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Effects of Acoustic Complexity on Processing Sound Intensity in 10- to 11-Year-Old Children: Evidence From Cortical Auditory Evoked Potentials

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Abstract

Objectives/Hypothesis—The environmental complexity that sounds are presented in, as well as the stimulus presentation rate, influences how sound intensity is centrally encoded with differences between children and adults.

Study Design—Cortical auditory evoked potential (CAEP) comparison study in children and adults examining two stimulus rates and three different stimulus contexts.

Methods—Twelve 10 and 11 year olds and 11 adults were studied in two experiments examining the CAEP to a 1-KHz, 50-ms tone. A Slow-Rate experiment at 750-ms stimulus onset asynchrony (SOA) compared the CAEPs of 78 dB to 86 dB SPL in 2 complexity conditions. A Fast-Rate experiment was performed at 125 ms SOA with the same conditions plus an additional complexity condition. Repeated measures and mixed-model analysis of variance (ANOVA) was used to examine the latency and amplitude of the CAEP components.

Results—CAEP amplitudes and latencies were significantly affected by rate, intensity, and age with complexity interacting in multiple mixed-mode ANOVAs. P1 was the only CAEP component present at the Fast Rate. There were main effects of rate, age, and stimulus intensity level on the CAEP amplitudes and latencies. Maturation differences were seen in the interactions of intensity with complexity for the different CAEP components.

Conclusions—Complexity of the sound environment was reflected in the relative amplitude of the CAEPs evoked by sound intensity. The effect of stimulus intensity depended on the complexity of the surrounding environment. Effects of the surrounding sounds were different in children than in adults.

Keywords

ERP; AEP; P1; fast rate; children; complexity; intensity

INTRODUCTION

Even in simple listening situations, the ability to detect changes in sound features depends on the ability to accurately process the previous sound input¹ (i.e., ongoing characteristics of

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the sound environment). Children with language impairments have been shown to have deficits in general acoustic processing of rapidly changing sounds or sound characteristics.²⁻⁷ Consequently, it has been suggested that the ability to detect rapidly changing nonlinguistic sound features is essential for normal language development, as well as for the ongoing interpretation of the sound environment.⁸ Therefore, it is first necessary to understand how the sound environment influences the acuity of sound change detection in typical language-developing children to improve our knowledge of acoustic processing mechanisms that contribute to normal and impaired language development.

We used cortical auditory evoked potentials (CAEPs) in the current study to assess how sound intensity would be coded within a complex sound environment, that is, with multiple changes in sound level. Despite the importance of processing rapidly occurring auditory information to real-world sound processing and speech perception,⁹ there exists only a small body of research that investigates the neurophysiology of rapid sound processing, especially in children. This may be due to the effects of rapid presentation rate on the CAEPs, which greatly reduces the amplitude and alters the morphology of the obligatory components. For example, Sussman et al.¹⁰ demonstrated that the P1 component was the only CAEP evoked by sounds presented at rapid rates.

Even fewer studies have investigated acoustic processing of rapid intensity changes, even though intensity cues significantly contribute to speech perception.¹¹ Word discrimination has been directly linked to the intensity level of consonants within syllables.¹² Liu et al.¹³ showed that increased intensity variations within word syllables improved speech understanding in listeners with a cochlear implant, especially in noisy environments. Their findings led to modifications of implant processor strategies.

CAEPs can be a particularly useful tool for studying auditory processing in children. They provide a direct measure of auditory neural activity,^{14,15} representing population activity from large sums of synchronously activated pyramidal cells, and can be recorded noninvasively at the scalp by using the electroencephalogram (EEG). In addition, this technique is advantageous for studying young children and children with language impairments because the CAEPs can be reliably obtained without attention focused on the sounds, such as while children watch a silent video.

Because the sounds are time-locked to the EEG, precise millisecond timing of the brain responses can be determined. The P1 component is the first cortical potential (with positive polarity) recorded in adults and children.^{14,16} The neural generators of the auditory P1 originate in the more lateral portion of Heschl's gyrus within the secondary auditory cortices.¹⁵ The N1 component has multiple cortical generators, mostly originating outside primary auditory cortex and reflecting both thalamocortical and cortico-cortical connections.^{15,16} Whereas P1 is the most prominent component observed in the child waveforms, N1 is the most prominent of the adult obligatory components when sounds are presented at slow stimulus rates.¹⁷ The N1 is not observed in children until they begin to mature during the preteen and teenage years.^{10,14}

The purpose of the current study was to determine whether amplitude or latency of the CAEPs would reflect the relative intensity value induced by the complexity of the stimulus environment. In a previous study in 9- to 11-year-old children, Dinces and Sussman,¹⁸ using a rapid stimulus presentation rate (100 ms stimulus onset asynchrony [SOA]), evaluated CAEPs to various intensity levels in the background of a changing sound frequency environment. They found that the sound with the softest intensity elicited the smallest amplitude P1 component, and the loudest sound elicited the largest P1 amplitude. However, the relationship of the P1 amplitude to intensity was not linear, in that P1 amplitudes evoked

by the middle intensity values were not distinguished by differing amplitude. This finding indicated that the effect of intensity level on P1 amplitude for rapidly presented sounds may be more dependent on the complexity of the sound environment than the stimulus value.¹⁸ The current study was therefore designed to test this hypothesis directly by evaluating the effects of two different stimulus intensities when presented either alone, together as the only two intensity levels, or together but within a group of five different intensities. If complexity of the sound environment influences intensity coding, then the amplitudes or latencies of the P1 component are expected to vary depending on the environment within which the sounds are presented.

MATERIALS AND METHODS

Subjects

Thirteen children with normal language development (7 boys, mean age 11.3 years $\pm$ 7 months) were recruited from local schools. Thirteen adults with no history of learning problems, (4 males, mean age 29.8 years $\pm$ 4 years) were recruited from the local community. All participants reported no history of neurologic disease or behavioral or developmental abnormalities. All participants passed a hearing screening (pure tone at 20 dB hearing level [at 250, 500, 2,000, and 4,000 Hz]) and had type A tympanograms. All 10- to 11-year-old children had a standard score of at least 85 on the Wechsler Abbreviated Scale of Intelligence and were fluent in English.

The Albert Einstein College of Medicine Internal Review Board approved all procedures. Informed assent was obtained from the 10 to 11 year olds, and informed consent was obtained from parents and adult participants. All subjects were compensated for their participation. Data from one child participant and two adult participants were excluded because of excessive electrical artifact. Data from the remaining twelve 10 to 11 year olds and 11 adults were included in the analysis.

Stimuli

The stimuli were 50-ms-duration (7.5 ms rise/fall times) pure tones, presented via insert earphones (E-A-R Tone 3A; Aeareo, Indianapolis, IN). All tones had a fixed stimulus frequency of 1000 Hz; only the intensity was varied in the different conditions. Five different stimulus intensities were used (70, 74, 78, 86, and 90 dB SPL) as described in the following section. Sounds were calibrated using a Brüel & Kjær 2209 (Denmark) sound level meter with an artificial ear.

Procedures

Two experiments were conducted in one session for both age groups: a slower-paced stimulus presentation rate (the Slow-Rate experiment) and a fast-paced stimulus rate (the Fast-Rate experiment). Participants sat quietly in a soundproof booth (Industrial Acoustics Company, Bronx, NY) and were instructed to ignore the tones and watch a silent captioned video of their choice. Breaks were given as needed.

The Slow-Rate experiment was conducted using a 750 ms SOA in three conditions. In the first condition, one tone with a stimulus intensity of 78 dB SPL was presented on 100% of the tones in two blocks of 760 stimuli. In the second condition, an 86 dB SPL intensity tone was presented on 100% of the tones in two blocks of 760 stimuli. These two conditions constitute the alone conditions. In a third condition, the two stimulus intensity values (78 and 86 dB SPL) were randomly presented (50% and 50%) in two blocks of 1,510 stimuli (2-mix condition).

The Fast-Rate experiment was conducted using a 125 ms SOA in four conditions. The two alone conditions and one 2-mix condition were the same as those for the Slow-Rate experiment, with the exception that they were presented at the more rapid rate. A fourth condition presented stimuli with five different intensity values (74, 78, 82, 86, and 90 dB SPL) randomly distributed at 20% probability for each value (5-mix condition), and presented in five blocks of 1,510 stimuli each (a total of 7,550 stimuli). The 78 and 86 dB SPL stimuli were common to all x-mix conditions.

EEG Recording and Data Analysis

EEG was recorded using a 32-channel electrode cap (international 10-10 configuration). Vertical eye movements and blinks were monitored using a bipolar configuration between FPl and an external electrode placed below the left eye (vertical electrooculogram). Horizontal eye movements were monitored using a bipolar configuration between the F7 and F8 electrodes (horizontal electrooculogram). The tip of the nose was used as the reference electrode. Impedances for each electrode were kept below 5 kOhms. The EEG was digitized at a sampling rate of 500 Hz (bandpass 0.05–100 Hz) using a Neuroscan Synamps amplifier (Compumedics Inc., Charlotte, NC). The experimenter monitored the EEG for electrical artifacts, excessive eye blinks, sleep spindles and motion artifacts.

All EEG data were digitally filtered offline using a Butterworth filter (zero-phase shift) 1 to 15 Hz. Epochs were created from 100 ms before the onset of the stimulus to 500 ms after stimulus onset. Epochs with signals exceeding $\pm 100 \mu\text{V}$ on any channel were rejected from analysis, resulting in approximately 1,300 trials for each participant at each intensity level in each condition.

Global field power (GFP) analysis was performed to identify the latencies of the CAEP components.^{19,20} GFP analysis minimizes electrode section bias in determining the latency of CAEP components by using information from all recorded electrodes.

All components of the CAEP found to be prominent in the GFP analysis were measured relative to the mean voltage in the 100 ms pre-stimulus period (baseline) for each age group. A 32-ms window around the peak latencies was used in a peak detection algorithm (Neuroscan 4.3) to determine the latencies of the peaks for each individual subject at F4, where signal-to-noise ratio was greatest. Using the same 32-ms window from the GFP analysis, the mean amplitude of the peaks was calculated for each individual in each group and each condition separately (area report algorithm in Neuroscan 4.3). Mixed-model repeated-measures ANOVAs (Statistica 10; Statsoft, Tulsa, OK) were performed with factors of rate (experiment), complexity (alone, 2-mix), and intensity (78 and 86 dB SPL) to look at rate and interactions on the amplitudes and latencies of the identified CAEP components in both groups. A separate mixed-model repeated-measures ANOVA was performed to look at the effect of the three different levels of complexity (alone, 2-mix, and 5-mix) in the Fast-Rate experiment in both groups. Greenhouse-Geisser corrections are reported. Post hoc analysis was performed using the Tukey honestly significant difference (HSD) test.

RESULTS

Figure 1 displays the grand-averaged CAEP waveforms evoked by the 78 (black lines) and 86 (gray lines) dB SPL sound intensities in the Slow-Rate experiment in the alone conditions (dashed lines) and 2-mix condition (solid lines), for 10 to 11 year olds (Fig. 1A) and adults (Fig. 1B). The CAEP waveforms elicited at the slower rate were typical for 10- to 11-year-old children,¹⁰ observed as a biphasic positive peak (denoting the P1 and P2) and

followed by a large negative (N2) component.¹⁴ The CAEPs elicited in the adults was also typical for slower presentations rates, with a clear P1-N1-P2 component waveform.¹⁷

Figure 2 displays the grand-averaged CAEP waveforms evoked in the Fast-Rate experiment for the 10 to 11 year olds, showing eight frontocentral electrodes. The circled graph, at the top right of Figure 1, shows the F4 electrode where the statistical analyses were performed for both 10 and 11 year olds and adults. The CAEP waveforms are greatly reduced in amplitude at the fast rate compared to those in the Slow-Rate experiment (Fig. 1A and 2). In addition, only the P1 component was observed at the fast rate. Within the 300-ms poststimulus epoch displayed, a P1 evoked by each stimulus is seen every 125 ms, which is the presentation rate in the Fast-Rate experiment. Sussman et al.¹⁰ showed that at rapid rates, only the P1 obligatory waveform was observed in the CAEPs. This may be due to faster recovery rates of neural population in the thalamocortical pathway that generates the P1 response.¹⁴

Figure 3 (10 to 11 year olds) and Figure 4 (adults) show the grand-averaged waveforms at the F4 electrode for both groups for the fast rate. Figures 3 and 4 display the CAEP responses evoked by the 78 and 86 dB SPL stimuli, separately for each age group, in the four conditions in the Fast-Rate experiment. In Figures 3A and 4A, the CAEP response to the 78 dB SPL stimulus is displayed for three different conditions (alone, 2-mix, and 5-mix conditions). The effect of complexity, and the interaction of complexity with intensity value, can be seen by comparing Figures 3A and 4A to Figures 3B and 4B (where the CAEP response to the 86 dB SPL stimulus is displayed). In the lower graphs of Figure 3 and Figure 4, CAEP responses evoked by both intensity values (78 and 86 dB SPL) in the 2-mix condition (solid line) can be compared with the CAEPs evoked in the alone conditions (lower left, Fig. 3C and 4C) and in the 5-mix condition (lower right, Fig. 3D and 4D).

Tables I and II show the mean peak latencies and amplitudes, respectively, for the identifiable CAEP components in Slow- and Fast-Rate experiments.

Latency for CAEP Components

A mixed-model repeated-measures ANOVA was performed to test effects of complexity on P1 latency. Overall, P1 latency was longer in children than in adults, (main effect of group, $F_{1,21} = 50.7$, $P < .001$). P1 latency was also overall longer in the Fast-Rate than the Slow-Rate experiment in both children and adults (main effect of rate, $F_{1,21} = 236.0$, $P < .001$), and the P1 latency was shorter for the louder stimulus than the quieter stimulus in both groups (main effect of intensity, $F_{1,21} = 6.8$, $P = .016$). There was no main effect of complexity on the P1 latency ($F_{1,21} = 1.1$, $P = .31$). There were significant interactions between group and rate ($F_{1,21} = 20.7$, $P < .001$) and between complexity and intensity, ($F_{1,21} = 7.3$, $P = .013$). Post hoc analyses showed that the P1 evoked by both stimulus intensities (78 and 86 dB SPL) had similar latencies in the alone and 2-mix conditions in the Slow-Rate experiment, but in children there was a significant effect of complexity on the latency for the 86 dB SPL stimulus in the Fast-Rate experiment. In the Fast-Rate experiment, the latency of the P1 component was longer for the 86 dB SPL stimulus in the alone condition than in the 2-mix condition and shorter for the 78 dB SPL stimulus in the alone condition when compared to the 2-mix condition (interaction of rate with complexity and intensity, $F_{1,21} = 50.7$, $P = .004$).

N1 latency was evaluated only in the adults in the Slow-Rate experiment, in which the N1 component was elicited. The N1 peak evoked by the 86 dB SPL intensity stimulus was longer than that evoked by the 78 dB SPL stimulus (a main effect of intensity, $F_{1,10} = 7.71$, $P = .020$). There was no main effect of complexity ($F_{1,10} = 3.57$, $P = .088$) and no interactions ($F_{1,10} = 3.24$, $P = .1$).

P2 latencies were evaluated in children and adults only for the Slow-Rate experiment, in which they were elicited. Overall, adults had a longer P2 latency than children (main effect of group, $F_{1,21} = 14.94$, $P = .001$). There was a longer P2 latency for the louder sound (main effect of intensity, $F_{1,21} = 6.68$, $P = .017$), but this was only significant for the adults (interaction of intensity with group, $F_{1,21} = 7.25$, $P = .014$). P2 latency was also longer in the 2-mix condition at 86 dB SPL compared to 78 dB SPL, but this was only for adults (interaction of intensity with complexity and group, $F_{1,21} = 5.11$, $P = .035$). There was no main effect of complexity ($F_{1,21} = 0.13$, $P = .73$).

N2 was only examined in children, where it was elicited. Longer N1 latencies were observed for the alone conditions compared to the 2-mix condition (main effect of complexity, ($F_{1,11} = 5.69$, $P = .036$). There was no main effect of intensity ($F_{1,11} = 1.26$, $P = .29$) and no interaction ($F_{1,11} = 0.90$, $P = .36$).

Amplitude for CAEP Components

P1 amplitudes were larger in children than adults (main effect of group, $F_{1,21} = 31.82$, $P < .001$). Overall, a slower rate and a louder intensity produced larger amplitudes (main effects of rate: $F_{1,21} = 44.59$, $P < .001$; and intensity: $F_{1,21} = 18.54$, $P < .001$, respectively). The louder intensity sound (86 dB SPL) elicited a larger amplitude P1 in the Slow-Rate experiment for the children only (interaction of group with rate and intensity, ($F_{1,21} = 8.92$, $P = .008$).

P2 was present only in the Slow-Rate experiment. Therefore the effect of rate was not analyzed for P2. There were no main effects of group ($F_{1,21} = 0.42$, $P = .53$), intensity ($F_{1,21} = 2.79$, $P = .11$), or complexity ($F_{1,21} = 0$, $P = .99$) on the P2 amplitudes.

N1 was only present in the Slow-Rate experiment in the adult group. The N1 amplitude was larger for the 86 dB SPL sound and smaller for the 78 dB SPL in the 2-mix condition as compared with the alone conditions (interaction of intensity with complexity, $F_{1,10} = 5.39$, $P = .043$). There was no main effect of intensity ($F_{1,10} = 2.65$, $P = .14$) or complexity ($F_{1,10} = 0.29$, $P = .60$).

The child N2 was only present in the Slow-Rate experiment. There was no main effect of intensity ($F_{1,11} = 1.17$, $P = .30$) or complexity ($F_{1,11} = 0.03$, $P = .86$) on the N2 amplitude and no interactions ($F_{1,11} = 3.14$, $P = .10$).

Effect of Complexity on P1 Latency and Amplitude at the Fast Rate

Separate analyses were performed to analyze the effect of complexity (alone, 2-mix, and 5-mix conditions) on the P1 in the Fast-Rate experiment (Fig. 3) for both groups, as the 5-mix condition was conducted only at the fast rate.

Overall, P1 latency was longer in children than adults (main effect of group, $F_{2,42} = 6.61$, $P = .018$). An interaction between complexity and intensity ($F_{2,42} = 7.93$, $\eta^2 = 0.95$, $P = .0015$) showed that there was a longer latency P1 evoked by the 78 dB SPL stimulus in the 2-mix condition, but there was a longer P1 latency to the 86 versus 78 dB SPL stimulus when presented in the alone conditions. There were no main effects of complexity ($F_{2,42} = 1.22$, $P = .31$) or intensity ($F_{2,42} = 1.42$, $P = .25$).

The louder sound (86 dB SPL) elicited a larger P1 amplitude (main effect of intensity, $F_{2,42} = 18.06$, $P < .001$). Overall, P1 amplitudes were larger for children than adults in the two alone conditions. In the children, a larger P1 amplitude was seen in the 2-mix condition for the 78 dB SPL stimulus (when compared to the alone or 5-mix conditions) and in the 5-mix condition for the 86 dB SPL stimulus (when compared to the alone or 2-mix conditions). In

adults, P1 amplitudes were largest for 86 dB SPL in the 2-mix condition (compared with the responses to the 78 dB SPL stimulus), but the two different intensity stimuli did not elicit different P1 amplitudes for alone or 5-mix conditions (interaction of group with intensity and complexity, $F_{2,42} = 8.09$, $\eta^2 = 0.996$, $P = .001$). There were no main effects of group ($F_{2,42} = 1.46$, $P = .24$) or complexity ($F_{2,42} = 0.51$, $P = .60$).

DISCUSSION

The purpose for the current study was to investigate how sound intensity would be coded when there were rapid changes occurring in the sound environment. This was assessed by determining whether the amplitude or latency of the scalp-recorded CAEPs evoked by the various intensity levels would reflect the complexity of the stimulus environment. We found that both the complexity and stimulus rate modulated the CAEPs differently in children and adults.

The key finding of the study was that modulation of the amplitude of the CAEPs was dependent on the complexity of the stimulus environment. A faster rate of sound presentation had a different effect on the CAEPs than the slower rate, which was mainly age-dependent. Finding that intensity influences the P1 amplitude in a manner dependent on the surrounding stimulus intensities suggests that intensity coding depends on the complexity of the stimulus environment and thus illustrates the importance of the environment in sound perception. The results also indicate the elaborate nature of how intensity is “handled” in central auditory processes, particularly in children.

As expected on the basis of previous studies, morphologic differences in the obligatory waveforms were observed between the children and adults in the Slow-Rate experiment.^{10,14} P1 amplitude was larger and peak latency was longer in the children showing maturational differences with the adults. In children (Fig. 2A), the P1 was immediately followed by the P2 component, separated by a small negative-going dip between the positive peaks.^{10,14} The N2 component observed in the child group was not seen in the adult group. At fast rates, P1 is the only robust CAEP component observed in the waveforms for both children and adults (Fig. 3 and 4), which is consistent with previous studies using similarly fast presentation rates.^{10,18,21}

P1 had a longer latency with a faster rate for both groups. P1 also had a longer latency with the louder sound in the less complex environments than with the quieter sound (two alone conditions) at the faster rate. In the Slow-Rate experiment, P1 amplitude was smaller when evoked by the quieter tone (78 vs. 86 dB SPL) in the alone conditions in the adults but not in the children, and in contrast to the children, there were no differences in P1 amplitude between the two intensity values in the 2-mix condition. This shows a significant difference in the processing of intensity in the P1 amplitude for the different complexity conditions between the children and adults at both rates, again reflecting maturational differences and the importance of complexity of the sound environment for intensity coding.

Additional effects of the complexity of the environment were found in the Fast-Rate experiment. As mentioned, only the P1 component of the CAEP was present when sounds were presented at the fast rate. In children, there was not a simple linear relationship of P1 amplitude with intensity, as the complexity of the environment interacted with the intensity of the stimulus to influence the P1 amplitude. That is, the amplitude of P1 was not larger for the 86 versus the 78 dB SPL stimulus in the 2-mix condition as it was in the alone and 5-mix conditions. In the 2-mix condition, the P1 component elicited by the quieter sound (78 dB SPL) was largest in children (Fig. 3C and 3D). The 2-mix condition was the only condition at the faster rate in which the relative amplitudes of the P1 component were different from

the expected increase in amplitude. In the 5-mix condition, both the 78 and 86 dB SPL stimuli were surrounded by higher and lower intensities, having similar “loudness” positions in relation to the other sounds in the environment. Therefore, the difference between the responses evoked by the 78 dB SPL stimulus in the 2-mix and 5-mix conditions at the fast rate may be due to the relative position of 78 dB SPL in the complex environments.

In the Slow-Rate experiment, in which additional ERP components were elicited, the P2 amplitude was larger and later when evoked by the louder (86 dB SPL) compared to the softer (78 dB SPL) stimulus in adults. This difference was not significantly observed in the children, indicative of a maturational difference. The child N2 was affected by the complexity of the experimental condition, with shorter latencies and larger negativities the more complex the condition. Surprisingly, in the 2-mix condition there was no difference between the child N2 amplitudes for 86 and 78 dB SPL. The fact that the louder sound did not elicit a more negative N2 for the 2-mix condition (as it did in the alone conditions) is expected only if the central auditory system is processing intensity value differently in the 2-mix condition than in the alone condition at 750 ms SOA (the Slow-Rate experiment). This result suggests that in children, intensity encoding reflected by the CAEPs is based at least in part on the environmental complexity and not solely on the absolute intensity value of the stimulus.

The specific details of how environmental complexity influences CAEP amplitudes and latencies (such as whether the rank of the stimulus—lowest, middle or highest value— influences central auditory encoding) cannot be fully determined by the current experiments. However, the current results indicate that the specific nature of the sound environment surrounding a particular stimulus affects how the central auditory system processes that stimulus at an automatic level, when stimuli are presented at fast and slow rates.

In our previous study,¹⁸ we found that the loudest sound in an environment of changing frequencies and intensities evoked the largest P1 amplitude and that the P1 amplitudes to the middle sounds within that same environment were not different from each other. In that study, 86 dB SPL was the loudest sound in the mixture and was associated with the largest amplitudes. In the current study in the 5-mix condition, the 86 dB SPL stimulus elicited a larger P1 amplitude than 78 dB SPL (dashed waveforms in the graphs in Fig. 3A, 3B, and 3D), when both amplitudes fell in the middle of the intensity range. Interestingly, when 86 dB SPL was the loudest sound (in the 2-mix condition) it did not elicit the largest P1 amplitude in children (solid lines in Fig. 3C and 3D). This indicates that the complexity of the sound environment, not simply the intensity value, plays a direct role in how intensity is encoded in the CAEP. Moreover, the current results show that adults and children process sounds differently in complex intensity environments. The data presented here are consistent with a longer developmental course for intensity coding.²²

Successful organization of the mixture of incoming sound stimuli is necessary to build a meaningful representation of our sound environment. As the time between rapidly presented stimuli is shortened, our ability to detect individual auditory stimuli as discrete auditory events is affected.²² Thus, an alternative interpretation of the data is that the stimuli, when presented at fast rates (125 ms SOA), were segmented into larger “packets of sound” and thus not encoded as discrete stimuli with separate intensities. However, we believe this was highly unlikely as we saw a distinct effect of sound environment on the specific time-locked stimuli, even though the sounds were randomly presented within each block. Further studies may include additional SOA rates to specify the role of presentation rate on the effect of environmental complexity effects.

CONCLUSION

We report findings of both environmental intensity and rate-dependence of CAEP amplitudes, demonstrating a new effect of environmental complexity on the central encoding of sound intensity in children. Complexity of the sound environment was reflected in the relative amplitude of the CAEPs evoked by sound intensity, in that a sound with a particular stimulus intensity evoked larger or smaller amplitudes depending on the levels of the surrounding sounds. Further, effects of the surrounding sounds were different in children than in adults. Thus, the current results indicate a potential richness of cortical sound encoding in the early preattentive central processes, with evidence of maturational differences for processes encoding intensity.

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Fig. 1.

The grand averaged waveforms at the F4 electrode for the Slow-Rate experiment in children and adults. The x axis represents time in milliseconds and the y axis represents amplitude in microvolts. The waveforms generated by the 78 and 86 dB SPL stimuli for both 10 and 11 year olds in (A) and adults (B) are presented. Each graph shows four responses for each group. The dotted lines are the responses in the alone conditions and the solid lines are the responses in the 2-mix condition, with black for 78 and grey for 86 dB SPL. The top graph shows a typical obligatory cortical auditory evoked potential waveform for children with a large double peaked P1–P2 complex, no N1 component, and a deep child N2. The adult waveforms in the bottom graph are also typical with a P1–N1–P2 complex.

Fast Rate - Children 10-11 y.o.

Fig. 2.

The topography of the obligatory waveform is shown above for 78 and 86 dB SPL stimuli in the Fast-Rate experiment in 10 to 11 year olds for the alone and 2-mix conditions. The graphs are of epics of the cortical auditory evoked potential with the x axis as time in milliseconds and the y axis in microvolts. The electrode labels are placed in the top left of each graph, and each graph contains the four waveforms indicated in the legend (bottom of figure). The dashed lines are the alone condition and the solid lines are the 2-mix condition with black for 78 and grey for 86 dB SPL at that electrode. Because of the fast rate, more than one P1 response is seen in each epic. The P1 component that is time locked to the response occurs in the middle of the graphed epic and is labeled at Cz in the middle graph. The responses to the stimuli are seen best in the frontal electrodes in children and were most robust at F4 (circled electrode graph) for this protocol.

Fast Rate at F4 - Children 10-11 y.o.

Fig. 3.

The grand averaged waveforms for the Fast-Rate experiment for the 10 to 11 year olds at F4. The x axes represent time in milliseconds and the y axes represent amplitude in microvolts. The top left graph (A) shows a black arrowhead indicating each stimulus onset. The middle positive peak (P1) is the only identifiable obligatory component to the stimulus (onset at 0 ms) at this fast rate. Because of the fast rate, more than one response is seen in the 300 ms epics, but only the center peaks are time locked to the stimulus. The upper graphs show responses to the four conditions (2 alone conditions: dotted line; 2-mix condition: solid line; and 5-mix condition: dashed line). In (A), responses to 78 dB SPL are shown in black, and in (B), the responses to 86 dB SPL are shown in grey. In (C), the alone conditions (dotted lines) and the 2-mix condition (solid lines) are shown for both 78 and 86 dB SPL stimuli. The interaction of condition with intensity can be seen in the similar amplitude of P1 components to the 78 and 86 dB SPL stimuli in the 2-mix condition and the differences between 78 and 86 dB in the alone condition. In (D), the 2-mix condition (solid line) can be compared with the 5-mix condition (dashed line).

Fig. 4.

The grand averaged waveforms for the Fast-Rate experiment for the adults at F4. The x axes represent time in milliseconds and the y axes represent amplitude in microvolts. In (A), a black arrowhead indicating each stimulus onset is shown. The middle positive peak (P1) is the only identifiable obligatory component to the stimulus (onset at 0 ms) at this fast rate. Owing to the fast rate, more than one response is seen in the 300 ms epics, but only the center peak of each graph is time locked to the stimulus. Each of the upper graphs shows responses to the four conditions (2 alone conditions: dotted line; 2-mix condition: solid line; and 5-mix condition: dashed line). In (A), responses to 78 dB SPL are shown in black. In (B), responses to 86 dB SPL are shown in grey. In (C), the alone conditions (dotted lines) and the 2-mix condition (solid lines) are shown for both 78 and 86 dB SPL stimuli. (D) The interaction can be seen again in the differences between the stimuli in the 2-mix condition (solid line) and can be compared with amplitude of the P1 component for the 5-mix condition (dashed line).

TABLE I

Mean Peak Latencies for Experiments 1 and 2 at F4.

	Alone 78 dB	Alone 86 Db	2-Mix 78 dB	2-Mix 86 dB	5-Mix 78 dB	5-Mix 86 dB
EXP 1						
Adult P1	48.7 (9.0)	48.2 (9.1)	46.2 (9.3)	46.2 (9.6)	—	—
N1	84.9 (7.9)	86.4 (8.4)	85.1 (7.6)	92.0 (6.8)	—	—
P2	156.2 (9.2)	157.0 (9.5)	153.8 (8.1)	161.1 (11.3)	—	—
Child P1	83.5 (16)	75.2 (8.4)	82.4 (12.7)	75.6 (8.2)	—	—
P2	143.4 (7.8)	143.6 (9.6)	143.6 (10.9)	143.2 (11.2)	—	—
N2	246 (19.7)	243 (19.6)	239 (17.9)	240 (19.7)	—	—
EXP 2						
Adult P1	98.5 (11.1)	102.4 (11.1)	99.6 (11.3)	92.9 (13.4)	92.5 (13.4)	95.5 (13.7)
Child P1	103.7 (3.2)	102.2 (3.8)	98.2 (3.2)	94.2 (3.4)	107.7 (10.8)	105.7 (10.1)

All results are given in milliseconds (standard deviation).

EXP = experiment.

TABLE II

Mean Peak Amplitudes for Experiments 1 and 2 at F4.

	Alone 78 dB	Alone 86 dB	2-Mix 78 dB	2-Mix 86 dB	5-Mix 78 dB	5-Mix 86 dB
EXP 1						
Adult P1	0.23 (0.42)	0.39 (0.33)	0.45 (0.31)	0.39 (0.41)	—	—
N1	-0.73 (0.75)	-0.71 (1.05)	-0.60 (0.83)	-1.12 (0.95)	—	—
P2	1.79 (1.06)	2.11 (1.28)	1.79 (1.06)	2.01 (1.29)	—	—
Child P1	1.97 (0.85)	2.40 (0.45)	2.21 (1.15)	2.65 (1.07)	—	—
N2	-2.19 (1.47)	-2.60 (1.46)	-2.44 (1.27)	-2.42 (1.65)	—	—
EXP 2						
Adult P1	0.28 (0.27)	0.36 (0.30)	0.22 (0.36)	0.44 (0.24)	0.33 (0.20)	0.37 (0.22)
Child P1	0.32 (0.44)	0.57 (0.37)	0.56 (0.53)	0.52 (0.51)	0.28 (0.39)	0.66 (0.55)

All results given in microvolts (standard deviation).

EXP = experiment.