioning sample of children with limited range of normal receptive language, working memory capacity, and hearing sensitivity. While this provides information about typically developing children that are equipped to compensate for the challenges related to task and noise, the extent to which these findings would generalize to samples including children with hearing loss, specific language impairments, cognitive impairments, and those acquiring a second language is unclear and should be evaluated in future studies. The findings of the current study should also be replicated in children with low- and high-working memory, as a previous study suggested that the degree of which task difficulty interacts with quality of acoustic input varies by working memory capacity (Lyberg-Åhlander et al., 2015). Finally, to verify the super-additive effects of SNR and task difficulty on cognitive processing load, future studies should include subjective self-rating measures (Klatte et al., 2010a) or objective measures (Zekveld et al., 2011) that can assess the degree of noise-induced disruption evoked in specific tasks.

## CLINICAL & EDUCATIONAL IMPLICATIONS

Our research informs educators, clinicians and researchers on the need for assessment materials that reflect the auditory and cognitive demands faced by elementary-school children in the classroom. Unlike word and single-sentence level repetition, more

difficult listening tasks that have storage and processing elements may disclose the challenges associated with understanding speech in background noise. Administering such tasks in classroom-relevant SNRs may serve as a reliable predictor of performance in noisy environments, guide hearing (re)habilitation decisions and programs, and add to the functional assessment questionnaires completed by a caregiver or teacher. Although it is not yet possible to assess the complex demands of storing, manipulating, and recalling information with currently available speech-in-noise measures, it is recommended audiologists use multi-talker babble at unfavorable SNRs to increase cognitive processing load. Our findings also provide support for improving the quality of the acoustic input in the classroom. Signal-to-noise ratios can be improved through the use of sound field FM/DM systems, installation of acoustic tiles and carpeting, insulated windows, quieter ventilation systems, reduced number of students per classroom, and fully-enclosed designs. As noted by Klatte et al. (2010a), children are poor judges of the detrimental effects of high noise levels on learning performance. Therefore, educators should be mindful of classroom noise levels when providing oral instructions, introducing new information, and during demanding listening activities. It is important that children have their limited cognitive resources available for complex learning tasks rather than for high levels of noise in the classroom.

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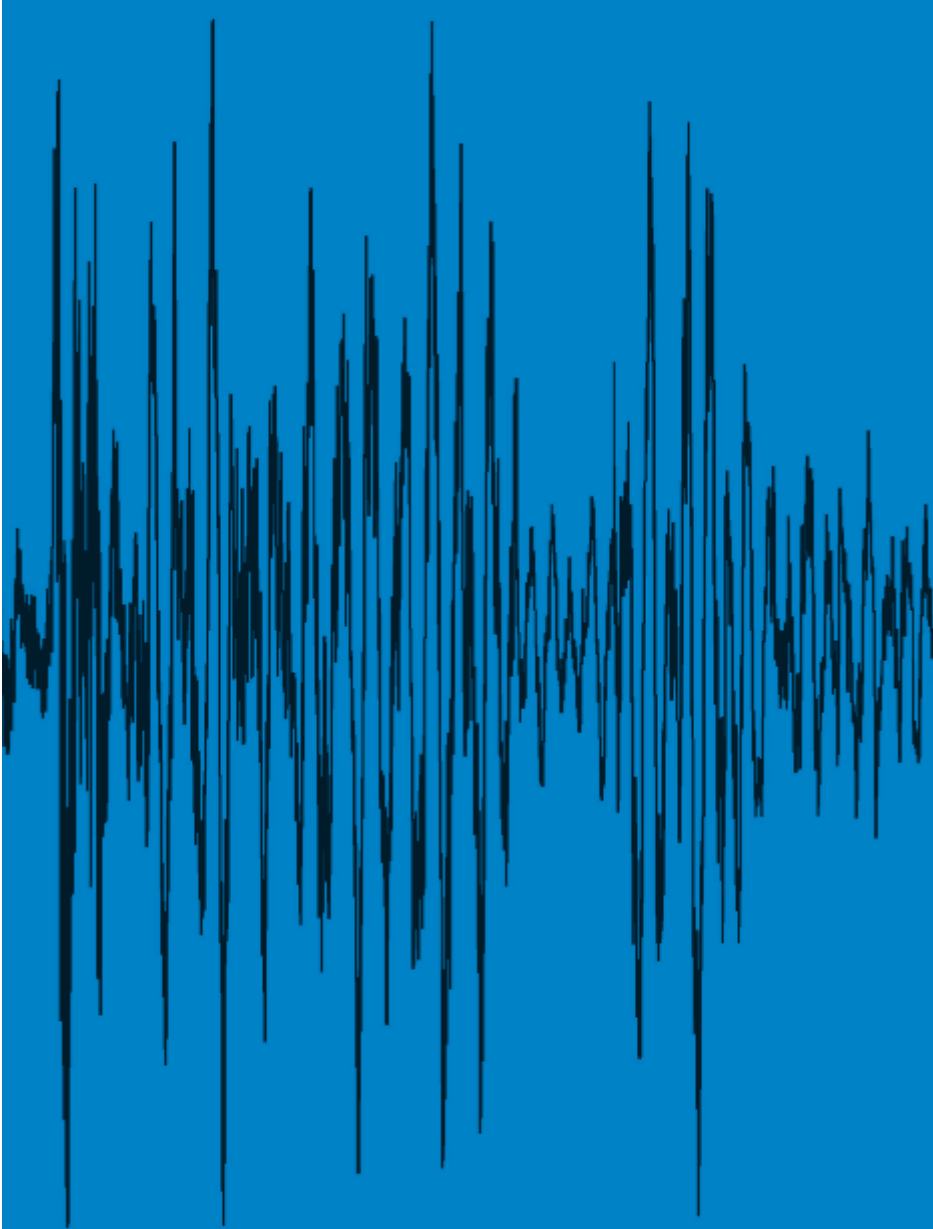
## **Appendix A**

### **AN ANALYSIS OF ERROR PATTERNS IN CHILDREN'S BACKWARD DIGIT RECALL IN NOISE**

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# An analysis of error patterns in children's backward digit recall in noise

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## Abstract

The purpose of the study was to determine whether perceptual masking or cognitive processing accounts for a decline in working memory performance in the presence of competing speech. The types and patterns of errors made on the backward digit span in quiet and multitalker babble at -5 dB signal-to-noise ratio (SNR) were analyzed. The errors were classified into two categories: item (if digits that were not presented in a list were repeated) and order (if correct digits were repeated but in an incorrect order). Fifty five children with normal hearing were included. All the children were aged between 7 years and 10 years. Repeated measures of analysis of variance (RM-ANOVA) revealed the main effects for error type and digit span length. In terms of listening condition interaction, *it was found* that the order errors occurred more frequently than item errors in the degraded listening condition compared to quiet. In addition, children had more difficulty recalling the correct order of intermediate items, supporting strong primacy and recency effects. Decline in children's working memory performance was not primarily related to perceptual difficulties alone. The majority of errors was related to the maintenance of sequential order information, which suggests that reduced performance in competing speech may result from increased cognitive processing demands in noise.

**Keywords:** Auditory memory, background noise, cognitive processing, digit span, hearing, working memory

## Introduction

Listeners with and without hearing loss have trouble with working memory tasks in the presence of background noise.<sup>[1-3]</sup> Reduced working memory performance amid noise may result from perceptual (auditory) difficulties at the encoding stage, increased (cognitive) processing load, or a combination of the two. In fact, Rabbitt<sup>[4,5]</sup> describes noise as an extrinsic factor that interferes with a listener's ease of perception and processing. Background noise challenges a listener's ability to perceive and process speech and consequently takes away cognitive resources that are available to a listener for usage on working memory storage and retrieval. This has potential negative consequences for learning in schoolgoing children who encounter degraded acoustic environments on a daily basis (e.g., classroom lectures, small group activities, and multiple-talker discussions).<sup>[6]</sup> If we can identify the relative contributions of perceptual and cognitive processing factors,

we may be able to help improve comprehension abilities under adverse listening conditions. Therefore, research to reveal the individual contributions of perceptual and processing factors involved in listening amid noise for schoolgoing children is warranted.

## Working memory

Working memory involves the active manipulation and maintenance of information over a short period of time.<sup>[7]</sup> It positively relates to a number of high-level cognitive abilities such as language comprehension,<sup>[8]</sup> reading ability,<sup>[9]</sup> arithmetic skills,<sup>[10]</sup> fluid intelligence,<sup>[11]</sup> learning, and scholastic achievement.<sup>[12]</sup> Working memory is limited in its capacity<sup>[13]</sup> and given this limit, extrinsic (e.g., background noise) and intrinsic factors (e.g., hearing loss) contribute to degraded speech, which consumes cognitive resources that can otherwise be used for processing

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information. Background noise, in particular, contributes to a substantial decline in working memory performance.<sup>[1,2,14]</sup> For example, children with normal hearing demonstrated worse auditory working memory performance in competing speech at commonly experienced signal-to-noise ratios (SNRs) compared to quiet.<sup>[3]</sup> The presence of noise impeded working memory processes in real-time and resulted in the inaccurate recall of target items. This finding is consistent with Rabbitt's<sup>[5]</sup> view that perceptual processing is of the utmost priority under adverse listening conditions; cognitive processing resources are directed toward decoding the target signal in noise and supporting auditory processing.<sup>[1,5]</sup> This priority for perceptual processing draws resources away from cognitive processing and storing of other information for later recall, which manifests as effortful listening, greater number of task errors, and loss of information from temporary storage.<sup>[10,15,16]</sup>

### Perceptual abilities in noise

When compared to adults, children with normal hearing perform worse on speech-in-noise tasks.<sup>[11,17]</sup> They require a more favorable SNR for successful communication, especially in the presence of competing speech.<sup>[12]</sup> For instance, children's word identification thresholds are worse for 12-talker babble than for filtered noise.<sup>[18]</sup> This difficulty with perceptually segregating a relevant word from competing background of speech is referred to as perceptual masking.<sup>[13]</sup> Children's increased susceptibility to perceptual masking explains their elevated, masked speech perception thresholds in competing speech.<sup>[13,19]</sup> The effects of competing speech have not only been observed in tone or word identification but also in working memory tasks that involve immediate recall of digits, syllables, and final words of sentences.<sup>[14,20]</sup> In one study, 8-11-year-old children were more affected by irrelevant competing speech as compared to tones.<sup>[14]</sup> The author suggested that competing speech interfered with the target stimuli because of their shared features (i.e., phonological code). This finding supports the view that children are less able than adults to separate irrelevant background speech and are thus, more susceptible to competing speech-induced disruption. It is unknown as to whether a child's immature attention or peripheral auditory abilities account for the difficulties in the presence of competing speech but the possibility of perceptual masking poses concern for any task administered in competing speech. Thus, it is important to examine the role that perceptual audibility plays in children's working memory in noise performance.

### Cognitive processing in noise

Although irrelevant competing speech may lead to perceptual masking, it may also contribute to increased cognitive processing demands. In fact, several studies have reported that listening to speech in degraded acoustical conditions can result in a high cognitive load;<sup>[15]</sup> "cognitive load" refers to any factor that places excessive demand on the central

attentional and mnemonic processes.<sup>[21]</sup> For example, when a listener's working memory capacity is mostly consumed with separating relevant speech from background noise, the listener has few cognitive resources available to inhibit distraction from irrelevant information. Thus, listening amid background noise has both perceptual and cognitive elements but can largely be a top-down and cognitive resource demanding process.<sup>[1,22,23]</sup> However, the degree of top-down involvement depends on the difficulty of the listening conditions and the complexity of the task.<sup>[24,25]</sup> An emerging cognitive hearing science model, the Ease of Language Understanding (ELU) model,<sup>[26,27]</sup> describes the role of working memory as implicit (automatic) in quiet or conditions with low levels of distraction (e.g., filtered noise).<sup>[28]</sup> However, when the input is degraded due to the presence of competing speech, a mismatch arises and explicit working memory resources are called upon. In addition to a mismatch between long-term memory information, subvocal verbal rehearsal (the ability to repeat items in memory before recall), and serial scanning (the rate at which each item is recalled), it may contribute to increased processing demand.<sup>[14,29]</sup> Subvocal rehearsal and serial scanning apply especially to digit span tasks of the working memory. In a group of pediatric cochlear implant users and their age-matched peers with normal hearing, the maintenance of a sequential order of information accounted for the majority of errors on the forward and backward digit span tasks.<sup>[30]</sup> In contrast, adult listeners committed a greater proportion of simple misidentifications or item errors on forward and backward digit span tasks in degraded listening conditions.<sup>[14]</sup> The authors explained that developmental factors (i.e., cognitive capacity and efficiency improve with age) and sensory deprivation (i.e., children with profound deafness were included) might account for the disparities in the findings.

In the current study, we investigated the types and patterns of errors made on the backward digit span task in children without sensory deprivation (i.e., hearing loss). The goal of this detailed error analysis was to determine whether perceptual masking or increased cognitive processing demands primarily account for the decline in working memory performance in the presence of noise. We expected that there would be a minimal contribution of perceptual masking (i.e., item errors) and instead, the majority of the errors will be related to increased cognitive processing demands (i.e., maintaining sequential order information while inhibiting competing speech).

### Methods

Error analysis data were drawn from four previous experiments. Detailed descriptions of materials, procedures, and levels of performance were reported by Osman and Sullivan.<sup>[3]</sup>

## Participants

A total of 55 children between the age of 7 years and 10 years [mean = 8.9 years, standard deviation (SD) = 1.2] were studied. All the children had hearing thresholds  $\leq 20$  dB(HL) bilaterally at octave frequencies between 0.25 kHz and 8 kHz, as determined by a hearing screening. The participants were typically developing monolingual American English speakers with no known neurological disorders, no history of recurrent otitis media, normal vision, and no reported cognitive difficulties or barriers to education as determined by parent interview.

## Stimuli

The data of interest were the errors made on the backward digit recall task from the Working Memory Test Battery for Children (WMTB-C)<sup>[31]</sup> administered in quiet and degraded listening conditions. Data from the forward digit recall task were not included because it involved only temporary storage and recall of auditory items. Our motivation for an in-depth analysis of the backward digit recall task data was twofold:

1. The backward digit recall is a comprehensive measure of working memory: It involves both storage and processing aspects of the working memory and has little linguistic influence,
2. The listening conditions are ecologically valid: Multitalker babble at  $-5$  dB SNR is representative of everyday acoustically degraded situations encountered by schoolgoing children.<sup>[32]</sup>

The four-talker babble consisted of one male and three female speakers and was supplied with the QuickSIN Speech-in-Noise test (version 1.3, Etymotic Research Elk Grove Village, IL USA).

## Procedure

The participants were tested individually in a double-walled sound booth in the presence of two examiners. One examiner managed the experimental equipment and monitored the child's performance. The other examiner monitored the child's behavior during testing. The child was seated 1.5 m from the front speaker. The target stimulus to be remembered was presented at  $0^\circ$  azimuth from the front loudspeaker at a fixed level of 65 dBA, as measured at the location of the participant's head with a Quest SoundPro 3M sound level meter (Quest Technologies, Medley, FL, USA). In the backward digit recall task, the examiner presented sequences of digits via monitored live voice and the child had to recall each sequence in the reverse order. For example, the sequence 5-1-3 presented at a rate of 1 digit/s would be correctly recalled as 3-1-5. Practice trials were given with two-digit and three-digit sequences in order to ensure that each child understood the concept of "backwards." Test trials began with two digits and increased by one digit in each block until the child was unable to recall four correct trials at a particular

block. A block consisted of six trials. For each child, a correct trial was scored as 1 and an incorrect trial was scored as 0.

## Classification of errors

In consistence with Burkholder *et al.*<sup>[14]</sup> the errors made during the backward digit span task were classified into the following two main categories: Item errors and order errors. Errors were considered item errors if a digit(s) that was not present in the list was repeated. Errors were classified as order errors if correct digits were repeated but in an incorrect order. To account for the different possible types of item and order errors, a template of error subtypes was generated [Table 1]. For example, if a participant hears 5-1-9, he/she is supposed to produce 9-1-5. However, if he/she produces 5-9-1 as his/her response, this is coded as an initial position order error. The reason behind this is that the initial input position is not produced third and the initial output position does not reflect the last input serial position. The template of errors was carefully constructed by one of the authors and reviewed by the other author to ensure that an error type could be identified for each to-be-remembered target stimulus [Table 1].

Incorrect responses were tallied and transferred to an error database ( $n = 869$ ). Two trained research assistants judged independently the type of error made for each item in the database. Point-to-point agreement was 98% (range = 94-100%), indicating excellent scoring reliability. The number of incorrect trials divided by six total trials (a block) was tabulated in percentages.

**Table 1: Descriptions and examples of item and order-error subtypes**

Error Type	Description	Example
<b>Item Errors</b>		
Omissions	The child did not provide a response within the 10-second response window.	Stimuli: 5-1-9 Target Response: 9-1-5 Omission: ---
Incorrect items/ incorrect order	The child recalled digits not included in the target stimuli.	Stimuli: 5-1-9 Target Response: 9-1-5 Incorrect items/incorrect order: 5-8-4
<b>Order Errors</b>		
Initial position error	The child correctly recalled the digits presented, but made an error in the initial position.	Stimuli: 5-1-9 Target Response: 9-1-5 Initial position error: 5-9-1
Intermediate position error	The child correctly recalled the digits presented, but made an error in the intermediate (middle) position.	Stimuli: 5-1-9 Target Response: 9-1-5 Intermediate position error: 9-5-1
Final position error	The child correctly recalled the digits presented, but made an error in the final position.	Stimuli: 5-1-9 Target Response: 9-1-5 Final position error: 1-5-9
Reversal error	The child correctly recalled the digits presented, but not in reverse order.	Stimuli: 5-1-9 Target Response: 9-1-5 Reversal: 5-1-9

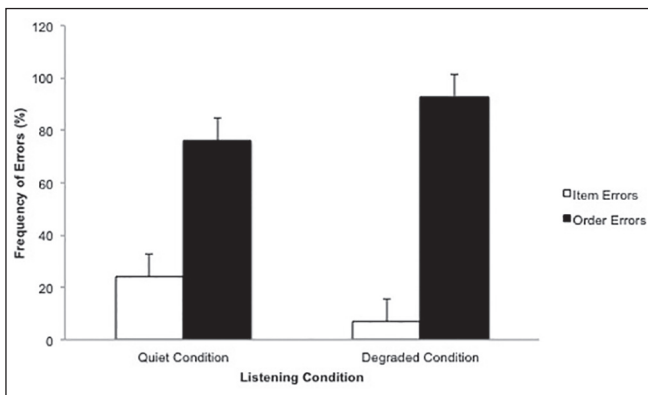
**Results**

Statistical analyses were performed using NCSS software, version 8 (Kaysville UT, USA). To analyze the effects of listening condition (quiet condition, degraded condition), error type (item errors, order errors), and digit span (two, three, four, five), a repeated measures analysis of variance (RM-ANOVA) was performed. The dependent variable was the number of incorrect trials divided by total six trials (a block) presented to each child. In order to equate the different number of total item errors made in quiet (235) and in the degraded listening condition (243), the proportions of errors and standard deviations were also calculated for each error type [Table 2].

The results of the RM-ANOVA revealed two significant main effects and three interactions. There was a main effect of error type [ $F(1, 869) = 127.66, P < 0.001$ ] whereby order errors occurred more frequently than item errors. An interaction was observed between the listening condition and error type [ $F(1, 869) = 7.88, P < 0.005$ ]; there was a substantial increase in the frequency of order errors in the degraded listening condition compared to the quiet condition [Figure 1].

**Table 2: Proportions of each error type in quiet and degraded listening condition**

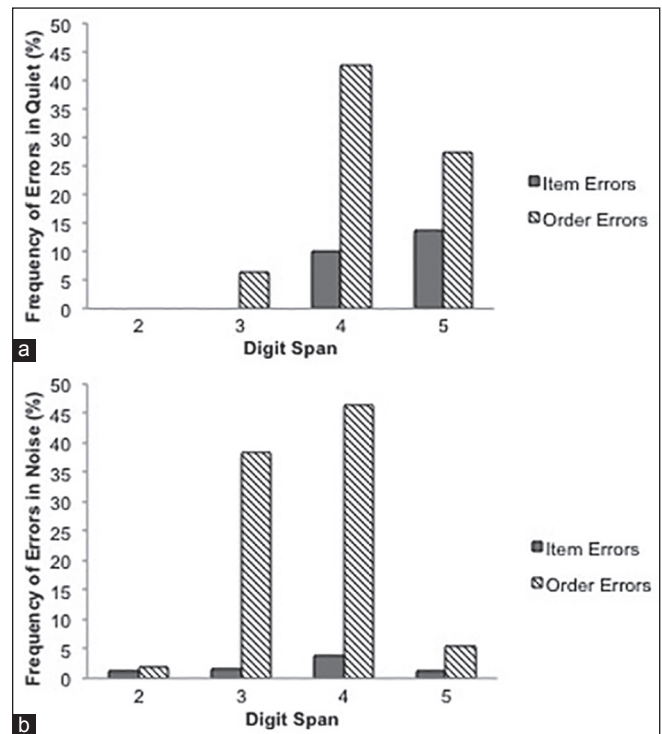
Error Type	Quiet Listening Condition (%)	Degraded Listening Condition (%)
<b>Item Errors</b>		
Omissions	6.80	4.10
Incorrect items/incorrect order	17.0	3.70
Total	23.8 % (11.0)	7.8 % (5.0)
<b>Order Errors</b>		
Initial position error	9.2	4.4
Intermediate position error	57.8	69.5
Final position error	3.4	3.79
Reversal error	5.8	13.7
Total	76.2 % (2.3)	92.2 % (2.7)



**Figure 1: Mean proportion of the item and order errors made on the backward digit span recall task in quiet and degraded listening conditions [+1 standard error (SE)]**

There was the main effect of digit span [ $F(3, 869) = 44.55, P < 0.001$ ]. As displayed in Figure 2, children committed the greatest proportion of errors in the fourth span (i.e., four digits per trial item). An interaction between error type and digit span [ $F(3, 869) = 28.33, P < 0.001$ ] and an interaction between listening condition and digit span [ $F(3, 869) = 21.33, P < 0.001$ ] were observed. *Post hoc* comparisons using the Tukey-Kramer multiple comparison tests indicated that item errors were mostly in later spans than in earlier spans in the quiet condition, suggesting that item errors were partly related to reaching working memory capacity limits [Figure 2a]. In the degraded listening condition, the patterns of item errors across the span were evenly distributed, suggesting that the errors were not capacity-related but rather a result of increased processing brought on by noise [Figure 2b]. A one-tailed chi-square test indicated that the profile of errors in quiet were significantly different from the profile of errors in the degraded listening condition [ $\chi^2(7, N = 200) = 57.3, P .003$ ].

Finally, to assess the specific errors made in quiet and the degraded listening condition more accurately, a separate univariate ANOVA was run on the subtypes of item and order error data. This analysis revealed a significant main effect of error subtype [ $F(5, 478) = 24.59, P < 0.01$ ]. *Post hoc* analyses indicated that intermediate position errors occurred more frequently than any other type of error, especially in the degraded listening condition, i.e., children had significantly more difficulty recalling the correct order of intermediate



**Figure 2: Frequency of item and order errors across digit span length in (a) quiet and (b) degraded listening condition**

middle items than recalling the order of initial and final items, supporting strong primacy and recency effects.

## Discussion

The purpose of the present study was to determine whether difficulties on the auditory backward digit span task were due to perceptual masking or cognitive processing demands. We evaluated the type and frequency of errors in two listening conditions in children with normal hearing. Overall, the results suggest that children's difficulty in recalling digits in the reverse order was primarily related to cognitive processing demands and not perceptual audibility.

### Cognitive processing demands

Models of working memory suggest that a limited capacity of cognitive resources is available to a child for online processing and storage of temporary information.<sup>[7]</sup> In consistence with the previously reported capacities, the mean working memory capacity in this study was four; children made the most errors when they were asked to recall a sequence of four digits in the reverse order. The errors were infrequent in short spans but increased rapidly as digit span length increased. As children approached their working memory capacity, their patterns of errors provided insight into two kinds of challenges: Capacity limits due to an individual's recall limit and capacity limits brought on by an extrinsic distractor (i.e., background noise). In the quiet listening condition, there was a large increase of item errors across the digit span. Children committed omissions and repeated fewer digits of a sequence as they approached the limits of their individual recall capacity. In the degraded listening condition, item errors were minimal and evenly distributed across digit span length. Instead, there was a large increase of order errors across the digit span. The increased proportion of order errors across the span suggests that the capacity limits were exceeded because of the concurrent processing demands of recalling digits in the reverse order and simultaneously ignoring the background sounds. Listening in noise-exhausted capacity limits by consuming working memory resources contributed to more order errors.<sup>[33-35]</sup> These findings reflect the limit to the quantity of information that can be held in working memory and the types of errors that arise when the limits are impeded by noise.

Order errors predominated in terms of type and frequency. A detailed examination of the order errors revealed bow-shaped serial position curves; this confirmed that order errors result from the loss of temporal order information during encoding or spoken recall. Most order errors were made with intermediate items, which is consistent with the order-error curves observed in previous studies.<sup>[36]</sup> This finding can be explained by the intermediate items' susceptibility to a greater number of possible order confusions and reflects processing demand.<sup>[37]</sup> While initial items and final position

items can be readily recalled, intermediate items require devoted attentional and processing resources for accurate recall. The fact that intermediate position errors occur more frequently in degraded listening condition further suggests that background noise competes and adds to the challenge of accurately recalling digits in the correct order. The demands of ignoring background sounds together with the demands of recalling temporal order information contributes to the majority of order errors observed in the degraded listening condition. Our results are consistent with Burkholder and Pisoni's<sup>[30]</sup> finding, where 8-10-year-old children with profound hearing loss and their age-matched typically developing peers made more order errors than item errors on the backward digit recall span task.

### Perceptual masking

Children, with and without hearing loss, have trouble extracting and attending to target acoustic information in the presence of competing background sounds.<sup>[38]</sup> Schoolgoing children are particularly susceptible to perceptual masking whereby multitalker maskers interfere with target speech.<sup>[13]</sup> We previously found that children experienced a significant decrease in accuracy on the backward digit span task in a four-talker masker at an unfavorable SNR compared to a quiet listening condition;<sup>[3]</sup> however, children's performance on the backward digit span task was unaffected in a broadband signal matched to the noise of an unoccupied classroom at a favorable SNR (air conditioning on at +15 dB SNR).<sup>[28]</sup> Thus, the use of a four-talker masker and a degraded SNR (-5 dB SNR) warranted concern for the possibility of perceptual masking in this study. If perceptual masking was a problem, we would have observed a large proportion of item errors; children would have reported digits that were not presented in the original target list or would have made omissions. However, the proportion of item errors was low in quiet and in the degraded listening condition. This indicates that even though children received a degraded auditory signal in the four-talker masker, errors on the backward digit span were mainly due to the retention of sequential order information and were not related to reduced audibility.

### Limitations

While our findings demonstrate processing-related errors in the degraded listening condition, it is unknown as to what specifically contributes to the increased cognitive load. It is possible that audibility affected the initial processing of the number sequence (i.e., the child heard 5-1-3 instead of 5-3-1) and the children did, in fact, recall it in the reverse order (i.e., produced 3-1-5) but it was scored as an order error. However, since the children are consistently able to produce an accurate response in the forward digit recall task in noise, we believe that this is the least likely case. We suspect that if audibility affected the initial encoding/processing of the digits, the pattern of order errors would have been more consistent across all spans rather than increase as the child

approached his or her capacity. In the future, we suggest the use of independent measures, which will systematically differentiate between auditory/encoding and cognitive processing demands brought by noise. Moreover, given the span procedure where testing stopped when a child was unable to remember four of the six lists of a block, every child had a different list length in every condition. Therefore, in the future, a separate analysis for children with different abilities (spans) is recommended.

## Conclusions

The error patterns observed in this study are supported by the load theory, which describes a passive perceptual mechanism and an active mechanism of cognitive control.<sup>[39]</sup> In this view, even if a target signal is well-perceived (i.e., minimal-to-no masking effects), there is an increased cognitive processing involvement inhibiting that irrelevant distractor. The large proportion of order errors and serial position effects reported in this study suggest that noise drains cognitive resources away from the primary task at hand (i.e., recall of digits in the reverse order). This has several clinical and educational implications. If decreased working memory performance in noise is a consequence of high cognitive processing demands, then auditory comprehension, language literacy skills, and other academic-related cognitive abilities might also be at risk.

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## Conflicts of interest

There are no conflicts of interest.

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