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Processing intensity at rapid rates: Evidence from auditory evoked potentials in 9–11-year-old children

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Summary

Objective—The ability to understand speech requires processing of rapidly changing acoustic information. Much more is known about processing the rapid spectro-temporal properties of speech than is known about processing of intensity, even though intensity is a fundamental cue for accurate speech perception. The purpose for the current study was to characterize, in 9–11-year-old typically language-developing children, the auditory event-related brain potentials elicited by different tone intensities when presented in complex environments (i.e., varying in frequency and intensity) at rapid rates.

Methods—Pure tones of four different intensity levels (66, 74, 78, and 86 dB SPL) and five different stimulus frequencies were presented at a stimulus rate of 10 Hz. The latency and amplitude of the auditory event-related brain potentials were measured.

Results—At this fast rate, a positive (P1) followed by a negative component was elicited. The lowest intensity sound elicited the lowest P1 amplitude and the highest intensity sound elicited the highest P1 amplitude. The P1 elicited by the two middle tone intensities had amplitudes that fell between the lowest and highest amplitudes but they were not significantly different from each other. The negative component following the P1 was unaffected by intensity variation.

Conclusions—Intensity variation of sounds presented in a complex environment at a rapid rate modulated only the amplitude of the earliest obligatory auditory component (P1), consistent with our previous studies in which only the P1 could follow the rapid stimulation rate. P1 amplitude changes reflected the relative differences among the sounds, not the absolute differences in loudness among the sounds presented together in the sequence.

The results suggest that the environment, or context, within which rapid sounds occur, influences the relative amplitude of the P1 in children.

Keywords

Auditory event-related potentials (AEPs); Event-related potentials (ERPs); P1; Children; Intensity; Stimulus rate

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1. Introduction

Normal spoken speech rates are fast, approximately 200 words per minute [3], or 150 ms from the onset of one syllable to the onset of the next. The ability to understand speech therefore relies on the accurate perception of the rapid acoustic variations within the speech stream [1,2].

Behavioral studies have shown that typically language-developing children can discriminate sound features when they are presented at fast, speech-like rates [4]. Deficits in processing rapid acoustic transitions crucial for speech perception are thought, at least in part, to contribute to language impairments [5–7]. Despite the importance of processing rapidly occurring auditory information to speech perception, there exists only a small body of research that investigates the neurophysiology of rapid sound processing.

The few studies that have investigated rapid acoustic processes using auditory event-related brain potentials (AEPs) have focused mainly on frequency transitions [2,8,9]. Little attention has been paid to understanding the central processing of rapid intensity changes, even though intensity cues significantly contribute to speech perception [10–12]. For example, word discrimination is linked to the differences in loudness of sounds within syllables [11,12] and directly to the intensity (dB) of consonants within syllables [13]. Liu et al. [12] showed that increased intensity variations within word syllables improve speech understanding in cochlear implant listeners, especially in noisy environments. Only one study we are aware of *specifically* investigated the effect of stimulus intensity on AEP in children [14]. However, in this study they presented stimuli at slow rates (3.2–5.2 s onset-to-onset), much slower than the rate of the naturally occurring intensity variations of speech.

The goal of the present study was to determine whether the amplitude and latency of the obligatory AEP components could reflect intensity variation within a complex sound sequence that also contained frequency variation. AEPs are useful for studying central auditory processing in children because young subjects are not required to perform a task related to the sounds. We focused our analysis on the P1 and the negative component following P1 because these components are prominent in child obligatory responses at fast rates [9,15].

2. Materials and methods

Eleven typically language-developing children, aged 9–11 years (7 girls), recruited from schools in the local community of the Bronx, were paid to participate in the study. All participants reported no history of neurological disease, behavioral or developmental abnormalities. All children had a standard score of at least 85 on the Wechsler Abbreviated Scale of Intelligence (WASI) and were fluent in English. Informed assents were obtained from children and informed consents, in English or Spanish, were obtained from their accompanying parent, in accordance with the human subjects' research protocol approved by the Committee for Clinical Investigations at the Albert Einstein College of Medicine (AECOM). Testing was conducted at the Cognitive Neurophysiology Laboratory at the Rose F. Kennedy Center for Research in Mental Retardation and Human Development of

AECOM. Data from two participants were excluded because of excessive electrical artifact. Data from the remaining nine children (5 girls, 4 boys, mean age 10.8 years) were analyzed.

All participants passed a hearing screening (pure tone auditory thresholds of 20 dB HL or better at 250, 500, 2000, and 4000 Hz) and had type A tympanograms.

2.1. Stimuli and procedure

The stimuli were 50 ms duration (5 ms rise/fall times) pure tones, presented with a stimulus onset asynchrony (SOA) of 100 ms via insert earphones (EA-R Tone 3A). Two pure tones of different frequencies (to be called tone “A” and tone “B”) were presented in a fixed order (ABBABB...). The A tones had a fixed stimulus frequency of 1046.5 Hz. The stimulus frequency of the B tones was set at one of five values (1244.5–1975.5 Hz), presented separately in five frequency conditions. Sounds were calibrated using a Brüel & Kjær 2209 sound level meter with an artificial ear. The intensity value of the A tones was randomized to 70 dB SPL 88% of the time and 82 dB SPL 12% of the time. The B tone's intensity was randomly varied with equal probability among four intensity values (66, 74, 78, or 86 dB SPL) for each frequency condition. Thus, the distance between the A and B tones was manipulated in each condition, while the intensity values of the A and B tones were the same in all five conditions. Fig. 1 displays a schematic of the stimulus paradigm. The paradigm was designed to evaluate higher-level complex auditory processes associated with the A tones. Analysis of the A tones will be presented in a future report. For this report, the AEP responses to the B tones from each condition were analyzed to assess the effect of intensity on the obligatory AEPs. Each condition was presented in three separate 1520-stimulus blocks, and the order of presentation was counterbalanced across participants.

Participants sat quietly in an acoustically dampened room, were instructed to ignore the tones, and watch a silent captioned video of the individual's choice. Breaks were given as needed.

2.2. Electroencephalogram (EEG) recording and data analysis

Continuous EEG was recorded using a 32-channel electrode cap (international 10–10 configuration [16]). Vertical eye movements (VEOGs) were monitored using a bipolar configuration between FP1 and an external electrode placed below the left eye. Horizontal eye movements (HEOGs) were monitored using a bipolar configuration between the F7 and F8 electrodes. The tip of the nose was used as the reference electrode [17]. Impedances were kept below 5 k Ω . The EEG was digitized at a rate of 250 Hz (bandpass 0.05–100 Hz) using a Nicolet SM2000 amplifier at a gain of 30,000. The experimenter monitored the EEG for electrical artifacts, excessive eye blinks, sleep spindles and motion. The experimenter also monitored EEG for regular eye saccades that would indicate that participants were reading the captions on the monitor. All EEG data were filtered offline at 1–15 Hz. Epochs were examined from 100 ms prior to the onset of the stimulus to 300 ms post-stimulus onset. Epochs with signals exceeding ± 75 μ V on any channel were rejected from analysis. This yielded approximately 960 trials for each participant at each intensity level.

Amplitude was measured relative to the mean voltage in the 100 ms pre-stimulus period (baseline). The peak latency of the P1 and of the first negative component was visually

chosen from the grand-averaged waveform for each intensity level at four electrodes where signal-to-noise ratio is greatest (Fz, FC1, FC2, and Cz [15]). A 32-ms window around the peak latencies was used in a peak detection algorithm (Neuroscan 4.3) to determine the latency and the mean voltage of the components for each subject.

Repeated measures ANOVA was performed (Statistica 8, Statsoft) to examine the effect of frequency, intensity (66, 74, 78, and 86 dB SPL) and electrode (Fz, Cz, FC1, and FC2) on the latency and amplitude of the obligatory components. Huynh-Feldt corrections are reported when appropriate. Post hoc analysis was performed using the Tukey Honestly Significant Difference (HSD) test.

3. Results

An initial analysis (repeated measures ANOVA with factors of intensity (four levels) and frequency (five) revealed no main effect of stimulus frequency on the amplitudes of the P1 ($F > 1$, $p = 0.60$) or on the negative component following it ($F > 1$, $p = 0.91$) and no interactions. Therefore, the data were collapsed across frequency conditions and all of the remaining analyses were performed on the pooled data of the B tones to increase signal-to-noise ratio. Fig. 2 displays the grand-averaged waveforms elicited by the four different intensity tones presented within the same sound sequences at four fronto-central electrodes, where the obligatory evoked potentials are expected to be largest in children [15]. A large prominent positive component peaking at 65 ms (P1) followed by a prominent negative component peaking at 127 ms were observed. The P1 component occurred at an earlier peak latency compared to that reported in other child studies [15,18,19]. The negative component following P1 also peaked earlier than the typical N2 latency that is characteristic of the child AEP (e.g., 250 ms; [18,19]). This is likely due to the fast presentation rate (100 ms SOA). The early negative component is likely the N2, based on our previous study using a slower 150 ms SOA [15], but will be referred to as the “negative component” for the purposes of this report (because of its early latency).

The negative component did not vary in amplitude ($F < 1$, $p = 0.50$) or latency ($F < 1$, $p = 0.67$) as a function of intensity value. P1 latency also did not vary with intensity ($F = 3.04$, $p = 0.10$) P1 amplitude, in contrast, was affected by the intensity values studied, demonstrated by an interaction of amplitude and electrode ($F[9,72] = 2.18$, $\epsilon = 0.97$, $p = 0.038$) with no main effects (intensity ($F[3,24] = 2.71$, $\epsilon = 1.0$, $p = 0.070$; electrode ($F[3,24] = 0.41$, $\epsilon = 0.42$, $p = 0.59$). Table 1 displays the grand-mean amplitudes for P1 and shows a summary of the post hoc results.

Post hoc analysis revealed that P1 amplitude was larger for 86 dB SPL than all other intensities (66, 74, and 78 dB SPL) at all four electrodes. The amplitudes elicited by the middle intensities (74 dB SPL and 78 dB SPL) were larger than that of the lowest intensity (66 dB SPL) at Fz and FC2, and the amplitude of the P1 at 78 dB SPL was also larger than 66 dB SPL at FC1. There was no difference in amplitude between the two middle intensities (74 and 78 dB SPL) at any electrode site.

4. Discussion

The purpose for the current study was to determine, in 9–11-year-old children, whether the obligatory AEP reflect variations in tone intensity when presented at stimulus rates similar to those relevant to speech processing. The amplitude of the P1 was significantly modulated by sound intensity when multiple levels of intensity varied randomly within the same sound sequence. There was a relationship between amplitude and intensity in that the loudest sounds in the sequence elicited the largest P1 amplitude and the softest sounds elicited the smallest P1 amplitude with the two middle intensity sounds eliciting a P1-amplitude in the middle. However, there was no direct relationship between the amplitude and a decrease in intensity level, as the middle intensity sounds in the sequences did not differ in amplitude from each other. Therefore, the data suggest that P1 amplitude reflects relative differences among the sounds and does not 'encode' or reflect absolute differences in loudness of the sounds presented sequentially at fast rates.

P1 amplitude varied significantly with the stimulus intensities studied, whereas the negative component following it did not. It is more likely that the negative component following P1 was the N2 than the N1 (but occurring with an earlier latency than is typically observed at slower presentation rates [20]). Although the N1 component has been identified in children with longer peak latency at slower rates than adults [14,18,19], N1 does not typically appear as a discrete component in child AEP [15,19,21]. Thus, it may be that the rapid pace used in this study decreased the latency of the child N2. Nevertheless, there were no significant differences in the amplitude or latency of the negative component as a function of intensity, which is consistent with the findings of Bruneau et al. [14] in younger children (<9 years).

An alternative explanation for our P1 results is that the amplitude was largest for the loudest sound because attention was captured by the loudest sounds in a sequence that contained varying intensities, as speculated by Carrillo-de-la-Peña [22]. Attention is known to increase the overall amplitude of the obligatory components of the AEPs [23] compared to when the sounds are ignored. This explanation suggests that the relative differences in P1 amplitude may have been due to attentional effects and not to the intensity level of the sounds as such. Carrillo-de-la-Peña [22] found significantly increased peak-to-peak (P1–N1 and N1–P2) amplitudes elicited by a 110-dB SPL sound presented among random 60, 80, and 90 dB stimuli presented at ~1550 ms SOA. However, one important difference with the current study, in which participants ignored the sounds and watched a video, was that participants in the Carrillo-de-la-Peña study listened to the sound sequence. Secondly, the loudest tone in the Carrillo-de-la-Peña study (110 dB SPL) was considerably louder than the loudest tone presented in the current study (86 dB SPL). Moreover, attention is thought to increase the overall gain of all the obligatory AEPs, not selected components. In our study, we found significant differences in the P1 amplitude but not in the negativity following. We observed significant effects on amplitude of the lower intensity sounds in the paradigm, not only to the highest intensity sounds. Therefore, we conclude that attention alone cannot explain the modulation of the P1 amplitude by intensity variations found in the current study.

5. Conclusion

We demonstrated a significant effect of intensity on the amplitude of the P1 component in 9–11-year olds when sounds were presented in a complex sound environment (varying in both intensity and frequency) at rapid rates of 1 sound per 100 ms. These results suggest that the environment, or context, in which rapid sounds occur, influences the relative amplitude of the AEPs in children.

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Figure 1.

Schematic of the stimulus paradigm. Intensity is represented on the y-axis in dB and time is represented on the x-axis in ms. Each square represents a single 50 ms tone. The dark boxes represent 1046.5 Hz (the A tones) and the lighter boxes represent a different frequency (B tones), which varied across condition blocks only (see text for further details).

Figure 2.

The grand-mean ERP waves are displayed for Fz, Cz, FC1, and FC2 for each intensity level separately (86 dB, solid line; 78 dB, wide dashed line; 74 dB, narrow dashed line; 66 dB, dotted line). The x-axis represents time in milliseconds and the y-axis represents amplitude in microvolts. The P1 and first negativity (N) are labeled with arrows at Fz. The P1 modulation by intensity is visible as a difference in the P1 voltage for each intensity level and is most evident at Fz and FC2.

Table 1Grand mean amplitude of the obligatory components (in μV) with standard deviations in parentheses

Intensity	Fz	Cz	FC1	FC2
P1 amplitudes				
66	-0.10 (0.53)	-0.02 (0.47)	-0.08 (0.50)	-0.08 (0.58)
74	0.12 (0.32)**	0.06 (0.36)	0.02 (0.30)	0.07 (0.27)*
78	0.15 (0.52)**	0.08 (0.49)	0.07 (0.53)*	0.14 (0.53)**
86	0.38 (0.33)**	0.29 (0.32)**	0.37 (0.33)**	0.38 (0.34)**
Negative component amplitudes				
66	-0.46 (0.37)	-0.51 (0.46)	-0.53 (0.36)	-0.57 (0.46)
74	-0.35 (0.39)	-0.43 (0.39)	-0.45 (0.36)	-0.46 (0.38)
78	-0.20 (0.61)	-0.26 (0.49)	-0.27 (0.57)	-0.36 (0.61)
86	-0.42 (0.77)	-0.43 (0.62)	-0.41 (0.61)	-0.49 (0.83)

Asterisks indicate the values that were significantly different from the amplitude elicited by the lowest (66 dB) sound.

*
 $p < 0.05$.**
 $p < 0.01$.