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Development and topography of auditory event-related potentials (ERPs): Mismatch and processing negativity in individuals 8–22 years of age

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Abstract

How do event-related potentials (ERPs) reflecting auditory processing develop across adolescence? Such development was described for five ERP components in four groups of 11 healthy participants with mean ages of 10, 14, 17, and 21 years. Data from 19 sites during diffuse (passive) and focused (discrimination) attention in a three-tone oddball were analyzed to see how ERP loci varied with age for tone type, attention condition, and for four types of difference waves reflecting nontarget and target comparisons. Age interacted with site for most components. P1 loci sensitive to rare tones moved posteriorly and N1 loci lost their right bias in early puberty. The P2 loci did not move anterior to Cz until adulthood. N2 amplitude, sensitive to attention condition, developed a frontal focus by 17 years. Right-biased P3 loci moved to the midline with focused attention similarly in all age groups. Difference waves developed in three stages: In 10-year-old participants, early deflections (<150 ms) were diffusely distributed; in midadolescent participants, the main frontal negative component (150–300 ms) became well formed and lost an earlier right bias; and for participants 17 years old and older, the late positive complex developed a right bias in target-derived waves. Latency decreases for early frontal components were marked in participants 10–14 years old and for later posterior components in participants 14–17 years old. Major developments appeared at the onset of adolescence in early stimulus selection processes and during adolescence in the differential use of this information (N2- and P3-like latencies).

Descriptors: Event-related potentials, Topography, Attention, Development, Mismatch negativity, Processing negativity

The size and latency of event-related potential (ERP) components 50–500 ms after a tone are indicators of the steps in the processing of information about the tone (e.g., pitch, loudness) and its context (e.g., rarity and task [ir]relevance). Earlier after a tone, more exogenous processes relate to the perception of stimulus salience. Later, more endogenous processes incur comparison with short- or long-term traces reflecting experience (reviews: Hillyard & Kutas, 1983; Olbrich, 1989; Straube & Oades, 1992). From about 7 years of age, five main negative- and positive-going peaks can be measured, and their expression during development reflects the anatomical and functional maturity of the mediating structures (e.g., transmission efficacy and connectivity; Kurtzberg et al., 1984).

Astonishingly, few researchers have reported how the ERP develops and matures across puberty and fewer still have reported on the topography of these recordings as an indication of which brain regions and functions mature at a given age. The goal of this study was to provide an age-by-topography profile from prepuberty to young adulthood of auditory perceptual and attention-related information processing as illustrated by five stimulus-elicited ERP components from P1 to P3 and in difference waves representing stimulus comparison processes. Three elements were important for the study: (a) ERP development, (b) the three-tone paradigm and topography, and (c) difference waves.

ERP Development

Complex discriminations place demands on the ability to concentrate and discriminate. Major improvements in vigilance capability have been reported at around the age of 8 years (Corkum & Siegel, 1993; Pasuraman & Davies, 1984). ERPs from P1 to P3 can be recorded from infants younger than 3 months (Shucard, Shucard, & Thomas, 1987), but measures vary widely up to 7 years of age (Kurtzberg et al., 1984; Martin, Barajas, Fernandez, & Torres, 1988). By 8 years of age, the ERP has achieved its adult form (Courchesne, 1978), although vestiges of a long slow negative component (Nc) may remain after 300 ms up to the age of 13 years (Kurtzberg et al., 1984). Thus, for these reasons, the current study investigated development from 8 years of age.

Most developmental studies have been restricted to the midline ERP. P3 amplitudes are reported to increase with age uniformly

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from 5 to 19 years (review, Ladish & Polich, 1989), or only to 14 years of age (Martin et al., 1988), or to show no correlation (Martin, Delpont, Suisse, Richelme, & Dolisi, 1993). The N1 peak also increases across the 8- to 16-year range (Tonnquist-Ihlen, Borg, & Spens, 1995), whereas the N2 peak is reported to decrease in size from 8 to 13 years (Friedman, Brown, Cornblatt, Vaughan, & Erlenmeyer-Kimling, 1984; Satterfield & Braley, 1977) or from 4 to 16 years (Enoki, Sanada, Yoshinaga, Oka, & Ohtahara, 1993). Most peak latencies decrease with increasing age (e.g., N1, P2, N2; Enoki et al., 1993; Johnson, 1989; Tonnquist-Ihlen et al., 1995), but reports vary on the nature of the curve (Finley, Faux, Hutcheson, & Amstutz, 1985; Martin et al., 1993; Mullis, Holcomb, Diner, & Dykman, 1985) and Pearce, Crowell, Tokioka, and Pachero (1989) found no such decrease for N2. Reports on topography have been limited to the waning influence of the slow Nc potential from childhood by 12 years of age, the frontal nature of N2, and the symmetrical, parietal nature of P3 by the same age (Friedman, Putnam & Sutton, 1989; Johnson, 1989).

Thus, a developmental study of several ERP components was needed to obviate the difficulties and conflicts arising out of comparing data about successive stages of information processing obtained with different methodologies. Further, the potentially differing influences of stimulus type or task condition had been largely neglected. Lastly, no overall picture of the topographical representation of the development of these stages of information processing that might reflect the uneven maturation of the underlying mediating brain structures had been presented.

Three-Tone Oddball Paradigm and ERP Topography

The role represented by ERP components in information processing can be dissected by varying the type of stimuli or task presented (Ritter, Simson, & Vaughan, 1988). Clarifying the role of ERP components was achieved for three features of information processing in the three-tone oddball paradigm. First, the use of a common standard and two rarer stimuli with higher tone frequencies allowed an investigation of the influence of tone type on the ERP. Using three tone types avoids confounding tone frequency and rarity with the task features of target/nontarget, as occurs in the two-tone oddball paradigm (Breton, Ritter, Simson, & Vaughan, 1988). Second, the tones were presented initially in a passive nontask situation and then in an active discrimination, in which one of the rare tones was designated as a target and the other nontarget as the deviant. This set-up allowed the investigation of the effect of two different attention requirements, in which the passive situation resulted in diffuse attention and the active task in focused attention. The third feature of information processing concerned the stimulus comparisons represented by four types of difference waves. These comparisons enabled analysis of aspects of processing otherwise confounded in this paradigm (e.g., rate of presentation and tone frequency), and the four types represented the perceptual trace of neural activity remaining after comparisons of nontarget stimuli and the attentional trace found in target-based stimulus comparisons. In two conditions, the more automatic processes of stimulus matching (e.g., mismatch negativity; Näätänen, 1990) could be contrasted with conscious information processing as required in the putative updating function reflected by the P3 (Donchin & Coles, 1988).

A three-tone oddball paradigm has been used in the study of healthy adults and normal aging (Pfefferbaum, Ford, Wenegrat, Roth, & Kopell, 1984; Woods, Alho, & Algazi, 1991), dementia and schizophrenia (Grillon, Ameli, Courchesne, & Braff, 1991; Grillon, Courchesne, Ameli, Geyer, & Braff, 1990; Pfefferbaum, Wenegrat, Ford, Roth, & Kopell, 1984), and with autistic or brain-damaged persons (Oades, Stern, Walker, Clark, & Kapoor, 1990; Oades, Walker, Geffen, & Stern, 1988; Rugg et al., 1993) but not in a developmental study.

Topographic recording in one form or another is basic to the resolution of anatomically separate contributions to a conventional peak (e.g., N1 peaks at the vertex subsume contributions from three different underlying sources; Knight, Scabini, Woods, & Clayworth, 1988). Similarly, a topographic map can illustrate in two dimensions the developmental shifts between age groups in component distribution. Resolution is limited by the amount of data, which in turn depend on the number of trials and recording sites. Because other methods (e.g., dipole calculation) require too many trials for routine use with children, we chose to compare simple frontal versus parietal and left versus right (frontal and temporal) contributions to each peak. To compare across sites and stimuli, data were normalized from each recording site with a vector taking into account the activity at all 19 electrodes available (O'Donnell et al., 1993; Shelley et al., 1991b). Separate normalizations allowed us to test for the potential independent effect of tone type and attention condition, as has been done in the comparison of ERPs elicited by visual and auditory stimuli (Naumann et al., 1992). In this way, the relative distribution of potentials could be visualized as a map and used in the study of attentional effects on ERPs (Teder & Näätänen, 1994).

Difference Waves

The purpose of subtracting tomographic or topographic data obtained in one condition from that obtained in a second one is to remove the elementary activity common to both conditions and expose that which is specific to the different requirements of the two situations. The comparison of nontarget stimuli (deviant minus common standard) thus provides a trace of the perceived mismatch of the rarer, higher tone with that from the expected lower tone (e.g., mismatch negativity; Näätänen, 1990)

This comparison opens up the exciting possibility of measuring an attention-related trace in the comparative processing of stimuli with the target. Historically, target comparator processes have been measured in three different ways, but all result in a trace generically known as *processing negativity*. Commonly, processing negativity derives from subtracting a standard from the target stimulus, but the distinction of target features is confounded by the feature of tone frequency. Another difference wave, the Goodin wave, attempts to reveal the intervening variables mediating the difference between passive and active two-tone oddball discriminations (see Faux, Shenton, McCarley, Torello, & Duffy, 1988, based on Goodin, Squires, Henderson, & Starr, 1978): The target-minus-standard wave is calculated in each attention condition, and then that in the passive condition is subtracted from the analogous wave in the active condition. But the third, and arguably the best, representation is the waveform elicited by the target in the discrimination less that elicited by the same stimulus before being designated the target in the passive condition; this waveform is the negative difference, which controls for tone frequency and rarity and leaves a trace reflecting the effortful requirements of selective focused attention. In these measures, we follow the work of Hansen and Hillyard (1980, 1988), Shelley et al. (1991a, 1991b), and Woods et al. (1991).

In summary, in the absence of reports of the development of difference waves, the relative absence of group comparisons in

developmental studies (Kurtzberg et al., 1984), and the appeal for more attention to scalp topography and multiple ERP profiles from the authors of a review on ERPs in children at high risk for schizophrenia (Friedman & Squires-Wheeler, 1994), our goal was to follow the influence of tone type, attention condition, and stimulus-comparator function on the topographic and temporal profile of auditory information processing from prepuberty to young adulthood. These results are presented (a) in the Results section in the sequence of the variables that were studied for an interaction with topographic electrode site (i.e., age, tone type, attention condition, and stimulus comparison), (b) in the temporal sequence of information processing (P1 to P3 components), and (c) in terms of successive phases of ERP development with age (Table 3).

Method

Participants

Recordings were taken from 58 healthy children of clinic staff and students who reported themselves to be free of psychiatric illness requiring consultation (past or present), a history of organic disorder, medication, and drugs. Participants were volunteers recruited by local advertisement and were paid for performing a psychological test battery, in connection with which a physical examination (hand X-ray and Tanner maturity ratings) was conducted by a resident clinician and a urine analysis was performed. All participants preferred to use the right hand on tests of writing and pointing.

Data for four groups of 11 participants, each with mean ages of 10, 14, 17, and 21 years, were analyzed (range = 8–22 years; see Table 1 for maturity measures). Of the 25 adult participants tested, 14 were not included to achieve groups balanced for numbers and showing comparable age increases in a study in which chronological and somatic age were paramount. Full data were reported in Oades, Zerbin, and Dittmann-Balcar (1995b). Could gender differences have affected the amplitudes? Among adults, women have been reported to show a larger P3 than men (Deldin, Duncan, & Miller, 1994), but we are unaware of reports of source or topographic differences. Further, although 10- and 21-year-old groups were balanced for gender, gender does not confound comparison of the other groups because gender differences have been reported to be absent in ERP studies of children (Kraus, Smith, Reed, Stein, & Cartee, 1985; Martin et al., 1988; Oades, Dittmann-Balcar, Schepker, Eggers, & Zerbin, 1996a). Testing followed approval of the protocol by the management of the clinic and the cooperation, understanding, and consent of the child and the legally responsible adult.

Procedure

All recordings were made from 9:30 a.m. to 11:00 a.m. between August and December. A three-tone oddball paradigm was presented in successive passive and active discrimination sessions. Blocks of 100 tones (0.8-, 1.4-, and 2.0-kHz tones at 65 dB) were presented in a Bernoulli sequence (p = 70, 15, and 15%, respectively). The tones had a rise and fall time of 10 ms and a duration of 50 ms, with an interval of 1,200–1,700 ms between the start of each stimulus. Output of the stimulus function generator (Hörniß and Zeisberg 001001) was presented through Beyer Dynamics DT 48 earphones. Hearing thresholds were measured immediately before recording (Audio-Med Audiometer BCA3) and levels adjusted if these differed between the ears by 5 dB or more (details available from R.D.O. on request).

Participants sat in a soft reclining chair in a sound-attenuated, electrically isolated room lit by a 25-W bulb. During recordings, participants were asked to fixate on a small cross 1.5 m away on the wall to reduce eye movement. They were told there would be a baseline recording over a few trial blocks and in the second part they should respond to one of the tones. At the end of the passive session, most participants had identified three tones, which were then demonstrated and identification practiced. Only in the active discrimination session were participants told which tone was the target and to respond by raising the finger from a metal contact as fast but as correctly as possible after the 1.4-kHz tone.

Recordings were made from 19 sites (electrocap: 10-20 system) using linked ear reference and Fpz and Oz as separate ground electrodes as required by the Siemens EEG 21, with an impedance of <2 kΩ at all sites. The reference sites were balanced to minimize lateralized artifacts. ERPs were evaluated at 15 sites: F7, F3, Fz, F4, F8; C3, Cz, C4; P3, Pz, P4; T3, T4, T5, T6. From these data and those from two Fp and two O sites (5×5 grid along the axes of the 10-20 system), topographic maps were made using a horizontal and vertical linear interpolation algorithm to establish a matrix of 180×180 points. Data were sampled at 250 Hz for

Table 1. *Participant Characteristics, Recording Data Accepted, Reaction Time, and Signal Detection Performance*

Group age (years)			Bone age		Tanner	SPM		Accepted active condition			RT		
mdn	*M*	Range	(years)	M/F	rating	IQ	% Artifact	C	D	T	(ms)	*ln-d*	Beta
10	10.1	8.2	10.1	5/6	1.4	111	34	225	31	30	661	4.9	8.2
SD	1.0	11.6	1.3		0.5	15	13	54	7	7	88	1.4*	1.7
14	14.2	12.1	14.2	9/2	2.9	106	24	211	38	34	650	5.9	8.2
SD	1.2	15.8	1.3		1.2	17	11	37	7	5	59	1.6	1.7
17	17.1	15.9	16.6	7/4	4.9	109	28	181	32	35	515	7.0	7.0
SD	1.0	18.9	1.4		0.5	15	13	29	5	6	79**	1.5	0.6
21	21.2	20.1	—	3/8	5.2	119	16	209	37	32	557	7.3	7.6
SD	0.6	22.2			0.3	12***	9	62	11	5	88	1.7	1.1

Note: Values listed are means unless otherwise indicated. C, D, T = common, deviant, and target tones; M/F = male/female gender ratio; age = chronological age; bone age = assessed from wrist X-rays in participants younger than 18 years to the nearest 0.5 year; Tanner rating = Scales 1–6 assessment of extent of secondary sexual development; %artifact = elimination of trials due to electrical artifact in the active condition. Accepted recordings and reaction time (RT) were derived from the active discrimination condition after removal of electrooculogram artifact and response errors (RT, **$p < .008$, 10- and 14- > 17-year-old participants). SPM = Raven's standard progressive matrices measure of performance IQ (***$p = .051$, Scheffé, 21- vs. 14-year-olds); *ln-d* and beta = signal detection measures of perceptual sensitivity (natural log d', 10 < 17- and 21-year-old participants, *$p < .03$, Scheffé) and criterion (beta, no significant differences).

1,024 ms (including 50-ms pretrigger time) and amplified by 12 K using a bandpass of 0.3–70 Hz (analog Butterworth filter). Monopolar electrooculogram (EOG) artifact of >65 μV recorded above the eye was used as a criterion to eliminate ERP trials from the data (Table 1). This criterion with the setting of low-pass filters reduced gross electromyographic (EMG) interference. Data were evaluated offline using a digital, low-pass, rectangular 25-Hz filter to reduce noise in the assessment of small peaks. These parameters satisfy recommendations for recording ERPs from N1 to P3 (Polich, 1991). Aliasing and delays in the topographic latency sampling were reduced by the sampling rate and the normalization of the latency data, respectively (Pivik et al., 1993).

ERP Definitions

Peak amplitude and latency for five components were evaluated after the common standard (C, 0.8 kHz), the deviant (D, 2.0 kHz), and the 1.4-kHz target tone (passive = t, active = T). These peaks were defined relative to the largest negative peak (evident as N1, occurring 80–140 ms poststimulus) and the start of the earliest P3 (window of 240–540 ms), where this was the largest positive deflection in the waveform. P1 (30–100 ms) was the largest positive-going dip before N1. P2 was the largest positive deflection after N1 preceding the P3 window (120–240 ms). N2 was the largest negative peak between P2 and P3 (140–300 ms). These responses are shown in Figure 1 for each age group for the common, target, and deviant tones.

Difference waves were derived from ERPs elicited by tones as follows: D-C, T-D, T-t, and the Goodin wave (G-wv) = [T − C(active)] − [t − C(passive)]. In each of these waves, there was a major negative deflection known respectively as mismatch negativity (D-C), processing negativity (T-D and G-wv), and negative difference (T-t; see Figure 2). The window for recognition of this "N2-like" component in each of the four waveforms was 150–300 ms. In each waveform, this "N2-like" component was succeeded by a late positive "P3-like" component reflecting processing of the distinctive features of the deviant or target (i.e., rarity and response requirement). The window for recognition of the "P3-like" component was 240–540 ms, but in some young participants components were delayed throughout the waveform and the "N2-like" window was extended to 400 ms and measured if a clear "P3-like" component followed it.

Under the term *precursor events*, positive and negative deflections prior to the "N2" are considered. The belief that difference waves should not contain earlier components cannot be maintained in a paradigm involving the averaging of many stimulus presentations when the presence or absence of attention clearly affects the expression of the early components (e.g., Hackley, 1993). Without empirical study, the relevance of difference waves to the putative effects of focused attention in a discrimination should not be excluded. Historically, the development of difference-wave recording suggests that such deflections may be minor by comparison with the "N2" (Näätänen, 1990). Nevertheless, with the presence of early negative deflections in studies of the effect of attention on mismatch negativity (Oades & Dittmann-Balcar, 1995) and particularly studies of children (Kurtzberg et al., 1984; Oades et al., 1996a; Winsberg, Javitt, Silipo, & Doneshka, 1993; see Figure 2), they merit consideration as developmental and functional precursors of later major potential changes. Early and late negative-difference components also have been described (Alho, Woods, & Algazi, 1994). In the present study, "N1" (60–180 ms poststimulus) was the largest negative peak before "N2" (150–300 ms poststimulus). Positive deflections before and after "N1" also were recorded and helped define the early negative deflection (up to 240 ms). Grand mean maxima were in the range of 1:2 to 1:3 of the N2 and P3 amplitudes and thus could reliably be evaluated against electroencephalographic (EEG) noise. For 10- and 21-year-old participants, respectively, amplitudes were 3.0 and 2.2 μV for P1 at Pz, −3.4 and −2.7 μV for N1 at Fz, 4.0 and 2.2 μV for P2 at Pz, −4.7 and −3.9 μV for N2 at Fz, and 8.9 and 7.8 μV for P3 at Pz.

Data Analysis

Stimulus-elicited ERP and difference-wave data were analyzed separately.

Stimulus-elicited ERPs. Data were normalized by vector analysis separately for the three tone types and the two attention conditions. The mean value of the measure at each site for each participant was divided by a vector obtained by taking the square root of the sum of the squared mean measures obtained for each of the 15 sites studied. This method corrected for (a) inhomogeneity in the raw data, (b) multiplicative effects on ERPs of changes of source strength in analysis of variance (ANOVA) (McCarthy & Wood, 1985), and (c) potential anomalies arising in percentage and minimum–maximum normalization methods by considering the variance at all sites (Naumann et al., 1992).

The aim of this study centered on the development of the topography of ERP components with age and on the influence of attention condition and tone type on topography across age groups. A four-way multivariate ANOVA (MANOVA) for four age groups in two attention conditions with three tones at 15 electrode sites with repeated measures was conducted for each component measure (e.g., Keselman & Rogan, 1980). The multivariate analysis treated electrode site as a within-subjects factor as a precaution against between-subject variability. Main site effects and site interactions with age, tone, and condition were analyzed (Table 2). Significant results were found after (a) the multivariate Hotelling's Trace, as recommended for profile analysis by Faux and McCarley (1990), and then (b) the averaged F test (Norusis, 1985) for 15 sites after correction with the appropriate Greenhouse–Geisser ϵ factor (Greenhouse & Geisser, 1959) to reduce the large numbers of degrees of freedom (Vasey & Thayer, 1987). The first procedure makes no assumptions about the variance–covariance matrix, whereas the second, mixed model is more powerful for small sample sizes, where the ϵ factor corrects for violations (Norusis, 1985). Significant results in both tests were followed by ANOVA for the main interactions and Scheffé post hoc tests to determine where the difference lay. Topographic results focused on anterior/posterior (F7/T5, Fz/Pz, F8/T6) and left/right comparisons (F7/8, T3/4, T5/T6). Clearly, insignificant effects were not reported. In the text, the terms *trend*, and *tend* refer to statistical significance of 5–10% or where Hotellings Trace and averaged F tests produced conflicting evidence of statistical significance. An appendix of the ANOVAs on raw data at Cz and the MANOVAs is available from R.D.O. on request.

Difference waves. Data from 15 sites were normalized by vector analysis to test for the potential independent effect of each waveform. For each ERP component, a 4 × 4 × 15, repeated measures MANOVA was run, the three independent variables being difference waves (D-C, T-D, T-t, G-wv), age group, and electrode site. The text describes the topography of component measures (main effects of site) and the interactions with age and waveform, where a significant interaction with site is required for interpretation of topographical locus (Johnson, 1989). Otherwise, the statistical testing procedure was the same.

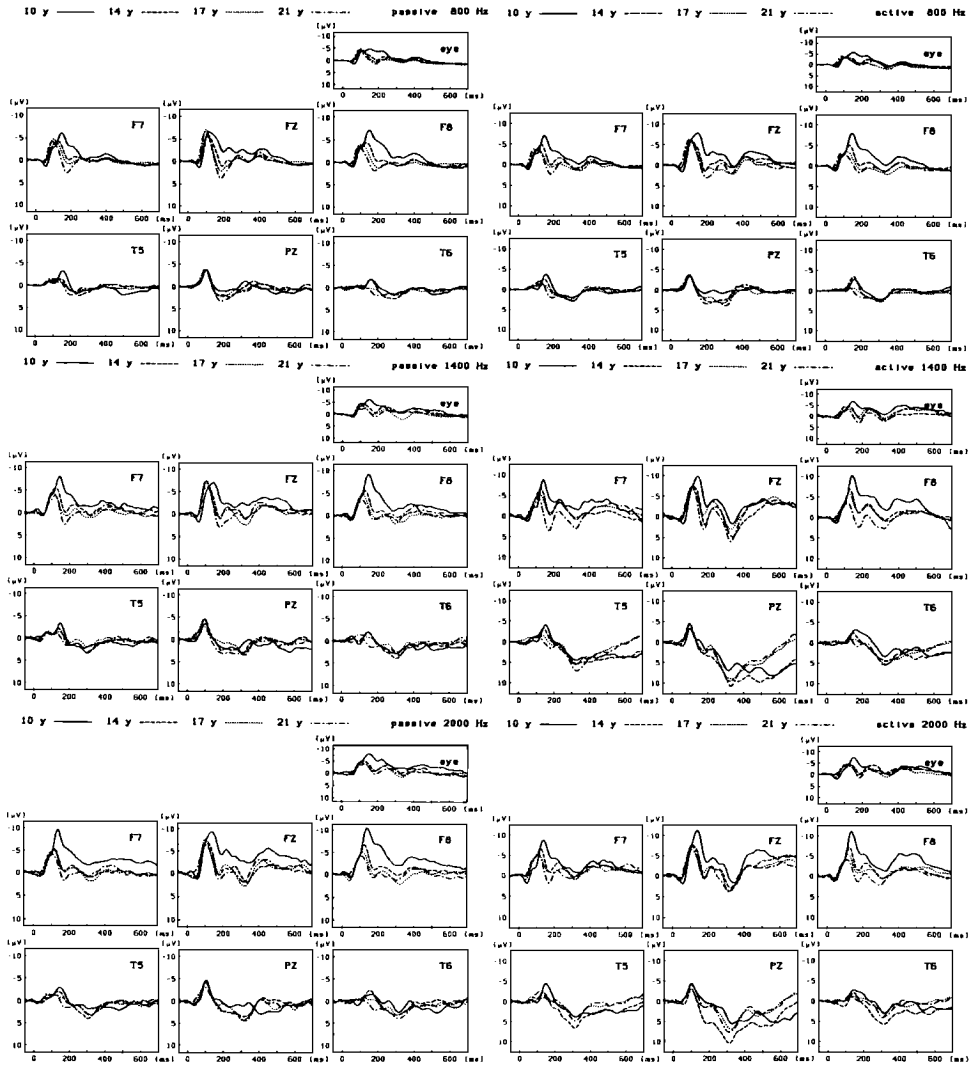

Figure 1. Grand mean event-related potential (ERP) waves (μV) for each of four age groups for participants (M = 10, 14, 17, and 21 years) at selected anterior (F7, Fz, F8) and posterior (T5, Pz, T6) recording sites for 700 ms. Left: Passive, diffuse-attention condition. Right: Active discrimination (focused attention). Upper panel: After the standard 0.8-kHz tone; middle panel: after the rare 1.4-kHz tone (target on the right); lower panel: after the deviant 2.0-kHz tone. The insets show the electrooculogram (EOG) representations of eye movements.

Results

Behavior

Analysis of variance for IQ, reaction time, and signal detection measures showed that the two younger groups were slower to respond than the 17-year-old group, $F(3,40) = 7.25$, $p < .001$, and the perceptual measure of d' was poorer in the 10-year-old participants versus the 17–21-year-old participants, $F(3,40) = 5.30$, $p < .005$ (Table 1). The response criterion (beta) did not differ among groups, and the variation of IQ resulted in no robust differences (14 < 21-year-old group, Table 1). The slower response

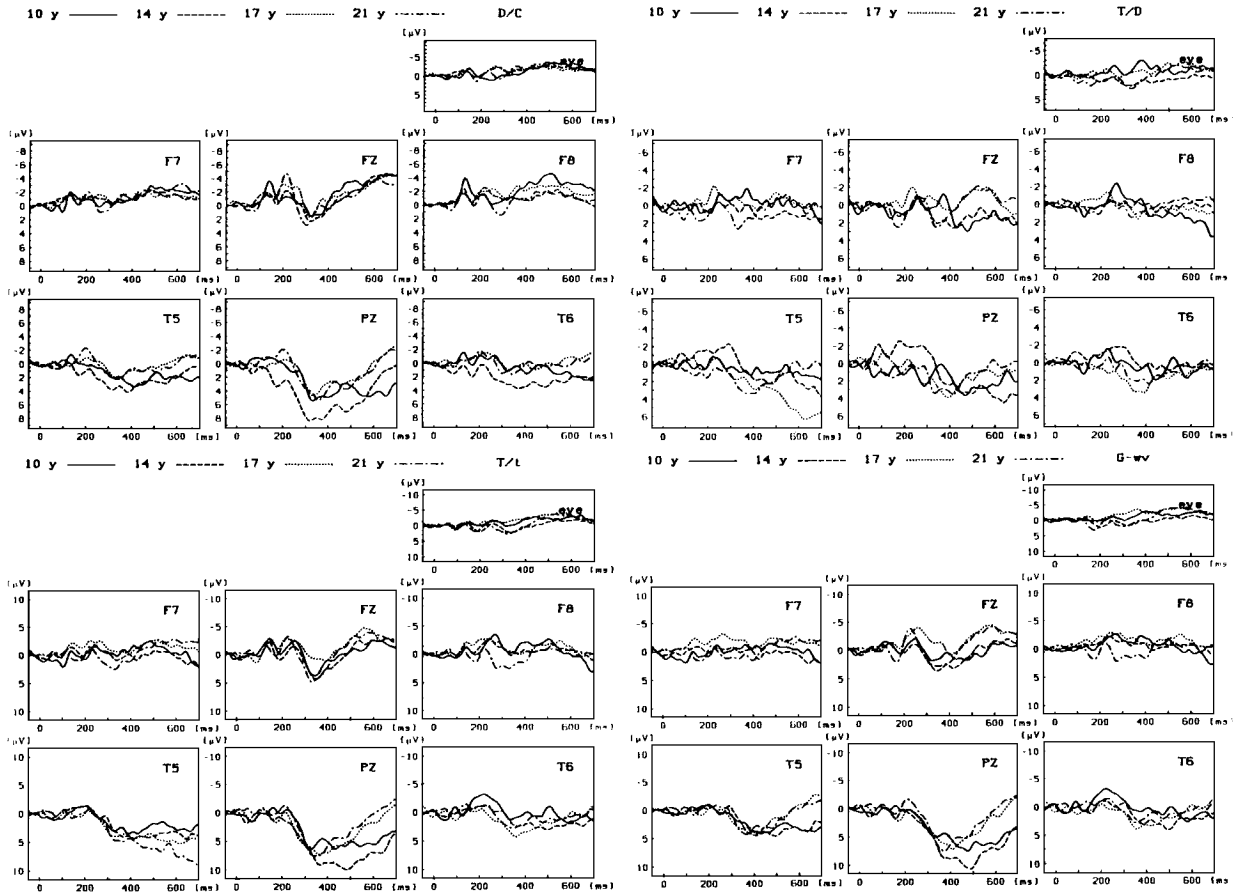

Figure 2. Grand means for four difference waveforms (μV) for the four age groups (M = age 10, 14, 17, and 21 years) over 700 ms after the tone presentation. Inset shows electrooculogram (EOG) representation of eye movements. Nontarget comparisons (including mismatch negativity: D/C = deviant common, upper left); target comparisons (including processing negativities: T/D = target deviant, upper right; T/t = negative difference, 1.4 kHz as target—same tone in passive nontask condition, lower left); and (G-wv, lower right) Goodin wave.

Table 2. *Summary of Significant MANOVAs on Normalized Data for Five ERP Components: Amplitudes and Latencies for Stimulus ERP and Difference Wave*

	Component				
Factor	P1	N1	P2	N2	P3
	Stimulus ERPs				
Amplitude					
Site	***	***	***	***	***
× Age	*o (**)	*** (−)	*** (***)	*** (***)	*** (−)
× Tone	*o (**)	— (*)	o (−)	**o (−)	*** (***)
× Condition	— (−)	— (o)	** (−)	*** (*)	*** (***)
× Condition × Age	— (−)	— (−)	— (−)	— (−)	o (−)
× Condition × Tone	— (−)	— (−)	— (−)	— (−)	— (**)
Latency					
Site	***	***	***	***	o
× Age	*o (***)	*** (***)	*** (***)	*** (***)	*** (***)
× Tone	— (−)	— (−)	— (−)	— (*)	— (−)
× Condition	*o (−)	* (*)	* (−)	* (−)	o (−)
× Condition × Age	— (−)	— (−)	— (−)	— (−)	o (−)
	Difference Waves Component				
Factor	"P1"	"N1"	"P2"	"N2"	"P3"
Amplitude					
Site	***	***	***	***	***
× Age	o (−)	*o (*)	*** (−)	*** (**)	*** (**)
× Wave	— (−)	o (−)	— (−)	— (−)	**o (***)
× Age × Wave	—	—	—	o	—
Latency					
Site	a	o	—	***	***
× Age	a (−)	* (−)	— (−)	o (−)	*** (*)
× Wave	— (−)	— (−)	— (a)	— (−)	— (**)

Note: ANOVAs on Cz raw data are listed in parentheses. After Greenhouse–Geisser correction, a = .1 > p > .05, *p < .05, **p < .01, ***p < .001 (averaged tests, where o = conflict with Hotellings test on degree of significance, e.g., *o = 5% definite, 1% possible). Interactions are listed only if an interaction for one ERP component was significant.

latency and the poorer d' in the two younger groups suggest that they had more difficulty detecting targets.

Stimulus-Elicited ERPs: Development With Age—General Group Effects

P1/N1. P1 maxima (larger in the young; Figure 1) were usually frontal, particularly for the common standard (p = .068, Scheffé; Table 2). Loci became biased laterally to the right in the oldest group (Figure 3). P1 latencies were shorter at anterior versus posterior sites, especially for comparisons in the youngest group (p = .03–.04, Scheffé).

N1 peaks were less localized in 10–14-year-old participants, who showed larger lateral frontal and temporal peaks (p < .05, Scheffé); in contrast, the 17–21-year-old participants had larger peaks in the midline (p < .05, Scheffé). As reported by Oades et al. (1996a), frontal N1 peaks were larger on the right in the younger group and on the left in the older two groups (Figure 3), but the significant ANOVA was not confirmed post hoc. N1 latencies were shorter on the left for all participants but became shorter at Fz versus Pz with increasing age (confirmed post hoc for adults, p < .05, Scheffé; Table 2).

P2/N2. P2 was largest in adults (Figure 1). In adults, P2 peaked at Cz, but in younger participants maxima were posterior to the vertex and clearly larger than at frontal sites in 10-year-old participants (p < .001, Scheffé; Figure 4). For the 10-year-old group, frontocentral maxima were smaller and posterotemporal maxima larger than in the 21-year-old group (p < .05, Scheffé). Paralleling these changes, shorter latencies in adults (vs. 10-year-old participants) were clearest at lateral frontal and temporal sites (p < .05, Scheffé).

N2 peaks (largest in the 10-year-old participants) were larger at frontal than at posterior sites from 14 years of age (p < .001, Scheffé). The tendency for peaks to be larger on the right in the 10-year-old group and larger on the left in the older groups was not confirmed post hoc (Table 2, Figure 4). A parallel tendency for latencies to decrease at posterior sites in older participants was not confirmed (e.g., p = .18, Scheffé).

P3. P3 amplitudes (smaller in the 10-year-old participants; Figure 1) were largest at posterior sites, but, compared with all other participants, those in the 10-year-old group showed the smallest responses at frontocentral sites and the largest at T5 and T6 (p = .05–.001, Scheffé). Although latencies decreased with age (Figure 1), a decreasing difference between anterior and posterior sites (Table 2) was not confirmed post hoc.

Summary. Effects of age were considered regardless of the particular features of tone type and attention condition. P1 positivity spread laterally (especially to the right) and posteriorly from frontal loci with increasing age. N1 negativity also was more widely distributed among the younger participants, but always showed frontal maxima. P2 maxima were more posterior in the young participants but became more centrally localized in the adults. P2

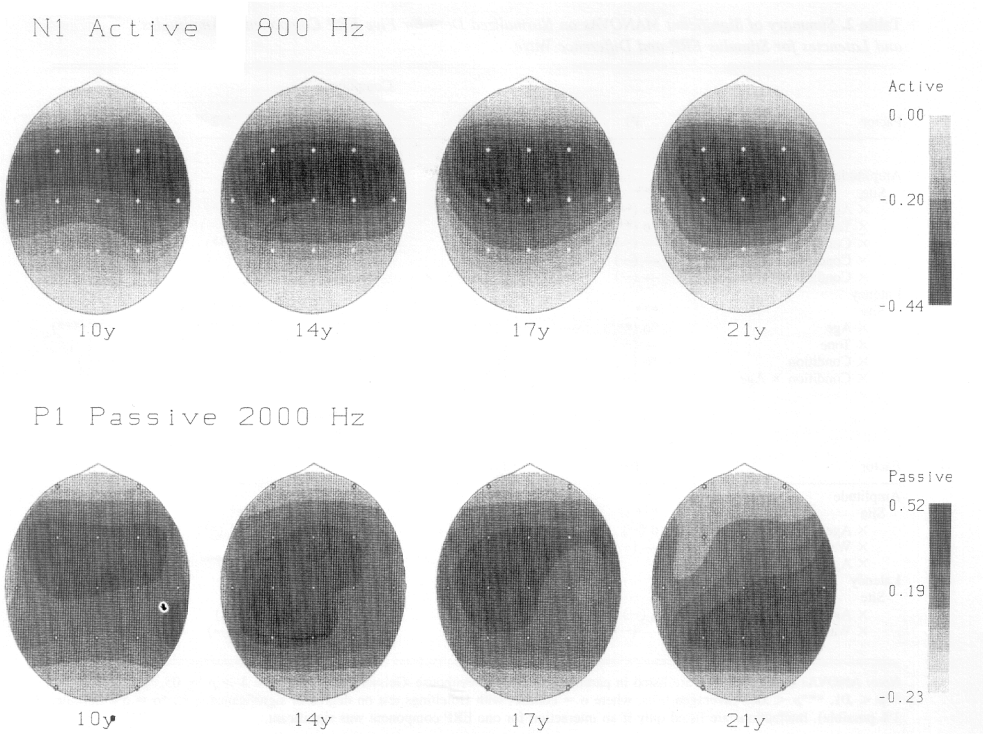

Figure 3. Topographic scalp distribution of mean vector-normalized peak amplitudes (adjusted to raw microvolt range; scale bar on the right). The anterior sites are uppermost in each map, and darker shading represents larger amplitudes. Maps are shown left to right for the four age groups (M = 10, 14, 17, and 21 years). Upper row: N1 in an active task condition after the 800-Hz common standard tone (focused attention). Lower row: P1 in a passive nontask condition after the 2000-Hz deviant tone (diffuse attention).

latencies decreased markedly at lateral sites with increasing age. N2 maxima were frontal in the midline, with a trend for a right bias in the young participants. Parietal P3 maxima were evident in all age groups, but frontal P3 positivity became more apparent with increasing age (Figure 4).

ERP Development—Effect of Tone Type

P1/N1. There were no differential effects of tone type among age groups, but across groups the common standard elicited larger P1 responses anteriorly (F7, F8; $p < .05$, Scheffé), and the rarer tones elicited a larger amplitude posteriorly (Pz, P4; $p < .05$, Scheffé; Table 2). No effects were found for N1.

P2/N2. Recalling the effect of the higher rarer tones on P1, the common standard elicited smaller P2 responses centroparietally but larger responses temporally ($p < .05$, Scheffé). In contrast, frontal N2 responses were usually larger after common than after rare tones, but the opposite pattern was recorded at temporal sites ($p < .05$, Scheffé). No effects of tone type for P2 latency were found; decreases of N2 latency that were shorter after rare than after common tones did not interact with site.

P3. Similar to the effect on P2, P3 responses generally increased with tone frequency, but over right temporal sites the least salient 0.8-kHz tone elicited larger responses ($p < .05$, Scheffé).

Summary. Responses to tone type did not vary with age. However, across groups, many components showed a differential topographic response to tone type. Only for P3 was the augmenting–reducing response clearly related to tone frequency. For other components, increasing tone frequency was confounded by rarity. Potentially reducing responses were seen for P1 (anterior), P2 (temporal), N2 (central), and P3 (temporal on the right). Potentially augmenting responses were seen for P1 (posterior), P2 (centroparietal), N2 (temporal), and P3 (nontemporal sites).

ERP Development With Age—Effect of Passive Versus Active (Diffuse vs. Focused Attention) Condition

P1/N1. Attention condition had no effect on peak topography. N1 amplitude and latency increased marginally in the active discrimination (Figure 1; $p = .1$, Scheffé). P1 latencies were shorter at temporal sites in the passive condition ($p = .031$, Scheffé) but at frontal sites in the active condition ($p < .001$, Scheffé).

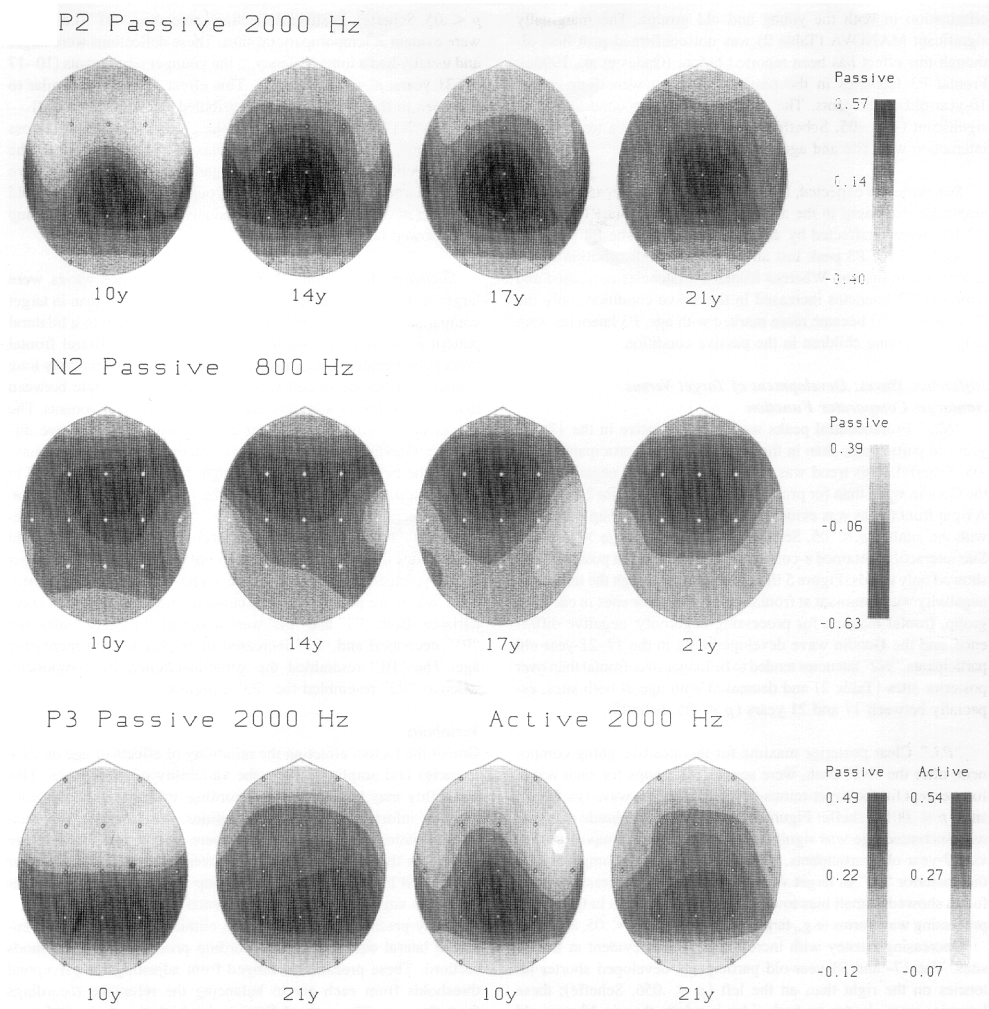

Figure 4. Topographic scalp distribution of mean vector-normalized peak amplitudes (adjusted to raw microvolt range; scale bar on the right). The anterior sites are uppermost in each map, and darker shading represents larger amplitudes. Maps are shown left to right for the four age groups (M = 10, 14, 17, and 21 years). Upper row: P2 in a passive nontask condition after the 2000-Hz deviant tone (diffuse attention). Middle row: N2 in a passive task condition after the 800-Hz common standard tone (diffuse attention). Lower row: The two maps on the left show P3 in a passive task condition after the 2000-Hz deviant tone (diffuse attention) for the 10- versus 21-year-old groups, and the two maps on the right show the same comparison in the active task condition (focused attention).

P2/N2. P2 amplitude decreased on the right in the active condition, $F(1,262) = 5.9–23.0$, $p = .016–.0001$ (Scheffé), leading to a left > right asymmetry, but this asymmetry did not interact significantly with age (Table 2). The decrease of P2 latency with age was more evident in the discrimination, especially at frontal sites, $F(1,262) = 3.6–11.6$, $p = .06–.0008$ (Scheffé).

N2 maxima were frontal ($p < .008$, Scheffé), with a nonsignificant bias to the left, in both attention conditions. (A decrease in peak size in the discrimination was noted at Cz in the raw data; Table 2.) N2 latencies were shorter at anterior temporal sites in the passive than in the active condition, $F(1,262) = 9.5$, $p < .0001$ (Scheffé). There was no significant three-way interaction.

P3. Peaks were larger in the active condition at centroparietal and temporal but not frontal sites, $F(1,262) = 7.0–11.7$, $p = .009–.0007$ (Scheffé). Figure 4 shows a right-biased response in the passive condition that moved to the midline in the active dis-

crimination in both the young and old groups. The marginally significant MANOVA (Table 2) was not confirmed post hoc, although this effect has been reported before (Oades et al., 1996a). Frontal P3 latencies in the passive condition were long in the 10-year-old participants. The difference between conditions was significant ($p < .05$, Scheffé), but there was only a trend for an interaction with site and age (Table 2).

Summary. As expected, N1 and P3 peak size increased and N2 amplitude decreased in the active discrimination, but P1, N1, and N2 loci were unaffected by attention condition. The P2 peak developed and the P3 peak lost an asymmetrical distribution in the active discrimination. Whereas frontal P2 latencies decreased and temporal N2 latencies increased in the active condition, only the P2 measure (Fz) became more marked with age. P3 latencies were longest in young children in the passive condition.

Difference Waves: Development of Target Versus Nontarget Comparator Function

"N2." Frontocentral peaks were more negative in the 17–21-year-old participants than in the 10–14-year-old participants ($p < .05$, Scheffé). This trend was clearer for mismatch negativity and the Goodin wave than for processing negativity (Figure 2, Table 2). A right frontal bias was evident in the 10-year-old group compared with the adults ($p < .05$, Scheffé; Figure 5). The Age × Wave × Site interaction obtained ϵ-corrected significance, but post hoc tests showed only trends. Figure 5 illustrates that, although the mismatch negativity was dominant at frontal versus posterior sites in each age group, frontal maxima for processing negativity, negative difference, and the Goodin wave developed only in the 17–21-year-old participants. "N2" latencies tended to be longer over frontal than over posterior sites (Table 2) and decreased with age at both sites, especially between 17 and 21 years ($p < .05$, Scheffé).

"P3." Clear posterior maxima for this positive-going component, after the "N2" peak, were seen in all groups for each waveform except for the target-minus-deviant difference wave (vs. frontal sites, $p < .001$, Scheffé; Figure 2, Table 2). An amplitude decrease with increased age was significant for the frontal component (10- vs. 17-year-old participants, $p < .05$, Scheffé). A comparison of the posterior "P3" in target versus the nontarget processing waveforms showed a small bias toward right temporal sites in the target-processing waveforms (e.g., target-minus-deviant, $p < .05$, Scheffé).

Decreasing latency with increasing age was evident at frontal sites. The 17- and 21-year-old participants developed shorter latencies on the right than on the left ($p < .056$, Scheffé); these latencies were shorter on both sides in adults than in 10-year-old participants ($p < .05$, Scheffé). For participants up to 17 years of age, latencies were usually longer in target versus nontarget processing waveforms (Table 2, Figure 2). (The data indicated more differentiation in adults, but there was much variance between sites and no significant Age × Waveform interaction.)

"Precursor" deflections. The earlier of two negative-going peaks in the difference waveforms (Figure 2), the "N1," was larger and more diffusely distributed in the 10-year-old participants. The "N1" became more localized over frontal than over posterior sites in the two older groups (e.g., mismatch negativity, $p < .05$, Scheffé). Like the stimulus-elicited N1 and the "N2" mismatch negativity, "N1" was biased to the right only in the 10-year-old group and was distributed more posteriorly in the target comparison waveforms (e.g., the processing negativity of the target-minus-deviant; Pz, $p < .05$, Scheffé). Positive deflections preceding "N1" (i.e., "P1") were evident at temporoparietal sites. These deflections were larger and usually had a longer latency in the younger participants (10–17 vs. 21 years, $p < .05$, Scheffé). This effect of age was similar to that seen in the more frontally distributed stimulus-elicited P1.

Post-"N1" positive deflections (i.e., "P2") were noted across waveforms, with temporoparietal maxima just posterior to the stimulus-elicited P2 component (Figure 2). These maxima were usually larger in the 17-year-old group than in the 21-year-old group ($p < .05$, Scheffé), but individuals in the 10-year-old group also showed large peaks.

Summary. In general, "N2" peaks in difference waves were larger in the older participants and larger in nontarget than in target comparisons. A right frontal bias in children matured to a bilateral pattern at 14 years for mismatch negativity, but bilateral frontal processing negativity was not seen before 17 years. Relatively long frontal latencies decreased with increasing age at a rate between that recorded for the stimulus-elicited N1 and N2 components. The late positivity complex in target comparisons (e.g., negative difference, Goodin wave) spread more anteriorly from parietal maxima in the two younger groups. A right temporal bias for "P3" in target comparisons was *not* seen in the nontarget comparison. Latencies decreased with increasing age. "N1" was similar to a precursor of "N2" (mismatch negativity) in being biased to right frontal sites in the 10-year-old group but dissimilar in being larger in the younger participants. In the target-processing waveforms, "N1" was more posteriorly distributed than during nontarget comparisons. Both "P1" and "P2" were maximal at posterior sites, but "P1" decreased and "P2" increased in amplitude with increasing age. The "P1" resembled the stimulus-elicited P1 component, whereas "P2" resembled the "P3" complex.

Variability

One of the factors affecting the reliability of effects of age on ERP latencies and amplitudes was the variability of group data. This variability may have reflected recording artifacts or the development of information-processing abilities. For example, the standard deviation ranges for latencies were comparable between age groups for the early components but were two- to threefold larger for N2 and P3 in the 10-year-old group versus other groups. This finding is suggestive of a developmental influence.

Many precautions were taken to eliminate artifacts and to ensure a lateral equivalence in recording procedures (see Methods section). These precautions ranged from adjusting for perceptual thresholds from each ear to balancing the reference recordings from the ears. The vertical EOG had a high threshold setting to avoid contamination from eyelid and body jerks, which are the main source of movement artifacts. The decision to maximize the channels for topographic recording led to the absence of a horizontal EOG. Horizontal eye movements are more likely to be a source of irregular artifact with a single reference electrode; however, by balancing left versus right differences, the attenuation becomes negligible under the assumption of no systematic left versus right differences of eye movement. Thus, skewing of our topographic results was less likely than an increase in the variance attributable to children being more restless than adults. A systematic left–right difference could occur in the comparison of conditions in which button responses occur during the discrimination, but, because only ERPs after a correct response were accepted, the effect was similar for all participants and did not alter between comparisons. Indeed, left versus right changes in P3 were inde-

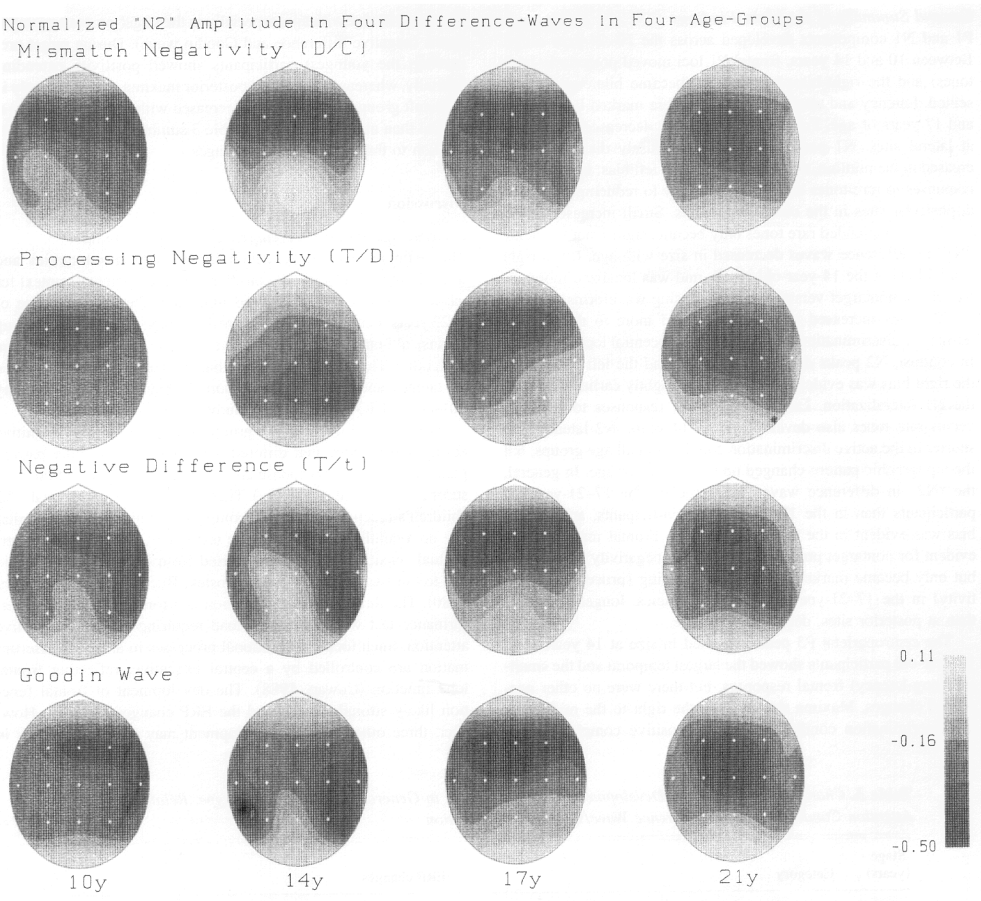

Figure 5. Topographic scalp distribution of mean vector-normalized "N2" peak amplitudes in four types of difference waveforms (adjusted to raw microvolt range; scale bar on the right). The anterior sites are uppermost in each map, and darker shading represents larger amplitudes. Maps are shown left to right for the four age groups (M = 10, 14, 17, and 21 years). Representations in the first row show the comparative processing of two nontarget stimuli and different measures of comparative processing with target stimuli in the other three rows. Top row: Mismatch negativity (MMN; D-C, ERP to deviant minus that to common standard tone). Second row: Processing negativity (PN; T-D, ERP to target minus that to deviant nontarget tone). Third row: Negative-difference (Nd; T-t, ERP to target minus that to the same 1.4-khz tone presented as nontarget in the passive condition). Fourth row: Goodin wave (ERP to target minus standard tone in the active condition minus the same comparison for the passive condition).

pendent of whether the tone was a target (Figure 4). Because artifact elimination through HEOG records in adults is typically <2% (Wright, Geffen, & Geffen, 1995), the variability in the records likely reflected functional development.

The implication that attentional abilities interact with age resulting in variable latencies in the young seems to be supported in the difference waves in which standard deviations were comparable for mismatch negativity but larger in the youngest group for the negative difference. Standard deviations for amplitude data showed small increases with attentional requirements for late components (e.g., P1 vs. P3, mismatch negativity vs. negative difference) independent of age. However, deviations were twice as large for early peaks in 10-year-old participants. Thus, the reliability of the data did not vary in a simple systematic way with age, but attentional demands increased variability in the young. This variability implies a difficulty in demonstrating differential effects of focused attention on the ERPs of children versus adults.

General Summary of the Main Findings

P1 and N1 components developed across the 10–21-year range. Between 10 and 14 years, frontal P1 loci moved posteriorly (rare tones) and the right-biased frontal N1 became bilaterally represented. Latency and amplitude changes were marked between 14 and 17 years of age. For P1, both measures decreased, especially at lateral sites. N1 peaks became less diffusely distributed, increased in the midline, and than developed a left bias. Increased P1 responses to rare tones anteriorly gave way to reducing responses at posterior sites in the older participants. Small increases of N1 amplitude to attended rare tones only became significant in adults. "N1" in difference waves decreased in size with age, lost a right frontal bias in the 14-year-old group, and was localized more anteriorly in nontarget versus target processing waveforms.

P2 peaks increased with age, localized more to the midline during the discrimination, but only attained a central locus in adults. In contrast, N2 peaks decreased with age and the left rather than the right bias was evident from 14 years, slightly earlier than with the N1 lateralization. Larger midline N2 responses to common versus rare tones also developed from 14 years. N2 latency was shorter in the active discrimination condition in all age groups, but the topographic pattern changed up to 21 years of age. In general, the "N2" in difference waves was larger in the 17–21-year-old participants than in the 10–14-year-old participants, and a right bias was evident in the 10-year-old group. Frontal maxima were evident for nontarget processing (mismatch negativity) at all ages, but only became marked for target processing (processing negativity) in the 17–21-year-old group. Latencies, longer at frontal than at posterior sites, decreased with age.

The centroparietal P3 peak increased in size at 14 years. The 10-year-old participants showed the largest temporal and the smallest (long-latency) frontal responses, but there were no other age-related changes. Maxima shifted from the right to the midline in the discrimination condition. The late positive complex ("P3") decreased in size with age, especially in the target-processing waveforms (negative difference and Goodin wave). During target processing, the youngest participants showed positivity extending frontally, whereas right-biased posterior maxima developed only in the adult group. "P3" latencies decreased with age more rapidly at frontal than at posterior sites. (Table 3 summarizes the findings in relation to three developmental stages.)

Discussion

General Age-Related Development and Background

The main results are described in the section summaries and Table 3. In this section, we consider the developmental context for participants whose age covered uniformly the 14-year range of 8–22 years. Performance IQ spanned 50 points (80–130), but group means, although marginally above average, did not differ from each other. Thus, bearing in mind that inverse correlations between P3 latency and IQ have been reported (Martin et al., 1993), any influence of IQ in the present study was counterbalanced.

The 10- and 14-year-old groups showed a similar cognitive ability and strategy that differed from those of the older participants (e.g., a slower response and decreased signal detection measures of perceptual sensitivity). These features are not unusual. The children's reaction times were comparable with those of a similar age on a continuous performance test (Levy, 1980), and low perceptual sensitivity has been reported from individuals similar in age to our two younger groups (Sostek, Buchsbaum, & Rapoport, 1980). The three-tone discrimination is a form of continuous performance test with a memory load requiring sustained selective attention. Such focused attentional processes in an active discrimination are controlled by a central executive, reflecting frontal lobe function (Cowan, 1988). The development of frontal function likely strongly influenced the ERP changes recorded. However, three other types of development may underlie changes in

Table 3. *Changes in Age-Related Development of ERP Features in General, Related to Tone Type, Related to Attention Condition, and in Difference Wave/Comparator Function*

Stage (years)	Category	ERP changes
10–14	General	Nc disappears; N1 less diffuse distribution; N1 latency decrease.
	Tone	More posterior P1 to rare/higher tones; lateral P2 peaks (large to standard) decrease; P3 peak sensitivity (increase with rarity) completed; P3 latency loses tone-type sensitivity (long for standard).
	Attention	Decreased influence of rarity eliciting larger N1 peaks; loss of longer N1 latency in passive vs. active condition; N2 latency decrease, 15% in passive, 25% in active condition; P3 latency decrease more in passive than active condition; frontal P3 response develops in passive condition.
	Comparator	Development of mature frontal mismatch negativity topography and latency decrease (nontarget processing).
14–17	General	Marked P1 amplitude decrease, continued latency decrease; N1 latency becomes less topographically differentiated (decrease at anterior and temporal sites); N1 peak develops left bias; anterior shift for P2 locus completed; N2 peak loci become more focal.
	Tone	Midline (not lateral) augmenting P2 response continues to develop; reducing response of N2 peak continues to develop (but see Attention).
	Attention	N2 peaks localize anteriorly (amplitude larger in passive vs. active condition); *abrupt shortening of reaction time.*
	Comparator	Development of mature frontal processing negativity topography; "P3" distribution becomes more posterior and lateralized.
17–21	General	P2 amplitude increase, maxima become central rather than parietal, and differentiated P2 latency topography disappears.
	Tone	Reducing tendency in P2 response starts to develop.
	Attention	Small N1 amplitude increase to target develops; N2 latency topography matures, (long frontocentral, short posterolateral); development of association of short P3 latency with large amplitude completed.
	Comparator	Latency decrease for negative difference and late positivity in target and nontarget processing (decrease more anterior than posterior).

the ERP and cognitive function with age, namely connectivity in the brain, sexual maturation (gonadal steroids), and neurotransmitter activity.

At the late prepubertal stage, large changes occur in the number and connectivity of synapses (Huttenlocher, 1990). Nevertheless, despite synaptic pruning, brain weights (including myelination processes) continue to increase by 5% in the second decade (Benes, Turtle, Khan, & Farol, 1994). Benes et al. reported that the ratio of myelination area to brain weight doubles in the second decade for some transition cortices. The cingulate, associated with these cortices, assumes important attentional functions (Morecroft, Geula, & Mesulam, 1993). The cingulate is closely interconnected with the frontal cortices, which together undergo marked functional development in the 9–12-year-old age range (e.g., "freedom from perseveration"; card sorting) and 13–15-year-old age range ("planning/strategy"; Tower-of-London: Levin et al., 1991). Crucial for the auditory discrimination in the present report, the frontal cortex is important for mediating nonepisodic rule learning (Winocur, 1991) and the application of rules in stimulus selection strategies (Diamond, 1990). These abilities develop in the late prepubertal stage, for example, reduction of errors of commission in 8–11-year-old individuals (Sostek et al., 1980) and acquisition of trace conditioning abilities (Woodruff-Pak, Logan, & Thompson, 1990), and they improve further in 14-year-old individuals (Levin et al., 1991).

Gonadal steroid levels reflected in the Tanner maturity ratings were also changing up to 21 years. A major change was evident between 14 and 17 years. Increasing hormone levels could have either directly altered neural function (e.g., refractory processes; Kendrick & Drewett, 1979) or influenced transmitter activity (Sar & Stumpf, 1981) and thus have affected ERP characteristics and attentional processes (Oades, 1979). A relationship between hormone levels and ERPs is indicated by, for example, the presence of P3 gender differences in adults (Deldin et al., 1994) but not in 6–14-year-old children (Martin et al., 1988), and by a series of studies by Tan (1990) showing correlations between early somatosensory ERP amplitudes and steroid levels.

Clearly, on anatomical/functional grounds, there is reason to regard the 10-year-old participants, and to a lesser extent, those 14 years-old as less well developed than the older participants. This point is emphasized by considering the dependence of ERP generation on neurotransmitter activity (Meador, 1995; Oades, 1995; Pineda, 1995). For example, the coordination of frontal and temporal lobe activity will depend on the maturity of the functionally important dopaminergic innervation of both regions (Oades & Halliday, 1987; Smiley, Williams, Szigeti, & Goldman-Rakic, 1992). We found major decreases of monoaminergic metabolism between the 10- and 14-year-old groups (Oades, Röpcke, & Schepker, 1996b).

Thus, three major developmental steps seem to approximate the changes between our four age groups, namely pertaining to anatomy and neurotransmitter activity (10–14 years), connectivity, hormonal and neuropsychological function (14–17 years), and a more minor hormonal and connectivity development between 17 and 21 years.

ERP Development—General Findings for Age

One of the more striking features shown in Figure 1 is the negative shift over early ERP components of the 10-year-old participants. This feature may correspond to the Nc recorded by Courchesne (1978) and others in children. The negative shift was evident earlier than usually reported (from 100 rather than from 300 ms) but was absent in 14-year-old participants, as reported elsewhere (Kurtzberg et al., 1984; Neville, 1977; Symmes & Eisengart, 1971). The shift was recorded mostly over frontal sites (see Friedman et al., 1984) and may reflect cortical excitability (Schupp, Lutzenberger, Rau, & Birbaumer, 1994). This finding would be consistent with the more impulsive nature of children on sustained and selective attention tasks and may reflect immaturity of frontal cortical function (Foster, Eskes, & Stuss, 1994).

P1 sources in adults may lie in the primary auditory cortex (Reite et al., 1988) and reflect firing in the thalamus (Erwin & Buchwald, 1986). We conjecture that the larger P1 responses recorded in the youngest participants may be an attempt to counteract the excitability indexed by Nc. P1 latency decreases with increasing age are broadly consistent with a drop of about 2 ms/year, as reported from 3-year-old children (Barnet, Ohlrich, Weiss, & Shanks, 1975) and young adults (review Polich & Starr, 1984), but were most marked between 14 and 17 years.

Negativity associated with N1 showed frontocentral maxima in all groups. It was distributed more diffusely in the 10-year-old participants and, biased to the right in the 10–14 years old, but biased to the left after the mid-teens. This timing coincides with fluency test measures of frontal lobe function that develop strongly around 13–15 years (Levin et al., 1991). Taking the Nc shift into account and consistent with other studies over a similar age range, no age-related amplitude changes were recorded (Courchesne, 1977, 1978; Friedman, Boltri, Vaughan, & Erlenmeyer-Kimling, 1985; Johnson, 1989). N1 latency decreases from 4 years to past adolescence have been reported (Johnson, 1989; Martin et al., 1988, 1993; but not Polich & Starr, 1984) and were marked between 10 and 14 years in the present study.

Martin et al. (1988) found N1–P2 amplitude increases up to 14 years of age, but Johnson (1989) reported no such change. We found that P2 amplitudes increased and latencies decreased with age. These inconsistent results imply that P2 measures are unreliable for inferring developmental change (Goodin et al., 1978), but perhaps significantly, P2 loci shifted anteriorly to the vertex from 10 to 17 years.

N2 amplitude decreases with age were marked after 10 years because of the waning of Nc, thus confirming reports from Friedman et al. (1984) and Enoki et al. (1993) but not from Johnson (1989). An increase of amplitude up to 14 years (Martin et al., 1988) coincides with the age at which we recorded widespread changes in the distribution of negativity. N2 latencies decrease across this age range (Courchesne, 1978; Goodin et al., 1978; Johnson, 1989; Polich & Starr, 1984). However, except for Enoki et al. (1993), reports have not referred to the flattening of the curve that we found from 14 years. Further, reflecting peak topography, latencies were usually shorter frontally than posteriorly in the young but longer for adults.

Our data showed a tendency for frontal P3a peaks to increase with age, but the overlap of Nc obscured an unequivocal interpretation. At posterior sites, P3b activity became more localized with increasing age. This differentiation could explain previous conflicting reports. Nonsignificant increases and decreases of P3 amplitude with age have been reported by Goodin et al., (1978), Johnson (1989), and Martin et al. (1988), whereas increases to 14 years (Holcomb, Ackerman, & Dykman, 1985) or to 19 years of age (Ladish & Polich, 1989) have been found. From a sample of 15 reports, P3 latency decreases with age at rates varying from 5 to 38 ms/year, with decrements of up to 1 ms for 1 ms shorter reaction time (Ladish & Polich, 1989; Martin et al., 1993). Our data broadly confirm a mean of 5 ms/year, but the largest drop occurred between 10 and 14 years.

ERP Development—Responses to Tone Type and Attention Condition

The tones were presented initially in a passive nontask situation (diffuse attention) and then in an active discrimination requiring focused attention, in which one of the rare tones was designated as a target and the other nontarget as the deviant. Across groups, the P1 response to standards was localized at frontal and lateral sites, but loci for responses to the higher deviants were more posterior from 14 years of age. In addition, during focused attention, P1 latency increased and lateral positivity after the less salient standards decreased. This finding is suggestive of a feedback influence of selective attention operating across trials at all ages (Hackley, 1993). An endogenous influence of attention on the following N1 was evident at the vertex where deviant tones, particularly in the discrimination, elicited the larger response (Woldorff, Hansen, & Hillyard, 1987). The lack of statistical confirmation in the topographic analysis may be an artifactual casualty of normalizing variable far-lateral responses. A modest augmenting response of N1 to increasing tone frequency disappeared with increasing age. Both P1 and N1 developments are consistent with the view that reducing properties may be expected from mature frontal cortex (Foster et al., 1994) and that functional growth and development of the primary sensory cortex, although marked from 10 to 14 years, is not complete before 17 years of age.

As with P1, lateral P2 positivity was more evident in the youngest participants, but for older participants this positively fell off sharply over frontal sites. In addition, midline P2 responses tended to augment with tone frequency in the two younger groups, but reducing tendencies became evident in the adults (Oades, Dittmann-Balcar, & Zerbin, 1995b). Although P2 sources in adults have been reported adjacent to those for N1 in the secondary auditory cortex and lateral temporal gyri (Makela & Hari, 1990; Vaughan & Arezzo, 1988), both features may reflect increasing maturity of frontal function and may reflect poorly developed response modulation in the 10-year-old participants. Indeed, this finding is reminiscent of the finding in children with attention deficit hyperactivity disorder (Oades et al. 1996a) for whom frontal development may be retarded (Reader, Harris, Schuerholz, & Denckla, 1994).

N2 amplitude increases with task difficulty (Novak, Ritter, Vaughan, & Wiznitzer, 1990), so it is not surprising that the youngest participants who had the most difficulty with the discrimination task also had the largest peaks. N2 peaks were modestly biased to right temporal sites after deviant attended tones and to left frontal sites after less salient standards. This lateralized pattern is relevant to a recent report in which *young* paranoid schizophrenic persons showed an exaggerated left-frontal/right-temporal topography of the negative-difference wave ("N2"), whereas nonparanoid persons showed the mirror-image pattern (Oades, Zerbin, & Eggers, 1994). This pattern illustrates the importance of intercortical monitoring for N2-indexed stimulus-categorization processes (Novak et al., 1990). In general, N2 latencies were shorter after deviants than after standards and shorter during focused than during diffuse attention, but the adult pattern of longer frontal than posterior latencies was absent before puberty.

The widespread finding that deviants elicit larger P3 responses than standards was confirmed (Johnson, 1989) but was least evident in the 10-year-old participants. Independent of age targets elicited the largest P3 response and the change from diffuse to focused attention brought P3 loci in from the right to the midline. (Temporal responses were more sensitive to augmenting tone frequency.) These data imply more stimulus analysis in right temporal areas and more task-related processing in the left hemisphere, where temporal lobe function is least differentiated in the youngest group (König, 1990). Compared with adults, young participants showed relatively short frontal P3a latencies after *nontarget* stimuli. This finding may reflect the relatively poor degree of development in the 10-year-old group of a frontal inhibitory capability essential to selective processing (Passler, Isaac, & Hynd, 1985). However, for P3b latencies, the largest drop also occurred between 10 and 14 years during diffuse attention. The association of short P3b latency, and large amplitude (e.g., after a target) was clearest in adults.

ERP Development—Stimulus Comparisons in the Difference Waves

Difference waves consisting of target versus nontarget stimulus comparisons represent different information-processing operations than that comparing nontargets, but the Goodin wave may show some aspects of both types. Differences between these two categories of waveform were predicted and found (e.g., the mismatch negativity latency was shorter than the latency in the negative-difference wave). However, the form of the deflection around "N2" in each waveform and a broadly similar topography suggest a feature that the categories have in common may override (i.e., the psychological stimulus-comparison process is essentially the same). This suggestion seems broadly true for the early deflections, but topographically differential rates of development were measured for later potential shifts (10–14- vs. 17–21-year-olds).

Relevant to the choice of measure in future applications are the relative merits of the four difference waves. The Goodin wave showed a poor differentiation across development for the early deflections versus target- and nontarget-derived waveforms but reflected the main aspects of target-derived waves in the late components. The T-D processing negativity measure showed equivocal patterns for the development of "N1" and the distribution of "P3" but provided useful comparisons with other difference waves for "N2" (e.g., a right-sided emphasis like other target-derived waves in development but an adult topography like the mismatch negativity). The most differentiated pattern of development was seen in the mismatch (D-C) and negative-difference waves (T-t).

"N2." In the nontarget comparison, mismatch negativity showed a mature topography by 14 years of age. Only in the youngest group was the peak weaker and biased to the right. In the target-derived waves, "N2" did not develop a mature frontal pattern until 17 years of age; in younger participants, this processing negativity tended to peak more posteriorly and on the right. Magnetoencephalographic and ERP studies have reported that the adult mismatch negativity derives from supratemporal primary auditory cortex (Novak, Ritter, & Vaughan, 1992; Tiitinen et al., 1993) and that the "N2" has a broadly symmetrical distribution in target- and nontarget-derived waves (Woods, Alho, & Algazi, 1993). Our data are consistent with these reports, but in young participants, large areas (especially on the right) were activated. This finding may mean that, although 10–14-year-old individuals are capable of performing cognitively demanding stimulus comparisons necessary for discrimination as well as adults, this activation involves widely distributed cortical regions (e.g., negative difference, T-t; Figure 5).

The "precursor N1" in mismatch negativity and negative-difference waveforms (cf., Nd early; Alho et al., 1994; Woods et al., 1993) increased with age and became more frontally localized, but in the other waveforms that confound stimulus deviance

and task relevance, the pattern was less clear. Our "N1" component may be similar to the "N1a" described by Novak, Ritter, and Vaughan (1992) in indexing the initiation of an attentionlike process. In the young, this was marked by pre- and post-"N1" positive deflections that decreased in size and became less diffusely distributed from 14 years.

"P3." Late positivity was well defined posteriorly. In the nontarget comparison, maxima were in the midline. For target-processing waveforms, a left-sided bias developed in the T-minus-t (negative difference) and Goodin wave (Faux et al., 1988) and a right-sided bias developed in the target-minus-deviant wave (T-D) in the 17–21-year-old participants. In contrast to the stimulus-elicited P3, frontal positivity was large in the 10-year-old participants. Being larger in the target versus nontarget waveforms supports the putative function for this positive shift in a late stage of stimulus comparison and selection. If the frontal component reflects a late stage of selective processing prior to the updating function of the posterior component (Donchin & Coles, 1988), then it is not surprising that immature regions have to generate relatively more effortful positivity to bring the necessary amount of inhibition to bear on selection. (The argument assumes that positive shifts reflect inhibitory processes; Schupp et al., 1994.) The different patterns of development for frontal and posterior positivity in the stimulus-elicited ERP and in the difference waves also point to potentially separate underlying functions of these components (e.g., stimulus weighting vs. trace updating; cf. Mecklinger & Ullsperger, 1996).

Latency decreases with increasing age were marked at the 10–14-year ("N2", nontarget comparison) and 17–21-year ("P3") stages. The meaning of latency changes in difference waves requires further study. For example, latencies were often shorter where local peaks were less than the overall maximum (e.g., parietal "N2"), but some decreases were associated with increased size (e.g., left "N1" in older participants). Was the component masked by other activity or was the function indexed less or more important at the loci considered? Do differential latency decreases in development reflect a change of function (P3a/P3b) and do increased latencies in target versus nontarget waveforms really imply the slower processing of more complex task-related information?

Conclusions

The maturation of ERP parameters is not always linear or even curvilinear; particular regions can show rapid developmental changes. Normalized data proved useful in confirming the migration of peak loci with developmental age and attention condition and in disconfirming changes of amplitude observed in the raw data (e.g., with tone type). The potential for difference-wave topography to index the differential maturation of information processing function and dysfunction was illustrated.

Changes of size, latency, and topography of ERP components suggest three developmental stages. The first (10–14 years) concerns the putative function of designating and allocating channels for further information processing (indexed by P1 and N1; Hansen & Hillyard, 1988). The topography of P1 and N1 becomes more localized, and the amplitude becomes more sensitive to tone type. The overlapping negative shift (Nc) disappeared by 14 years of age. Latency decreases may reflect an increased efficacy in connectivity between brain regions mediating later components. The ability to develop perceptual traces matures (e.g., mismatch negativity). During the second stage between 14 and 17 years, topographic patterns mature (e.g., N1 lateralization, P2 more central, N2 more focal). The coincidence with the maturation of processing negativity in the target-processing waveforms emphasizes the development of the bases for selective attention abilities. During the third stage between 17 and 21 years, the completion of the development of efficient endogenous interactions that underly selective information processing is illustrated by maturation of topographic latency patterns for N2, P3, and late positivity in the difference waves.

Major contributions to these changes probably arise from the maturation of frontal structures (Foster et al., 1994), especially during early puberty, and across the age span studied from improved connectivity and transmission (myelination and brain weight changes; Benes et al., 1994; Dustman, Shearer, & Emmerson, 1993). The relative contributions to ERP development of specific brain regions and neuromodulators require an experimental design that includes neuropsychological, tomographic, mapping, and physiological measures.

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