Cortical Associates of Speech-In-Noise Perception from Childhood to Adulthood

By

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For Jule Wilson, who first ignited the spark within me
to serve children with special needs.

May the memory of your kind heart and enthusiastic spirit continue
to improve the lives of others.

You will be forever missed, Mama Jule.

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CHAPTER I

INTRODUCTION

Modern hearing aid and cochlear implant technologies have significantly improved speech perception in quiet environments for individuals with hearing loss; however, the presence of background noise continues to be a significant barrier to successful communication. This is particularly concerning for the 1.2 million children with hearing loss in the United States who receive daily education in classrooms where noise levels typically exceed recommendations (Boulet, Boyle, & Schieve, 2009; Crukley, Scollie, & Parsa, 2011; Knecht, Nelson, Whitelaw, & Feth, 2002; Larsen & Blair, 2008; Sato & Bradley, 2008). Because children with hearing loss demonstrate poor speech perception in background noise even when using prescribed hearing aids and/or cochlear implants, these challenging acoustic environments place children with hearing loss at risk for academic and social deficits (Crandell, 1993; Finitzo-Hieber & Tillman, 1978; Gifford, Olund, & DeJong, 2011; Pittman, Lewis, Hoover, & Stelmachowicz, 1999).

Although the problem is well documented, our understanding of how background noise affects the sensory and cognitive mechanisms responsible for speech perception in children remains unclear. This critical shortcoming limits our ability to improve evaluation methods and intervention strategies intended to reduce the speech perception difficulties of children with hearing loss. The goal of the proposed research is to advance our understanding of the effects of background noise on sensory and cognitive processes important for speech perception in typically developing children using brain-based measures. Identifying whether noise differentially affects sensory and cognitive neural representations of speech in typically developing children will contribute to our understanding of auditory development and inform future research examining the additional difficulty children with hearing loss encounter when listening in noise.

Speech-in-Noise Perception

Background noise is ubiquitous in the typical day of a child's life. From talking with a friend in the cafeteria, making recess plans in the hallway, or learning content from a teacher's lecture in a classroom, the need to understand speech in the presence of background noise is essential for successful, daily communication. The level of the background noise in relation to the level of the signal of interest is termed the signal-to-noise ratio (SNR). As the level of the background noise increases above speech presented at a fixed level, the SNR becomes smaller, causing less of the signal of interest (speech) to be audible for the listener. There is a well-established relationship between SNR and performance on behavioral speech perception tasks – as SNR increases, performance improves (Beattie, 1989; Chung & Mack, 1979; Cooper & Cutts, 1971; Dirks, Morgan, & Dubno, 1982; Killion, Niquette, Gudmundsen, Revit, & Banerjee, 2004; Neuman, Wroblewski, Hajicek, & Rubinstein, 2010). Although adults are able to understand speech presented at relatively unfavorable SNRs, children are more negatively impacted by background noise, requiring more favorable SNRs to reach comparable performance levels (Neuman et al., 2010).

Importance of speech-in-noise perception. The additional difficulty experienced by children compared to adult listeners when listening to speech in the presence of background noise is particularly concerning because children spend the majority of their day in classroom environments where they are expected to listen and learn. Ambient noise caused by audible heating, venting, and air conditioning systems and activity noise caused by other children in the classroom combine to create unfavorable listening environments in many classrooms (Moodley, 1989; Sanders, 1965; Sato & Bradley, 2008). To provide optimal learning environments and ensure that children can understand approximately 95% of the teacher's speech present in the noise, the level of noise in classrooms is recommended to be at least +15 dB SNR (American Speech-Language-Hearing Association, 1995). Some children require SNRs even more favorable than +15 dB. For example, children in early elementary grade levels require between +18 and +20 dB SNR to understand 95% of the teacher's speech (Bradley & Sato, 2008). Unfortunately, measured classroom SNRs range from +1 to +16 dB SNR (Larsen & Blair, 2008; Sato & Bradley, 2008), suggesting that children in the majority of active classrooms face difficult listening environments, particularly if they are seated far from the teacher. Furthermore, young children who are most vulnerable to the detrimental effects of noise also tend to be in classrooms with the highest noise levels (Crukley et al., 2011; Picard & Bradley, 2001). Understanding how the complex skill of speech-in-noise perception improves during development could lead to more targeted recommendations for noise-management and assist in identifying children who struggle more than would be expected based on their age.

Development of behavioral speech-in-noise perception. Behavioral research shows that speech-in-noise perception abilities improve steadily between 5 and 11 years of age (Bradley & Sato, 2008; Elliott, 1979; Etymotic Research, 2005; Johnson, 2000; Neuman et al., 2010; Talarico et al., 2007); however, development after this preadolescent period is not well understood. Table 1 provides an overview of the methods used in these previous studies.

Table 1. Methodological details of previous studies examining behavioral speech-in-noise perception in children.

Study	Age Range	Task Type	Speech Materials	Noise Type	Noise Levels
Elliot (1979)	9-17 years	Open-set	Sentences	12-talker babble	-5, 0, +5 dB SNR
Johnson (2000)	6-15 years	Open-set	Nonsense syllables	4-talker babble	+13 dB SNR
Etymotic Research (2005)	5-15 years	Open-set	Sentences	4-talker babble	Adaptive - SNR for 50% accuracy
Talarico et al. (2007)	6-16 years	Closed-set	Words and Syllables	Speech-shaped noise	Adaptive - SNR for 71% accuracy
Bradley & Sato (2008)	6-11 years	Closed-set	Words	Classroom noise	Adaptive - SNR for 95% accuracy
Neuman et al. (2010)	6-12 years	Open-set	Sentences	4-talker babble	Adaptive - SNR for 50% accuracy
Rashid et al. (2016)	12-18 years	Closed-set	Words	Speech-shaped noise	Adaptive - SNR for 50% accuracy

Talarico and colleagues (2007) found no significant improvements in children's syllable identification between nine and 16 years of age. In contrast to these findings, Elliot (1979) found that the ability to recognize sentences in noise continues to develop until 17 years of age. In the two studies that have compared children to adults, consonant recognition in noise reached adult levels by 14-15 years of age (Johnson, 2000), while the identification of words in noise continued to improve beyond 18 years of age (Rashid, Leensen, & Dreschler, 2016). Potentially contributing to these variable findings are the differences in methodologies (Table 1) and the individual differences in speech-in-noise perception ability across listeners within similar age groups. That is, speech recognition performance at +5 dB SNR, a typical classroom listening condition, can range from 65% to 100% for children ages 6 to 11 years (Bradley & Sato, 2008). Although there is consistent evidence showing improvement of speech-in-noise perception from early school-age (i.e., 5 years of age) to preadolescence (i.e., 10-12 years), these developmental trends include considerable within-age variability and are not clearly defined for adolescent (i.e., >12 years of age) children.

Neural processes underlying speech-in-noise perception. Understanding the processes essential for speech-in-noise perception could help explain individual differences found in behavioral performance. The relative contribution of neural processes underlying behavioral speech-in-noise perception can be evaluated using objective measures of sound processing that quantify changes in electrical activity in the brain following an auditory stimulus. These measures are called auditory evoked potentials. The magnitude of the response (i.e., amplitude) and the time course relative to the stimulus onset (i.e., latency) provide valuable information about various stages of stimulus processing.

Beginning with the detection and neural coding of the stimulus, auditory evoked potentials can be used to represent the synchronous neural encoding of the stimulus along the sub-cortical pathways of the brainstem (Chandrasekaran & Kraus, 2010). These brainstem responses represent the acoustic properties of the speech signal with remarkable precision through neural synchrony at the level of the brainstem and are reduced in amplitude and delayed in time when speech is embedded in background noise (Russo, Nicol, Musacchia, & Kraus, 2004). Listeners who show this weakened neural synchrony to speech in background noise at the level of the brainstem also show reduced performance on behavioral speech-in-noise perception tasks (Anderson, Skoe, Chandrasekaran, & Kraus, 2010; Song, Skoe, Banai, & Kraus, 2011). These findings suggest that successful perception of speech in noise is dependent upon the integrity of the coding of the speech signal at the brainstem – if the speech signal is adequately encoded, successful perception should be possible.

As processing of the auditory signal continues beyond the brainstem, these degradations of brain responses and subsequent behavioral performance can be indexed by systematic, noise-induced changes in auditory evoked potentials originating from the cortex (Parbery-Clark, Marmel, Bair, & Kraus, 2011). Importantly, cortical auditory evoked potentials (CAEPs) can be affected by top-down processing. For instance, CAEPs indexing sensory processing of speech in noise are enhanced when adult listeners direct attention to the speech sounds compared to when they listen passively (Billings, Bennett, Molis, & Leek, 2011; Zendel, Tremblay, Belleville, & Peretz, 2015). These findings suggest that higher-level cognitive abilities known to be active when listening to speech in noise (Salvi et al., 2002) might compensate for the degraded neural encoding present in earlier processing stages.

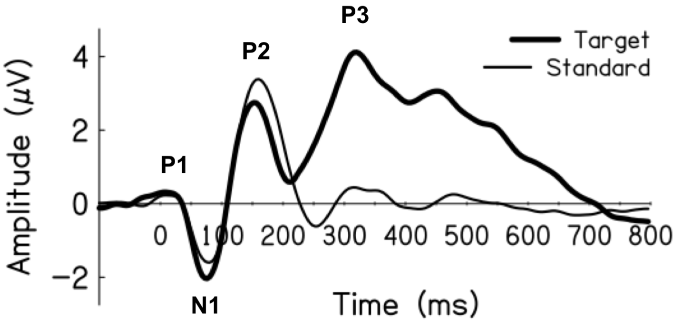
It is unclear if children show similar compensatory effects of higher-level processing when listening to speech in noise; as previous studies using speech embedded in background noise to elicit CAEPs in children have only been completed using passive paradigms where children are instructed to ignore the stimuli (Almeqbel & McMahon, 2015; Anderson, Chandrasekaran, Yi, & Kraus, 2010; Cunningham, Nicol, Zecker, Bradlow, & Kraus, 2001; Hassaan, 2015; E. A. Hayes, Warrier, Nicol, Zecker, & Kraus, 2003; M. Sharma, Purdy, & Kelly, 2014; Warrier, Johnson, Hayes, Nicol, & Kraus, 2004). It is possible that cortical processing of speech in noise might differ in children, as maturation of both sensory and cognitive cortical processing extends into adolescence (Polich, Ladish, & Burns, 1990; Ponton, Eggermont, Kwong, & Don, 2000) and children show immature top-down processing of speech in noise on behavioral measures (Kalikow, Stevens, & Elliott, 1977; Leibold & Buss, 2013; Wightman & Kistler, 2005).

Cortical Auditory Evoked Potentials

CAEPs can be divided into two classes, sensory and processing-contingent potentials (Steinschneider, Kurtzberg, & Vaughan, 1992). Sensory potentials reflect activation of the auditory pathways from the cochlea to the cortex, while processing-contingent potentials are associated with additional processing of the stimuli such as attention monitoring and stimulus evaluation (Hillyard & Picton, 1987; Polich, 2004). For the purposes of this study, we will refer to processing-contingent potentials as cognitive potentials, as they will be used to represent the top-down processing that occurs after stimulus detection.

Sensory CAEPs. Sensory CAEPs primarily reflect the acoustic properties of the stimuli and the integrity of the primary auditory pathway. Sensory CAEPs of potential use for evaluating the effect of background noise on speech perception across development are P1, N1, and P2 (Figure 1). These potentials are maximal over central electrodes (Key, Dove, & Maguire, 2005). The auditory evoked P1 occurs approximately 50 ms after the onset of an auditory stimulus and reflects the sensory representation of the acoustic stimulus at the level of the cortex (Čeponien, Rinne, & Näätänen, 2002; A. Sharma, Dorman, & Spahr, 2002). Occurring approximately 100 ms after stimulus onset, the auditory evoked N1 is one of the most prominent peaks recorded in adult CAEPs. The N1 response is elicited by any detected stimulus, regardless of whether the listener can discriminate the stimulus from another sound (B. A. Martin, Kurtzberg, & Stapells, 1999). The auditory evoked P2 peak generally occurs between 150 and 275 ms after the onset of the stimulus in adults and is thought to reflect auditory processing occurring beyond sensation such as stimulus familiarization and auditory object representation (Crowley & Colrain, 2004; Tremblay, Ross, Inoue, McClannahan, & Collet, 2014). Maturation of N1 and P2 CAEPs continues with a relatively linear reduction in latency and increase in amplitude until approximately 15-16 years of age (Polich et al., 1990; Ponton et al., 2000). Unlike N1 and P2, peak amplitude and latency of P1 decreases with age until eventually the peak is no longer discernable from baseline activity (Coch, Grossi, Coffey-Corina, Holcomb, & Neville, 2002).

Figure 1. Schematic of sensory and cognitive cortical auditory evoked potentials in a mature listener. The thin line refers to the CAEP response following the standard stimulus while the thick line refers to the response following the target stimulus.



Aside from these three peaks, the negative deflection, termed the mismatch negativity (MMN; Näätänen & Alho, 1995), has been used to study the effect of noise on speech processing in toddlers (Niemitalo-Haapola, Haapala, Jansson-Verkasalo, & Kujala, 2015). However, the MMN is not reliably evoked in all healthy listeners and generally requires a long test-time, therefore, it will not be considered for the present study.

Cognitive CAEPs. The presence and characteristics of cognitive CAEPs are determined by the nature of the interaction between the listener and the auditory stimulus/event. Of interest to the evaluation of speech perception in background noise is the P3 response, also shown in Figure 1. An "oddball" paradigm is used to elicit the P3 response, where an infrequent stimulus (target) is presented in a string of frequent stimuli (standards) at unpredictable intervals. The P3 is a large, positive component peaking over the centro-parietal area approximately 300 ms after the onset of a rare stimulus (Sutton, Braren, Zubin, & John, 1965). The presence of the P3 response is thought to reflect a processing phase when the voluntary evaluation of the perceived (target) stimulus is made against the attentional memory trace of the preceding (standard) stimuli (Polich, 2007). Children as young as six years of age show an auditory P3 response visible in the centro-parietal location (Goodin, Squires, Henderson, & Starr, 1978; L. Martin, Barajas, Fernandez, & Torres, 1988). Polich and colleagues (1990) showed that the maturation of the P3 response changes nonlinearly, with reductions in latency and increases in amplitude leveling off for listeners around 15-16 years of age.

Both sensory and cognitive CAEPs can be affected by top-down processing; however, cognitive CAEPs require this top-down processing while sensory CAEPs do not. As shown in previous studies in children and adults, speech-evoked sensory CAEPs can be elicited even when the listener ignores the stimulus. Due to the immature cortical and cognitive processing in children (Leibold & Buss, 2013; Polich et al., 1990; Ponton et al., 2000; Wightman & Kistler, 2005), cognitive CAEPs may demonstrate potential age-related effects of noise on speech processing more so than sensory CAEPs.

Effects of Noise on CAEPs

To evaluate how noise-induced degradations of sensory and cognitive CAEPs relate with speech-in-noise perception, we must first understand how background noise influences CAEPs in children and adults. Table 2 shows a summary of findings from previous studies examining the effect of background noise on sensory and cognitive CAEPs. It is important to note that there is variability in waveform peak labeling across previous studies conducted with children. This creates particular difficulty when comparing results across studies conducted with children and adults, as the morphology of CAEPs significantly changes throughout adolescence. For the purposes of this study, we have identified peaks in previous research by examining the reported waveforms and labeling the first and second positive deflections as P1/P2, respectively, and the first negative deflection as N1.

Table 2. Summary of findings from previous studies with adults and children comparing sensory and cognitive CAEP amplitude and latencies elicited with speech sounds in quiet and in various levels of background noise.

					Amplitude				Latency			
	Study	**Paradigm**	**Noise Type**	**SNRs**	**P1**	**N1**	**P2**	**P3**	**P1**	**N1**	**P2**	**P3**
Adults	Whiting et al. (1998)	Active	Broad-band	Q, +20 to -5 dB		-		-		+		+
	Kaplan-Neeman et al. (2006)*	Active	White	Q, +15 to -6 dB		-				+	+	
	Parbery-Clark et al. (2011)	Passive	6-talker babble	Q, +10 dB		+	-			+	+	
	Billings et al. (2011)	Both	Speech-shaped & 4-talker babble	Q, -3 dB	=	-	-		+	+	=	
	Bennett et al. (2012)	Active	Speech-shaped & 4-talker babble	Q, -3 dB				-				+
	Billings et al. (2013)	Passive	Speech-shaped	+ 35, to -10 dB	=	-	-		+	+	+	
	Papesh et al. (2015)	Passive	Speech-shaped	Q, +30, +10 dB	-	±	-		+	+	+	
	Zendel et al. (2015)	Both	4-talker babble	Q, +15, 0 dB	-	-	-		+	+	+	
	Billings & Grush (2016)	Passive	Speech-shaped	+ 35, to -5 dB	=	-	-		+	+	+	
Children	Cunningham et al. (2001)	Passive	White	Q, +5 dB			-			+	+	
	Hayes et al. (2003)	Passive	White	Q, 0 dB			-				+	
	Warrier et al. (2004)	Passive	White	Q, 0 dB	-	-			=	+		
	Anderson et al. (2010)	Passive	6-talker babble	Q, +10 dB	-	±						
	Sharma et al. (2014)	Passive	White	Q, +3 dB	=	-			=	+		
	Hassaan (2015)	Passive	White	Q, 0 dB	-	-			+	+		
	Almeqbel & McMahon (2015)	Passive	Broad-band	+ 20, 0, -10 dB						+		

Note. SNR = signal-to-noise ratio; Q = quiet; - reduction; + increase; ± both increases and reductions; = no change.

*P3 response from Kaplan-Neeman and colleagues is not included due to the derivation of P3 response measured with an equiprobable rather than an oddball paradigm

The addition of background noise to speech generally results in reduced amplitudes and increased latency of sensory CAEPs recorded in adults (Billings et al., 2011; Billings, McMillan, Penman, & Gille, 2013; Billings & Grush, 2016; Kaplan-Neeman, Kishon-Rabin, Henkin, & Muchnik, 2006; Parbery-Clark et al., 2011; Zendel et al., 2015). Although studies conducted in children have used less variable noise types and more restricted noise levels than adult studies, results still show amplitude reductions and latency elongations for sensory CAEP responses recorded from children ages 5 to 14 years (Anderson, Chandrasekaran, et al., 2010; Hassaan, 2015; E. A. Hayes et al., 2003; M. Sharma et al., 2014; Warrier et al., 2004). In these studies of children, the magnitude of reduction in N1 amplitudes is similar to what is documented in adult studies (e.g., 20-50% reduction in amplitude; Billings et al., 2011; Kaplan-Neeman et al., 2006; Papesh, Billings, & Baltzell, 2015; M. Sharma et al., 2014; Warrier et al., 2004; Whiting, Martin, & Stapells, 1998).

Alternatively, children appear to show smaller increases in latency than do adults when noise is present. For example, studies with children report less than 10% increase in latency (Hassaan, 2015; E. A. Hayes et al., 2003; M. Sharma et al., 2014; Warrier et al., 2004) while those with adults show a 30% to 60% increase (Billings et al., 2011; Kaplan-Neeman et al., 2006; Papesh et al., 2015; Whiting et al., 1998). This suggests that the effect of noise on sensory CAEP amplitude might be independent of age but that background noise might affect the timing of sensory information as it arrives at the auditory cortex to a greater extent for adults than for children. Much less is known about the effect of background noise on cognitive CAEPs, however, a reduction in amplitude and elongation in latency of the P3 response has also been found with the introduction of background noise in adult listeners (Bennett, Billings, Molis, & Leek, 2012; Whiting et al., 1998). To date, no study has evaluated the effect of noise on the P3 response to speech in children.

Compensation through top-down processing. The only study to directly compare effects of noise on sensory and cognitive CAEPs within the same listeners was conducted in adults (Whiting et al., 1998). Their study measured amplitude and latency changes in sensory and cognitive CAEPs as the level of background noise systematically increased, causing the SNR to worsen from +30 to -5 dB SNR. Amplitudes of sensory (N1) and cognitive (P3) CAEPs remained stable until detrimental listening conditions (≤0 dB SNR), when the amplitudes were reduced. Alternatively, even low levels of noise (+20 dB SNR) caused delays in latencies of the sensory CAEP while latencies of the cognitive CAEP remained stable until listening conditions became more adverse (+10 dB SNR). Whiting and colleagues concluded that CAEP latency was a more sensitive measure of the detrimental effect of background noise than amplitude on neural representation of speech-in-noise processing in adult listeners. These findings suggest that even low-level background noise can delay sensory processing in the mature auditory cortex, but later stages of stimulus evaluation are more resilient potentially due to top-down processing. The disproportionate effect of noise on latency of sensory and cognitive CAEPs might be more pronounced in children, whose cognitive processing systems are still developing. This would support the notion that top-down processing factors contribute to the greater difficulty children have with speech-in-noise perception when compared to adults (Eisenberg, Shannon, Martinez, Wygonski, & Boothroyd, 2000; Johnstone & Litovsky, 2006; Leibold & Buss, 2013).

Effects of noise type on CAEPs. As can be seen in Table 2, previous studies used a variety of noise types. Although the general effects of noise on amplitude and latency appear to be consistent across type of noise, adult studies have found that sensory and cognitive CAEPs may be differentially affected by a more ecologically valid, speech babble noise (Bennett et al., 2012; Billings et al., 2011). Specifically, while the degradation of both sensory (N1) and cognitive (P3) CAEPs in the presence of steady-state noise suggests interference with the sensory encoding and subsequent cognitive processing of the signal, only cognitive CAEPs are further degraded when the noise is comprised of multiple talkers overlapping with differing messages (babble noise). These additional changes in cognitive CAEPs but not sensory CAEPs signify that, even though further decrements are not present during encoding of the acoustic properties of the speech, background babble noise has additional detrimental effects on attentional and cognitive resources required to continuously monitor and separate the intended speech signal from the interfering noise – a consequence referred to as *informational masking* (Brungart, Simpson, Ericson, & Scott, 2001; Wightman & Kistler, 2005). These more extensive effects of babble noise on cognitive compared to sensory CAEPs may be larger in children than adults, as children demonstrate more pronounced effects of informational masking on behavioral assessments when compared to adults (Hall, Grose, Buss, & Dev, 2002; Leibold & Buss, 2013). Therefore, the use of babble, rather than steady-state noise best allows for the evaluation of developmental differences in sensory encoding and subsequent cognitive processing of speech in noise.

Relating CAEPs with Behavioral Perception

Previous studies with adult listeners have shown that CAEPs elicited with speech syllables in background noise relate with behavioral speech-in-noise perception – those with poorer behavioral performance show more noise-related degradation in CAEPs (i.e., reduced amplitude, increased latency) than those with good behavioral performance. Table 3 shows a summary of these findings.

Table 3. Summary of findings from previous studies with adults and children relating CAEPs elicited with speech embedded in noise to behavioral performance.

Study	Age	CAEP	Behavioral Task	Outcome	Result
Billings et al. (2013)	23-34 years	N1 Amplitude to /ba/	Sentence recognition in speech-shaped noise	Percent Correct	Large N1 amplitude ~ good performance
Parbery-Clark et al. (2011)	19-34 years	N1 Amplitude to /da/	Adaptive sentence recognition task in speech-shaped noise	SNR-50	Large N1 amplitude ~ good performance
Anderson, Chandrasekaran et al. (2010)	8-13 years	N1 Amplitude to /da/	Adaptive sentence recognition task in speech-shaped noise	SNR-50	Large N1 amplitude ~ poor performance
Bennett et al. (2012)	19-31 years	P3 Latency to /ba-da/	Sentence recognition in 4-talker babble and speech-shaped noise	Percent Correct	Short P3 latency ~ good performance

Note. SNR-50 = signal-to-noise ratio required for 50% correct sentence recognition

Adult listeners with larger N1 peak amplitudes to the syllable /da/ embedded in babble noise performed better on a behavioral speech-in-noise perception task than those with smaller N1 amplitudes (Parbery-Clark et al., 2011). Billings and colleagues (2013) examined amplitudes and latencies of multiple sensory CAEPs (P1-N1-P2) in adults listening to the syllable /ba/ embedded in speech-shaped noise and discovered that the best predictor of performance on a behavioral speech-in-noise perception task was the amplitude of the sensory N1 CAEP. In cognitive CAEPs recorded from adult listeners using an oddball paradigm with the syllables /ba-da/ embedded in babble noise, P3 peak latency correlated with speech-in-noise perception, showing longer latencies in listeners with poor performance (Bennett et al., 2012). Bennett and colleagues did not report the relationship between P3 amplitude and behavioral speech-in-noise perception. Note that the tasks used to measure behavioral performance and the subsequent outcome measures differ across studies. While some used an adaptive, clinical task to measure the listener's speech reception in noise ability (Anderson, Chandrasekaran, et al., 2010; Parbery-

Clark et al., 2011), others measured sentence recognition in the same conditions used to elicit CAEP responses (Bennett et al., 2012; Billings et al., 2013). Regardless of these methodological differences, findings in adult studies are consistent – larger sensory CAEPs and earlier cognitive CAEPs elicited with speech in noise were found in listeners with better speech-in-noise perception. From these studies, it is unclear if amplitude or latency of sensory, cognitive, or a combination of sensory and cognitive CAEPs might best explain one's ability to recognize speech in noise successfully. If noise-related degradations in sensory processes are compensated for with top-down processing, cognitive CAEPs, by themselves or in combination with sensory CAEPs, could be a useful tool in understanding the processes underlying speech-in-noise perception. They could also be useful in monitoring incremental responses to treatment that might not be detected on a global measure of behavioral speech-in-noise perception.

Only one study has extended this comparison of CAEP and behavioral speech-in-noise perception to children (Anderson, Chandrasekaran, et al., 2010). Their study examined amplitudes of sensory CAEPs (P1, N1) to the speech syllable /da/ embedded in babble noise and behavioral speech-in-noise perception in children (ages 8-13 years) to find that peak amplitudes of N1 were *smallest* for children who had the best speech-in-noise perception. Despite consistent methodologies (see Tables 2 and 3), findings from this study in children are in direct opposition with those from a previous study of adults (Parbery-Clark et al., 2011). If replicated, these divergent relationships across developmental stages could suggest that the relative contribution of sensory processing to speech-in-noise perception might change as the auditory system matures. Because top-down processing abilities associated with speech-in-noise perception, such as attention and working memory, develop throughout childhood (Gomes, Molholm, Christodoulou, Ritter, & Cowan, 2000; Vuontela et al., 2003), it is likely that the relationships between cognitive processing and behavioral speech-in-noise perception might also differ across age.

In sum, previous research has revealed that, while latency appears to show greater sensitivity to the effects of noise on sensory CAEPs in adult listeners, it is the amplitude of sensory CAEPs, particularly the amplitude of N1, that relates best with behavioral speech-in-noise perception. This suggests that successful perception of speech in noise is more dependent on the synchronous sensory processing of the stimuli than the time window in which this processing occurs. Because there is limited research examining the relationship between behavioral speech-in-noise perception and noise-induced changes in cognitive CAEPs, it is unclear if latency or amplitude of the cognitive P3 response would relate best with behavioral performance. When examining the effects of different noise types on P3 amplitude and latency, Bennett and colleagues (2012) found P3 latency to be sensitive to informational masking. These findings suggest that P3 latency might provide the index of top-down processing of speech in noise that relates best with behavioral measures of perception. Although Bennett and colleagues did not report P3 amplitude, the sensitivity of P3 latency is supported by previous studies showing that the latency of P3 responses to speech sounds in quiet was more strongly associated with behavioral speech perception than P3 amplitude (Beynon, Snik, Stegeman, & Van den Broek, 2005; Kutas, McCarthy, & Donchin, 1977). If P3 latency is found to relate stronger with behavioral speech-in-noise perception than P3 amplitude, it would suggest that the timing in which stimulus evaluation occurs is also important for accurate speech-in-noise perception. Additionally, it is possible that asynchronous sensory processing of the stimuli in noise (as reflected by N1 amplitude) might influence the efficiency of the cognitive system to disambiguate speech sounds in noise (as reflected by P3 latency). Because children continue to undergo maturation of both of these sensory and cognitive systems into adolescence (Goodin et al., 1978; L. Martin et al., 1988; Ponton et al., 2000), it is likely that consequences arising from a breakdown in either stage of this processes could be greater for children compared to adults.

Research Hypotheses

The systematic nature by which sensory and cognitive CAEPs are affected by the presence of background noise and their known relationships with speech-in-noise perception of adult listeners suggest that CAEPs elicited with speech embedded in noise are a potentially valuable tool to explore the processes underlying the well-documented relationship between age and behavioral speech-in-noise perception. Because the majority of research in this area has been conducted in adults and has focused on sensory CAEPs alone, further research is needed to expand our knowledge of cortical associates of speech-in-noise perception to children. Table 4 outlines the two specific aims that were addressed in the current study. We first evaluated how neural representations of sensory and cognitive speech processing were affected by the presence of background noise and how the influence of background noise on these representations differed among typically developing children and adults. We then explored the relationship between these brain-based measures of speech-in-noise processing and an adaptive, clinical assessment of behavioral speech-in-noise perception to expand our understanding of the sensory and cognitive contributions to speech perception.

Table 4. Aims of this study are shown with accompanying research questions and hypotheses.

Aim 1	**Describe the effects of background noise on sensory and cognitive neural mechanisms of speech perception in adults and children.**
Question 1a	How do amplitude and latency of sensory and cognitive CAEPs change when elicited in background noise as compared to those elicited in quiet?
Hypothesis 1a	Sensory and cognitive CAEPs elicited in noise will show longer latency and decreased amplitude for all listeners when compared to those elicited in quiet.
Question 1b	Does age influence the effect of noise on sensory or cognitive CAEPs?
Hypothesis $1b_1$	Listener age will show no relation with noise-induced changes in amplitude and a positive relation with noise-induced changes in latency for sensory CAEPs. Specifically, it is expected that younger listeners will show smaller changes in latency than adult listeners.
Hypothesis $1b_2$	Listener age will be negatively correlated with change in amplitude and latency for cognitive CAEPs. It is expected that the youngest listeners will show the largest magnitude of cognitive CAEP change in the presence of noise.
Aim 2	**How do sensory and cognitive processing affect the relationship between listener's age and behavioral speech perception in noise?**
Question 2a	Is there a relationship between behavioral speech-in-noise perception and age?
Hypothesis 2a	Listener-age will be significantly correlated with behavioral measures of speech-in-noise perception such that younger listeners will show poorer perception than older listeners.
Question 2b	Do effects of noise on sensory or cognitive CAEPs mediate the relationship between age and speech-in-noise perception?
Hypothesis 2b	Noise-induced changes in amplitude of sensory CAEPs will not mediate the relationship between age and speech in noise perception by themselves; instead, noise-induced changes in latencies of cognitive CAEPs will significantly mediate the relationship between age and behavioral speech-in-noise perception.

CHAPTER II

METHOD

Participants

Fifty-eight participants (28 females) between the ages of 7 and 25 years of age (*M* = 16.6, *SD* = 5.55) were recruited via hospital-wide announcements and from undergraduate psychology courses. Three participants at each age were represented, apart from 20-year-old participants, of whom there were four participants. Participants or their parents reported no significant history of neuropsychological issues, suspected or diagnosed attention deficits, or use of medications known to affect the central nervous system (e.g., stimulants, antidepressants).

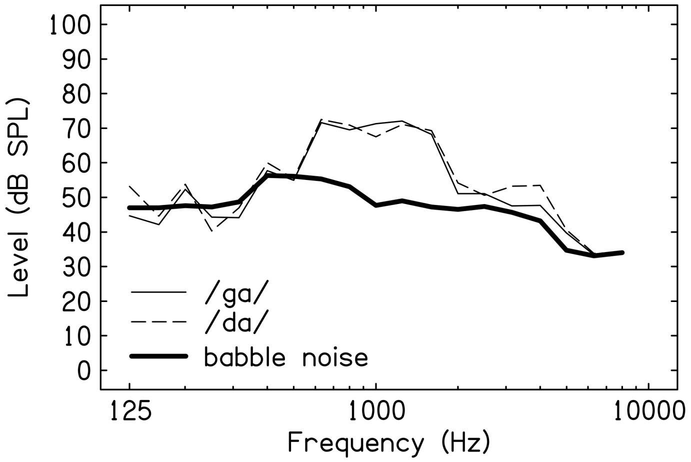
Participants had normal hearing as verified by a standard hearing screening at 20 dB HL for octave frequencies ranging from 1000-8000 Hz. All participants exhibited average or above-average intelligence capability as measured by the Kaufman Brief Intelligence Test, second edition (Kaufman & Kaufman, 2004). Participants were compensated for their participation. Informed consent and assent were obtained according to the procedures required by the Institutional Review Board at Vanderbilt University.

Materials

CAEP stimuli. Naturally-spoken digital samples of the syllables /da/ and /ga/ vocalized by the same female talker (Shannon, Jensvold, Padilla, Robert, & Wang, 1999) were used as the speech syllables. Speech syllables were trimmed to 411 ms using a free digital audio editor (Audacity, version 2.0.2; Audacity Team, http://audacity.sourceforge.net/). These consonants were selected because they differ by one significant phonetic feature known to be susceptible to noise – place of articulation (Miller & Nicely, 1955). Also, the perception of these syllables is known to be similarly affected by background babble noise (Parikh & Loizou, 2005). Furthermore, spectral differences between these two consonants are primarily isolated to the steepness of the second and third formant transitions of the consonant burst (Stevens & Blumstein, 1978), so discriminating these two syllables in noise was expected to be difficult enough to require top-down processing – even for listeners with normal hearing.

The same four-talker babble noise that was used to obtain behavioral measures (Auditec, 1971) was used for CAEP measures. This babble noise included three female talkers and one male talker reading aloud. The noise level was adjusted relative to the average level of the speech syllables to create a +15 dB SNR. The condition of +15 dB SNR was selected to represent the SNR recommended by the American National Standard for Classroom Acoustics (American National Standards Institute, 2010). Intensity of the stimuli and the noise were calibrated using a Larson-Davis sound pressure level meter (Model 824) measured with a 2 cc, artificial ear coupler (AEC202). Left and right ear channels were calibrated separately. Figure 2 shows one-third octave band levels of the speech tokens and the noise that were used to elicit CAEPs.

Figure 2. One-third octave band levels for the syllables /ga/ and /da/ and the background babble noise used as CAEP stimuli. Levels were adjusted to reflect an average overall level for the speech syllables of 75 dB SPL and an overall level of 60 dB SPL for the background noise (+15 dB signal-to-noise ratio).



Procedures

All testing was completed in a sound dampened room in a single visit lasting less than two hours.

Behavioral measures. Behavioral speech-in-noise perception was assessed using the Bamford-Kowal-Bench Speech-in-Noise test (BKB-SIN, 2005). The BKB-SIN test is a standardized, norm-referenced assessment with high validity and reliability (BKB-SIN, 2005; Donaldson et al., 2009; Schafer & Wolfe, 2008; Wilson, McArdle, & Smith, 2007). The test contains 18 sets of paired lists, equated for difficulty, spoken by a male talker in four-talker babble (Auditec, 1971) and is appropriate for children five years of age and older. Sentences were originally obtained from speech samples of children with hearing loss and are at a vocabulary level typical of a first-grade child (Bench & Bamford, 1979; Bench, Kowal, & Bamford, 1979). Each sentence is preceded by a verbal "ready" and contains three or four key words scored as correct or incorrect. This test was chosen due to its modified-adaptive nature in hopes of avoiding floor and ceiling effects.

Consistent with CAEP procedures, the BKB-SIN test sentences were presented at a fixed-level of 75 dB SPL through ER-3A insert earphones. As per the test manual, the level of the competing noise was increased in three dB steps (+21 to -6 dB SNR) through each list of the test to determine the SNR required for 50% correct sentence recognition (SNR-50). The BKB-SIN sentences and competing noise were routed from a portable playback device and presented binaurally. A total of three list-pairs was administered to all participants, providing test reliability between 0.9 and 1.4 dB for all participants (Etymotic Research, 2005). Key words were scored in real time by an examiner as correct or incorrect, no partial credit given, using the score sheets provided in the manual.

CAEP task. CAEPs were recorded using a 128-channel Geodesic sensor net (EGI, Inc., Eugene, OR) with electrodes embedded in soft electrolytic sponges. Prior to application, the net was soaked in warm saline solution. The electrode impedances were kept at or below 50 kOhms. The use of high-impedance amplifiers allowed for collection of high-quality data without having to abrade the scalp, thus minimizing any discomfort and reducing infection risks. The CAEP signals were sampled every 4 ms with filters set at 0.1 Hz - 30 Hz. During data collection, all electrodes were referenced to vertex (Cz).

The syllables were presented using an oddball paradigm, where the target stimulus appeared infrequently among more frequent presentations of the standard stimulus. Consistent with previous research in this area (Bennett et al., 2012; B. A. Martin & Stapells, 2005; Whiting et al., 1998), target stimuli comprised 20% of the trials. A total of 200 trials (160 trials of standard stimuli vs. 40 trials of target stimuli) were presented within each condition (Quiet and Noise). Both syllables served as target and standard stimuli, with assignment of speech syllables to the target/standard conditions counterbalanced across participants. Stimuli were presented using an automated presentation program (E-prime, PST, Inc., Pittsburgh, PA) with an interstimulus interval (ISI) randomly varying between 1400-2400 ms.

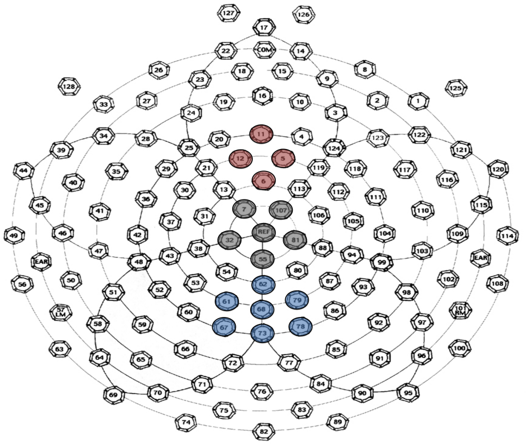
Each participant was tested individually while sitting quietly in a cushioned chair. Four blocks of CAEP testing were completed: Quiet-Attend, Quiet-Ignore, Noise-Attend, and Noise-Ignore. The Quiet conditions consisted of syllables presented without background noise while the Noise conditions included background noise of +15 dB SNR. Consistent with previous studies in adults and children (Kaplan-Neeman et al., 2006; M. Sharma et al., 2014; Zendel et al., 2015), stimuli were presented to each participant binaurally using insert earphones. The level of the stimulus syllables remained constant at 75 dB SPL across Quiet and Noise conditions. Babble noise was presented through the earphones continuously throughout each recording session.

The Ignore testing was used to measure sensory processing of the speech syllable. During the Ignore tests, participants were asked to watch a silent movie and ignore any sounds they heard through the earphones. To capture the effects of top-down processing of speech syllable discrimination on sensory and cognitive CAEPs, participants were instructed during the Attend testing to indicate which stimulus (standard or target) was presented by pressing the corresponding button on a response pad. Assignment of stimuli (standard vs. target) to buttons was counterbalanced. In this active task, both accuracy and speed were emphasized. To allow child participants to become familiar with the task, a practice session lasting less than one minute was completed in quiet. All participants demonstrated performance better than 80% correct syllable identification before proceeding to the main task. Test conditions were counterbalanced across participants to account for fatigue effects. Each CAEP testing block lasted approximately 6-9 minutes.

Preliminary processing of CAEP data. The EEG data were filtered offline using a 30 Hz low pass filter. Segmentation of the CAEP data for each trial was performed automatically using the Net Station 5.3 software (EGI, Inc. Eugene, OR), starting 100 ms prior to each stimuli onset and continuing for 800 ms post-syllable period. Next, data were screened for movement artifacts and channels with poor signal quality. Automated artifact removal was confirmed by human verification by an examiner blinded to the participant's age, session type (Attend vs. Ignore), and condition (Quiet vs. Noise) under which data were collected. A minimum of 18 artifact-free trials per condition (i.e., standard and target stimulus) was required for a data set to be included in the statistical analyses. Data for electrodes with poor signal quality within a trial were reconstructed using spherical spline interpolation procedures. Trials where more than 10% of the electrodes were deemed bad were discarded. Following artifact screening, individual AEPs were averaged, re-referenced to an average reference, and baseline-corrected by subtracting the average microvolt value across the 100-ms pre-stimulus interval from the post-stimulus segment.

Derivation of CAEP variables. Mean amplitude and peak latency values for sensory (N1) and cognitive (P3) CAEP waves were obtained separately for each electrode cluster shown in Figure 3. Voltages measured from electrodes within each cluster were averaged to represent traditional Fz, Cz, and Pz locations (Polich, 2007). To characterize the effect of noise and age on sensory processing of speech, we examined the amplitude and latency of the N1 response to standard stimuli in the Ignore test at the Cz electrode cluster. The use of responses to the stimuli having the most trials (i.e., standards) provided the best quality data in the youngest children (i.e., ages 7-8 years old) who are known to show inconsistent N1 responses (Goodin et al., 1978; L. Martin et al., 1988; A. Sharma, Kraus, McGee, & Nicol, 1997). The Cz electrode cluster is where the N1 response was expected to be maximal (Key et al., 2005). The effects of noise and age on attentive discrimination of the speech sounds were examined using the amplitude and latency of the P3 response to target stimuli at the Pz electrode cluster during the Attend test.

Figure 3. Map of the 128-channel Geodesic Sensor Net (EGI, Inc). Colored shading indicates electrode clusters used for analysis (Fz = red, Cz = grey, Pz = blue).



Amplitude and latency of N1 and P3 responses were measured automatically by the Net Station 5.3 program to avoid examiner bias. Time windows for analysis were selected by examining the grand-average waveform across all participants collapsed across condition. Previous research reported differences in morphology of the N1 response between children and adults (Goodin et al., 1978; Pang & Taylor, 2000; Tomé, Barbosa, Nowak, & Marques-Teixeira, 2015). To accommodate latencies of the N1 response in Quiet and Noise conditions across participants of all ages, N1 peak amplitude was defined as the minimum amplitude between 60 and 180 ms post-stimulus onset. N1 peak latency was defined as the time point of the minimum amplitude within this same window. Recall that P3 was measured using responses to target stimuli, of which there were only 40 trials per participant. Because the measurement of average responses from a small number of trials has the potential to yield artificially increased peak amplitudes, we chose to use adaptive mean amplitude. Adaptive mean amplitude accommodates for variations in trial numbers across participants and provides a stable measure less susceptible to measurement noise (Luck, 2014). P3 amplitude was measured using adaptive mean amplitude protocols in Net Station 5.3 software. This algorithm identified the most positive peak between 280 and 600 ms post-stimulus onset and then defined a new time window (+/- 100 ms around the peak) from which the mean amplitude was calculated. P3 latency was defined as the latency of the most positive peak within the 280-600 ms window.

Data Analysis

Behavioral speech-in-noise performance.

Speech-in-noise perception on the BKB-SIN test. Behavioral speech-in-noise performance was quantified using SNR-50 scores from the BKB-SIN test for each participant. A multiple regression analysis was used to explore the expected effect of age on speech-in-noise perception, as measured using the BKB-SIN test. To account for the potential curvilinear relationship between age and speech-in-noise perception, a quadratic effect of age was included in the regression model.

Speech-sound discrimination. E-Prime software recorded behavioral performance on the speech discrimination task during the CAEP Active test. Median reaction time of response selection and accuracy (percent correct) of the target stimulus detection were analyzed to verify that participants were actively engaged in the task. Separate repeated measures analyses of covariance (RM ANCOVA) on accuracy and response time data examined effects of stimulus (Standard vs. Target) and condition (Quiet vs. Noise). Pearson product-moment correlations were used to assess the relationship between the two variables (reaction time, accuracy) and participant age.

Auditory evoked potential data quality.

Trial count. Exploratory RM ANCOVAs were conducted to confirm that the number of usable CAEP trials was not affected by condition (Quiet vs. Noise), test (Ignore vs. Attend), or age. Data for standard and target stimuli were analyzed separately.

Morphology. Visual examination of the individual N1 responses at Cz in the Quiet-Ignore condition and P3 responses at Pz in the Quiet-Attend condition was used to ensure that any potential morphological differences would not influence the automated calculation of amplitude and latency values prior to exploring the effects of background noise on CAEP responses to speech.

Effect of noise on CAEPs. Generalized least squares multiple regression analyses (Equation 1) were conducted separately for the N1 responses at Cz in the Ignore test and P3 responses at Pz in the Attend test to assess if the independent variables predicted the amplitude or latency of the CAEP response (Y). Independent variables included age (X_1), condition (Quiet vs. Noise; X_2), gender (X_3), and interaction between listener age and CAEP condition (Age x Condition; X_1X_2). Because the effect of age on the P3 response has been shown to be nonlinear (Polich et al., 1990), we also included a quadratic term for age in each model (Age^2; ${X_1}^2$).

$$Y = \beta_0 + \beta_1(X_1) + \beta_1(X_1^2) + \beta_2(X_2) + \beta_3(X_3) + \beta_4(X_1X_2) + \varepsilon \qquad (1)$$

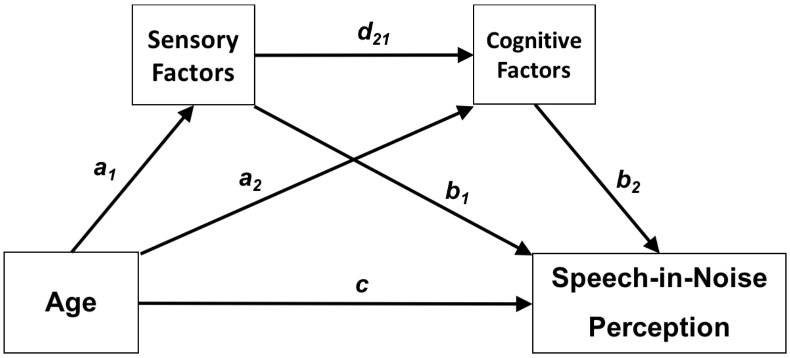
The standard multiple regression model was used, with all predictors entered simultaneously into the model. Prior to each analysis, linearity was assessed by partial regression plots and a plot of studentized residuals against the predicted values. The Durbin-Watson statistic was used to evaluate the independence of residuals. Plots of studentized residuals versus unstandardized predicted values were visualized to determine homoscedasticity. Multicollinearity was considered if tolerance values were greater than 0.1. Outliers were identified using studentized deleted residuals greater than ±3 standard deviations, leverage values greater than 0.2, and values for Cook's distance above 1. The assumption of normality was assessed by a Q-Q Plot. Unless otherwise specified, each model met all assumptions. Adjusted *R*-squared was used to assess the goodness of fit of each model. The variable Age was centered around the mean (16.58 years) to facilitate interpretation and to avoid computational difficulties associated with collinearity anticipated for the multiplicative term (Age^2) included in each regression model. Four multiple linear regression models were conducted: N1 amplitude, N1 latency, P3 amplitude, and P3 latency.

Using CAEPs to explain age-related changes in speech-in-noise perception. The effect of noise on CAEPs was quantified as the percent change between the quiet and noise conditions in N1 amplitude in the Ignore test and P3 latency in the Attend test. Calculating the percent change allowed us to account for any potential differences in morphology across this wide age range. Noise-induced changes in N1 amplitude and P3 latency were chosen a priori based on previous research showing significant associations between behavioral speech-in-noise perception and these specific attributes (Anderson, Skoe, et al., 2010; Bennett et al., 2012; Billings et al., 2013; Parbery-Clark et al., 2011).

To evaluate the degree to which noise-induced changes to each sensory (N1) and cognitive (P3) CAEPs mediated the relationship between age and SNR-50, we used the serial multiple mediator model shown by the conceptual diagram in Figure 4. In serial mediation, the first mediator (Sensory: N1 amplitude change) is assumed to have a direct effect on the second mediator (Cognitive: P3 latency change; path d_{21}), and the independent variable (Age) is assumed to influence these mediators in a serial way that ultimately influences the dependent variable (Speech-in-Noise Perception). To examine how Sensory or Cognitive factors influence the effect of Age on Speech-in-Noise Perception, we assessed three indirect pathways: (1) influence of Sensory factors (a_1b_1), (2) influence of Cognitive factors (a_2b_2), and (3) influence of

Sensory and subsequent Cognitive factors ($a_1d_{21}b_2$). Significance of indirect pathways was examined to assess how the effect of age on behavioral speech-in-noise perception was influenced by noise-induced changes to cortical processing of speech (if at all). We expected that noise-induced changes to cognitive processing of speech would have significant influence on the relationship between age and behavioral speech-in-noise perceptual abilities. This hypothesis would be confirmed if indirect effects a_2b_2 or $a_1d_{21}b_2$ are significant. A significant indirect effect of a_1b_1 would be required to reject this hypothesis.

Figure 4. Conceptual diagram of the serial multiple mediator model of age on speech-in-noise performance that was assessed in this study.



CHAPTER III

RESULTS

Behavioral Speech-in-Noise Performance

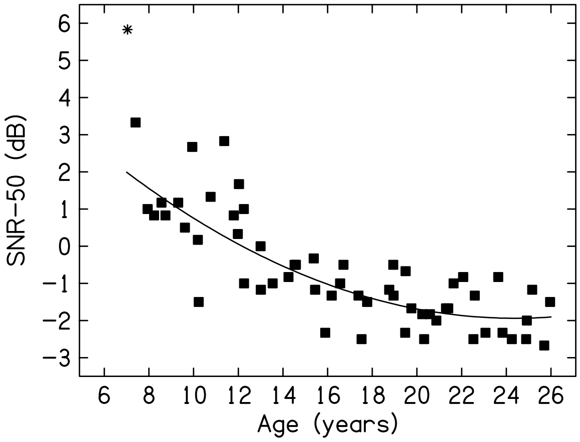
Speech-in-noise perception on the BKB-SIN test. Data from the youngest child (male, 7 years old) were removed due to studentized deleted residuals greater than ±3 standard deviations. The final sample size for the SNR-50 regression analysis included 57 participants. The multiple regression model significantly predicted SNR-50, $F(2,56) = 54.85$, $p < .001$, adj $R^2 = .658$. Both Age and Age^2 added statistically significantly to the prediction, $p < .05$. Regression coefficients and standard errors can be found in Table 5. Children showed higher (poorer) SNR-50 scores indicating that they require a more favorable SNR to achieve 50% correct when compared to adult listeners. Figure 5 shows the curvilinear nature of this relationship between age and speech-in-noise perception.

Table 5. Summary of the regression model predicting SNR-50.

	Multiple Regression Weights		
	B	SE_B	β
Intercept	-1.15	.169	
Age***	-.203	.021	-9.72
Age^2**	.013	.004	.241

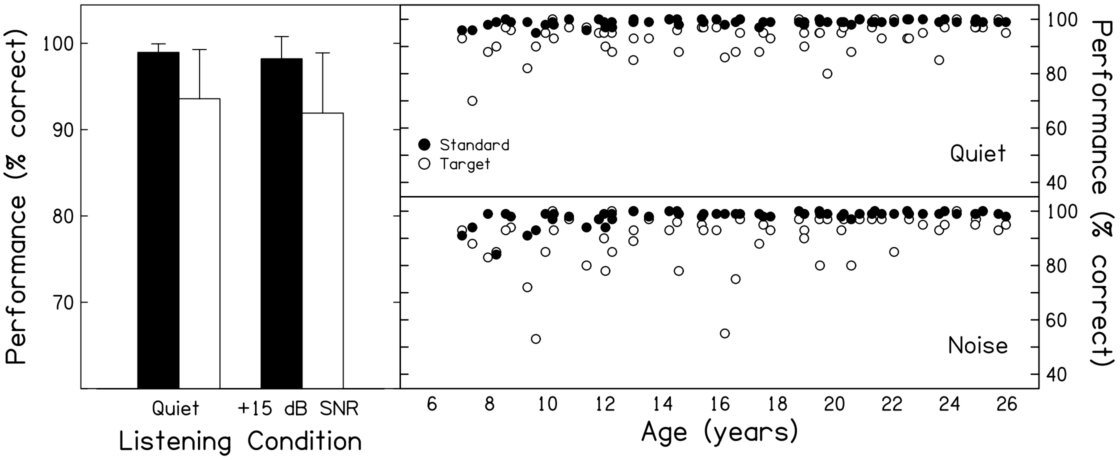
Note. adj $R^2 = .658$; $*p < .05$ $**p < .01$ $***p < .001$;
B = unstandardized regression coefficient; SE_B = standard error of coefficient; β = standardized coefficient.

Figure 5. SNR-50 scores as a function of age. Asterisk represents the data point excluded from analyses. Best-fit regression line is also shown.



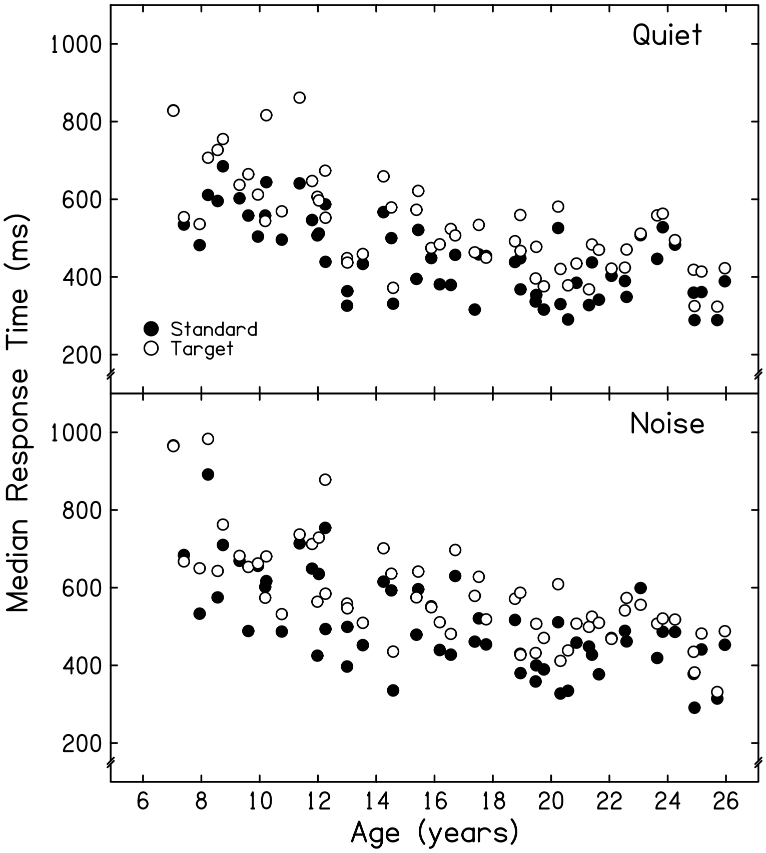
Speech-sound discrimination. Age was significantly correlated with accuracy and response times (accuracy *r*s from .316 to .503; response time *r*s from -.664 to -.708) showing that children performed less accurately and responded slower than adults in each condition and for each stimulus type (*p*s = .016 to <.001). Therefore, Age was included as a covariate in further analyses. Figure 6 shows mean accuracy data for the two stimulus types collapsed across age (left panel) and displayed as a function of age in each listening condition (right panel). Mean accuracy data showed significant main effects of Stimulus, $F(1,56) = 22.55, p < .001, \eta_p^2 = .287$, and Condition, $F(1,56) = 8.46, p = .005, \eta_p^2 = .131$. Specifically, accuracy was better (higher) in the quiet compared to the noise condition, and syllable identification for standard stimuli was more accurate than for target stimuli. Stimulus x Age, $F(1,56) = 4.66, p = .035, \eta_p^2 = .077$, and Condition x Age, $F(1,56) = 4.26, p = .044, \eta_p^2 = .071$, interactions were significant. That is, the differences in accuracy between Stimuli (target < standard) and between Conditions (noise < quiet) were greatest for child listeners and smallest for adult listeners. No other interactions were significant (*p*s > .05).

Figure 6. Left panel: Mean (SD) response accuracy for standard (filled bars) and target (open bars) stimuli in the quiet and noise conditions. Right panels: Mean response accuracy for standard (filled symbols) and target (open symbols) stimuli in the quiet (upper panel) and noise (lower panel) conditions, as a function of age.



Median response times in the two listening conditions and for each stimulus type can be seen in Figure 7. Median response time data showed significant main effects of Stimulus, $F(1,56) = 26.90, p < .001, \eta_p^2 = .325$, and Condition, $F(1,56) = 8.84, p = .004, \eta_p^2 = .136$. Responses were faster in the quiet compared to the noise condition, and syllable identification for standard stimuli was quicker than for target stimuli. The Condition x Stimulus interaction did not reach statistical significance, $F(1,56) = 3.97, p = .051, \eta_p^2 =.066$. No significant 2-way or 3-way interactions with Age were found (*p*s from .106 - .304).

Figure 7. Median response time for syllable identification during Attend CAEP task shown for standard (filled circles) and target (open circles) stimuli in the quiet and noise conditions.



Auditory Evoked Potential Data Quality

Trial count. All 58 participants successfully completed CAEP testing. Because inference about the absence or reduction of the P3 response is inappropriate when the participant is unable to perform the task (Duncan et al., 2009), we excluded participants who demonstrated poor performance on behavioral speech-sound discrimination. Two participants (9 and 16 years old, both female) were excluded from the Attend data set due to chance level (53% and 55%, respectively) behavioral performance on target identification in the noise condition. One participant (7 years old, male) failed to provide a minimum of 18 artifact-free CAEP trials in both quiet and noise conditions during the Attend test. Trial counts for each stimulus type, test type, and noise condition are shown in Table 6. A set of exploratory repeated-measures analyses of covariance (RM ANCOVA) with Age as a covariate showed no significant effects of Test (Ignore vs. Attend) or Condition (quiet vs. noise) and no significant effect of Age (*p*s from .246 - .989) on the number of trials retained for the standard and target stimuli.

Table 6. Mean (SD) trial counts included in analysis for CAEP data.

	Ignore (n=58)		Attend (n=55)	
	Quiet	Noise	Quiet	Noise
Standard	99.7 (22.8)	98.7 (20.3)	98.0 (23.4)	96.0 (24. 9)
Target	25.6 (4.97)	25.4 (5.44)	26.0 (5.36)	25.9 (5.65)

Morphology. Depicting the sensory (N1) responses across age, Figure 8 shows responses at the Cz electrode cluster in the Quiet-Ignore condition. The N1 responses were visible for each age group within the time window chosen for analysis (60-180 ms as shown in shaded area). P3 responses recorded in the Quiet-Attend condition are shown in Figure 9. Robust P3 responses are visible within the 280-600 ms window for all age groups except for the group of children 7-8 years old. Visual inspection of individual data from the five children included in this age group revealed that all but one child showed a P3 response at the Pz location. The child without a P3 response at the Pz location (8 years old, female) showed an increase in response following target stimuli at the Cz and Fz location. These data were included in the data set to better represent possible individual variability.

Figure 8. Responses to standard stimuli in the Quiet-Ignore condition at the Cz electrode cluster. The shaded region shows the time window used for N1 peak amplitude and latency calculation.

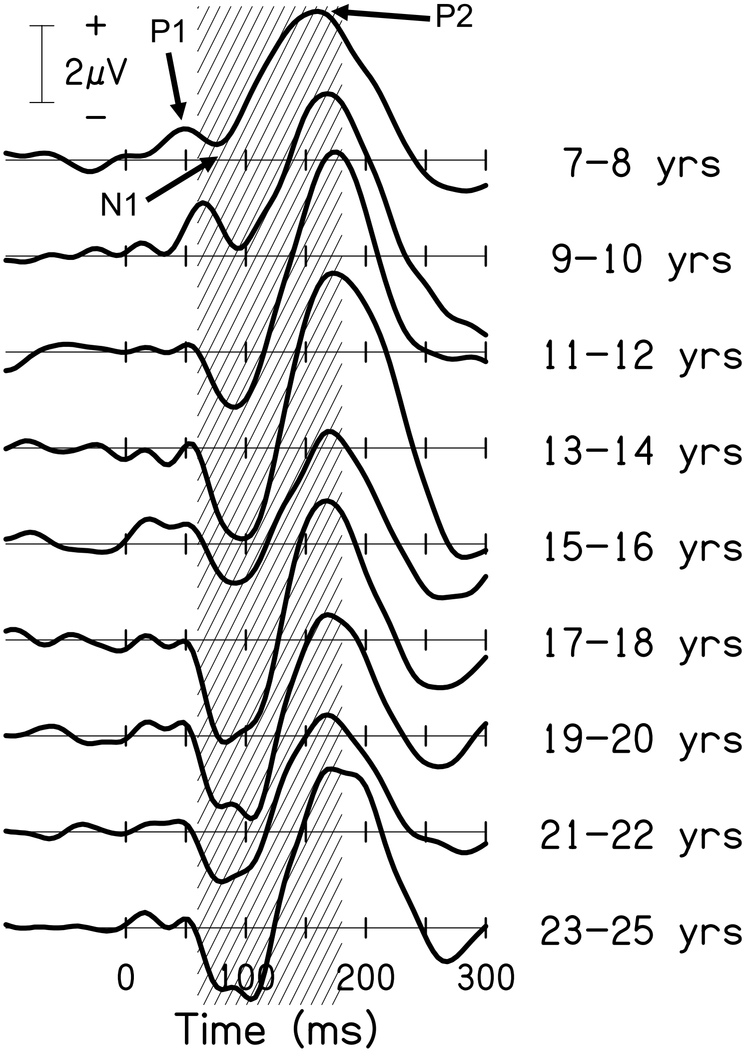
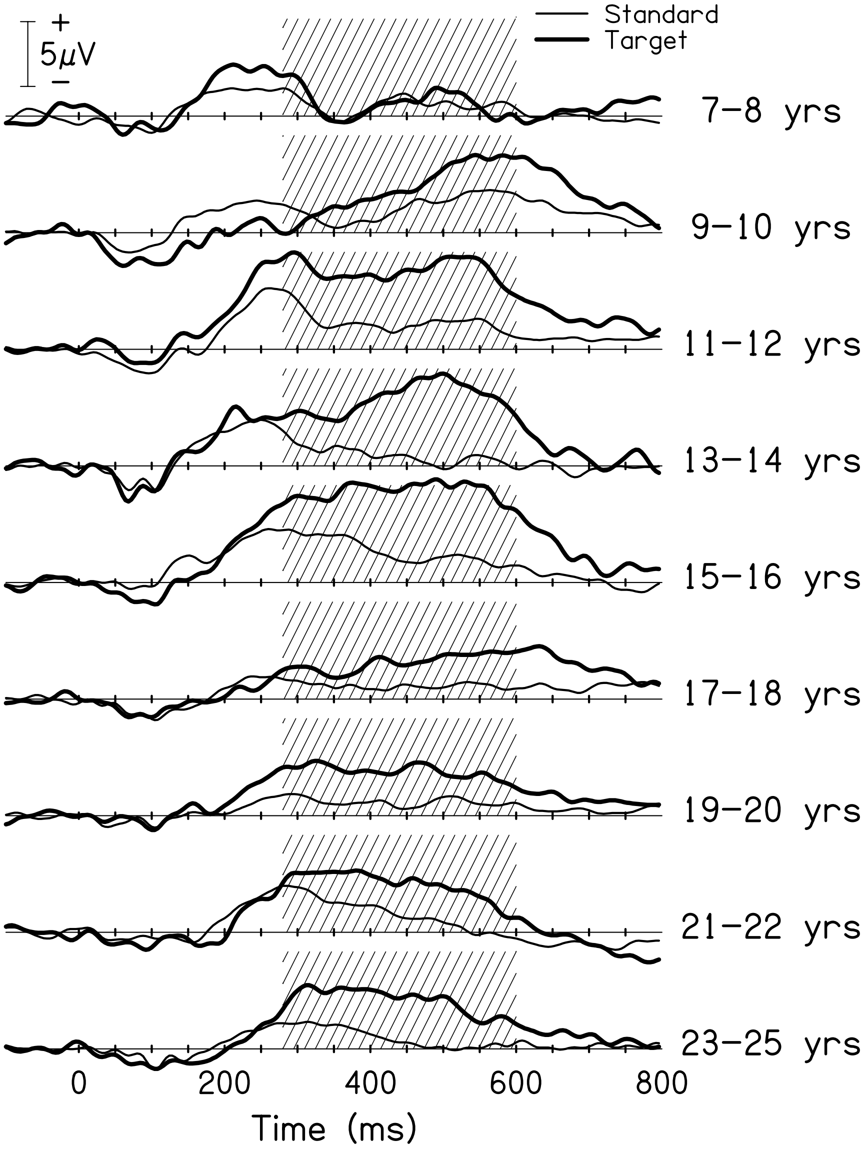


Figure 9. Responses to standard (thin lines) and target (thick lines) stimuli in the Quiet-Attend condition at the Pz electrode cluster. Shaded regions depict the boundaries of the time window used for P3 peak amplitude and latency calculation.



Effect of Noise on CAEPs

Grand average waveforms to standard stimuli at each electrode cluster in the Ignore test for quiet and noise are shown in Figure 10. As expected, N1 responses were diminished in amplitude and delayed in latency in noise as compared to the quiet condition. Grand average responses recorded during the Attend test for participants with usable data (n = 55) can be seen in Figure 11 for quiet and noise conditions. Although present at both Cz and Pz electrode clusters, P3 responses appear maximal at the expected Pz location in quiet and noise conditions.

Figure 10. Grand average waveforms for responses in quiet (solid lines) and noise (dashed lines) for the Ignore test at the three electrode clusters.

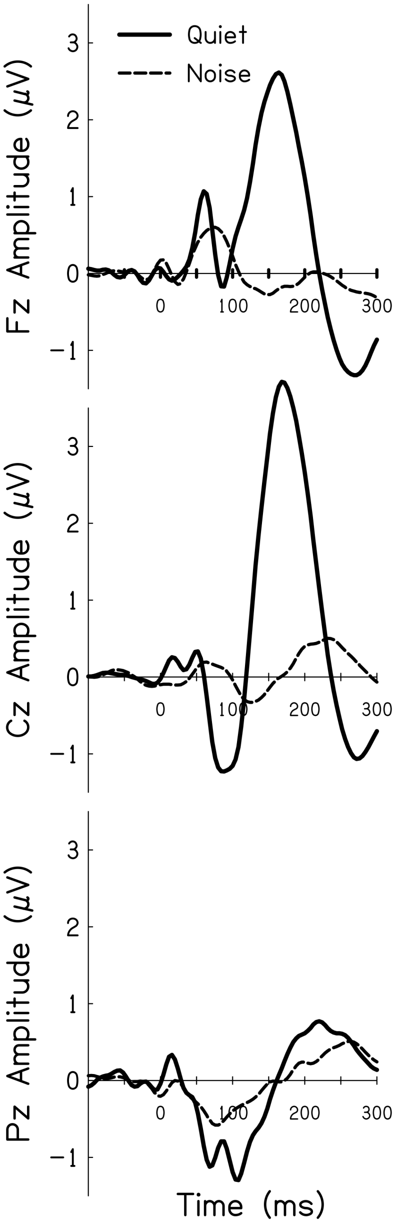
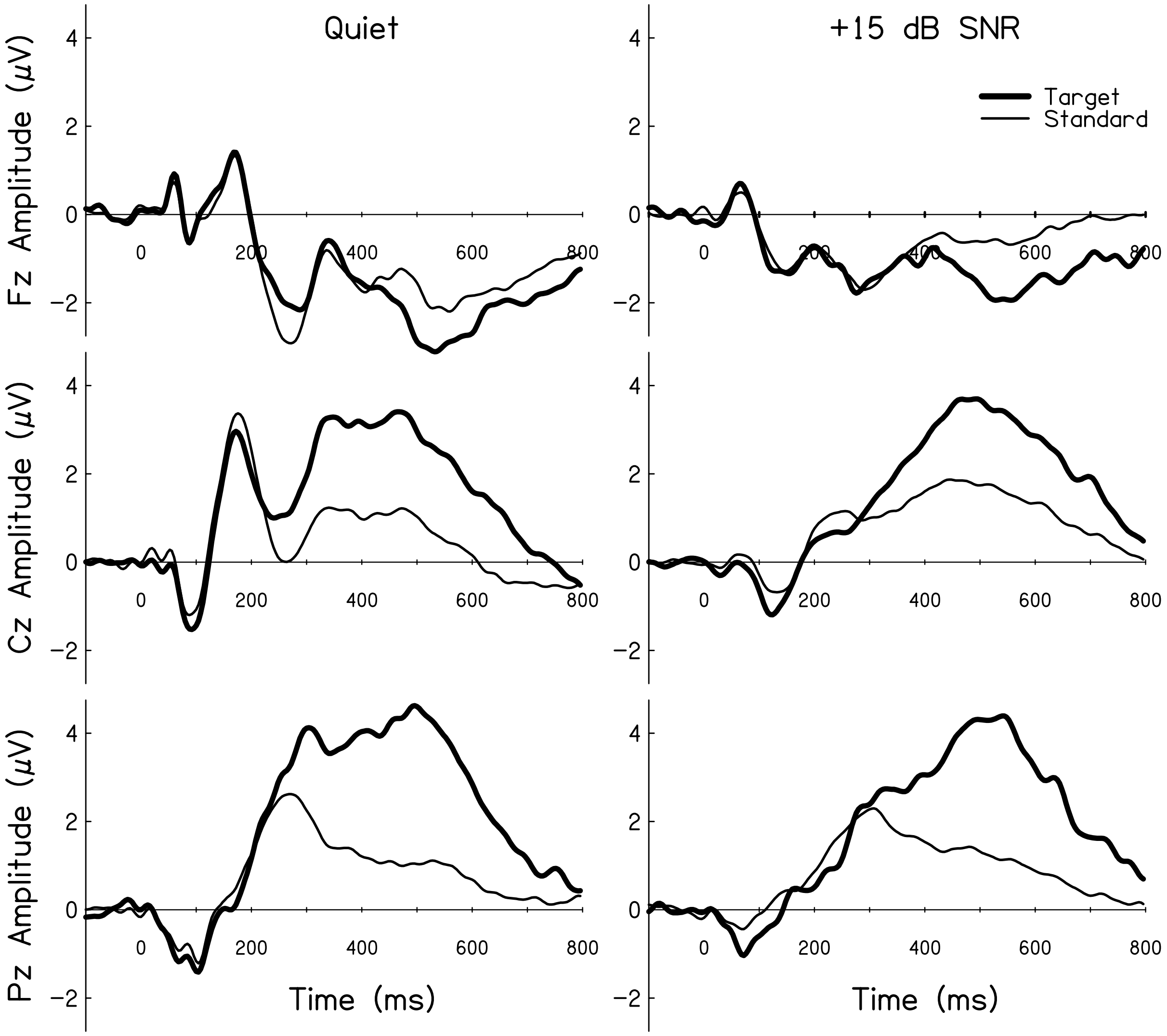


Figure 11. Grand average waveforms for responses to standard (thick lines) and target (thin lines) stimuli during the Attend test at the three electrode clusters.



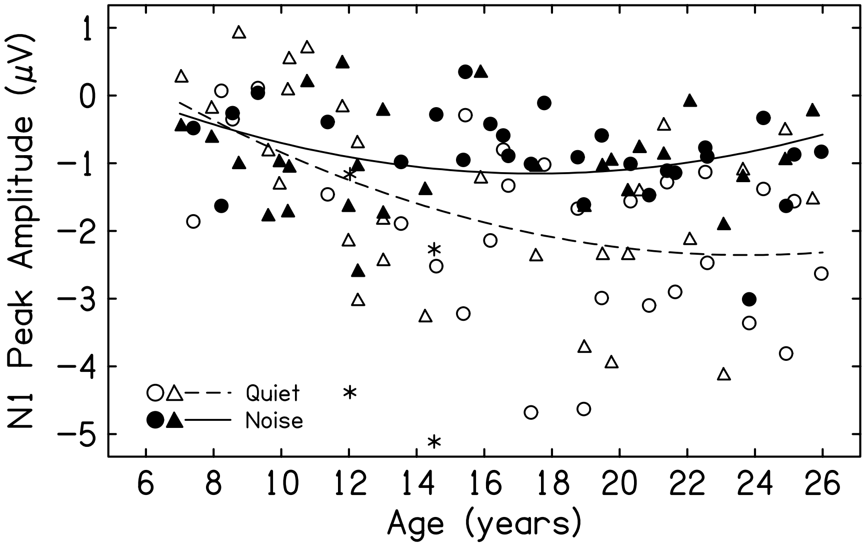
N1 amplitude. Prior to final analysis, two data points were removed (both male, 12 and 14 years old) due to studentized deleted residuals greater than ±3 standard deviations. The final sample size for the N1 amplitude regression analysis included 56 participants. The multiple regression model significantly predicted N1 amplitude, $F(5,106) = 10.26$, $p < .001$, adj $R^2 = .294$. Four of the five variables added significantly to the prediction, $p < .05$. Regression coefficients and standard errors can be found in Table 7. Notably, the effect of noise on the N1 amplitude was dependent upon the age of the listener. That is, for children 7-9 years of age, an increase in N1 amplitude was present in the noise condition compared to the quiet condition. Conversely, listeners age 10 years and older showed a decrease in N1 amplitude in the noise condition when compared to the quiet condition. The nonlinearity of this age-related effect of noise on the N1 amplitude is shown in Figure 12.

Table 7. Summary of the regression model predicting N1 amplitude.

	Multiple Regression Weights		
	B	SE_B	*β*
Intercept	-2.71	.323	
Age***	-.215	.052	-1.04
Age^2*	.008	.003	.183
Condition***	.798	.183	.347
Age x Condition**	.100	.033	.763
Gender	-.062	.187	-.027

Note. adj $R^2 = .294$; *$p < .05$ **$p < .01$ ***$p < .001$;
B = unstandardized regression coefficient; SE_B = standard error of coefficient; *β* = standardized coefficient.

Figure 12. N1 peak amplitudes for responses in quiet (open symbols) and in noise (filled symbols) conditions as a function of age. Circles represent female participants while triangles represent male participants. Asterisks represent data points excluded from analyses. Best-fit regression lines are also shown.



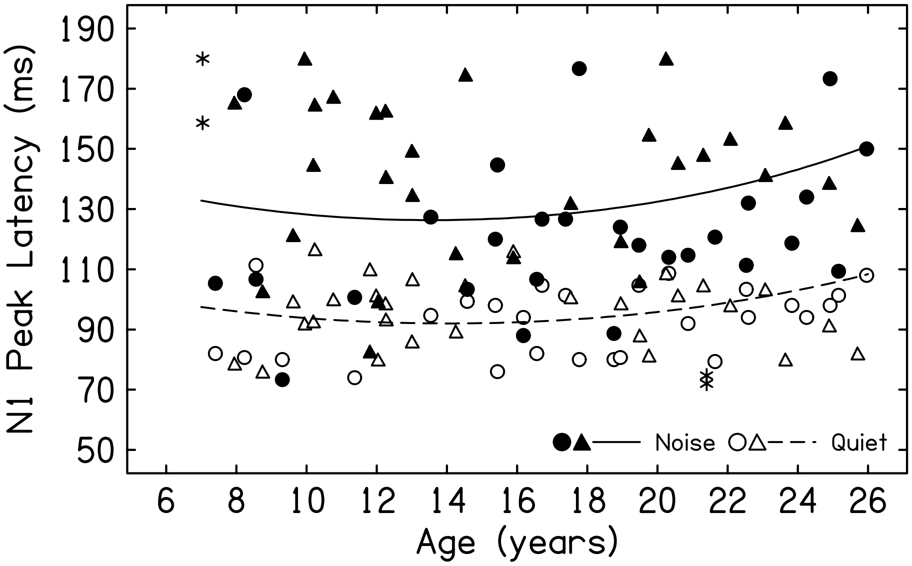
N1 latency. N1 latencies were not normally distributed, showing a positive skewness of 0.767 (*SE* = .226). To account for this non-normal distribution, N1 latencies were log transformed. Prior to analysis, two data points were removed (one male, 7 years old; one female, 21 years old) due to studentized deleted residuals greater than ±3 standard deviations. The final sample for the N1 latency regression included 56 participants. The multiple regression model significantly predicted N1 latency, $F(5,106) = 23.07$, $p < .001$, adj $R^2 = .498$. Two of the five variables added significantly to the prediction, $p < .05$. Regression coefficients and standard errors can be found in Table 8. As depicted in Figure 13, N1 responses in the noise condition had significantly longer latencies than N1 responses in the quiet condition. Additionally, male participants showed longer latencies than female participants.

Table 8. Summary of the regression model predicting N1 latency.

	Multiple Regression Weights		
	B	SE_B	*β*
Intercept	1.85	.024	
Age	.002	.004	.108
Age^2	<.001	<.000	.013
Condition***	.139	.014	.684
Age x Condition	<.001	.003	.012
Gender**	-.044	.014	-.219

Note. adj $R^2 = .498$; *$p < .05$ **$p < .01$ ***$p < .001$;
B = unstandardized regression coefficient; SE_B = standard error of coefficient; *β* = standardized coefficient.

Figure 13. N1 peak latencies for responses in quiet (open symbols) and in noise (filled symbols) conditions as a function of age. Circles represent female participants while triangles represent male participants. Asterisks represent data points excluded from analyses. Best-fit regression lines are also shown.



P3 amplitude. No participants were excluded due to violations of the assumptions. The final sample for this regression analysis included 55 participants. The multiple regression model significantly predicted P3 amplitude, $F(5,104) = 4.87, p < .001$, adj $R^2 = .151$. Only Gender added significantly to the prediction ($p < .05$), with male participants showing larger P3 amplitudes than female participants. Figure 14 shows the P3 amplitudes between the quiet and noise conditions. Regression coefficients and standard errors can be found in Table 9 (below).

Figure 14. P3 peak amplitudes for responses in quiet (open symbols) and in noise (filled symbols) conditions as a function of age. Circles represent female participants while triangles represent male participants. Best-fit regression lines are also shown.

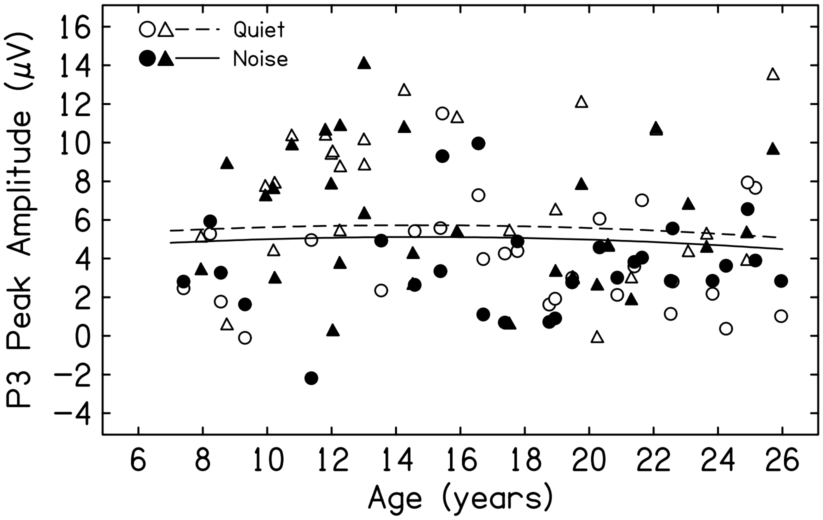


Table 9. Summary of the regression model predicting P3 amplitude.

	Multiple Regression Weights		
	B	*SE_B*	*β*
Intercept	7.75	1.07	
Age	-.022	.179	-.035
Age^2	-.005	.012	-.040
Condition	-.607	.611	-.088
Age x Condition	.002	.113	.005
Gender***	-2.88	.621	-.416

Note. adj R^2 = .151; *p < .05 **p < .01 ***p < .001;
B = unstandardized regression coefficient; SE_B = standard error of coefficient; *β* = standardized coefficient.

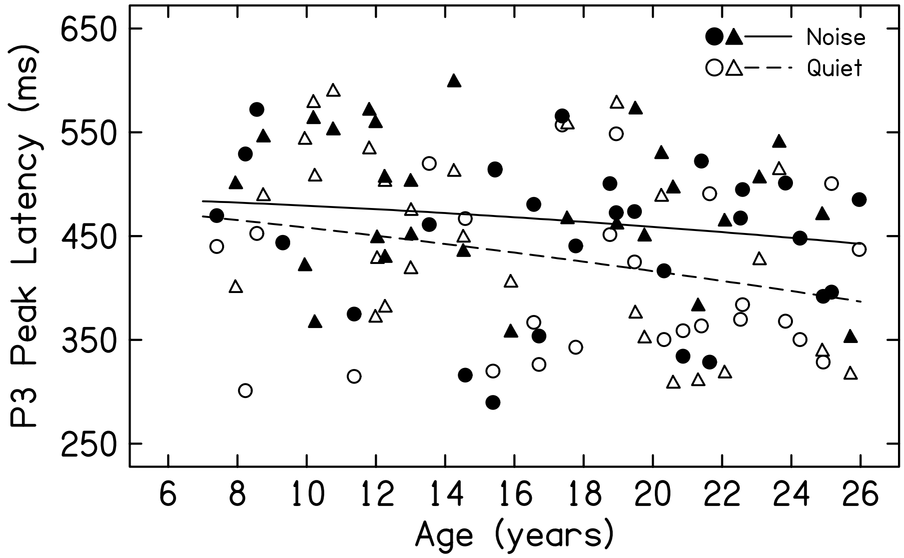
P3 latency. No participants were excluded due to violations of the assumptions. The final sample for this regression analysis included 55 participants. The multiple regression model significantly predicted P3 latency, $F(5,104) = 3.74$, $p = .004$, adj $R^2 = .112$. Only Gender and Condition added significantly to the prediction, $p < .05$. As depicted in Figure 15, P3 latencies are longer in the noise condition than in the quiet condition. Also, male participants showed longer P3 latencies than female participants. Regression coefficients and standard errors can be found in Table 10.

Table 10. Summary of the regression model predicting P3 latency.

	Multiple Regression Weights		
	B	SE_B	β
Intercept	411	25.5	
Age	-6.48	4.27	-.434
Age^2	-.044	.281	-.014
Condition*	35.3	14.6	.218
Age x Condition	2.16	2.70	.228
Gender*	-30.3	14.9	-.187

Note. adj $R^2 = .112$; $*p < .05$ $**p < .01$ $***p < .001$;
B = unstandardized regression coefficient; SE_B = standard error of coefficient; β = standardized coefficient.

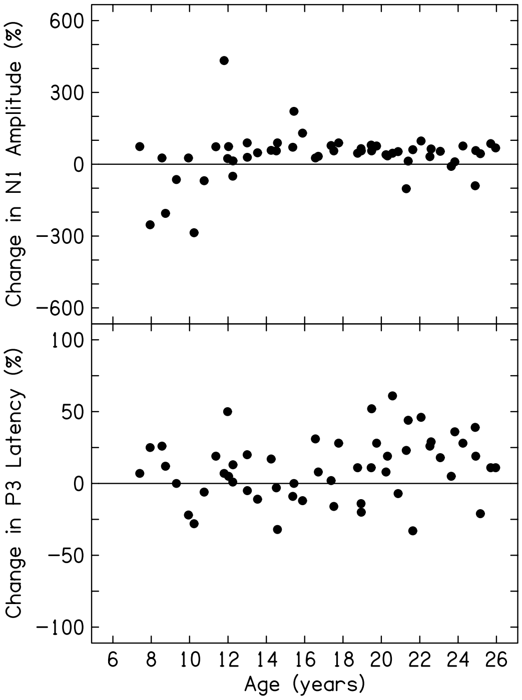
Figure 15. P3 peak latencies for responses in Quiet (open symbols) and in Noise (filled symbols) conditions as a function of age. Circles represent female participants while triangles represent male participants. Best-fit regression lines are also shown.



Using CAEPs to Explain Age-Related Changes in Speech-in-Noise Perception

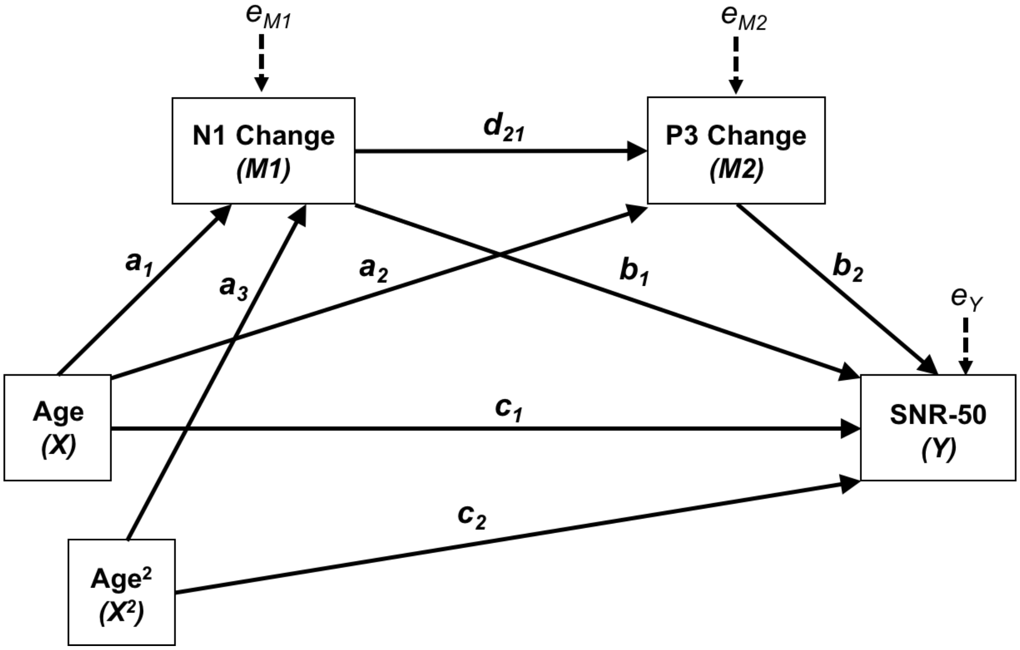
To explore if noise-induced changes in sensory (N1 amplitude) or cognitive (P3 latency) CAEPs mediated the relationship between age and speech-in-noise perception, we conducted a series of mediation analyses. To be included in the mediation analyses, participants were required to have usable data during the Ignore and Attend tests. Of these 55 participants, data for two additional participants (8-year-old female and 10-year-old male) were removed due to studentized deleted residuals greater than ±3 standard deviations for N1 amplitude changes. The final sample for mediation analyses included 53 participants. Recall that for this analysis, changes in N1 amplitude (Mediator 1; *M1*) and P3 latency (Mediator 2; *M2*) measures were quantified as the percent change in each measure between the quiet and noise conditions. Figure 16 shows the distribution of the noise-induced changes in N1 amplitude and P3 latency as a function of age for the 53 participants included in the mediation analyses. For N1 amplitude, a negative value indicates that the N1 response was larger (more negative) in the noise condition when compared to the quiet. For P3 latency, a positive value indicates that the P3 latency was increased (delayed) in the noise condition when compared to the quiet.

Figure 16. Noise-induced change in N1 amplitude (top panel) and P3 latency (bottom panel). Negative values indicate an increase in N1 amplitude (more negative) or a quickening of P3 latency (earlier response) when elicited in noise compared to quiet conditions.



The proposed serial multiple mediation analysis (shown in Figure 4) was modified to allow for the curvilinear relationship between Age (i.e., the predictor *X*) and SNR-50 (i.e., the dependent variable *Y*). Given the results of multiple regression analyses reported above, we allowed Age^2 to predict N1 amplitude change (*M*1) but not P3 latency change (*M*2). A statistical diagram of the revised serial multiple mediation model is shown in Figure 17.

Figure 17. A statistical diagram of the revised serial multiple mediation model.



In this model, the predictor (Age) was mean-centered prior to computing the squared effects. This model is characterized using the following set of equations:

$$M1 = i_{M1} + a_1 X + a_3 X^2 + e_{M1} \tag{2}$$

$$M2 = i_{M2} + a_2 X + d_{21} M1 + e_{M2} \tag{3}$$

$$Y = i_Y + c_1 X + c_2 X^2 + b_1 M1 + b_2 M2 + e_Y \tag{4}$$

Regression coefficients, standard errors, and model summary information for this serial multiple mediator model is shown in Table 11. Regarding the relationship between the predictors and the mediators (i.e., the *a*-paths in Figure 17), results show that, as age increases, noise-induced changes in N1 amplitude also increase ($a_{1;}$ greater degradation). This significance of the quadratic term (Age^2) indicates that noise-induced change becomes smaller in magnitude as age increases. The 1% latency increase with every one-year increase in age (a_2) was not significant.

Relationships between the mediators and the outcome (i.e., the *b*-paths in Figure 17) revealed that, for every 1% increase (degradation) in N1 amplitude, SNR-50 increases by 0.298 dB (b_1), leading to poorer speech-in-noise perception. The 0.149 dB increase in SNR-50 scores with each 1% increase in P3 latency (b_2) was not statistically significant. The direct effects of the predictors on the dependent variable (i.e., the *c*-paths in Figure 17) depict the previously discussed curvilinear relationship between age and SNR-50 scores (Table 5, Figure 5). The significance of these direct effects using Equation 4 suggests that the relationship between age and SNR-50 scores is not fully mediated by changes in N1 amplitude or P3 latency.

Table 11. Unstandardized regression coefficients, standard errors, and model summary information for the serial multiple mediator model.

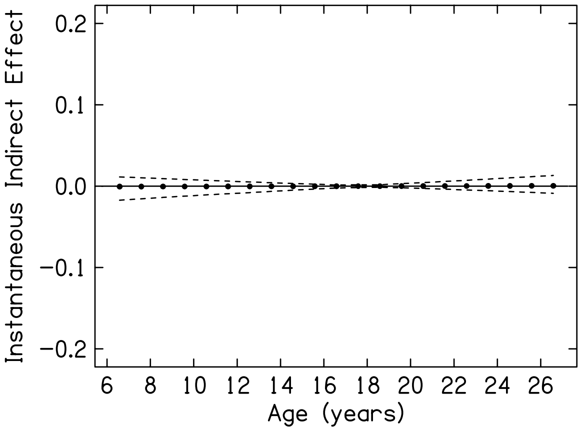
	Consequent											
	*M*1 (N1 Change)				*M*2 (P3 Change)				*Y* (SNR-50)			
Antecedent		*Coeff.*	*SE*	*p*		*Coeff.*	*SE*	*p*		*Coeff.*	*SE*	*p*
X (Age)	a_1	0.037	0.025	0.140	a_2	0.010	0.006	0.078	c_1	-0.227	0.023	<.001
X^2 (Age^2)	a_3	-0.014	0.005	0.010		--	--	--	c_2	0.019	0.005	<.001
*M*1 (N1 Change)		--	--	--	d_{21}	-0.012	0.030	0.688	b_1	0.298	0.122	0.018
*M*2 (P3 Change)		--	--	--		--	--	--	b_2	0.149	0.543	0.785
Constant	i_{M1}	0.735	0.196	<.001	i_{M2}	0.106	0.032	0.001	i_Y	-1.37	0.197	<.001
	Adj R^2 = .124				Adj R^2 = .023				Adj R^2 = .683			
	$F(2,50) = 4.69$, $p = .014$				$F(2,50) = 1.62$, $p = .208$				$F(4,48) = 29.0$, $p < .001$			

A formal test of the potential full indirect mediation effect was conducted following the approach of Hayes and Preacher (2010), which allowed for the assessment of nonlinear mediation. Considering the quadratic form of the *a*-paths and the linear form of the *b*-paths, the full mediation effect was computed with the following equation:

$$\theta = (a_1 + 2a_3X) \times d_{21} \times b_2 \tag{5}$$

With this equation, the mediation effect depends on the value of the predictor (*X*), causing the effect of age on SNR-50 through CAEP changes to depend on the listener's age. Termed the *instantaneous indirect effect*, the effect of the predictor on the outcome through the mediators is defined at a specific value of the predictor (Age). Indirect effects were estimated with 95% confidence intervals (CIs) using the Monte Carlo method (20,000 simulations; Preacher & Selig, 2012). Figure 18 shows the instantaneous indirect effect of age on SNR-50 scores through N1 amplitude and subsequent P3 latency changes. CIs spanned zero at all values of the predictor showing that the indirect effect of age on SNR-50 through noise-induced changes in N1 amplitude and subsequent changes in P3 latency was not significant at any point of the age range.

Figure 18. Instantaneous indirect effect of noise-induced N1 amplitude and P3 latency changes on the relationship between age and SNR-50 scores. Dotted lines represent upper and lower 95% confidence intervals.



Given the non-significant findings of the serial multiple mediation above, we conducted exploratory analyses on simpler mediation models to determine if noise-induced changes in amplitude or latency of sensory or cognitive CAEPs would mediate the relationship between age and SNR-50 individually. Four mediation models were tested, using noise-induced changes in N1 amplitude, N1 latency, P3 amplitude, and P3 latency as single mediators. The indirect effects of changes in N1 latency, P3 amplitude, and P3 latency on the relationship between age and SNR-50 were all not significant (CI ranges included zero at all values of the predictor). Conversely, significant indirect effects of N1 amplitude were found on the relationship between age and SNR-50. The single-mediator model including N1 amplitude changes was characterized by two equations:

$$M1 = i_{M1} + a_1X + a_3X^2 + e_{M1} \tag{6}$$

$$Y = i_Y + c_1X + c_2X^2 + b_1M1 + e_Y \tag{7}$$

Table 12 shows regression coefficients, standard errors, and model summary information for the mediation model testing the effect of age on SNR-50 through noise-induced changes in N1 amplitude. As in the full, serial multiple mediation model discussed above, young ages related with larger changes in N1 amplitude, and this relationship was curvilinear, showing smaller changes in N1 amplitude at older ages. In general, positive changes in N1 amplitude (degraded responses) were associated with higher SNR-50 scores (poorer performance). The significance of the direct effect (i.e., c-paths) suggests that the indirect effect of noise-induced N1 amplitude changes, if significant, only partially mediates the effect of age on SNR-50 scores. Equation 8 was used to calculate the instantaneous indirect effect of noise-induced N1 amplitude changes on the relationship between age and SNR-50 scores.

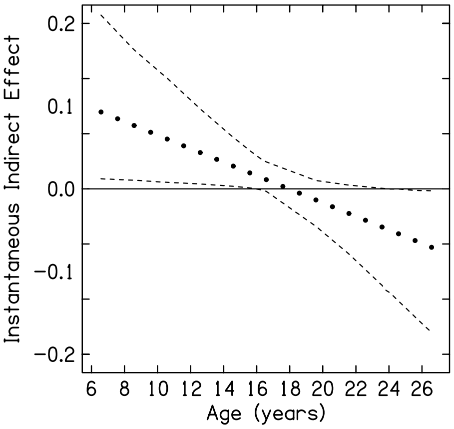
$$\theta = (a_1 + 2a_3X) \times b_1 \tag{8}$$

Table 12. Unstandardized regression coefficients, standard errors, and model summary information for the single mediator model.

				Consequent				
		*M*1 (N1 Change)				*Y* (SNR-50)		
Antecedent		*Coeff.*	*SE*	*p*		*Coeff.*	*SE*	*p*
X (Age)	a_1	0.037	0.025	0.140	c_1	-0.225	0.022	<.001
X^2 (Age^2)	a_3	-0.014	0.005	0.010	c_2	0.019	0.005	<.001
*M*1 (N1 Change)		-	-	-	b_1	0.297	0.121	0.018
Constant	i_{M1}	0.735	0.196	<.001	i_Y	-1.36	0.190	<.001
		Adj R^2 = .124				Adj R^2 = .689		
		$F(2,50) = 4.69$, p =.014				$F(3,49) = 39.4$, p <.001		

Figure 19 shows the instantaneous indirect effect of age on SNR-50 scores through N1 amplitude changes and 95% CIs. Results show that the indirect effect of changes in N1 amplitude on the relationship between age and SNR-50 scores depends on the age of the participant. That is, for participants younger than 16 years of age, age predicts poorer performance (higher SNR-50 score) through noise-induced changes in N1 amplitude, and the strength of this prediction due to changes in N1 amplitude is stronger for younger children compared to adolescents. Additionally, for adult listeners >23 years of age, age predicts better performance (lower SNR-50 scores) through noise-induced changes in N1 amplitude. For 16-22 year olds, however, the relationship between age and performance is not due to noise-induced changes in N1 amplitude.

Figure 19. Instantaneous indirect effect of noise-induced N1 amplitude changes on the relationship between age and SNR-50 scores. Dotted lines represent upper and lower 95% confidence intervals.



CHAPTER IV

DISCUSSION

Aim 1 of this study was to describe the effects of background noise on sensory (N1) and cognitive (P3) neural mechanisms of speech perception in adults and children using CAEPs elicited with speech sounds. Results showed a medium-sized effect of noise on N1 amplitude and a large effect of noise on N1 latency. Although noise-induced N1 latency delays were stable across ages from 7-25 years, noise-induced changes to N1 amplitude were not. Instead, background noise at +15 dB SNR resulted in increases in N1 amplitude for 7-9 year olds and reductions in N1 amplitude that increased in magnitude from 10 to 25 years of age. P3 amplitude was not affected by background noise at any age; however, P3 latency showed a small delay in noise compared to the quiet condition that was consistently observed for listeners 7-25 years of age.

Aim 2 of this study sought to explore if noise-induced changes in sensory (N1 amplitude) or cognitive (P3 latency) neural mechanisms of speech perception could explain the relationship between age and performance on a clinical test of speech-in-noise perception. We theorized that listener age would affect the noise-induced changes in the sensory response (N1 change), these sensory changes would then contribute to the changes in the cognitive response (P3 change) and subsequently affect speech-in-noise perception (SNR-50). Contrary to this hypothesis, age differences in speech-in-noise performance were not explained by noise-induced changes to sensory and cognitive neural processing of speech. Rather, we found that the relationship between age and behavioral speech-in-noise perception could be explained, in part, by noise-induced changes in sensory processing (N1 amplitude change) without the subsequent influence of cognitive processing (P3 latency change).

Effects of Noise on Sensory CAEPs

Results of this study generally support our hypothesis that noise affects processing of sensory characteristics of speech sounds, as reflected by the reduced amplitude and increased latency of N1 responses in +15 dB SNR compared to the quiet condition. However, further examination of the effect of age and noise revealed that the effect of noise on N1 amplitude was complex when considering listeners of different ages. Based on previous literature, we did not expect noise effects on N1 amplitude to vary with age but did expect the younger listeners to show smaller effects of noise on N1 latency than adult listeners. The results were opposite to our hypotheses. That is, the effect of noise on N1 amplitude, not latency, showed significant effects of age.

N1 amplitude. For adult listeners, the 53% reduction in the N1 amplitude in noise compared to the quiet condition was consistent with the 20-50% reduction of N1 amplitude shown in previous studies (Billings et al., 2011; Kaplan-Neeman et al., 2006; Papesh et al., 2015); however, the direction of change in N1 amplitude for children in this study was more variable than anticipated. Specifically, the increase of N1 amplitudes for children 7-9 years old in the noise condition was not expected but might be explained by variations in refractory properties of the neural components underlying the N1 response. The refractory period is the time required for a neural population to recover after responding to a stimulus. In a comprehensive study of developmental changes in refractoriness, Gilley and colleagues (2005) showed systematic, age-related changes in N1 morphology with varying ISIs. While traditional

N1 responses were recorded in adult listeners and children 11-12 years of age using ISIs as short as 360 ms, N1 responses did not appear in younger children unless longer ISIs were used. Specifically, morphology of the response from children <11 years old was dominated by a broad positive peak centered around 100 ms followed by a broad negative peak around 200 ms when using the same ISI of 360 ms. As ISI increased systematically from 360 to 2000 ms, traditional N1 responses began to appear as a bifurcation of the broad positive peak. In this case, the N1 response (bifurcation) reached its peak at a positive value despite being a negative deflection from the surrounding positive peaks. This immature morphology can be found in our data for children 7-10 years old in the quiet condition (see Figure 8), as N1 peak amplitudes of the average waveforms for children in these age ranges are above zero.

A further examination of children 7-9 years old in this study revealed that, although responses in noise were still dominated by a broad positive peak with a small bifurcation (N1 response) within this positivity, the overall amplitude of the response in the noise condition was markedly reduced. This overall reduction in amplitude of the broad positivity allowed for the measured N1 peak amplitude to occur at or near baseline and thus have a smaller numerical value, giving the appearance that the N1 peak amplitude was more negative in noise than in quiet. Thus, the more negative N1 response in noise for children 7-9 years of age appears to be the byproduct of immature response morphology and the overall reduction in response magnitude rather than a true increase in neural synchrony. These findings are in contrast with previous studies of adults (Parbery-Clark et al., 2011) and children (Anderson, Chandrasekaran, et al., 2010), where enhanced amplitudes of the first negative peak in noise were observed. Further research is needed to determine under what circumstances the presence of background noise causes the enhancement of sensory responses and to understand the functional significance of enhanced vs. generally diminished responses in child listeners.

N1 latency. There are several potential reasons why, contrary to our hypothesis, we did not find a significant effect of age on noise-induced latency changes. First, previous studies reporting N1 latency in quiet and noise for child listeners presented stimuli with a fast presentation rate (ISI 490-910 ms; E. A. Hayes et al., 2003; M. Sharma et al., 2014; Warrier et al., 2004). In these studies, reported N1 latencies in quiet and in noise were significantly longer (i.e., latencies >200 ms) than the N1 latencies recorded from children in the current study. As discussed above, this might be attributed to the influence of the fast presentation rate and immature refractory periods causing variations in morphology. For instance, if the long response latency in previous studies was due to immature morphology, it is possible the effects of noise on N1 latency were small because the immature auditory systems were already maximally delayed in quiet. The use of a slower presentation rate in our study elicited earlier N1 responses and thus allowed for greater noise-induced delays in sensory encoding to be detected before the process of sensory encoding was no longer apparent.

An alternative explanation for our finding is that N1 responses in noise recorded from child listeners in previous studies (Cunningham et al., 2001; Hassaan, 2015; M. Sharma et al., 2014; Warrier et al., 2004) do not functionally represent the immature versions of the traditional N1 responses upon which the effects of noise are reported in adult studies. Recall that we labeled the first negativity reported in previous studies as the N1 response. Although it was the first negative peak, previous studies have used other labels for this response (e.g., N1', N2, N250). Given that immature morphology discussed above can lead to missing N1 responses (Ponton et al., 2000) and that latencies of the first negativity reported previously (e.g., 161-280 ms) were considerably longer than the latencies observed in this study, the aforementioned studies in children could have reported the effects of noise on the immature N2[1] response rather than the N1 response. This distinction is important, as underlying components and functional significance of these two negativities are different. Recall that the N1 response is present in adult listeners when the signal is detected, even if not discriminated from another signal (B. A. Martin et al., 1999). Conversely, the presence of N2 is linked to sound discrimination processes (Sams, Paavilainen, Alho, & Näätänen, 1985), and when elicited using a passive oddball paradigm, relates to the automatic detection of stimulus changes (Pritchard, Shappell, & Brandt, 1991). Detailed exploration of the effect of noise on N2 responses reported in the literature is outside the scope of this study; however, the noise-induced delays of the negative peak latency reported in previous studies of children (Hassaan, 2015; M. Sharma et al., 2014; Warrier et al., 2004) are similar in magnitude (<10 %) to N2 latency delays reported for adults (Papesh et al., 2015). If previous studies in children have, in fact, been recording noise effects on N2 responses, our findings coupled with previous results suggest that noise-induced latency shifts of N1/N2 may be stable across childhood and into adulthood. Further research is needed to confirm this hypothesis and to understand whether the effect of noise on either of these responses is associated with behavioral performance in children.

Effects of Noise on Cognitive CAEPs

We hypothesized that P3 amplitudes would be reduced and P3 latencies delayed in the presence of +15 dB SNR babble noise compared to quiet. Results of this study offered partial

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[1] The auditory evoked N2 is generally characterized as a large, negative peak occurring between 200 and 250 ms following the stimulus. When passively elicited, the N2 response has been historically labeled as N2a (Pritchard, Shappell, & Brandt, 1991). The use of this label has been largely replaced by MMN (Folstein & Van Petten, 2008); however, we will refer to N2a as N2 here because we are only interested in the response to the standard stimulus and not the difference between the two stimuli.

support for this prediction, as they showed a significant elongation of P3 latency with background noise compared to the quiet condition.

P3 amplitude. Contrary to our hypothesis, the regression analysis showed that babble noise at +15 dB SNR had no significant effect on P3 amplitude. This could be attributed to our choice of a relatively favorable SNR (+15 dB), as previous research in adults using broadband noise shows that P3 amplitude is not affected by low levels of noise (+20, +15, +10, +5 dB SNR) but is reduced when the noise levels increase to match or exceed the level of the signal (0, -5 dB SNR; Whiting et al., 1998). We anticipated that background babble noise presented at +15 dB SNR might affect P3 amplitude, as babble has been shown to be more detrimental than broadband noise (Bennett et al., 2012). Yet, we observed no significant reduction in P3 amplitude in noise compared to quiet, possibly due to the effect being too small to detect with our study sample. Indeed, a post-hoc power analysis indicated that our study sample (n=55) only achieved power of 0.100 for detection of this small effect of noise (f^2 = .008). Previous studies using higher levels of babble noise (-3 dB SNR; Bennett et al., 2012; Koerner et al., 2017) have shown larger effects of noise on P3 amplitude (e.g., Cohen's *d* of 2.46 and 1.34). The small effect of noise at +15 dB SNR observed in this study is trivial in comparison (Cohen’s *d* of 0.176). Taken together, these findings suggest that the P3 amplitude can be expected to remain robust at low levels of babble noise just as it does at low levels of broadband noise (Whiting et al., 1998).

P3 latency. Findings from this study replicate previous studies in adults (Bennett et al., 2012; Koerner et al., 2017; Whiting et al., 1998) and extend the finding of noise-induced delays in P3 latency to children. It is noteworthy that the effect of noise on P3 latency found in this study (Cohen’s *d* of 0.456) is smaller than the effect that has been elicited when using less-favorable SNRs (-3 dB SNR; Cohen’s *d*s of 4.84 and 0.710; Bennett et al., 2012; Koerner et al., 2017). As with P3 amplitude, this trend is consistent with the work of Whiting and colleagues (1998) that reported a growth in latency delay as SNR worsened when noise was broadband rather than babble.

Because younger children show immature top-down processing of speech in noise (Kalikow et al., 1977; Leibold & Buss, 2013; Wightman & Kistler, 2005) and demonstrate poorer speech-sound discrimination in noise when compared to older children and adults (Talarico et al., 2007), it was expected that the youngest listeners would show the largest magnitude of cognitive CAEP (P3) change in the presence of noise compared to the adult listeners. Contrary to our hypotheses, noise-induced effects on P3 amplitude and latency did not vary across the age range of this study sample. The nonsignificant effect of condition (Quiet vs. Noise) on P3 amplitude discussed above was consistent across ages, revealing no condition x age interaction. Furthermore, when controlling for the small but significant effect of noise condition ($f^2 = .053$) on P3 latency, it is not surprising that the even-smaller effect of age x condition ($f^2 = .005$) was not significant. Nonetheless, post-hoc power analysis showed that with n=55, this study was underpowered to reject the hypotheses that noise-induced changes on P3 amplitude (achieved power = 0.050) or P3 latency (achieved power = 0.081) vary as a function of age (condition x age). These findings do suggest that the +15 dB SNR recommendation for classrooms (American Speech-Language-Hearing Association, 1995) should offer children as young as 7-years-old the opportunity for successful speech discrimination without requiring the use of additional cognitive resources. However, because most classrooms do not achieve this favorable acoustic recommendation (Larsen & Blair, 2008; Sato & Bradley, 2008), future research should include more realistic, less favorable SNRs to determine if any degrading effects of noise present at less favorable SNRs would vary across age.

Brain-Behavior Relationships

Our hypothesis that age would be significantly related with behavioral measures of speech-in-noise perception was confirmed. Results demonstrate the anticipated negative correlation between age and SNR-50, with younger children requiring a greater SNR to reach 50% correct than older children and adults. Consistent with test norms (Etymotic Research, 2005), this relationship was curvilinear, with changes in SNR-50 reducing as age increased.

To date, the body of literature examining the relationship between CAEP responses and speech-in-noise perception is small, including only three studies in adults and one study in children (see Table 3). Results of the current study expand our knowledge of these relationships in adults and children. Recall that previous studies in adults have found that large N1 amplitudes in noise relate with good speech-in-noise performance (Billings et al., 2013; Parbery-Clark et al., 2011). To compare our findings with previous results, we examined the relationship between N1 amplitude in noise and SNR-50 for the adults included in the current study (ages 18-25 years old, n = 25). Our sample of adults did not replicate the findings of the two previous studies reporting significant relationships between N1 amplitude in noise and behavioral measures of speech-in-noise perception (*r* = .015, *p* = .945). The reason for this conflicting result is unclear. Billings and colleagues presented noise at +5 dB SNR while Parbery-Clark and colleagues used an SNR of +10 dB. It is possible that +15 dB SNR was too favorable to affect N1 amplitudes enough to detect any influence on behavioral speech-in-noise perception.

Contrary to previous findings in adults, large N1 amplitudes have been reported to relate with poor speech-in-noise performance in children 8-13 years old (Anderson, Chandrasekaran, et al., 2010). In similar-age children from this study (8-13 years old, n=18), we observed the opposite effect. When controlling for age, children with larger N1 responses in noise tended to show better, not poorer, speech-in-noise perception (*r* = .408, *p* = .074). This conflicting finding in children could be due to the differences in stimulus presentation parameters and CAEP measurement techniques. That is, children included in Anderson, Chandrasekaran, et al. demonstrate a broad positivity followed by a broad negativity even in the quiet listening condition rather than the adult-like P1-N1-P2 morphology as we recorded in this study. Responses from Anderson, Chandrasekaran, et al. were elicited with speech sounds embedded in babble noise at +10 dB SNR presented at a fast ISI of 1000 ms. As discussed above, the increased demands of the recording paradigm could have led to a more immature brain response pattern compared to responses observed in the current study. It is unclear if the effects of noise on CAEPs would be consistent across waveforms with differing morphology due to maturation. Finally, because Anderson, Chandrasekaran, and colleagues recorded CAEP responses from frontal electrodes (Fz) while we recorded responses from central electrodes (Cz), morphological differences and subsequent disparities in brain/behavior relationships could also be due to topographic variations of the N1 response by age (Ponton et al., 2000). Future work is needed to understand the many factors that could influence the relationship between CAEP responses and behavioral speech-in-noise perception in child listeners.

Our hypothesis that changes in cognitive CAEPs would best mediate the relationship between age and behavioral speech-in-noise perception was based, in part, upon the only previous study showing significant associations between P3 latency and behavioral performance in adults (Bennett et al., 2012). The relationship between brain and behavior found by Bennett et al. may have been due to the inclusion of data elicited with multiple noise types (e.g., steady-state, interrupted, babble noise) into one analysis. Individual data displayed graphically by Bennett et al. showed that the significant correlation between P3 latency and behavioral speech-in-noise perception could have been driven by additional degradation of P3 latency and behavioral performance in the babble condition when compared to the other noise conditions. A recently published study (Koerner et al., 2017) was not able to replicate the findings of Bennett and colleagues. Using speech embedded in babble noise and a sample size nearly double that of Bennett and colleagues, Koerner and coworkers did not find a significant relationship between speech-in-noise perception and P3 latency. Consistent with Koerner and colleagues, we also did not find a significant relationship between behavioral speech-in-noise perception and noise-induced changes in P3 latency for 7-25 year olds (Table 11, coefficient b_2). Furthermore, the relationship between P3 latency in noise and SNR-50 in adult listeners (n=25) was not significant ($r = .230$, $p = .268$). These results add to the limited amount of research in this area and suggest that the rapid allocation of attentional resources when discriminating speech sounds in noise may not have an impact on more complex, sentence-level behavioral speech-in-noise perception.

Understanding the Relationship between Age and Speech-in-Noise Perception through CAEPs

This study is the first to report how the effects of noise on speech processing, as measured by CAEPs, influence age-related changes in speech-in-noise perception using mediation analysis. We hypothesized that noise-induced changes in sensory CAEPs (N1 amplitude) coupled with subsequent changes in cognitive CAEPs (P3 latency) would account for the relationship between age and behavioral speech-in-noise perception. In partial support of our hypothesis, noise-induced changes in sensory but not cognitive CAEPs explained the age-related changes in speech-in-noise perception. However, this effect of noise-induced change on the sensory CAEP was dependent on listener age. Specifically, for listeners younger than 16 years and those older than 23 years, the successful perception of speech in noise appears to be supported by the preservation of robust sensory processing of the speech embedded in noise. That is, young ages predicted poor performance and older ages predicted good performance due to measured noise-induced changes in N1 amplitude. For listeners 16-23 years of age, noise-induced changes in sensory CAEPs did not have a significant influence on the relationship between age and speech-in-noise perception.

Our findings suggest that sensory CAEPs elicited with speech are a potentially valuable tool to explore the development of speech-in-noise perception during childhood and adolescence. Specifically, the age-range during which the effect of noise on sensory processing influences the relationship between age and speech-in-noise perception aligns with developmental timelines reported in previous studies regarding maturation of the N1 response (Pang & Taylor, 2000; Ponton et al., 2000; Tomé et al., 2015). This suggests that the sensory processing system's sensitivity to background noise at +15 dB SNR is important when considering speech-in-noise perception during maturation (<16 years of age). The lack of significant indirect effects for listeners 16-23 years of age is likely because speech-in-noise perception abilities had reached maturity by 16 years of age. This is evidenced by a weak and non-significant relationship between age and SNR-50 between 16-23 years (n=25, $r = -.283$, $p = .171$) and is consistent with previous behavioral research (Corbin, Bonino, Buss, & Leibold, 2016; Elliott, 1979). Because a significant relationship between age and SNR-50 is required to determine if changes in N1 amplitude act as a mediator, the lack of significant indirect effects are not surprising. Although the confidence intervals suggest that noise-induced changes in sensory processing explain the relationship between age and behavioral performance of listeners 24-25 years old, the small sample of participants within this age range (n=6) is insufficient to draw strong conclusions. Furthermore, participants in this two-year age range do not show considerable variability speech-in-noise perception abilities (SNR-50s range from -1.17 to -2.67 dB), demonstrating a medium but not significant effect of age on SNR-50 ($r = .333$, $p = .519$). Future studies are needed to determine if there might be additional development changes outside of this window (ages >25 years) that could provide information about the influence of background noise on sensory processing of speech.

It is important to reiterate that analyses of brain-behavior relationships conducted in this study used percent-changes of CAEP amplitude and latency between quiet and noise conditions. Previous studies examining relationships between CAEPs and speech-in-noise perception have used CAEP amplitude or latency in noise rather than the magnitude of change due to the presence of noise (Anderson, Chandrasekaran, et al., 2010; Bennett et al., 2012; Billings et al., 2013; Parbery-Clark et al., 2011). We chose to focus on changes caused by noise rather than responses in noise, as we hypothesized that it was how speech processing was degraded by noise, rather than the end-result, that would be useful in understanding developmental differences of speech-in-noise perception. Our results confirmed this hypothesis, as a follow-up mediation analysis showed no significant indirect effects of N1 amplitudes in noise on the relationship between age and behavioral speech-in-noise perception. Considering that we observed morphological differences in responses from young children between quiet and noise conditions and found that noise-induced changes of sensory CAEPs significantly mediated the relationship between age and speech-in-noise perception, future research should consider using noise-induced changes to CAEPs as a metric for examining the effect of noise on speech processing in children.

Success of the full serial mediation model proposed in this study (see Figure 17) was based upon several assumptions. First, we assumed that age would influence noise-induced changes in N1 amplitude. This assumption was confirmed – although an overall decrease in N1 amplitude was found for all listeners, this amplitude decrease manifested differently for young children due to immature response morphology. Second, we theorized that noise-induced changes to sensory processing (N1 amplitudes) would have a significant effect on noise-induced changes to cognitive processing (P3 latencies). Evaluation of this relationship was exploratory, as previous research has reported mixed results, with significant associations observed between N1 and P3 amplitudes (Ford et al., 1995) but not latencies (Michalewski, Prasher, & Starr, 1986). In this study, we did not find a significant relationship between changes in N1 amplitude and changes in P3 latency (see Table 11, coefficient d_{21}). These findings are consistent with Michalewski and colleagues who concluded that earlier and later components (e.g., N1 vs. P3) reflect independent processing phases. Finally, we expected noise-induced changes in cognitive processing (P3 latency) to relate with speech-in-noise perception (SNR-50); however, this relationship was not significant. Given that serial multiple mediation analysis relies on the a priori assumption that the two mediators are causally associated (A. F. Hayes, 2013) and that it is highly unlikely that an indirect effect would be present when the mediator is not significantly correlated with the outcome (K. Preacher, personal communication, August 31, 2017), it is no surprise that the serial multiple mediation model was not significant in this study.

Limitations

There are several methodological caveats that must be addressed when considering the findings of this study. First, the use of a relatively favorable SNR likely influenced the magnitude of the effect of noise on CAEPs and potentially affected how CAEPs related (or did not relate) with behavior. It is possible that noise presented at +15 dB SNR might not have provided enough interference with the stimuli to require the use of top-down resources during the Attend test. As discussed above, a more challenging SNR may be required to determine if cognitive processes contribute to the development of speech-in-noise perception. Another limitation may have been the method used to measure N1 amplitude. In this study, we used an automatic calculation of baseline-to-peak amplitude, which provided us with an objective measure of this variable and allowed us to compare data with previously published studies of adults and children. Nevertheless, the baseline-to-peak amplitude approach might not be as sensitive to maturational differences in waveform morphology as other measures of CAEP responses such as peak-to-peak amplitude or global field power (Skrandies, 1989). These measurement methods might prove more sensitive to noise effects when examining responses with immature morphology and could account for noise-related changes to other portions of the CAEP response (e.g., P2) that have the potential to influence the N1 amplitude, particularly for CAEP responses demonstrating immature morphology.

This study is also limited by the small number of participants included for each age and the convenience sample of university faculty/staff children and high-achieving college students. That is, this sample of participants likely represents a portion of the population with high language proficiency and superior cognitive/attentional skills. P3 responses are known to relate with language, cognitive, and attention abilities, such that listeners with superior abilities yield larger and earlier P3 responses than listeners with poorer abilities (Evans, Selinger, & Pollak, 2011; Fjell & Walhovd, 2003; Picton, 1992; Polich, 2007). It is possible that less advantaged listeners would be more likely to show noise-induced decrements in P3 responses. However, because we assessed the N1 response obtained during the Ignore test condition, any potential influence of superior language/cognition is not likely to have affected this exogenous sensory response. Therefore, while this advantaged sample of listeners might have prohibited us from detecting effects of noise on the cognitive response, the effect of noise on the sensory response and the relationships observed between sensory CAEPs and behavior can be expected to remain consistent in a more representative and larger sample of participants.

Conclusions and Future Directions

This study used brain-based measures to understand how background noise affects different stages of speech processing for listeners of different ages and to describe how sensory and cognitive processing of speech in noise contributes to age-related performance variation on a clinical speech-in-noise perception task. Results presented here show that the presence of noise, even at a relatively favorable SNR, diminishes and delays the synchronous sensory processing of speech; however, this degradation in sensory processing does not affect the active speech discrimination process. These findings provide support for the +15 dB SNR recommendation for classrooms (American Speech-Language-Hearing Association, 1995). Future research should include more realistic, less favorable SNRs to allow for the improved understanding of how background noise affects sensory and cognitive processing of speech and how these effects contribute to communication of children in listening conditions more representative of their daily environments.

Results of this study suggest that successful sensory encoding of speech information is critical to understand speech when background noise is present for children and adolescents with normal hearing. Therefore, attempts to mitigate age-related challenges faced in background noise should focus on improving the potential for adequate sensory encoding. Fortunately, research is beginning to show that interventions such as musical training (Strait, Parbery-Clark, O'Connell, & Kraus, 2013) and technology use (Hornickel, Zecker, Bradlow, & Kraus, 2012) can improve sensory encoding and facilitate better speech-in-noise perception in children with normal hearing. This importance of sensory encoding of speech in background noise could be particularly relevant for future research including children with hearing loss, who have delayed and, in some cases, less mature sensory encoding responses compared to children with normal hearing (Koravand, Jutras, & Lassonde, 2012; Ponton, Don, Eggermont, Waring, & Masuda, 1996). It is unclear at this time if these abnormalities of sensory encoding abilities in children with hearing loss are accompanied by atypical cognitive CAEPs. However, it is reasonable to posit that children with hearing loss might show greater negative effects of background noise on sensory and potentially cognitive processing than children with normal hearing, as children with hearing loss show more adverse effects of noise on behavioral assessments of speech perception (Leibold, Hillock-Dunn, Duncan, Roush, & Buss, 2013). Future research is needed to characterize the effects of hearing loss on sensory and cognitive CAEPs and to determine if CAEPs might be used to evaluate if readily available interventions (e.g., advanced signal processing, remote microphone systems) can improve sensory encoding in noise and thus, contribute to improved speech-in-noise perception.

Although we found that sensory encoding of speech was markedly degraded in background noise for all listeners, children and adults in this study were still able to successfully discriminate speech syllables. This suggests that the noise-level used in this study was not poor enough to disrupt processes underlying speech sound discrimination – processes such as attention that likely compensated for the degradation of sensory information. While attention has been shown to enhance sensory encoding in adults and children when listening in quiet (Coch, Sanders, & Neville, 2005; Hillyard, Hink, Schwent, & Picton, 1973; Määttä, Pääkkönen, Saavalainen, & Partanen, 2005; R. Näätänen, Gaillard, & Mäntysalo, 1978), it is unknown if attention can compensate for noise-induced sensory degradation or if this top-down compensatory process is dependent on age. Preliminary analysis of data in the Ignore and Attend test conditions suggest that children and adults in this study demonstrated similar attention-derived compensation of sensory processing in background noise, with no noise-induced sensory degradation observed when participants were paying attention to the task. This suggests the possibility of a more complex connection between sensory and cognitive stages of speech perception: rather than noise-induced sensory encoding degradation influencing cognitive processing as we originally hypothesized, cognitive processing in noise could influence speech-in-noise perception through compensation of degraded sensory encoding. While the relationship between attention abilities and speech-in-noise perception has been shown in adult listeners (Salvi et al., 2002; Strait & Kraus, 2011; Wong, Uppunda, Parrish, & Dhar, 2008), future studies are needed to understand the role that this top-down compensatory process might play on the development of speech-in-noise perception in children.

Results of this study replicate previous work conducted in adults and children that showed reductions in amplitude and delays in latency of the N1 response when background noise is present and extend the limited literature including P3 responses to children. Notably, nearly half of our findings were opposite of what we expected. These hypotheses were based upon a small number of studies that used different noise types, presentation parameters, and analysis methods. The discrepancies between our results and previous research highlight the limited amount of work that has been conducted on the effect of noise on CAEPs, particularly in children. As this field of research continues to grow, future work must consider the importance of sensory encoding when examining behavioral speech-in-noise recognition in children and adolescents. Furthermore, additional research is needed to determine if sensory encoding remains more supportive of behavioral performance than cognitive processing in more realistic listening conditions.

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