COGNITIVE NEUROSCIENCE

Cortical-evoked potentials reflect speech-in-noise perception in children

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Abstract

Children are known to be particularly vulnerable to the effects of noise on speech perception, and it is commonly acknowledged that failure of central auditory processes can lead to these difficulties with speech-in-noise (SIN) perception. However, little is known about the mechanistic relationship between central processes and the perception of SIN. Our aims were twofold: to examine the effects of noise on the central encoding of speech through measurement of cortical event-related potentials and to examine the relationship between cortical processing and behavioral indices of SIN perception. We recorded cortical responses to the speech syllable [da] in quiet and multi-talker babble noise in 32 children with a broad range of SIN perception. Outcomes suggest inordinate effects of noise on auditory function in the bottom SIN perceivers compared with the top perceivers. The cortical amplitudes in the top SIN group remained stable between conditions, whereas amplitudes increased significantly in the bottom SIN group, suggesting a developmental central processing impairment in the bottom perceivers that may contribute to difficulties in encoding and perceiving speech in challenging listening environments.

Introduction

Many children show considerable difficulty in processing speech in background noise, and these deficits can impair communication (Cunningham *et al.*, 2000, 2001; Bradlow *et al.*, 2003; Ziegler *et al.*, 2005, 2009). Understanding how sensory systems adapt to challenging listening conditions is an important concern facing auditory neuroscience research. However, few studies have examined the mechanisms by which sensory systems adapt to challenging listening conditions. As learning often occurs in noisy environments (e.g. a school classroom), children who have difficulty in excluding background noise are particularly vulnerable to the debilitating effects of challenging listening conditions (Sperling *et al.*, 2005). Indeed, the level of noise in classrooms is directly related to academic achievement in school (Shield & Dockrell, 2003, 2008), with a 4–6% decrease in academic test scores noted with as little as a 10 dB increase in ambient noise. Here, we aim to understand the impact of noise on cortical-evoked speech processing in children and to examine the

neural factors that determine successful or unsuccessful speech perception in challenging listening environments.

The obligatory components of cortical potentials (P1, N1, P2 and N2) have a systematic developmental time-course (Sharma *et al.*, 1997; Ponton *et al.*, 2000; Sussman *et al.*, 2008; Cunningham *et al.*, 2001). In adulthood the cortical response is dominated by the N1–P2 complex, but in childhood the P1 and N2 components dominate the response (Ceponiene *et al.*, 2002). The P1 component serves as a central auditory developmental marker, with shorter latencies and smaller amplitudes as children mature from infancy to young adulthood (Sharma *et al.*, 2002). Likewise, the N2 amplitude decreases, whereas the N1 component becomes more prominent with development (Sussman *et al.*, 2008). Furthermore, the P1 and N2 components may reflect different aspects of sound processing, with P1 encoding the acoustic features of sound, such as frequency and timing, and N2 synthesizing these features into a sensory representation (Shtyrov *et al.*, 1998; Ceponiene *et al.*, 2005). Ceponiene *et al.* (2001) found a decreased N2 amplitude for vowels vs. complex tones and speculated that fewer neural resources may be required for representing the more familiar vowel sound.

Few studies have empirically examined the effects of background noise on the neural encoding of speech at the level of the cortex. Broad-band noise causes a reduction in speech-evoked cortical response amplitudes in young adults (Whiting *et al.*, 1998) and children (Cunningham *et al.*, 2001). Speech-evoked cortical responses

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in noise differentiate children with normal learning abilities from children with impaired learning (Cunningham *et al.*, 2001; Wible *et al.*, 2005), with the P1–N1 amplitude excessively affected by background noise in the impaired group.

Although cortical-evoked potentials have been studied in the context of both maturation and background noise, no study has yet examined the relationship between cortical responses and speech-in-noise (SIN) perception in children. Such knowledge is necessary to understand why some children succeed more than others in challenging listening conditions. Here, we study the relationship between SIN perception and the cortical encoding of SIN in children. We examine the cortical encoding of speech in babble noise due to its ecological validity, and also because the neural mechanisms of SIN processing have been shown to differ when using speech babble vs. white noise as masking (Scott *et al.*, 2004). Given that the N2 component reflects the synthesis of stimulus features into a perceptual representation as indexed by amplitude, we hypothesized that the differences between children with good and poor SIN perception would correspond to differences in N2 amplitudes, with greater amplitudes reflecting more resources required to form a perceptual representation.

Materials and methods

Participants

Thirty-two children (aged 8–13 years, mean 10.41 years) were recruited from schools in the Chicago area. Audiometric thresholds were measured at octave intervals from 250 to 8000 Hz using air conduction and from 500 to 4000 Hz using bone conduction. Participants were excluded if they had pure-tone thresholds greater than 20 dB or air–bone gaps greater than 15 dB at two or more frequencies in either ear. All children had normal cognitive abilities as demonstrated by standard scores of ≥85 on Wechsler Abbreviated Scales of Intelligence Verbal, Performance and Overall scores (Zhu & Garcia, 1999). Informed consent was obtained from all children and their legal guardians. All procedures conformed to the protocol approved by the Institutional Review Board of Northwestern University.

Behavioral measure of speech perception in noise

Speech understanding in noise was evaluated with a commonly used clinical test, the Hearing in Noise Test (HINT) (Bio-logic Systems Corporation, Mundelein, IL, USA), developed using the Bamford-Kowal-Bench (Bench *et al.*, 1979) phonetically-balanced sentences. The Bamford-Kowal-Bench sentences are appropriate for use with children at the first-grade reading level and above. The HINT uses an adaptive paradigm that varies the level of the target sentence relative to the fixed speech-shaped noise masker until a threshold signal-to-noise ratio is determined. For our analyses, we used the HINT-Front condition, in which the target sentences and the masking noise emanate from the same loudspeaker directly in front of the subject. Because previous studies have demonstrated a relationship between working memory and SIN performance (Pichora-Fuller & Souza, 2003; Heinrich *et al.*, 2007; Parbery-Clark *et al.*, 2009a), we assessed working memory using the Woodcock Johnson III Numbers Reversed subtest (Mather *et al.*, 2001). In addition, because previous findings have suggested a relationship between SIN performance and reading (Bradlow *et al.*, 2003; Ziegler *et al.*, 2005), we assessed reading and phonological processing using the Woodcock Johnson III Word Attack and Basic Reading test (Woodcock *et al.*, 1989–1990), Test of Oral Word Reading Efficiency (Torgesen *et al.*, 1999) and Comprehensive Test of Phonological Processing (Wagner *et al.*, 1999).

Participant groups

Top and bottom SIN groups (16 in each group) were formed from the top and bottom halves of the group distribution of the HINT-Front scores. These groups did not differ in average pure-tone audiometric thresholds from 250 to 8000 Hz ($P = 0.924$), verbal IQ ($P = 0.230$) or working memory ($P = 0.178$). There were significant differences in age ($P = 0.031$) between the top (mean 11.13 years, SD 1.46 years) and bottom (mean 9.69 years, SD 1.62 years) SIN groups. Refer to Table 1 for specific means, SD and independent *t*-test *P*-values.

Electrophysiology

Stimulus

The speech syllable [da] was a six-formant syllable synthesized at a 20 kHz sampling rate using a Klatt synthesizer (Klatt, 1980). The duration of the syllable was 170 ms, the first 5 ms of which was a burst of noise, representing the initial unvoiced portion of the stop consonant preceding the voicing onset. Except for the initial noise burst, this syllable was voiced throughout with a steady fundamental frequency ($F_0 = 100$ Hz). The formant transition from the [d] to the [a] was 50 ms in duration and was characterized by a linearly rising first formant F_1 (400-720 Hz) and linearly falling F_2 (1700-1240 Hz) and F_3 (2580-2500 Hz). F_4 (3300 Hz), F_5 (3750 Hz) and F_6 (4900 Hz) remained constant for the duration of the stimulus. The steady-state (i.e. vowel) portion was characterized by a constant F_1 (720 Hz), F_2 (1240 Hz), F_3 (2500 Hz), F_4 (3300 Hz), F_5 (3750 Hz) and F_6 (4900 Hz). The [da] stimulus was presented in the right ear at 80 dB Sound Pressure Level, through an insert earphone (ER-3, Etymotic Research, Elk Grove Village, IL, USA) via the stimulus presentation software NeuroScan Stim2, Sound module (Compumedics Inc., Charlotte, NC, USA). The stimulus waveform and spectrogram are shown in Fig. 1.

TABLE 1. Means and SDs for top and bottom SIN groups for HINT-Front signal-to-noise ratio (SNR) scores, pure-tone averages (0.5–4 kHz), age, Wechsler Abbreviated Scales of Intelligence (WASI)-Verbal standard scores, Woodcock Johnson III (WJIII) Numbers Reversed and WJIII Reading standard scores, Test of Oral Word Reading Efficiency Total (TOWRE-T) standard scores, and Comprehensive Test of Phonological Processing Rapid Naming (CTOPP-RN) and Phonological Awareness (CTOPP-PA) standard scores.

| Measure *t*-test *P* value	HINT front SNR (< 0 .001)	Age (years) (0.031)	Pure tone average (dB) (0.941)	Verbal IQ (WASI) (0.230)	WJIII – basic reading (0.070)	TOWRE-total (0.223)	CTOPP-RN (0.648)	CTOPP-PA (0.648)	Auditory memory (WJIII – Numbers Reversed) (0.178)
Top SIN mean (SD)	−4.49 (.72)	11.13 (1.46)	3.31 (4.13)	114.19 (16.68)	110.25 (15.41)	107.37 (21.68)	98.88 (17.00)	103.56 (14.21)	103.38 (16.70)
Bottom SIN mean (SD)	−2.30 (1.18)	9.69 (1.62)	3.2 (3.79)	106.81 (17.34)	99.75 (16.17)	98.12 (20.33)	95.69 (21.77)	98.88 (15.05)	96.94 (8.37)
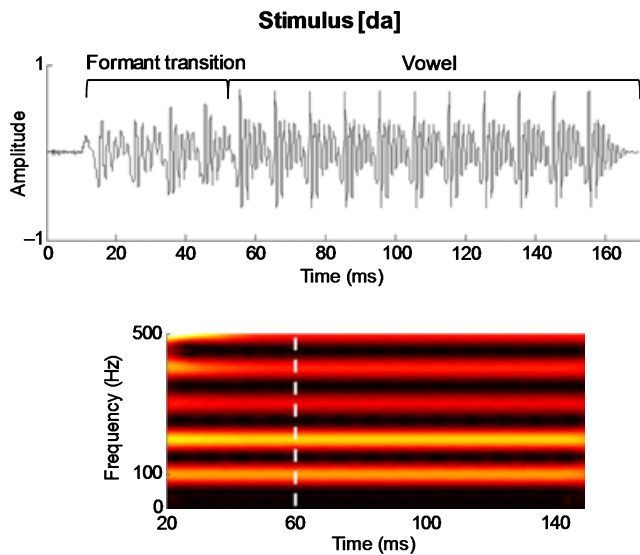
Stimulus [da]

FIG. 1. Top: The acoustic waveform of the target stimulus [da]. The formant transition and vowel regions are bracketed. Bottom: The spectrogram (stronger amplitudes represented with brighter colors). The boundary between the consonant–vowel formant transition and the steady-state vowel portion of the syllable is marked by a dashed white line.

Recording

Cortical responses were recorded using NeuroScan Acquire 4.3 with a 32-channel electrode cap that incorporates a subset of the International 10–20 system (Jasper, 1958). Reference electrodes were placed on the right and left earlobes. Additional electrodes were placed above the left eye and adjacent to the outer canthus of the left eye. Impedances were maintained at < 5 kΩ at each electrode site. The [da] syllable was presented to the right ear with a 1 s interstimulus interval. The left ear was unoccluded and participants were told that they were not required to pay attention to the stimuli in the right ear. They watched movies of their choice with the soundtrack presented in sound field at < 40 dB Sound Pressure Level. The use of movies ensured participant cooperation, minimized movement-related artifacts and enabled the participants to sit quietly for 90-min sessions (the total time required for cap application and event-related potential recording).

The event-related potentials were recorded to the stimulus in two conditions: quiet and six-talker babble background noise. The six-talker babble, created by mixing six tracks of semantically anomalous but grammatically correct sentences in Cool Edit Pro 2.1 (Syntrillium Software, 2003, Chicago, IL, USA), combined four female and two male voices. The 4.7 s babble track was presented at a signal-to-noise ratio of +10 dB in a continuous loop. The Stim2 Sound program automatically tracked the level of the babble relative to the [da] syllable, keeping the signal-to-noise ratio constant at +10 dB. The quiet and noise conditions were presented in blocked presentation mode.

Data reduction

Data processing and analysis were performed in Matlab (The MathWorks, Inc., Natick, MA, USA). In order to remove the vertical electro-oculographic blink artifact, a spatial filtering algorithm in Neuroscan 4.3 Edit was used to perform a principal components analysis decomposition of the blink while retaining the electroen-cephalographic activity of interest. The file was then bandpass filtered from 1 to 40 Hz (24 dB/octave) and averaged over a window of −100 to 500 ms, with time 0 corresponding to the stimulus onset. After the electroencephalographic epochs were baseline corrected (shifted so that their mean voltage was zero), an artifact rejection criterion of ± 100 µV was applied to remove sweeps that contained large myogenic (muscle) noise. The remaining sweeps were each correlated with an average of all artifact-free sweeps. The sweeps were then ranked according to how well they correlated with the average, and only the top 70% of sweeps with the highest correlations were included in the final average response, which included approximately 500 sweeps. Global field power (GFP) was then computed using the root of the mean of the squared potential differences between all possible electrode pairs within the field. The GFP provided a reference-free measure of cortical activity that was free of experi-mental bias in selecting a single electrode or set of electrodes (Skrandies, 2005; Sussman *et al.*, 2008).

Data analysis

The P1 and N2 were identified on the grand average GFP and *F*z electrode, and 50 ms windows (65–115 ms for P1 and 175–225 ms for N2) centered on the mean peak latencies were used to calculate the mean amplitudes of P1 and N2 for each individual. The same window was used to analyze the recordings from the *F*z electrode. The *F*z electrode site was chosen in addition to GFP because it had the best signal-to-noise ratio.

Statistical analyses

A two-way mixed model multivariate ANCOVA was conducted using SPSS (Statistical Package for the Social Sciences; SPSS Inc., Chicago, IL, USA) with group (top SIN vs. bottom SIN) serving as the between-group independent variable and condition (quiet vs. noise) as the within-group variable. The amplitudes for GFP and *F*z served as dependent variables. Pearson's correlations were calculated for the entire group ($N = 32$) between HINT scores and GFP and *F*z amplitudes, between HINT scores and age, and between HINT scores and reading. Because of its effect on cortical potentials as well as its relationship with SIN perception, age served as a covariate in all analyses. In SPSS, we used partial correlations and entered HINT scores and GFP and *F*z amplitudes as variables and age as the covariate. For the repeated-measures MANCOVA, we entered the amplitudes for GFP and *F*z in both quiet and noise, the HINT group as the between-subjects factor, and age as the covariate. In a secondary analysis, we created a subset of 24 children aged 9–12 years to minimize any effects of age. We repeated the correlations as well as the repeated-measures ANCOVA with this subset.

Results

Effects of noise

Background noise had a different effect on N2 amplitude in the top and bottom SIN groups. The addition of babble noise resulted in a significant increase in N2 amplitude in the bottom SIN group in the *F*z channel (quiet mean: −2.44 µV; noise mean: −3.20 µV; $F_{1,14} = 4.861$, $P = 0.045$) and a smaller N2 amplitude increase in GFP (quiet mean: 2.91 µV; noise mean: 3.17 µV; $F_{1,14} = 3.647$, $P = 0.077$). In contrast, there were no significant noise-induced amplitude changes in the top group in either the *F*z channel (quiet mean: −2.09 µV; noise mean: −2.18 µV; $F_{1,14} = 0.699$, $P = 0.471$) or GFP (quiet mean: 2.66 µV; noise mean: 2.41 µV; $F_{1,14} = 0.029$, $P = 0.868$) (Fig. 2). A significant

Quiet

Noise

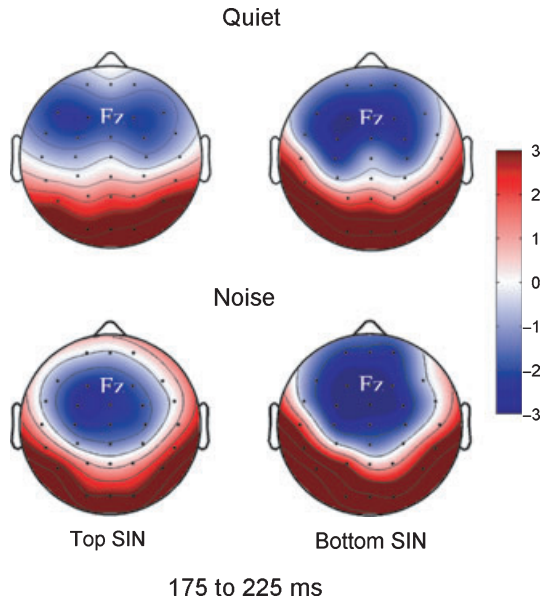Top SIN   Bottom SIN

175 to 225 ms

FIG. 2. Effects of noise in top vs. bottom SIN groups. Headplots demonstrate greater neural activity in the noise condition in the bottom SIN group at 175–225 ms. There were significant effects of noise for the Fz channel in the bottom SIN group ($F_{1,14} = 4.861$, $P = 0.045$) but not in the top SIN group ($F_{1,14} = 0.699$, $P = 0.471$).
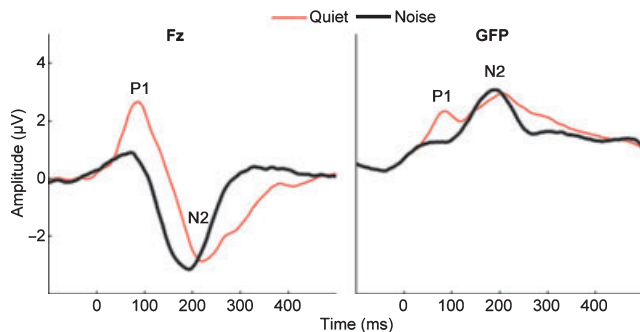

FIG. 3. Effects of noise on cortical-evoked responses to speech in grand averages across all subjects ($N = 32$). The P1 component disappears in noise in both GFP and the Fz channel. In addition, the GFP waveform shows more focused activity in the noise condition.

interaction was found between the quiet and noise conditions for the two groups for GFP ($F_{1,29} = 4.1922$, $P = 0.048$).

In both the top and bottom SIN groups, the addition of noise resulted in significantly decreased P1 amplitudes. Figure 3 demonstrates a main effect of noise on the P1 component in GFP ($F_{1,31} = 5.644$, $P = 0.024$) and an effect in the Fz channel that approached significance ($F_{1,31} = 3.725$, $P = 0.056$) across all participants ($N = 32$).

Between-group differences

The bottom SIN group had greater N2 amplitudes than the top SIN group in the noise condition, but not in quiet. An effect of group was noted in the noise condition ($F_{2,28} = 4.340$, $P = 0.049$) with *post-hoc* independent *t*-tests indicating a significant P-value for GFP ($F_{1,29} = 6.802$, $P = 0.014$) and a P-value close to significant for the Fz channel ($F_{1,29} = 4.1922$, $P = 0.050$). In quiet, there were no

significant differences between groups for either GFP ($F_{1,29} = 0.009$, $P = 0.925$) or the Fz channel ($F_{1,29} = 0.082$, $P = 0.925$) (Fig. 4).

Correlations

Correlations using the entire group ($N = 32$) were significant between HINT scores and N2 amplitudes in the noise condition for the Fz electrode ($r = -0.383$, $P = 0.033$) and approaching significance for GFP ($r = 0.355$, $P = 0.050$) and when partialling for age (Fig. 5). SIN performance correlated with reading on Woodcock Johnson III Basic Reading ($r = -0.392$, $P = 0.027$) and Test of Oral Word Reading Efficiency Total ($r = -0.383$, $P = 0.031$) but did not correlate with phonological processing as assessed by Comprehensive Test of Phonological Processing cluster scores (Rapid Naming: $r = -0.130$, $P = 0.478$; Phonological Awareness cluster score: $r = -0.147$, $P = 0.422$). As noted in Table 1, there were no significant differences for any of the reading or phonological processing measures between the top and bottom SIN groups.

The differences in N2 magnitude between the top and bottom SIN groups could not be attributed to differences in the overall noise levels of the participants. There were no group differences in signal-to-noise ratio, computed as the root mean square amplitude of the response portion (50–250 ms) of the waveform divided by the root mean square of the pre-stimulus portion (−100 to 0 ms), in GFP ($F_{1,29} = 0.266$, $P = 0.610$) or the Fz ($F_{1,29} = 0.000$, $P = 0.983$) electrode in the noise condition.

Effects of age

There was no effect of age for either group ($F_{2,28} = 1.559$, $P = 0.228$) or condition ($F_{2,28} = 1.422$, $P = 0.258$), indicating that age was not a significant factor in our findings. Although age correlated with SIN performance ($r = -0.420$, $P = 0.017$), correlations between HINT and N2 amplitudes in noise remained significant when partialling for age, as noted above.

To demonstrate that SIN perception rather than age is the principal factor in our results, we restricted the age range to 9- to 12-year-olds, eliminating eight children from the dataset, thereby creating more closely age-matched top and bottom SIN groups. This analysis ($N = 24$) revealed that age did not correlate with HINT ($r = 0.276$, $P = 0.193$), and top and bottom SIN groups were not significantly different in age ($P = 0.198$). The correlations between HINT scores and N2 amplitudes were slightly stronger with this subset of children after partialling for age (Fz: $r = -0.426$, $P = 0.043$; GFP: $r = 0.510$, $P = 0.013$).

In this data subset, the N2 amplitude significantly increased in noise in the bottom SIN group in GFP (quiet mean: 2.60 μV; noise mean: 3.13 μV; $F_{1,11} = 5.869$, $P = 0.034$), and this increase in noise approached significance in the Fz channel (quiet mean: −1.81 μV; noise mean: −2.88 μV; $F_{1,11} = 4.638$, $P = 0.054$), but not in the top SIN group in either GFP (quiet mean: 2.82 μV; noise mean: 2.52 μV; $F_{1,11} = 1.102$, $P = 0.316$) or the Fz channel (quiet mean: −2.28 μV; noise mean: −2.16 μV; $F_{1,11} = 0.078$, $P = 0.785$). A significant interaction was found between the quiet and noise conditions for the two groups for GFP ($F_{1,21} = 6.955$, $P = 0.015$). The persistence of these results in a smaller age-restricted subset supports our hypothesis that the N2 amplitude reflects differences in SIN perception.

Discussion

Our aim was to examine the relationship between SIN perception and cortical encoding of SIN in children. We found considerable
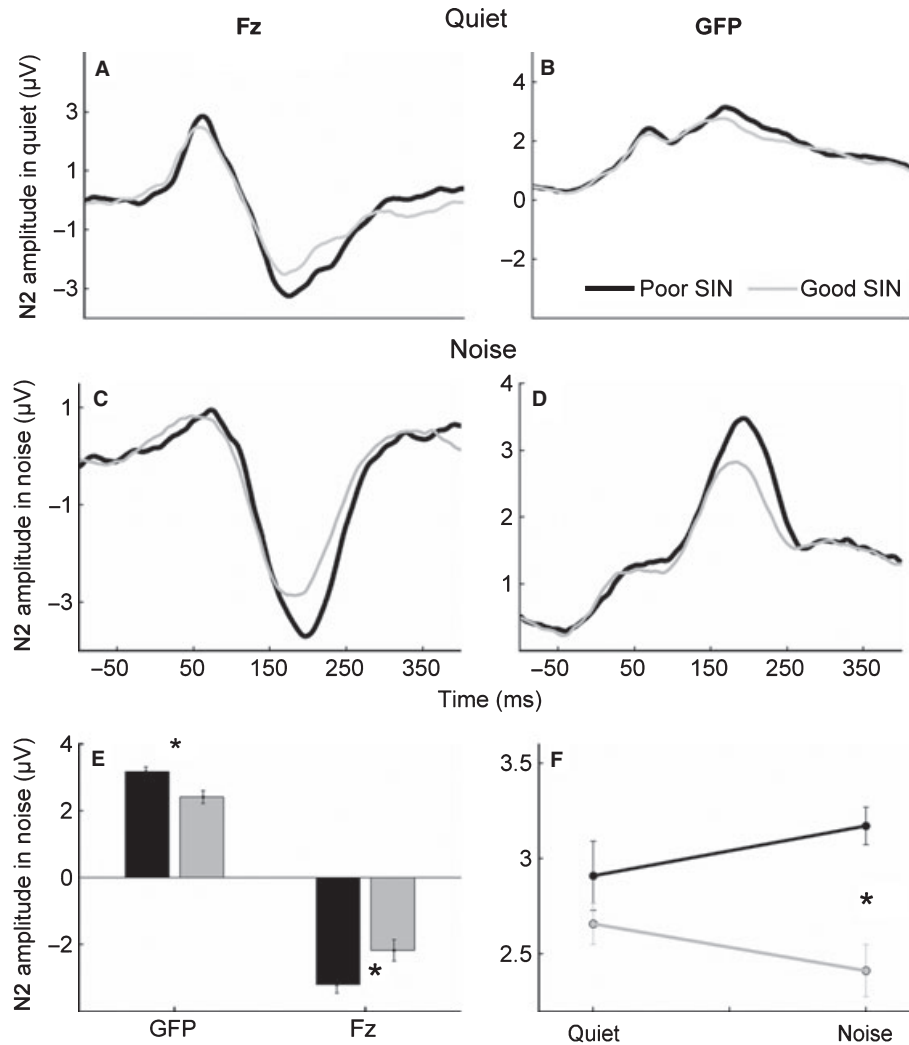
FIG. 4. Differences between top and bottom SIN groups in the quiet and noise conditions. Greater amplitudes are noted in the poor SIN group compared with the good SIN group in both GFP and the *F*z channel in the noise but not in the quiet condition. Grand average waveforms in the quiet condition show no significant differences in the *F*z channel (A) or GFP (B) between the bottom (black) and top (gray) SIN group. Grand average waveforms in the noise condition demonstrate higher N2 amplitudes in the bottom SIN group (black) compared with the top SIN group (gray) for both the *F*z channel (C) and GFP (D). (E) Bar graphs demonstrate group differences in the noise condition (bottom SIN > top SIN, *$P < 0.05$). (F) A significant interaction between the quiet and noise conditions for the two groups in GFP ($P < 0.05$) with bottom SIN > top SIN only in noise.

variability in child SIN perception, as reflected by a standardized measure of hearing in noise. To examine the nature of this variability, we divided participants into top and bottom SIN groups. Overall we found that, irrespective of group, the P1 component was significantly reduced in the noise condition. Bottom SIN perceivers had greater N2 amplitudes in noise than top SIN perceivers.

The reduction of P1 amplitude across both groups indicates that sensory representation, as indexed by P1 (Sharma *et al.*, 2002), is affected by the addition of noise. It has been suggested that the P1 component reflects a non-specific, pre-perceptual response to acoustic stimuli (Shtyrov *et al.*, 1998; Ceponiene *et al.*, 2005) and that the N2 component reflects a higher-order processing of sound content. We therefore expected to see differences in the N2 component, and not in P1. This selective enhancement of specific response components has also been found in musicians, in that musical experience does not result in an overall increase in gain but rather an enhancement of salient aspects of the response (Lee *et al.*, 2009; Strait *et al.*, 2009).
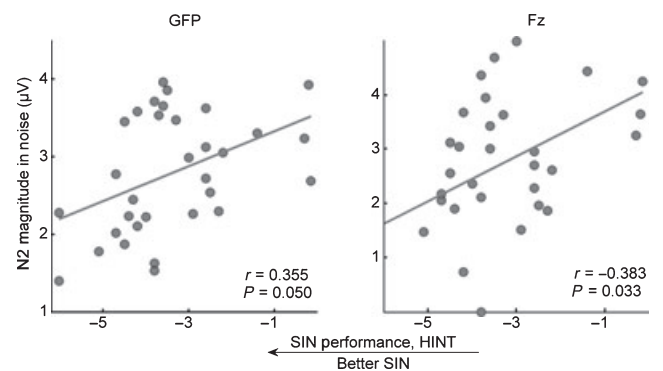

FIG. 5. Relationships between N2 magnitudes and SIN perception. Scatterplots of the relationships between HINT-Front raw scores and N2 magnitudes in the noise condition in GFP and the *F*z channel, demonstrating that better SIN perception is related to smaller N2 magnitudes in noise.

For example, musicians have stronger responses to the combination tones and higher harmonics of musical chords (important for melody recognition) but not for the fundamental frequency (Lee *et al.*, 2009; reviewed in Kraus & Chandrasekeran, 2010). Therefore, the selective enhancement of N2 co-occurring with a decrease in P1 amplitudes supports the notion that these cortical peaks reflect different aspects of auditory processing.

The finding of larger rather than smaller N2 amplitudes in the bottom SIN perceivers suggests that the top SIN perceivers may be recruiting fewer neural resources due to greater neural efficiency. Relationships between neural efficiency and cortical amplitudes have been previously offered as an explanation for the finding that cortical amplitudes are correlated with higher IQ scores (Robaey *et al.*, 1995; Zhang *et al.*, 2006), and our study implies a similar possible relationship between neural efficiency and SIN perception. The addition of babble noise results in an apparent increase in neural activity or effort, even when children are not attending to the stimulus. Decreased N2 amplitudes in the good SIN group may reflect greater inhibitory control (Ceponiene *et al.*, 2002), a necessary function for suppressing unwanted background noise. Children with greater inhibitory ability, as determined by N2 amplitude, may be able to suppress the unwanted effects of background noise more effectively, thereby improving signal quality. The relationship between SIN perception and the inhibitory effects of the medial olivocochlear auditory efferent system has been demonstrated (Kim *et al.*, 2006; de Boer & Thornton, 2008). The high frequency range of medial olivocochlear efferent function, as measured by contralateral suppression of distortion product otoacoustic emissions, correlates with speech perception ability in older adults (Kim *et al.*, 2006). Furthermore, it has been noted that auditory training can result in improvements in speech perception that correlate with an increase in medial olivocochlear activity (de Boer & Thornton, 2008). In addition to these known effects of peripheral inhibition on SIN ability, our results suggest a link between cortical inhibition and SIN perception.

An important aspect of our findings is that children in the bottom SIN group differed from those in the top SIN group only in the noise condition. This suggests that children with poor SIN do not suffer from a general sensory deficit. Rather, these results suggest a noise-specific difficulty that appears only when speech is processed under challenging listening conditions. Thus, the children with poor SIN performance may suffer from a noise-exclusion issue, similar to the deficits described by previous studies in the visual domain (Sperling *et al.*, 2005). A noise-exclusion deficit may indicate a less efficient auditory system that is unable to dynamically adapt to challenging backgrounds (Chandrasekaran *et al.*, 2009; Ahissar *et al.*, 2009; Anderson *et al.*, 2010). It is noteworthy that auditory expertise (musical training) is linked to enhanced perceptual and neural processing of SIN, suggesting that SIN ability is, at least in part, experience-dependent (Parbery-Clark *et al.*, 2009b; Chandrasekaran & Kraus, 2010).

Noise-induced increases in evoked magnetic fields are thought to enhance concurrent sound segregation, ultimately leading to improved SIN perception (Alain *et al.*, 2009). The greater amplitudes in children with poor SIN may be indicative of greater neural effort to facilitate the sound segregation process. Such results are consistent with imaging studies demonstrating that older adults with poor SIN perception use greater cognitive resources than younger adults with good SIN perception, who show sparser processing of SIN (Wong *et al.*, 2009).

The finding of greater cortical-evoked deficits in children with poor SIN is a further demonstration that mechanisms central to the cochlea can contribute to deficits in SIN perception (Pienkowski & Eggermont, 2009, 2010). This aligns with studies showing a link between SIN perception and the subcortical encoding of spectrotemporal features of speech in children (Cunningham *et al.*, 2001; Hornickel *et al.*, 2009, in press; Anderson *et al.*, 2010) and adults (Parbery-Clark *et al.*, 2009b). Similarly, deficits in subcortical temporal processing have been linked to specific language impairment and dyslexia (Basu *et al.*, 2010; Banai *et al.*, 2005, 2009; Billiet & Bellis, 2010). Although peripheral hearing impairment is known to reduce spectrotemporal resolution contributing to impaired SIN ability, children and adults with audiometrically-normal hearing can still experience SIN deficits, indicating that hearing in noise depends on other factors in addition to audiometric thresholds (Billiet & Bellis, 2010; Lewis *et al.*, 2010). These factors probably reflect the interplay of corticofugal and afferent processes. Although we employed a passive paradigm, it is likely that pre-conscious attentional processes affect the top-down modulation of responses (Tervaniemi *et al.*, 2009; Hugdahl *et al.*, 2003).

In conclusion, our findings demonstrate a relationship between higher-level perception and obligatory cortical activity and, specifically, demonstrate that a greater N2 response magnitude in noise is associated with poorer SIN perception. These differences in cortical processing emerge only in challenging listening conditions. Cortical processing in children is malleable in response to short-term training (Warrier *et al.*, 2004; Hayes *et al.*, 2003); therefore, the evidence of deficits in central auditory processing suggests the viability of auditory training targeting these deficits.

Acknowledgements

Abbreviations

GFP, global field power; HINT, Hearing in Noise Test; SIN, speech-in-noise.

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