Published in final edited form as:

Hear Res. 2008 February ; 236(1-2): 61–79. doi:10.1016/j.heares.2007.12.001.

The maturation of human evoked brain potentials to sounds presented at different stimulus rates

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Abstract

The current study assessed the normal development of cortical auditory evoked potentials (CAEPs) in humans presented with pure tone stimuli at relatively fast stimulus rates. Traditionally, maturation of sound processing indexed by CAEPs has been studied in paradigms using inter-stimulus intervals (ISIs) generally slower than 1 Hz. While long ISIs may enhance the amplitude of CAEP components, speech information generally occurs at more rapid rates. These slower rates of sound presentation may not accurately assess auditory cortical functions in more realistic sound environments. We examined the effect of temporal rate on the elicitation of the P1—N1—P2—N2 components to unattended sounds at four levels of stimulus onset asynchrony (SOA, onset to onset, 200, 400, 600, and 800 ms) in children grouped separately by year (ages 8, 9, 10, 11 years), in adolescents (age 16 years) and in one group of young adults (ages 22–40 years). We found that both age and stimulus rate produced profound changes in CAEP morphology. Between the ages of 8–11 years, the P1 and N2 components dominated the ERP waveform at all stimulus rates. N1, the dominant CAEP component in adults, appeared as a bifurcation in a broad positive peak at earlier ages, and did not emerge as a separate component until adolescence. While the P1—N1—P2 components are more “adult-like” than “child-like” in the adolescent subjects, the N2 component, a hallmark of the child obligatory response, was still present. Faster rates resulted in the suppression of discrete components such that by 200 ms, only P1 in the adults and adolescents, and both P1 and N2 in the youngest children were discernable. We conclude that both age and ISI are important variables in the assessment of auditory cortex function and maturation. The presence of N2 in adolescents indicates that auditory cortical maturation persists into teen years.

Keywords

Auditory; Event-related potentials (ERPs); Maturation; Cortex; Children; Adolescents

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1. Introduction

The obligatory P1, N1, P2, and N2 components of cortical auditory evoked potentials (CAEPs) provide an important index of auditory system function and plasticity (Kraus, 1999; Ponton et al., 2000; Ponton and Eggermont, 2001; Sharma et al., 2002; Wunderlich and Cone-Wesson, 2006). CAEP methodology is especially advantageous for assessing functional maturation of the brain, as neural activity can be obtained while young participants ignore the sound input. Traditionally, sound processes associated with obligatory auditory responses have been studied in paradigms using long inter-stimulus intervals (ISIs), generally slower than one stimulus per second (Čeponienė et al., 1998; Ohlrich et al., 1978; Ponton et al., 2000; Wunderlich et al., 2006). Long ISI's enhance the amplitude of CAEP components and improve signal-to-noise ratios. However, most of the sound information we receive in daily life occurs at rapid and varying rates. For instance, our ability to understand speech is highly dependent on the accurate perception of rapid variations within the speech stream (Darwin, 1981, 1984; Kraus et al., 1996; Tallal, 1976, 2004; Benasich et al., 2002). Typical speech rates, for example, range from 100 to 200 words per minute, which is equivalent to about 150 ms from the onset of one syllable to the onset of the next (Krause and Braid, 2002). Moreover, deficits in processing acoustic transitions at rates that are crucial for speech perception are thought to contribute to language impairment (Heath et al., 1999; McArthur and Bishop, 2001; Oram Cardy et al., 2005). Despite the importance of temporal processing in auditory event formation, there are few studies that have recorded CAEPs in children at rapid rates (<1000 ms; Čeponienė et al., 1998; Gilley et al., 2005; Ponton et al., 2000; Wang et al., 2005). To maximize the utility of CAEPs as an index of childhood auditory functions in real-world environments, a systematic study of the effect of processing rate on these obligatory components is necessary.

Major developmental features of CAEP morphology have generally been measured by assessing the peak amplitude and latency of individual components. For instance, P1 maturation is characterized by decreases in peak latency and amplitude (Ponton et al., 2000; Sharma et al., 2005). Contributions to the concurrent decrease in amplitude of the P1 component with maturation are not clear but may in part reflect the emergence of the N1 component with age (Ponton and Eggermont, 2001). Most research has focused on maturation of the N1 component because of its prominence in the adult CAEP (Näätänen and Picton, 1987). Information about the P2 and N2 components is less consistently reported across studies. Notably, only Ponton et al. (2000) has examined maturation of the N2 component of the child obligatory response despite its prominence within the CAEP waveform. A summary of the maturational characteristics of the P1—N1—P2 components obtained under slower rates of stimulation have been thoroughly reviewed elsewhere (see Crowley and Colrain, 2004 for review of the P2 component; Ponton et al., 2000, 2002; Tonnquist-Uhlen et al., 1995; Wunderlich and Cone-Wesson, 2006). The focus of the current study is on maturational changes of the CAEP under conditions of rapid and more environmentally realistic ISIs.

An effect of ISI on CAEP morphology is evident from the small number of studies that have addressed this issue of physiological development (Čeponienė et al., 1998; Gilley et al., 2005; Gomes et al., 1999; Trehub et al., 1995; Wang et al., 2005; Werner et al., 1992). While the previous studies are invaluable, they suffer the limitations that children were in mixed age groups and there was no systematic reporting of the full complex of obligatory ERP components (P1—N1—P2—N2) elicited at rapid stimulus rates. Despite these limitations, it is clear that at ISIs faster than 1 s, the most characteristic feature of the waveform recorded in children is the presence of a large positive component, peaking at about 100 ms, followed by a large negative component, peaking at about 250 ms. These waves have generally been identified as P1 and N2, respectively. Prolongation of the ISI above 1 s results in the emergence of an N1-like component which is generally not observed at shorter ISIs. One notable exception is a study by Ponton et al. (2000), who observed a prominent N1 evoked by click trains at an

ISI of 769 ms in children 10 years and older, but with a longer latency than found in adults. While the relatively faster stimulus rates (≤ 1000 ms) appear to obscure the appearance of the N1, it can also be argued that N1 is absent from the waveform because the refractory periods for its generators are generally longer than the ISIs of rapidly presented stimuli.

The present investigation focuses on maturation of CAEP components as modulated by stimulus rates commonly encountered in the environment. Thus, CAEPs were obtained by stimulus onset asynchronies (SOA, i.e., onset-to-onset), of 200, 400, 600, and 800 ms (yielding an offset-to-onset pace of 150, 350, 550, and 750 ms, respectively) in children between the ages of 8–11 years, adolescents aged 16 years, and young adults between the ages of 22–40 years. Adolescents are an understudied population in auditory neuroscience research, and only a handful of studies have included this age range in their investigations (Goodin et al., 1978; Oades et al., 1997; Pang and Taylor, 2000; Ponton et al., 2000; Sharma et al., 1997; Tonnquist-Uhlen et al., 1995). However, they provide an important developmental time point for examining the maturation of auditory evoked potentials from childhood to young adulthood.

2. Methods

2.1. Participants

Forty-nine children and 12 adults participated in the study. All procedures were approved by the Internal Review Board at Albert Einstein College of Medicine. Subjects received a small payment for their participation. Adult participants and parents gave informed consent, and children gave assent, after the experimental protocol was explained to them. Table 1 shows the assignment of the participants by age group and the gender distribution. Participants were recruited by flyers posted in the immediate medical/research community and in local schools. Recruits were pre-screened by phone interview (by a parent for children) to exclude past or present diagnoses of learning, speech/language, hearing, emotional/behavioral, or neurological disorders, or report of special educational services or school grade retention. All of the children were in the age-appropriate grade in school. Recruits who met these criteria were scheduled for a 2-h screening session with a licensed psychologist (author K.L.). To meet criteria for ERP testing, standard scores on all screening tests for cognitive and language function, reading/decoding skills, and phonological processing abilities had to be at least within the average range. Specifically, participants had to have standard scores of at least 85 on the following instruments: Wechsler Abbreviated Scale of Intelligence (WASI) for cognitive function; Woodcock—Johnson-III Tests of Achievement (WJ-III) Letter/Word Identification and Word Attack for reading/decoding; WJ-III Understanding Directions and Children's Essentials of Language Fundamentals-3 (CELF-3) Sentence Repetition for language function; The Phonological Awareness Test (PAT) Rhyming; and The Comprehensive Test of Phonological Processing (CTOPP) core screening tests for phonological awareness, phonological memory, and rapid naming. In addition, participants had to report (parent report for children) fewer than six symptoms of inattention and hyperactivity/impulsivity on a DSM-IV based checklist. There were no significant differences between the children's groups for any of the screening measures (F 's = .01–2.1, p 's = .99–.12). All participants passed a hearing screening test (hearing threshold of 20 dB HL or better from 250 through 4000 Hz).

2.2. Stimuli

Two pure tone stimuli with 50 ms duration (7.5 ms rise/ fall time, calibrated to 75 dB SPL using a Brüel & Kjær 2209 sound level meter) were presented binaurally through insert earphones. One had a frequency of 880 Hz ("A" tone) and the other a frequency of 988 Hz ("B" tone). The two tones were presented continuously in a repeating pattern in which the B tone occurred as every fifth tone in the sequence (AAAABAAAABAAAAB...). Tones were presented with SOAs (onset-to-onset) of 200, 400, 600, and 800 ms in separate conditions. The

current study reports analysis performed for CAEPs elicited by the “A” tones. Responses were derived from 1200 tone presentations for each stimulus condition. Data analysis of the “B” tones will be presented in a separate report.

2.3. Procedure

Participants sat in a comfortable reclining chair in an electrically-shielded and sound-attenuated booth. Participants were instructed to ignore the stimuli and watch a self-selected, captioned video that was presented without sound during electroencephalography (EEG) recording. The order of presentation of the conditions was counter-balanced across participants. Breaks were given as required. During short breaks (1–3 min), participants remained seated but took a moment to shift position. During longer breaks (10–15 min), participants were disconnected from the recording system and allowed to walk and have a snack break. The total recording session was 1.5–2 h, which included the time for electrode placement.

2.4. Electrode placement and EEG recording

The EEG recordings were obtained using a 32-channel electrode cap that incorporates a subset of the International 10–20 system (Jasper, 1958). Additional electrodes were placed over the left and right mastoids (LM and RM, respectively). The tip of the nose was used as the reference electrode during recordings. F7 and F8 electrode sites were used in a bipolar configuration to monitor the horizontal electro-oculogram (HEOG). FP1 and an electrode placed below the left eye were used in a bipolar configuration to monitor the vertical electro-oculogram (VEOG). All impedances were maintained below 5 k Ω for adults and below 10 k Ω for children. The EEG and EOG were digitized (Neuroscan Synamps amplifier, Compumedics Corp., El Paso, TX) at a sampling rate of 500 Hz (0.05–100 Hz bandpass) for adults and 1000 Hz (0.05–200 Hz) for children. EEG was filtered offline with a bandpass of 1–15 Hz. Artifact rejection was set to exclude activity exceeding 75 μ V for adults and 100 μ V for children after EEG epochs were baseline corrected. Epochs were 500 ms in duration, starting 100 ms pre-stimulus onset and ending 400 ms post-stimulus onset.

2.5. Data reduction and analysis

2.5.1. Global field power—Global field power (GFP) analysis provides a reference free measure for component identification that is based on the spatial root mean of the squared voltage deviations across electrode recordings from the entire scalp (Lehmann and Skrandies, 1980,1984; Michel et al., 2004). Thus, GFP provides a global measure of the electric field at the scalp without the bias of the experimenter’s selection of a single electrode (or set of electrodes) for identifying the components within the epoch used to visualize the waveform. GFP was calculated from the grand mean waveforms for each age group and condition separately. There has been considerable discrepancy regarding the identification of CAEP components in children, which may be in part due to the electrode sites chosen to measure the components. Although EEG is generally recorded from at least 32 electrodes, statistical analyses of the obligatory responses often rely on a single electrode, such as Cz (e.g., Gilley et al., 2005), which is generally the site of greatest signal-to-noise ratio in the adult obligatory responses, or on a small subset of electrodes around Cz (e.g., Gomes et al., 1999; Ponton et al., 2000). GFP aided in the identification of the obligatory components and was used in comparison with the evoked potentials for assessing maturation and rate effects.

2.5.2. Event-related potentials—CAEPs evoked by “A” tones were separately averaged together for each subject in each condition. Responses evoked by the “A” tone following the “B” tone were excluded from analysis. 720 epochs remained. Approximately 10% of the epochs were rejected due to artifact, leaving an average of about 640 epochs per individual per condition.

The peak latency of each component of the obligatory CAEPs (the P1, N1, P2, and N2) was identified by the GFP calculation on the grand averaged waveforms for each group (Table 2 shows the GFP peak latency for each component in each condition and age group; Fig. 1 presents the GFP peaks). The latency and amplitude of P1, N1, P2 and N2 were statistically analyzed for the 400, 600, and 800 ms conditions from the ERP waveforms as opposed to the GFP to be comparable with the extant literature. The data from the 200 ms SOA condition were analyzed separately because of the dramatic change in morphology of the waveforms relative to longer SOA conditions. A 30 ms window, centered on the peak latency determined from the GFP, was used to obtain the mean amplitude of the components in each individual. Amplitudes were measured relative to the average voltage of the pre-stimulus baseline. Measurement windows determined from the GFP were used to analyze the recordings from Fz, Cz, and Pz. The latency of each component was determined for each individual using a peak detection program that finds the maxima (negative or positive) within the specified measurement window (Neuroscan 4.3).

In the fastest 200 ms condition, the full range of components elicited in the 800 ms condition was not discernable in any of the age groups. A positive and negative component dominated the child waveforms and a repeating positive component, following the stimulus rate, was evident in the adolescents and adults. The components were measured accordingly. The “positive component” was referred to as P1, and the “negative component” in the pediatric waveforms was referred to as N2. Statistical measurements comparing the amplitude and latency by age group were made separately for this condition using the GFP peak to determine the interval for measuring the individual data as described above.

Mixed-model repeated-measures ANOVA was used to separately compare amplitude and latency, using factors of Age $\times$ Rate (Age was the between-subjects factor and Rate was the within-subjects factor). One-way ANOVAs were used for the 200 ms condition. Greenhouse Geisser corrections were applied and *p* values reported. Post hoc analyses were calculated using Tukey HSD for unequal *N*.

2.5.3. Topography

2.5.3.1. Global dissimilarity: To identify potential differences in the topographic distribution of the recorded CAEP components at different stimulus rates, we obtained an index of global dissimilarity, by calculating the square root of the mean of the squared differences between all corresponding electrodes after normalizing the data by dividing the mean voltage by its own GFP (Lehmann and Skrandies, 1980; Michel et al., 2004). The global dissimilarity provides an index of the degree of topographic similarity between two electrical fields. Numbers closer to 2 indicate topographic incongruence and numbers closer to 0 indicate topographic homogeneity. Thus, the index of global dissimilarity was used to indicate whether the same component elicited at different stimulus rates within an age group arose from similar or different underlying neural generator configurations. Additionally, this measure was used to indicate degree of similarity of topographic distributions for different CAEP components (P1, P2, N2) elicited within an age group at the longest (800 ms) SOA condition.

2.5.3.2. Scalp current density: A reference-free measure of the current scalp density (CSD) was also used to assess the P1 and N2 components. Maps showing CSD were computed from the mean amplitude waveforms, corresponding to the peak latency of the component for each group in each condition as defined by the GFP (see Table 2). The CSD analysis, an estimate of the second spatial derivative of the voltage potential using the spherical spline surface Laplacian algorithm (Perrin et al., 1989) was performed with BESA 2000 FOCUS software to sharpen the differences in the scalp fields and obtain additional information about potential cortical generators. This method uses information from all electrodes on the head, providing

a more accurate estimation for showing the scalp areas where the current either emerges (sources) from the brain into the scalp or enters (sinks) from the scalp into the brain. The CSD maps, expressed in $\mu\text{V}/\text{cm}^2$, display the 21 interpolated channels. This facilitates interpretation of the spatio-temporal contributions from multiple overlapping sources.

3. Results

3.1. Maturation effects

To provide data unbiased by analysis at a single electrode site, component identification was initially performed using GFP analysis (Lehmann and Skrandies, 1980,1984;Michel et al., 2004;Shafer et al., 2007). Table 2 reports the GFP peak latency for each component in each condition and age group. Fig. 1 presents the GFP waveforms. Because of the profound ISI effects on CAEP morphology, component identification is best revealed in responses evoked by the slowest stimulus rate (800 ms SOA condition). Using the field strength as the indicator of components in the waveform, the response in adults consisted of components peaking at 40, 90, and 162 ms (Fig. 1A, black trace). The relationship between components identified through GFP analysis and the CAEP in the 800 ms SOA condition is readily observed from recordings at the Fz electrode (Fig. 2). These peaks correspond to the P1, N1, and P2 CAEP components (Fig. 2, black trace). In contrast, markedly different patterns of GFP and CAEP morphology were observed in the youngest age groups. GFP in the response evoked in 8-year-old was characterized by an initial large amplitude biphasic increase in power with peaks at 85 and 142 ms, followed by a third peak at 243 ms (Fig. 1A, dashed blue trace). When compared to the CAEP recorded at Fz, these peaks correspond to the P1, P2, and N2 CAEP components (Fig. 2, dashed blue line). This profile is characteristic of the child obligatory ERP waveform and consistent with results from other studies (Čeponienė et al., 1998;Gilley et al., 2005;Ponton et al., 2000;Vidal et al., 2005;Wunderlich and Cone-Wesson, 2006).

The peaks identified with GFP analysis in the 8 year-old were still present in the older children (ages 9–16 years), though the overall power of each component decreased with progressive age (Fig. 1A). In parallel with the power decreases was a concurrent decrease in the CAEP amplitude recorded from Fz (Fig. 2). No distinct peak of power corresponding with the adult N1 was visible for any of the child or adolescent waveforms (Fig. 1A). The CAEP did reveal, however, a small N1 for 16-year-old subjects, and a negative-going deflection for 11-year-old subjects in the CAEP recorded at Fz (Fig. 2). Complex shifts in component latency also occurred with maturation of the CAEP. The latency of the first peak (P1) progressively decreased toward adult values (Table 2), whereas the second component peak (P2) and the third component peak (N2) remained stable into adolescence.

3.2. Effects of stimulus rate

The effects of rate on GFP are profound at all age groups (Fig. 1). Key changes that occur as a function of stimulus rate in adults include the progressive suppression of the GFP peak identified as N1. No peak corresponding with the N1 component was observed in the GFP at SOAs faster than 600 ms. The peak corresponding to the P2 component had a different time course than N1, and could be observed in the adults at SOAs as rapid as 400 ms. In the 200 ms condition, only the peak corresponding to the P1 was observed.

In the youngest age group (8 years), peaks of power corresponding to P1 and N2 persist through all stimulus rate conditions, while P2 was no longer observed as a discrete peak in the GFP at SOAs faster than 800 ms. GFP profiles at ages 9 and 10 were remarkably similar to those seen at age 8. Major differences in the maturation of rate effects begin at age 11, in which a discrete peak of power corresponding to P2 can be seen in the 600 ms condition and as an inflection point in the 400 ms condition. The inflection of P2 at 400 and 600 ms SOA condition in the 9-

and 10-year-old children transitions into the more discrete response of the 11-year-old. At 200 ms SOA, the peaks corresponding to P1 and N2 components dominate the waveforms in all the younger child age groups. Patterns seen at age 16 are similar to that of age 11, except that the peak corresponding to N2 was not observed as a discrete component at the fastest 200 ms condition. In summary, the key effect of rate as a main factor was the suppression of discrete components such that by 200 ms, only P1 in the adults and 16-year-olds, and P1 and N2 in the youngest children, remained.

These patterns are partly mirrored in the waveforms recorded at Fz (Fig. 3), which illustrates the grand-averaged waveforms for each SOA condition in each age group. In the younger children (8–10 years), the waveforms were dominated by a broad, biphasic positive component, followed by a large amplitude negative component peaking around 250 ms at SOAs slower than 200 ms (blue, green, and black traces). A minor negative-going deflection distinguishing the first (P1) and second (P2) positive peak occurred at about 100 ms. P2, as a second distinct peak, was most evident in the 800 ms SOA condition (black trace). More extreme differences in morphology based on SOA began with the 11-year-old. A decrease in amplitude of the P1 component was seen along with a larger negative deflection in the biphasic positive peak at the slower conditions (black trace). The appearance of N1 component occurred in the 16-year-old in the 800 ms condition (black trace) and was clearly present in the 400–800 ms SOA conditions in the adults. In contrast, the GFP-defined N1 in the adults occurs only in the 800 and 600 ms conditions (see Fig. 1). The decrease in CAEP amplitude that occurred with age was most pronounced in the two oldest groups (adult and adolescents) when compared to those of the 8–11-year-old children (note the decreased μV scale for the adults and 16-year-old). The dramatic overall decrease in amplitude along with the simplification of the morphology of the waveforms was evident in the 200 ms condition (red trace). CAEPs evoked at 200 ms SOA in the 8–11-year-old children, at the Fz electrode, were characterized by positive and negative deflections time-locked to the 200 ms stimulus repetition rate. In contrast, CAEPs in the adults and adolescents were dominated by positive deflections time-locked to the SOA without the intervening negativities.

3.3. Topographic features of CAEP components

Topographic features of the CAEP components elicited in the 800 ms SOA condition are presented in Fig. 4, which illustrate the responses recorded along the midline electrodes Fz, Cz, and Pz and lateral, temporal electrodes T7 and T8 (anterior lateral). CAEPs recorded from T7 and T8 are notable for the locally generated “T-complex” that was present in all age groups (Ponton et al., 2000; Wolpaw and Penry, 1977). The T-complex was not observed in the 200 ms condition for any of the age groups (data not shown). The GFP peaks do not differentiate the activity of the lateral fields, thus demonstrating dominant field activity of the supratemporal plane for the exogenous potentials, with peaks of power matching the ERP components observed at Fz and Cz. Moreover, important age-related differences in the scalp distribution of the individual components of the CAEPs can be identified along midline sites that are not distinguished in the GFP (Table 3). Interestingly, for example, the biphasic positive peak is seen at Fz but only the second peak (P2) is evident at Cz.

The latency and amplitude of P1, N1, P2 and N2 were statistically analyzed for the 400, 600, and 800 ms conditions from the ERP waveforms as opposed to the GFP to be comparable with the extant literature. The data from the 200 ms SOA condition were analyzed separately (see Section 2).

3.3.1. P1 component—GFP peaks for P1 were observed for all age groups and stimulus conditions and were included in the latency (with factors of stimulus rate and age group,

measured at Fz only) and amplitude (with factors of electrode [Fz, Cz, and Pz], stimulus rate, and age group) measurements.

3.3.1.1. Latency: Both age and rate affected the latency of the P1. There was a main effect of age ($F(5, 55) = 48.8, p < 0.0001$) and rate ($F(2, 110) = 27.90, \epsilon = 0.98, p < 0.0001$) with no interaction. Post hoc Tukey calculations revealed that the latency decreased significantly with increasing age (except that the 9- and 10-year-old latencies did not differ, which may be due to the lower number of subjects in the 9-year-old group), with its shortest latency in adults (see Figs. 2 and 3). Additionally, latency of the P1 component was longer with faster SOAs ($800 < 600 < 400$).

3.3.1.2. Amplitude: There was a main effect of age ($F(5, 55) = 8.98, p < 0.0001$), rate ($F(2, 110) = 11.57, \epsilon = 0.97, p < 0.0001$), and electrode ($F(2, 110) = 273.69, \epsilon = 0.65, p < 0.0001$) on the amplitude of P1. Post hoc analyses revealed that, in general, the amplitude of the P1: (1) was larger for the 8-year-old compared to all other age groups; (2) was larger at the two fastest stimulus rates; and (3) was largest at Fz.

In the child groups (8–11 years), the P1 amplitude decreased along the midline ($Fz > Cz > Pz$), whereas in the 16-year-old P1 amplitude was maximal at fronto-central electrodes (i.e., amplitude at Fz and Cz were not significantly different) and in adults there was no difference in P1 amplitude by electrode (electrode $\times$ group interaction, $F(2, 110) = 15.33, \epsilon = 0.65, p < 0.0001$). Stimulus rate did not affect the amplitude of P1 at the Pz electrode (rate $\times$ electrode interaction, $F(4, 220) = 3.14, \epsilon = 0.65, p = 0.034$). A three-way interaction ($F(20, 220) = 1.81, \epsilon = 0.65, p < 0.05$) occurred because the effects of stimulus rate and electrode were dependent upon age. In adolescents, P1 amplitude decreased along the midline in the 400 ms condition (similarly as occurred at all stimulus rates in the younger children) but not in the slower conditions. These effects are depicted in Fig. 5.

3.3.2. N1 component—The N1 amplitude (using factors of electrode [Fz, Cz, Pz] and stimulus rate [600 and 800 ms SOA]) and latency were analyzed in the Adult group where the GFP peaks corresponding to the N1 component were observed.

3.3.2.1. Latency: There was no main effect of rate on the latency of N1 ($F < 1, p > .95$).

3.3.2.2. Amplitude: There was a main effect of rate ($F(1, 11) = 21.64, \epsilon = 1.0, p < .001$) and a rate $\times$ electrode interaction ($F(2, 22) = 19.32, \epsilon = 0.70, p < .001$). N1 was largest in the 800 ms condition. Post hoc analysis revealed that the N1 amplitude was largest at Cz in the 600 ms condition but not different than Fz in the 800 ms condition (fronto-central distribution).

3.3.3. P2 component—The latency (factors of stimulus rate [400, 600, 800 ms] and age group [9 years-adults]) and amplitude (factors of electrode [Fz, Cz, Pz], stimulus rate [400, 600, 800 ms], and age group [9 years-adults]) measurements of P2 were analyzed in all groups except for the 8-year-olds because distinct GFP peaks for P2 were not present in this age group across all SOA conditions (see Fig. 1).

3.3.3.1. Latency: There was a main effect of age ($F(4, 46) = 7.97, p < .0001$), rate ($F(2, 92) = 18.64, \epsilon = 0.90, p < .0001$), and an interaction between age and rate ($F(8, 92) = 2.13, \epsilon = 0.90, p < .05$) on P2 latency. There was no difference in P2 latency among the children (9–16 years). Adult latency was longer than the 9–11-year-olds but not different from the adolescents. P2 latency was shorter with faster SOAs ($800 > 600 > 400$ ms), though the decreased latency caused by more rapid stimulus rates was also dependent upon age. The adult latency of the P2 was longer than all children (but not adolescents) in the 800 and 600 ms conditions but did not differ from the children in the 400 ms condition.

3.3.3.2. Amplitude: There was no main effect of rate. Rate effects were seen, however, in the interaction with electrode ($F(4, 184) = 7.45, \epsilon = 0.60, p < .001$). P2 amplitude was smaller in the 400 ms condition compared to the 600 and 800 ms SOA conditions at Cz and Pz, but there was no such difference in amplitude across stimulus rates at Fz. There was also a main effect of electrode ($F(2, 92) = 31.38, \epsilon = 0.75, p < .0001$). Post hoc analysis revealed that P2 amplitude was largest at Cz ($Cz > Fz > Pz$). There was also a main effect of group ($F(4, 46) = 3.36, p < .02$), though post hoc analysis showed only that the 10-year-old had a larger amplitude than the adults. There was no interaction of age with rate or electrode. These effects are depicted in Fig. 6.

3.3.4. N2 component—Adults were not included in the analysis for N2 as no GFP peak was observed for this component. Amplitude (factors of electrode [Fz, Cz, Pz], stimulus rate [400, 600, 800 ms], and age group [8–16 years]) and latency (factors of stimulus rate [400, 600, 800 ms], and age group [8–16 years]) were measured.

3.3.4.1. Latency: There was a main effect of age ($F(4, 44) = 3.37, p < .02$), but no main effect of rate ($F(2, 88) = 2.11, p > .12$), and no interaction ($F(8, 88) = 1.06, p > .40$). Post hoc analyses revealed that the 8-year-old had a longer N2 latency than the 10-year-old.

3.3.4.2. Amplitude: N2 amplitude was modulated by age ($F(4, 44) = 7.28, p < .001$), rate ($F(2, 88) = 7.21, \epsilon = 0.96, p < .01$), and electrode ($F(2, 88) = 164.20, \epsilon = 0.74, p < .0001$). The factor of electrode interacted with both age ($F(8, 88) = 3.81, \epsilon = 0.74, p < .01$) and rate ($F(4, 176) = 10.76, \epsilon = 0.65, p < .0001$). N2 amplitude had a frontal scalp distribution, with a maximum amplitude at Fz electrode ($Fz > Cz > Pz$). N2 amplitude was smaller in the adolescents than in the 8–11-year-olds, but interacted with electrode. There was no difference in amplitude at Pz for any age group. N2 amplitude was also smaller in the 400 ms SOA condition compared to the 600 ms SOA condition, but interacted with electrode site. N2 amplitude was smaller in the 400 ms SOA condition than both 600 and 800 ms SOA conditions at Fz. These effects are depicted in Fig. 7.

3.3.5. 200 ms SOA condition—Latency and amplitude of the CAEP components in the 200 ms condition were analyzed in separate ANOVAs because the waveform morphology was so distinctive from the other SOA conditions. Adults and adolescents were included in the P1 analysis but not N2 because GFP peaks were not present in these groups for this component. Latencies of P1 and N2 latency were measured at Fz.

3.3.5.1. P1 component: There was a main effect of electrode ($F(2, 110) = 122.83, \epsilon = 0.83, p < .0001$) and an interaction of electrode with age ($F(2, 110) = 2.80, \epsilon = 0.83, p < .01$) on the amplitude of the P1. There was no main effect of age. In general, the amplitude of P1 was largest at Fz and smallest at Pz. However, in the adults there was no difference in amplitude among the midline electrodes. In the 16-year-old, P1 was largest at Fz and there was no amplitude difference between Cz and Pz. In the 11-year-olds, $Fz > Cz > Pz$, and in the three youngest groups, both Fz and Cz were larger than Pz.

There was a main effect of age on P1 latency ($F(5, 55) = 22.630, p < .0001$). Post hoc analysis showed that there was no difference in latency among the 8–10-year-old children (~114 ms). P1 latency significantly decreased in 11-year-old (93 ms) and again in adults (79 ms).

3.3.5.2. N2 component: There was a main effect of electrode on the amplitude of N2 ($F(2, 70) = 14.28, \epsilon = 0.78, p < .0001$), with no main effect of age and no interaction. Post hoc analysis revealed that amplitudes at Fz and Cz were larger than Pz. There was a main effect of age ($F(4, 44) = 3.36, p < .02$) on N2 latency. The 8-year-olds had a longer N2 latency than the 16-year-olds.

3.4. Topography (global dissimilarity and CSD)

The topographic features of the CAEPs and global dissimilarity measures offer complementary insights into the configuration of the generators contributing to the scalp-recorded activity. The index of global dissimilarity was calculated to indicate whether the P1, P2, and N2 components elicited at different stimulus rates within an age group arose from similar or different underlying generator configurations (Fig. 8A—C). N1 was excluded from analysis as GFP was absent for this component in the younger age groups. Additionally, a global dissimilarity index was calculated to discern topographic distributions for the different CAEP components (P1, P2, N2) elicited within-subjects at the longest (800 ms) SOA condition (Fig. 8D).

Marked differences in global dissimilarity were observed between responses recorded in children and adolescents on the one hand, and adults on the other hand. A high degree of similarity in overall global distribution of the P1 generators was observed for the 8–16-year-old children across stimulus rate conditions when compared to the adults. In marked contrast, a high degree of dissimilarity between the 200 and 800 ms SOA conditions was observed in adults (Fig. 8A, black trace). These findings indicate a profound developmental shift in the contributions of generators for P1 that occurs between adolescents and adults. Interestingly, the P1 elicited in the 400 vs. 600 ms SOA conditions in the adults showed similar neural configurations, indicating that major topographic configuration changes occurred between the 200 and 400 SOA and 600 and 800 SOA conditions. Whereas profound developmental changes occur in the generator configuration for P1, there was marked stability of the configuration for P2 at all ages and at all examined SOA conditions (Fig. 8B). P2 was absent in the 200 ms SOA condition, and was therefore not included in the analysis. Although the N2 component was present at all stimulus rates in children, global dissimilarity measures were more variable than other components across ages, and it appears to have a different underlying generator configuration at the 200 ms stimulus rate compared to the slower rates.

The within age-group comparisons of global dissimilarity measures for the waveforms evoked in the 800 ms SOA condition (Fig. 8D) indicate that the neural configuration underlying generation of the P1, P2, and N2 became increasingly dissimilar with maturation. The 8-year-old responses indicated a high degree of topographic similarity even at this relatively long SOA condition. In contrast, there was indication of some dissimilarity of the neural configuration underlying the CAEP components in the 9- and 10-year-olds, and then an increase in dissimilarity again with the 11- and 16-year-olds.

CSD maps provide a striking example of the similarity in topographic configuration for the P1 and N2 components across age and stimulus rate when compared against configurations in adults. Fig. 9 displays the left and right hemisphere views of CSD maps for P1 for each age group and stimulus rate. The bilateral frontal maxima of P1 are seen consistently across stimulus rate and age group in children and adolescents. In contrast, a central distribution of P1 is seen in the adults except in the 200 ms condition. Now, maxima are centered at frontal electrodes in a pattern that is similar to that in children and adolescents. The CSD configurations are consistent with the index of global dissimilarity, showing homogeneity of topographic configurations for the P1 components in the pediatric waveforms.

CSD maps for N2 are depicted in Fig. 10 for the children and adolescents, as this component was not evident in the adult CAEPs or GFP. A frontal maximum for N2 can be observed across all SOA conditions. In contrast with the P1 component, and in conformity to global dissimilarity measures, the neural configuration for N2 differs between the 200 ms SOA condition and all slower rates of presentation.

4. Discussion

The present study used a sequence of pure tone stimuli to assess effects of maturation and stimulus presentation rate on the CAEPs in childhood and adolescence. Overall, there was an interaction between age and stimulus rate on the morphology, amplitude, and latency of the obligatory auditory evoked potentials.

4.1. Maturation effects

Maturation of the CAEPs is an extended process with profound effects on the appearance and disappearance of some components, and on the amplitude and latency of other components. The principal changes with age were observed in the peak latency of the components in the longest SOA condition (800 ms). For example, in contrast to the 40 ms peak of the P1 component in adulthood, in the youngest age group tested (8 years), P1 was maximal at 85 ms, decreased to 73 ms at 11 years of age, and to 66 ms in adolescence (Ponton et al., 2000; Sharma et al., 2005). The P2 component, on the other hand, was stable in latency across childhood ages (approx. 140 ms peak latency), consistent with previous studies (e.g., Ponton et al., 2000). The child waveforms were dominated by a broad biphasic positive component with an inflection between the two peaks that slowly emerged as a negative-going deflection, finally appearing as a discrete N1 component in the adult. With the emergence of N1 in adolescents, there was a lengthening of the peak latency of P2 and decrease in its amplitude through adulthood. The following N2 component showed relative stability in amplitude and latency through age 10, followed by a progressive decrease in amplitude of the component to the point where an N2 was not seen in the mature adult waveform. The N2 should not be construed as an endogenous waveform of target detection, but instead as a developmentally specific exogenous waveform (Takeshita et al., 2002). Thus, persistent changes in the morphology, latency, and amplitude of the CAEP waveforms continued into adulthood. These data indicate that maturation of the obligatory auditory evoked potentials progresses well into the teen years.

Human auditory cortex is known to have an extended period of anatomical development (Moore and Guan, 2004). The current data demonstrate aspects of this continuing development through maturation of the CAEP, and which are consistent with findings from other laboratories (Johnstone et al., 1996; Oades et al., 1997; Ponton et al., 2000, 2002). The P1 peak latency was still significantly longer in the 16-year-old group than in adults, and although the N1 peak clearly emerged as a separate component, the amplitude was still significantly smaller than the amplitude of N1 in adults and not distinguished as a peak in the GFP. Moreover, the N2 component persisted into adolescence. These differences indicate continuing maturation of basic sound detection processes. Continued development of auditory cortex, such as volumetric changes in the cytoarchitecture (Moore and Guan, 2004), maturation of synaptic efficacy (e.g., increase in the amount of transmitter released at the presynaptic terminal) and continuation of myelin formation of axons, likely contributes to the modification in CAEP morphology observed at the scalp (Eggermont, 1985, 1988).

4.2. Effects of stimulus rate

Key changes that occurred as a function of stimulus rate included the progressive suppression of the amplitude of the N1 in adults. The N1 component was not observed as a peak of power in the GFP analysis for the 200–400 ms conditions, and moreover, in the 200 ms condition only the peak corresponding to the P1 was observed. In the youngest age group tested (8 years), the peaks corresponding to P1 and N2 persisted through all stimulus rate conditions, while the P2 component was no longer observed as a discrete peak in the GFP at stimulus rates slower than 800 ms. The identifiable peaks in the 9- and 10-year-old groups were remarkably similar to those seen for age 8. Significant differences in the child waveforms mainly occurred starting

at age 11, in which a discrete P2 peak was present in the 600 ms condition and as a distinct inflection point in the 400 ms condition.

Another major feature of increasing stimulus rate was the dramatic switch in the morphology of the waveform that occurred at the fastest stimulus rate tested in this study, the 200 ms condition (150 ms stimulus offset-to-onset). At 200 ms, the peaks corresponding to P1 and N2 components dominated the waveforms in all of the younger child age groups, including the 11-year-olds. Responses observed at age 16 were similar to those observed for 11-year-old group, except that the peak corresponding to N2 was not seen as a discrete component at the fastest, 200 ms condition. In summary, the key effects of rate by itself, was the suppression of discrete components such that by 200 ms, only P1 in the adults and 16-year-olds, and P1 and N2 in the youngest children remained. The waveform switched from a three-component complex to a two-component complex in children and a one-component complex in adolescents and adults. The overall amplitude of the waveforms was also reduced compared to the other, slower conditions (400–800 ms).

Importantly, the effects of stimulus rate on the CAEP mirrored maturation effects. The changes in amplitude and latency that occurred with decreasing age were also observed with increasing stimulus rate within an age group. That is, as stimulus rate increased, the overall latency and amplitude of the components appeared with fewer features of the mature waveform: the P1 latency was longer, the N1 amplitude (or negative deflection in the biphasic positive peak) was smaller, and P2 latency was longer at both faster rates and in younger children (see Fig. 3). The increased speed of presentation resulted in waveforms which appeared to reflect patterns observed in younger age groups, possibly due to the extra processing load that is put on the auditory system. For example, the morphology of the waveforms elicited in the 400 ms condition in the 16-year-old group appeared similar to those elicited in the 800 ms condition in the 11-year-old group.

Alternatively, it is possible that the reduction of components seen at the faster rates is due to overlap of the longer latency components with earlier portions of the waveform (e.g., N2). One possibility is that the positive peak, observed with a later latency in the 200 ms SOA condition in all age groups, represents the fusion of the P1 and P2 components (Ponton and Eggermont, 2001). This would be suggested in the slower conditions as well, such that fusion of P1 and P2 appears as a positive biphasic peak in the children, whereas at the fastest rate only the positive fused peak and N2 remains. Although this is a possibility, we do not think that overlap of components is a main contributing factor to the observed effects of stimulus rate on the CAEPs for the following reasons: (1) Effects of stimulus rate were observed in adults. The N1, which was stable in latency in the 400–800 ms SOA conditions, was not elicited in the 200 ms SOA condition. This effect of stimulus rate cannot be explained by overlap because the longest latency obligatory component (P2) peaked at approximately 160 ms (i.e., prior to the onset of the next stimulus) and no N2 was elicited. (2) The peak of the P2 in all longer conditions occurred prior to 200 ms in children and adolescents, but was absent from the evoked waveform in the 200 ms SOA condition. In the 200 ms SOA condition, the onset of the next tone occurred when P2 returned to baseline, yet the N2 component was still elicited. In addition, the P1 to the next tone can still be observed in the waveforms 100 ms post-stimulus onset, at approximately 300 ms in the epochs displayed. Therefore, overlap with N2 does not explain the absence of the biphasic peak observed in the children's CAEPs at the fastest stimulus rate. Moreover, the modification in the waveforms observed at the fastest rate is similar to the effect observed in adults, in which no overlap occurred.

Regardless of the underlying mechanisms contributing to the CAEPs elicited at 200 ms SOA, empirically, the waveform looks similar to the steady-state response of the middle-latency (ML) CAEPs in all age groups. The ML steady-state response is observed as a quasi-sinusoidal

waveform that is elicited by repetitive sounds matching the modulation frequency of the stimulus, usually at 40 Hz. It is thought to represent a composite of the ML components (Herdman et al., 2002; Poulsen et al., 2007). In the current data, the oscillating waveform elicited at the 200 ms SOA rate has the appearance of a steady-state response for long-latency components. However, the characterization and significance of this oscillating waveform, elicited at a rate similar to syllable duration, remains to be determined.

Some effects of maturation were seen in the amplitude and latency of the CAEP components in the current study using faster rates that have not been observed in previous studies using longer stimulus rates. For example (1) N1 is observed as a discrete component at ISIs longer than 1 s but with longer peak latency in children compared to adults (e.g., Bruneau et al., 1997; Čeponienė et al., 1998; Gomes et al., 1999). In the current study, the N1 component was not present in the pediatric waveforms as a discrete component; rather, it appeared as a negative deflection within the positive waveform. The biphasic positive component of the child waveform is consistent with other reports using stimulus rates faster than 1 s (e.g., Gilley et al., 2005; Ponton et al., 2000; Shafer et al., 2007; Sharma et al., 1997, 2005). (2) The N2 has been observed in previous studies at a consistent latency of 250 ms, when ISIs were over 1 s, and therefore has often been called the “N250” (Shafer et al., 2000; Vidal et al., 2005). However, in the current study, the peak latency of the N2 decreased with faster rates and was observed with peak latencies varying by age group from 216 to 247 ms.

While there are multiple simultaneous generators for P1 that include mesial Heschl’s gyrus (primary auditory cortex) and the planum temporal, the predominant generator is thought to encompass more intermediate portions of Heschl’s gyrus (Liégeois-Chauvel et al., 1994; Godey et al., 2001; Yvert et al., 2005). P1 is the only CAEP component that is consistently reported across stimulus paradigms and laboratories as decreasing in latency and amplitude with increasing age. This effect of maturation on P1 latency has been found in studies using both the shorter SOAs of the current study and at longer SOAs of previous studies (Sharma et al., 1997, 2002; Ponton et al., 2000, 2002). Of note is the dramatic increase in the peak latency of the P1 that occurs at the fastest 200 ms condition, even in adults (Wang et al., 2005). The P1 thus appears to have distinctive characteristics from the N1 and the P2 components. P1 persists in the waveform regardless of age or stimulus rate, which in part indicates a different refractory period for this component and its generators (Rosburg et al., 2004) relative to the other obligatory components of the CAEP. The persistence of the N2 waveform at all stimulus rates in the child evoked responses suggests similar generator properties as P1.

The dominance of the N1 component in adults has brought considerable speculation about its absence in the childhood waveform. One speculation is that the N1 is absent at longer ISIs in children because the refractory periods for its generators are longer in childhood than adulthood. This is concordant with our data showing an interaction with age and rate. Increasing the rate in adults also led to the disappearance of the N1, when the refractory period for its generators in adulthood was exceeded. Interestingly, rates at which N1 dissipated from the waveforms are consistent with common, real world values routinely present in speech, music, and the environment in general. This raises some fundamental questions about what crucial perceptual processes are indexed by N1, given the ease with which we decode complex sound information in rapidly occurring acoustic environments typical of speech and music. Although N1 has been suggested to represent multiple perceptual processes, such as pitch (Guiraud et al., 2007; Hirose et al., 2005; Seither-Preisler et al., 2006), stream segregation (Gutschalk et al., 2005), or consciousness (Kotchoubey, 2005; Plourde and Picton, 1991), these relationships may not serve as key indices of the underlying neural events relevant for perception.

4.3. Topographic features of the response

Dramatic differences in the scalp topography of the CAEP responses were observed in children compared to adults. The most striking finding was the strongly frontal scalp distribution of the P1 component in the children compared to adolescents and adults (Figs. 4 and 7 and Table 3). The scalp distribution observed for the P1 and N1 components in adults is typically fronto-central, often with a maximum at the vertex (Cz) (Näätänen and Picton, 1987). This topography was also found in the current study. P2, on the other hand, had a central distribution in the children, whereas in adolescents and adults it was maximal at fronto-central sites (Crowley and Colrain, 2004). A difference in distribution for P2 and P1 is consistent with the report by Crowley and Colrain (2004) suggesting that P2 arises from different generator configurations within auditory cortices than P1. The N2 component, which may not be present in adults at stimulus rates under 1 s, had a frontal distribution in the child and adolescent waveforms.

Although the GFP peaks indicated no discrete N1 component in adolescents and children, the development and emergence of the N1 component can be seen in the CAEP waveforms at Fz. The prominence of the P2 component, with a broader distribution in children than adults or adolescents, can also be seen in the scalp potentials. Moreover, a distinct T-complex, which is localized over the T7/8 electrodes, is present in the CAEP waveforms even though it is not identified in the GFP. These distinctive differences in surface scalp topography of the CAEP components illustrate both the utility and limitations of the GFP as a measure for identifying the obligatory components. On the one hand, the choice of a single electrode for determining the presence and absence of childhood CAEP components within a waveform could lead to dramatically different conclusions if only a single electrode site were chosen as a measurement point. On the other hand, GFP alone as an index of the components would miss the distribution of characteristic features that are identifiable at the local level of scalp topography, such as the T-complex which was not identified as a separate component in GFP.

5. Summary and conclusions

The current results provide insight into some important considerations for using CAEP to study auditory system functions, and may clarify, at least in part, some discrepancies in the previous results reported in the child ERP literature. Our main finding was an interaction between age and ISI on the amplitude and latency of the CAEP waveform components: P1, N1, P2, and N2, and is consistent with Gilley et al. (2005). The main effects of maturation were seen as (1) a decrease in P1 latency and amplitude; (2) an increase in N1 amplitude until its appearance as a discrete component in adulthood; (3) an increase in P2 latency along with a decrease in its amplitude; and (4) a decrease in N2 latency and amplitude. The overall effect of increasing the stimulus rate was the loss of features of the mature CAEP waveform evoked by a sound, ultimately resulting at the fastest rate in a two-component complex (P1—N2) in children or a single-component (P1) in adolescents and adults.

There are three main points to consider regarding electrophysiological recordings in children:

1. The scalp topography of the CAEP components fundamentally differs in children (8–16 years) compared to adults. P1, N1, and P2 are all maximal at fronto-central sites in adults. In contrast, P1 is maximal at frontal sites and P2 maximal at central sites in children. The adolescent group was more similar to the adult distribution for P1 and P2 but still had the frontal N2 of childhood. The differences in scalp distribution highlights the importance of the choice of recording sites and electrodes used to measure the CAEP components, as these choices hold important implications for the conclusions drawn about the presence or absence, and the amplitude and latency of the responses.

2. The CAEP morphology changes fairly rapidly from 8 to 16 years and interacts with stimulus rate. Differences in both amplitude and latency of the various CAEP obligatory components were observed, sometimes from year-to-year. The most dramatic shift in morphology occurred at 11 years, in which the negative deflection within the positive peak is largest, affecting the amplitude and latency of the emerging P1 and P2 peaks. Thus, developmental studies should consider the ages that are grouped together when the P1—N1—P2—N2 components are to be studied. The subject population chosen to group data across (e.g., 7–11 years or 8–12 years) may fundamentally diminish critical features of the components that are indicative of a particular maturational level, such as the bifurcation of the P1—N1—P2 complex, and may further obscure any associated latency changes in the components.
3. Finally, the choice of stimulus rate will have an effect on the resulting CAEP waveforms. The slower the stimulus rate, the more adult-like are the features of the waveform. This is clearly demonstrated in the Gomes et al. (1999) study. Using a very long 8 s ISI, the N2 component, which has become a classic characteristic of the child CAEP waveform, was not present in the 8–12-year-old group. Instead, there was a prominent N1 component, not previously reported in studies using shorter (<5 s) ISIs. In contrast, at the very fast stimulus rate of 200 ms of the current study, only the P1 (in adult) and the P1—N2 (in children) components tracked the stimulus rate and were observed in the waveform. Thus, the choice of ISI will greatly impact on the CAEP morphology.

Acknowledgements

This research was supported by the National Institutes of Health (R01 DC006003) and the Institute for Human Communication at the Montefiore Medical Center. We thank two anonymous reviewers for their insightful comments.

Abbreviations

CAEPs, cortical auditory evoked potentials; SOA, stimulus onset asynchrony; ISI, inter-stimulus interval; EEG, electroencephalogram; ERP, event-related potential; Hz, Hertz; GFP, global field power; CSD, current source density; ANOVA, analysis of variance.

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Fig. 1.

Global field power (GFP) is displayed by stimulus rate for each age group (adolescents, solid gold line; 11 years, solid blue line; 10 years, dashed green line; 9 years, dashed pink line; and 8 years, dashed light blue line). The adults (black solid line) are shown below the time scale of each stimulus rate condition. The GFP is calculated as the spatial root mean of the squared voltage deviations across electrode recordings from the entire scalp to provide a reference-free measure used for component identification. The peaks of power are designated by their corresponding component peaks seen in the ERP waveforms (see Figs. 2 and 3). (For interpretation of the references in color in this figure legend, the reader is referred to the web version of this article.)

Fig. 2.

800 ms condition. The longest SOA condition is shown for all age groups to illustrate the major maturational changes of the CAEP waveform. The same color traces representing each age group are used as in Fig. 1. Notice the decrease in P1 latency along with the increase in P2 latency as the N1 component emerges from within the biphasic, dominant positive peak of the child waveforms. The N2 component dominates in the child waveform, is still present in adolescence (gold trace), and is absent at this SOA in adults (black trace). (For interpretation of the references in color in this figure legend, the reader is referred to the web version of this article.)

Fig. 3.

Stimulus rate by age group. Changes in the CAEPs that occur as a function of stimulus rate and age are displayed. A smaller y-axis μV scale was used for the adults and 16-year-old so that the features of the waveforms could be seen. The evoked response is overlain by stimulus rate (800 ms, black line; 600 ms, green line, 400 ms, blue line, and 200 ms, red line). Notice the decrease in amplitude with increase in stimulus rate that occurs by stimulus rate change in the older (left column) but not younger (right column) groups. At 200 ms (red trace) in all age groups, the waveforms switch from a multi-component to a two-component waveform. Note the longer peak latency of the P1 in the adults. Two successive P1 peaks can be observed within the epoch for the 200 ms condition, which follow the stimulus rate (i.e., the P1 peaks occur every 200 ms in all age groups). (For interpretation of the references in color in this figure legend, the reader is referred to the web version of this article.)

Fig. 4.

Scalp topography for the 800 ms SOA condition. The midline (Fz, Cz, Pz) and lateral (T7, T8) electrodes are displayed for the 800 ms condition for all age groups. The color and style of the lines is the same as used for Figs. 1 and 2. Notice the frontal distribution of the P1, N1, and N2 components in children and the centroparietal distribution of the P2. This contrasts adults, in whom there is a central scalp distribution for the P1 and N1 and the frontal distribution of the P2. The T-complex is clearly observed at the lateral electrodes. (For interpretation of the references in color in this figure legend, the reader is referred to the web version of this article.)

Fig. 5.

Effects on the amplitude of the P1 component. The mean amplitude (vertical bars indicate 95% confidence intervals) is displayed for each age group (8 years-adults) by stimulus rate (400 ms, left column; 600 ms, middle column; and 800 ms, right column) and electrode (Fz, solid blue lines; Cz, dashed red lines; and Pz, dotted green lines). (For interpretation of the references in color in this figure legend, the reader is referred to the web version of this article.)

Fig. 6.

Effects on the amplitude of the P2 component. The mean amplitude (vertical bars indicate 95% confidence intervals) is displayed for 9 years-adults by stimulus rate (400 ms, left column; 600 ms, middle column; and 800 ms, right column) and electrode (Fz, solid blue lines; Cz, dashed red lines; and Pz, dotted green lines). (For interpretation of the references in color in this figure legend, the reader is referred to the web version of this article.)

Fig. 7.

Effects on the amplitude of the N2 component. The mean amplitude (vertical bars indicate 95% confidence intervals) is displayed for child age groups (8–16 years) by stimulus rate (400 ms, left column; 600 ms, middle column; and 800 ms, right column) and electrode (Fz, solid blue lines; Cz, dashed red lines; and Pz, dotted green lines). (For interpretation of the references in color in this figure legend, the reader is referred to the web version of this article.)

Fig. 8.

Global dissimilarity index (GDI). The same color code as used in the other figures is used to represent age group. The GDI indicates homogeneity of underlying neural configurations for each component across different stimulus rates (A—C) and between components of the 800 ms condition (D). The higher the score, the more dissimilarity there is for the comparison. See Section 2 for details of how the GDI was calculated. (For interpretation of the references in color in this figure legend, the reader is referred to the web version of this article.)

Fig. 9.

The CSD maps of the P1 component. CSD maps were calculated on the grand mean waveforms at the peak latency of the P1 component elicited in each age group and stimulus rate. Negative voltage and current sinks are shown in red, and positive voltage and currents sources are shown in blue (stippled) for the left and right hemispheres (expressed in $\mu\text{V}/\text{cm}^2$). Circles represent the scalp locations of the 32 electrodes. (For interpretation of the references in color in this figure legend, the reader is referred to the web version of this article.)

Fig. 10.

The CSD maps of the N2 component. CSD maps were calculated on the grand mean waveforms at the peak latency of the N2 component elicited in 9–16-year-old children at each stimulus rate. Negative voltage and current sinks are shown in red, and positive voltage and currents sources are shown in blue (stippled) for the left and right hemispheres (expressed in $\mu\text{V} / \text{cm}^2$). Circles represent the scalp locations of the 32 electrodes. (For interpretation of the references in color in this figure legend, the reader is referred to the web version of this article.)

Table 1

Age groups and numbers of subjects

Age (years)		8	9	10	11	16	22-40
n = 61 M/F	10		7	12	10	10	12
	3/7		4/3	6/6	3/7	6/4	6/6

Table 2
Global field power (GFP) peak latency for each component and stimulus rate (in ms)

	Adults	16 years	11 years	10 years	9 years	8 years
<i>P1</i>						
200 ms	86	81	93	108	104	114
400 ms	60	76	80	84	84	93
600 ms	48	69	76	83	78	92
800 ms	42	65	73	79	76	85
<i>N1</i>						
200 ms	●	●	●	●	●	●
400 ms	●	●	●	●	●	●
600 ms	92	●	●	●	●	●
800 ms	90	●	●	●	●	●
<i>P2</i>						
200 ms	●	●	●	●	●	●
400 ms	148	137	137	146	●	●
600 ms	146	142	140	142	141	139
800 ms	162	146	142	140	147	139
<i>N2</i>						
200 ms	●	●	216	221	232	224
400 ms	●	240	236	238	234	239
600 ms	●	247	240	233	232	239
800 ms	●	247	226	232	233	243

● = no GFP peak.

Table 3

Summary of scalp distribution for the ERP components

Components	Age groups		
	Adults	Adolescents	Children
P1	Fronto-central	Fronto-central	Frontal
N1	Fronto-central	-	-
P2	Fronto-central	Fronto-central	Central
N2	-	Frontal	Frontal