
Speech-Sound Discrimination in School-Age Children: Psychophysical and Neurophysiologic Measures

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This study measured behavioral speech-sound discrimination and a neurophysiologic correlate of discrimination in normal school-age children (ages 6 to 15) to determine if developmental effects exist. Just noticeable differences (JNDs) and mismatch responses (MMNs) were assessed for synthetic syllables that differed in third-formant onset frequency (/da-ga/) and formant transition duration (/ba-wa/). These stimuli were selected because children with learning problems often find it difficult to discriminate rapid spectrotemporal changes like /da-ga/, whereas the ability to distinguish /ba-wa/ is relatively unimpaired. Results indicate that JNDs for /da-ga/ show no developmental effects and that JNDs for /ba-wa/ decrease slightly with age (although likely for task-related reasons). MMNs elicited by two /da-ga/ stimulus pairs (onset frequency differences = 20 Hz, 280 Hz) and three /ba-wa/ stimulus pairs (transition duration differences = 3, 5, 15 ms) showed no systematic or significant differences for onset latency, duration, or area as a function of age. Normative JND and MMN data are provided. These norms provide a metric against which children with suspected central auditory processing difficulties or auditory-based language disorders can be compared.

KEY WORDS: auditory development, learning disabilities, speech-sound perception, central auditory physiology, mismatch negativity

A better understanding of the biological mechanisms underlying normal and impaired speech perception can be achieved by a combination of psychophysical and neurophysiologic data elicited by similar speech sounds and obtained in the same individual. Therefore, the purpose of this study was to characterize perceptual and neurophysiologic responses to speech sounds in normal children, thereby providing norms against which to evaluate school-age children with auditory-based learning problems. More theoretically, the data provide insight into the development of perceptual and related physiologic processes in school-age children.

Speech Perception and Learning Problems

Learning disabilities and attention disorders are a common diagnosis in a significant number of school-age children. It is estimated that as many as 9% exhibit learning and reading disabilities, and as many as

5% evidence attention deficit disorders (Torgeson, 1991). Many children with those diagnoses have difficulty processing auditory information, especially speech. Moreover, it has been reported that a subset of children with learning problems has difficulty with perception of certain fundamental acoustic differences within speech sounds (Elliott, Hammer, & Scholl, 1989; Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Reed, 1989). Those perceptual deficits, in turn, appear to be associated with poor phonologic processing and poor reading skills (Godfrey et al., 1981; McBride-Chang, 1996; Reed, 1989).

The origin of this speech-sound perception difficulty is unclear and remains controversial. Some investigators believe that a basic inability to perceive fine-grained acoustic signals underlies language and learning impairment (Elliott et al., 1989; Tallal, 1980; Tallal et al., 1996). Others believe that the basic auditory capabilities of these children are normal but that their phonologic categories are less defined than those of normally developing children (Fletcher et al., 1994; Share, Jorm, Maclean, & Matthews, 1984; Stanovich & Siegal, 1994; Studdert-Kennedy & Mody, 1995). Further confusing the issue is the heterogeneity of the population, which makes it likely that these deficits do not represent a unitary phenomenon. Put another way, the origin of the perceptual problem undoubtedly differs from child to child.

Furthermore, the auditory perceptual measures currently used clinically are unable to pinpoint the exact nature of these auditory processing deficits. In tests that use speech stimuli, the acoustic dimensions of the stimuli are not well defined. Typically, the stimuli are presented live voice or are taped classic exemplars of phonemes and are acoustically redundant (Gardner, 1985; Woodcock, 1976, 1977). Consequently, these tests are confounded by higher-order cognitive and linguistic factors and do not assess fine-grained acoustic perception. More acoustically controlled tests of central auditory function also do not assess fine-grained acoustic-phonetic perception (Berlin, Lowe-Bell, Jannetta, & Kline, 1972; Jerger & Jerger, 1974; Katz, 1962; Musiek, 1983; Wexler & Hawles, 1983). Other tests of central auditory processing use nonspeech signals, and it is unknown whether the perceptual processes engaged in the perception of those stimuli are engaged similarly when listening to a complex speech signal (Pinheiro & Ptacek, 1971).

Kraus and colleagues have hypothesized that, for some children, the difficulty in perceiving fundamental acoustic parameters stems from abnormalities in the *central sensory representation* of speech stimuli that occurs after peripheral sensory encoding and before conscious perception. Although this preconscious level of representation is closely tied to the acoustic characteristics of the stimulus, it is also modifiable depending on

an individual's auditory experience (Kraus et al., 1995; Tremblay, Kraus, Carrell, & McGee, 1997; Tremblay, Kraus, & McGee, 1998). The experimental approach of Kraus and colleagues involves evaluating behavioral speech-sound discrimination and a neurophysiologic correlate of discrimination in school-age children with and without learning problems. Using this combined electrophysiological/behavioral approach, it has been possible to identify subgroups of children with abnormalities relating to the central sensory processing of acoustic information (Kraus et al., 1996).

However, in order to make these behavioral and electrophysiologic measures clinically applicable to learning-disabled children, it is important to describe the discrimination abilities and corresponding neurophysiologic responses of normal school-age children. It is particularly essential to document any age-related phenomena that might influence the interpretation of those responses in an impaired population. A description of these responses across a sufficient population of normal children is necessary in order to make definitive statements about the relative normality/abnormality of these measures for the learning disabled children.

Development of Auditory Behavior and Physiology

The importance of characterizing the effects of normal development on speech-sound discrimination and associated neurophysiologic responses stems from what is known about speech perception and auditory-system development in children. Behavioral and physiologic evidence indicate that although the auditory system is largely developed by school age, certain functions continue to develop during the school-age years. Behavioral studies suggest that many aspects of auditory perception of nonspeech and speech stimuli are largely mature by school age (Allen & Wightman, 1992; Bargones, Werner, & Marean, 1995; Bertoncini, Bijeljac-Babic, Blumstein, & Mehler, 1987; Jensen & Neff, 1993; Nittrouer, 1992, 1996; Nittrouer & Studdert-Kennedy, 1987; Ohde, Haley, & McMahon, 1996; Olsho, 1985; Schneider, Morrongiello, & Trehub, 1990; Schneider, Trehub, Morrongiello, & Thorpe, 1989; Trehub, Schneider, & Henderson, 1995; Veloso, Hall, & Grose, 1990; Walley & Carrell, 1983; Walley, Pisoni, & Aslin, 1984; Werner & Marean, 1996; Wightman, Allen, Dolan, Kistler, & Jamieson, 1989). Nevertheless the perception of certain speech sounds may continue to develop during the school-age years, and these perceptual abilities are modifiable in terms of an individual's auditory experience throughout life (Bradlow, Pisoni, Akahane-Yamada, & Tohkura, 1997; Elliott, Longinotti, Meyer, Raz, & Zucker, 1981; Kraus et al., 1995; Nygaard,

Sommers, & Pisoni, 1994; Ohde et al., 1996; Oyama, 1976; Sussman, 1993; Sussman & Carney, 1989; Tahta, Wood, & Loewenthal, 1981; Tremblay et al., 1997, 1998; Yamada, 1995). Similarly, physiologic evidence indicates that auditory brainstem and certain cortical responses are mature by school age (Csépe, 1995; Hecox & Galambos, 1974; Kraus et al., 1993; Steinschneider, Kurtzberg, & Vaughan, 1992), whereas other responses to sound continue to develop during that same time period (Courchesne, 1990; Cunningham, Nicol, Bradlow, McGee, & Kraus, 1997; Eggermont, 1989; Kraus & McGee, 1995; Ponton et al., 1996; Sharma, Kraus, McGee, & Nicol, 1997).

The immaturity and variability in young children's psychophysical and speech perception abilities may be attributable to an inability of younger children to attend to tasks and to filter out noise. On the other hand, it may represent inherent physiologic variability that underlies the speech-learning plasticity intrinsic to young children. Unfortunately, it is difficult to separate the physiologic limits of the auditory system from other developmental variables, which subsequently mature with age (Allen, Wightman, Kistler, & Dolan, 1989). Thus, it would be valuable to assess the brain's processing of acoustic information without confounding attention and developmental factors.

A neurophysiologic response exists that reflects biological processes underlying auditory discrimination. The mismatch response, or MMN, is an auditory cortical potential that can be elicited by small (as well as large) acoustic changes in both simple and complex stimuli (Kraus, McGee, Carrell, Sharma, & Nicol, 1995; Näätänen, 1986; Sams et al., 1985). It provides an index of the neurophysiologic representation of the acoustic dimensions that underlie speech perception and can be elicited in a passive paradigm that does not require attention or a behavioral response from the listener (Näätänen, 1991; Novak, Ritter, & Vaughan, 1992). Thus, the MMN provides a tool for examining how different neural generator systems are engaged depending on the acoustic characteristics of the stimuli used to elicit the response (Alho, 1995; Giard et al., 1995; Kraus et al., 1994).

Focus of This Study

This report describes behavioral discrimination abilities and neurophysiologic responses for normal children ages 6 to 15 years using synthesized speech syllables. The /da-ga/ stimuli used in the experiments were chosen because children with learning problems often find it difficult to discriminate the spectrotemporal changes associated with those consonant contrasts. The /ba-wa/ stimuli were selected because the perception of

/ba-wa/ contrasts is relatively unimpaired and thus provides a measure of comparison with /da-ga/ (Kraus et al., 1996). The effects of maturation, gender, hemispheric specialization, and stimulus variables were examined.

Method

Psychophysical Experiments

Participants

Participants were 134 normal school-age children between the ages of 6 and 15 years distributed evenly over the age span. There were 64 boys and 70 girls. They were considered normal on the basis of their histories, audiograms, and performance on a psychoeducational test battery.¹ Data from 18 young adults (20–25 years old) were included (Koch, Bradlow, Bellis, Cunningham, & Kraus, 1999).

Stimuli

Two continua of synthetic speech syllables were generated in order to evaluate just noticeable differences (JNDs) for acoustic contrasts that are known to be important for ongoing speech perception (Stevens & Blumstein, 1978; Walley & Carrell, 1983). They consisted of a /da/ to /ga/ continuum—in which the third-formant onset frequency was varied—and a /ba/ to /wa/ continuum—in which the duration of the first and second formant transitions was varied. These two continua were chosen because the discrimination of rapid spectrotemporal changes like those present in /da/ versus /ga/ may be particularly vulnerable to disruption, on the basis of behavioral data from learning-disabled children and upon neurophysiologic studies in auditory thalamus and cortex (Bradlow et al., 1999; Elliott et al., 1989; Kraus et al., 1996; Kraus et al., 1994; Tallal, 1990). In contrast, data suggest that discrimination of /ba-wa/ is not so affected by auditory-based learning disabilities (Kraus et al., 1996). Consequently future comparisons among the responses to these stimuli in children with learning disabilities may enable us to determine whether disruption in the encoding of rapid spectrotemporal change is a key factor underlying auditory learning problems in some children.

The syllables were synthesized using a Klatt (1980) software serial synthesizer. The endpoints of the continua were defined by ideal examples of the syllables

¹Participants were evaluated on six subtests of the WJ-PEB-R (Woodcock & Johnson, 1989): Cross Out, Sound Blending, Memory for Words, Sound Patterns, Listening Comprehension, and Incomplete Words; and on two subtests of WRAT-3 (Wilkinson, 1993): Spelling and Reading. I.Q. was evaluated using the Brief Cognitive Scale from the WJ-PEB (Woodcock & Johnson, 1977). Finally, participants' parents completed the ADHD Rating Scale (DuPaul, 1990).

(Pisoni, Carrell, & Gans, 1983; Walley & Carrell, 1983) and were the same as those used by Kraus et al. (1996). To summarize the key stimulus differences, along the /da-ga/ continuum, the third-formant onset frequency varied from 2580 Hz (/da/) to 2180 Hz (/ga/) in 40 steps of 10 Hz each. Along the /ba-wa/ continuum, the transition durations of the first and second formants varied from 10 ms (/ba/) to 40 ms (/wa/) in 30 steps of 1 ms each. Total stimulus duration was 100 ms. (Short-duration stimuli were necessary for the MMN recordings.) Stimuli were presented binaurally at 75 dB SPL through headphones (Sennheiser HD 540).

Synthetic speech stimuli were used because, although it is essential that the stimuli have the acoustic characteristics of speech, it is also important to specify and control the acoustic parameters of the stimuli. Because any acoustic change will elicit an MMN, meaningful characterization of the MMN requires precise manipulation of the acoustic characteristics of the eliciting stimulus.

Psychophysical Procedure

Behavioral discrimination thresholds for the two continua were determined using an adaptive tracking algorithm (Parameter Estimation by Sequential Tracking) (Carrell, Bradlow, Nicol, Koch, & Kraus, 1999; Taylor & Creelman, 1967) with a four-interval AX discrimination task (4IAX). The "anchor" stimulus was always the initial syllable in each continuum. (That syllable also served as the deviant stimulus in the electrophysiologic testing.) In each trial block, one stimulus pair consisted of two anchors ("same"), and one stimulus pair consisted of the anchor paired with a contrasting stimulus in the continuum ("different"). The task was to indicate whether members of the first or the second pair of syllables were different. The order of same and different pairs within trials was randomized. In accordance with the PEST algorithm, a correct response resulted in the presentation of the anchor stimulus paired with a syllable closer to it on the continuum. An incorrect response was followed by a more disparate "different" pair. The listener's JND was defined as the distance between stimuli in the "different" pair when the listener reliably reached an accuracy level of 69% correct. However, if that accuracy level was not reached after 128 trials, the block was coded as "failed to converge." Three to five experimental blocks were run on each listener, and the JND was computed as the mean JND of the two best blocks.

JNDs for the /ba-wa/ continuum always were assessed first. The hypothesis was that the /da-ga/ contrast would be more difficult to discriminate, and therefore the listeners should be familiarized with the JND task using the easier continuum (Kraus et al., 1996). Then, the results for the /da-ga/ continuum would more

likely indicate true perceptual abilities rather than reflecting a task-related difficulty. In addition, the data could be analyzed for learning or familiarization effects.

Statistical Analysis

Regression analyses were performed on the data across the entire age range for both stimuli. Age effects were examined further by dividing the data into three age groups and performing an analysis of variance (ANOVA) with and without the adult data. Chi square analyses further examined the distribution of JND scores in the three age groups. Group mean JNDs, standard deviations, and percentile cutpoints were calculated.

Neurophysiologic Experiments

Participants

Neurophysiologic data were obtained from 71 children for two /da-ga/ contrasts and from 81 children on three /ba-wa/ contrasts. Some participants were members of both groups. To be included in either neurophysiologic data set, participants had to have participated in JND experiments for both /ba-wa/ and /da-ga/ contrasts. Neurophysiologic data from 9 young adults (20–25 years old) tested on both /da-ga/ contrasts also were included (Koch et al., 1999).

Stimuli

The MMN was evaluated using procedures that have been described previously (Kraus et al. 1996). Two syllable pairs from the /da-ga/ continuum and three pairs from the /ba-wa/ continuum served as the standard and deviant stimuli in an oddball paradigm. The first stimulus of the continuum always served as the deviant stimulus. The standard stimulus was selected so that the stimulus pairs ranged from easy-to-discriminate to very-difficult-to-discriminate. From the /da-ga/ continuum, the syllables with an F_3 onset frequency of 2500 Hz or 2300 Hz served as standards, and the syllable with an F_3 onset frequency of 2580 served as the deviant. These pairs were termed /da-ga/₁ and /da-ga/₂ and corresponded to JNDs of 80 Hz and 280 Hz, respectively. From the /ba-wa/ continuum, the syllables with 37-ms, 35-ms, or 25-ms transitions served as the standards and the syllable with a 40-ms transition served as the deviant. These pairs were termed /ba-wa/₁, /ba-wa/₂, and /ba-wa/₃. These three pairs corresponded to JNDs of 3 ms, 5 ms, and 15 ms.

For the /da-ga/ pairs, the deviant probability of occurrence was 10%, and the stimulus repetition rate was 1.7 per s. For the /ba-wa/ pairs, the deviant probability of occurrence was 15%, and the stimulus repetition rate was 1.4 per s. The optimum balance between probability of occurrence and repetition rate varies depending on the stimulus. Pilot studies showed these parameter

values to be appropriate for these stimulus pairs.

Stimulus files from the Klatt synthesizer were downloaded to a PC-based stimulus delivery system, which controlled time of delivery, the stimulus sequence, and the stimulus intensity. That system also triggered the PC-based evoked-potential averaging system and indicated whether the trial contained a standard or deviant stimulus. The synthesized syllables were presented to the right ear at 75 dB SPL through insert earphones (Etymotic ER-3). Stimuli were presented in a pseudo-random sequence, with at least three standard stimuli separating presentations of deviant stimuli. Twenty standard stimuli preceded the occurrence of the first deviant stimulus. Responses to standard stimuli immediately following deviant stimuli were excluded from the standard average.

During testing, participants watched self-selected videotaped movies or cartoons and were instructed to ignore the test stimuli. The left ear was unoccluded, and videotape audio levels were kept below 40 dB SPL (A-weighted). Although the MMN can be affected by attention (Alho, Woods, Algazi, & Näätänen, 1992; Woldorff, Hackley, & Hillyard, 1991; Woods, Alho, & Algazi, 1992), it is unlikely that the participants attended to test stimuli because (a) stimulus differences were barely perceptible even in a focused behavioral experiment, (b) each child was questioned about the content of the video following the test session, and (c) the video soundtrack is inherently more interesting than the test stimuli.

Response Recording and Measurement

Evoked responses elicited by standard stimuli and by deviant stimuli were averaged separately. For each person, about 250 responses to the deviant stimuli (/da/ and /wa/) were obtained, along with about 2200 and 1500 responses to the frequent stimuli (/ga/ and /ba/ respectively). In addition, responses were obtained to 1500 stimulus presentations of the deviant stimulus presented alone (termed the deviant-alone condition) for each pair.

For the two /da-ga/ contrasts, responses were recorded from frontal (Fz, F3, F4), central (Cz), temporal (T3, T4), and mastoid (A1, A2) electrodes, with a reference on the nose tip (see schematic in Figure 3). For the three /ba-wa/ contrasts, evoked responses were recorded from Fz only, with a reference on the earlobe contralateral to the stimulus ear. (Equipment upgrades during the course of this study provided more channels by the time the /da-ga/ data collection was initiated.) For all stimulus contrasts, the forehead served as ground. Eye movements were monitored with a bipolar electrode montage (supraorbital-to-lateral canthus). Before data collection, participants were instructed to blink and move their eyes while amplifier settings were adjusted

to ensure detection of eye movements. Averaging was suspended automatically when the eye channel registered movement. The recording window included a 100-ms pre-stimulus period and 500-ms post-stimulus time, with sampling rates of 1000 points/s for /da-ga/ and 850 points/s for /ba-wa/. Evoked responses were analog bandpass filtered on-line from 0.1 to 100 Hz (12 dB/octave rolloff).

Because the MMN should be elicited by the deviant stimulus only when it signals an acoustic change, difference waves were computed for each person by subtracting the response to the deviant presented alone from the response to the deviant presented within the oddball paradigm (Kraus et al., 1995). Then, MMN responses were identified visually in the difference waves as a relative negativity following the N1, occurring between 100 and 500 ms. Onset, peak, and offset latencies were measured. MMN duration was computed by subtracting the onset latency from the offset latency. Amplitude of onset-to-peak latency was measured. Area was computed by integrating the overall response area between the onset and offset latencies.

Statistical Analysis

Regression analyses were performed on the data across the entire age range for MMN parameters (duration, area, onset, and peak latency, amplitude) for each of the stimulus contrasts. Age effects were examined further by dividing the data into three age groups and performing analyses of variance (ANOVA) with and without the adult data. Scheffé post hoc tests were performed when the ANOVA revealed significant findings. Means and standard deviations were calculated for MMN parameters at all electrode locations.

Results

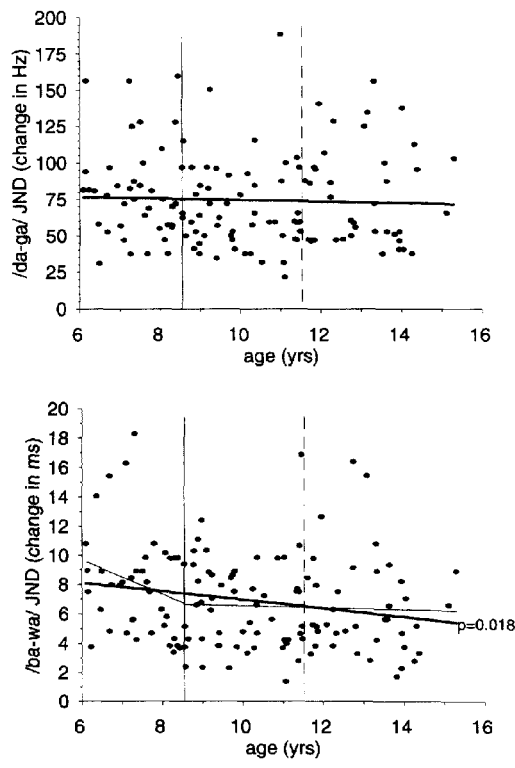
Behavioral Discrimination Abilities

Specifically examined were whether speech-sound discrimination ability changes as a child gets older and whether male and female children differ in these abilities. Normative data on the ability to discriminate fine-grained variants of /da/ versus /ga/ and /ba/ versus /wa/ are provided.

Effects of Age on /da-ga/ Discrimination

No age effects were observed for discrimination of this contrast. Figure 1 shows individual JNDs as a function of age. Correlation analyses indicated no significant effect of age on the /da-ga/ JND ($r = -.04, p = .66$). The children were divided into three age ranges (6–8.5 years, 8.5–11.5 years, and 11.5–15 years), and an analysis of variance (ANOVA) revealed no significant age effects both across

Figure 1. JNDs as a function of age. Top: JNDs for 134 children for the /da-ga/ continuum. There was no significant change in JND with age. Bottom: JNDs for 134 children for the /ba-wa/ continuum. The bold best-fit line indicates a significant decrease in JND with age for the entire population of children. The thin best-fit line illustrates a decrease in JND with age for the young group but not for the older two groups.



the school-age years [$F(2, 127) = 1.4, p = .25$] and when the adult data were added [$F(3, 114) = .48, p = .7$].

Effects of Age on /ba-wa/ Discrimination

Developmental effects on /ba-wa/ discrimination were more complex. Correlation analyses indicated a significant decrease of JND with age ($r = -.2, p = .018$). In order to examine maturational trends more closely, regression analyses were performed on the data within the age groupings (Figure 1, top, thin lines), showing that the decrease in JNDs observed between 6 and 8.5 years was not significant ($r = -.24, p = .13$). Analysis of variance also failed to yield a significant main effect for age, thereby indicating no significant differences in mean

JNDs across age [$F(2, 127) = 2.8, p = .064$]. Moreover, chi square analyses indicated that the distribution of responses in the youngest group was not different from the distribution in the two older groups ($\chi^2 = 8.6, p = .071$ and $\chi^2 = 3.8, p = .43$, respectively).

Some of the younger children had JNDs as low as the older children, suggesting that any differences observed for /ba-wa/ in the youngest children may have been due to attention, motivation, or task familiarity factors rather than to true perceptual differences. It should be recalled that this contrast was always tested first. If the youngest group is divided equally into two smaller groups (younger and older than 7.5 years), the standard deviations for the youngest children are twice those of the older children (4.2 and 2.6, respectively), consistent with greater variability for the very youngest children. Nevertheless, it should be noted that considerable response variability exists across the entire school-age range for this task.

Figure 2 shows mean, standard deviation, and median JNDs for the three groups of children and for adults for the /da-ga/ and /ba-wa/ contrasts. It is apparent that mean and median JNDs do not change with age for /da-ga/, whereas younger children had elevated JNDs compared to those of the older groups for /ba-wa/. Median data indicate that lower JND scores were more prevalent than higher scores.

For /da-ga/, cumulative percentiles were calculated for a single group consisting of all the children (Table 1). For example, if a child has a JND of 35 Hz, he is performing in the 97th percentile—that is, better than 97% of children. For /ba-wa/, because some maturation effects were evident for children younger than 8.5 years and none were apparent for children between 8.5 and 15 years, percentiles were calculated for the younger group and for the combined older groups (Table 1). These percentiles provide a metric against which individual JNDs can be compared.

Effect of Sex

JNDs were compared between boys and girls for 94 children, age-matched to within a year. JNDs obtained from males and females were remarkably similar across both stimulus continua. No significant differences were found for JNDs obtained in males as opposed to those in females (/da-ga/: $t = .39, p = .70; \chi^2 = 3.4, p = .50$; /ba-wa/: $t = .32, p = .75; \chi^2 = 1.5, p = .82$). Thus the same normative data can be used for school-age boys and girls.

Neurophysiologic Testing

Specifically examined were effects of maturation, gender, hemispheric symmetry (and other electrode location issues), and stimulus differences.

Figure 2. Mean, median, and standard deviations of /ba-wa/ and /da-ga/ JNDs for four age groups. Filled circles indicate the mean JNDs for the /ba-wa/ and /da-ga/ continua. The x-marks indicate the median JNDs. The bars represent one standard deviation.

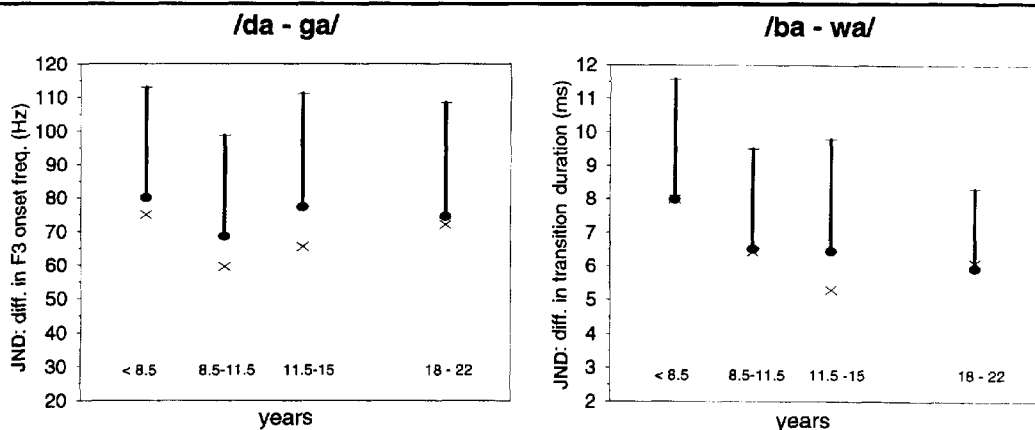


Table 1. Cumulative percentiles for just noticeable differences (JND) for the /ba-wa/ and /da-ga/ contrasts.

/da-ga/		/ba-wa/		
JND (Hz)	all ages	JND (ms)	<8.5 yrs	>8.5 yrs
15	100%	1.5	100%	99%
20	100%	2	100%	97%
25	100%	2.5	100%	93%
30	99%	3	100%	90%
35	97%	3.5	99%	86%
40	90%	4	91%	76%
45	87%	4.5	86%	68%
50	77%	5	78%	60%
55	67%	5.5	74%	51%
60	55%	6	67%	48%
65	51%	6.5	63%	45%
70	47%	7	62%	40%
75	43%	7.5	60%	37%
80	39%	8	53%	29%
85	31%	8.5	44%	25%
90	27%	9	31%	20%
95	24%	9.5	30%	16%
100	17%	10	20%	11%
105	15%	10.5	17%	9%
110	13%	11	13%	7%
120	11%	12	12%	6%
130	7%	13	11%	4%
140	5%	14	11%	4%
150	5%	15	9%	3%
160	2%	16	6%	3%
170	1%	17	4%	0%
180	1%	18	3%	0%

Note. For /ba-wa/, two sets of percentiles are given, one for children younger than 8.5 years and one for children older than 8.5 years.

Morphology

Representative grand averaged responses are shown across electrode locations in response to /da-ga₂/ in Figure 3. The response to the /da/ stimulus presented alone (deviant-alone condition) is shown (upper thin line) along with the response to the same /da/ stimulus when presented within a sequence of /ga/ stimuli (upper thick line). The mismatch response is seen in the difference wave (lower thick line) as a deflection below the zero line beginning at about 150 ms. The boxes below indicate the latency ranges over which a significant mismatch response occurred ($p < .01$).

For both /da-ga/ contrasts, the MMN was largest frontally and at the midline, and the polarity of the MMN inverted over the mastoids using a derived reference (not shown). Whereas the MMN is reportedly largest over Fz in adults, there is some indication that it may be slightly larger over Cz in children (Ponton, personal communication). Here, the MMN tended to be larger at Cz than at Fz, reaching significance for area and duration for /da-ga₁/ and /da-ga₂/, respectively ($p < .05$). For that reason, all analyses were computed for data measured at both sites. Nevertheless, no differences between the two sites were apparent when maturation and sex effects were examined. Figure 3 also illustrates that the MMN is symmetrical between the two hemispheres (see below).

Effect of Age

Various criteria can be used to identify the MMN in individual subjects. Table 2 summarizes the percentage of subjects with an MMN for all stimulus contrasts and

Figure 3. Grand average electrophysiologic responses elicited by the /da-ga/₂ stimulus contrast ($n = 71$). The panels represent responses measured from seven electrode sites, indicated on the head diagram. Each panel shows the response to /da/ presented alone (deviant-alone condition, upper thin line), the response to the same /da/ when it signaled an acoustic change in an ongoing sequence of homogeneous /da/₂ stimuli (upper thick line), and the resulting difference wave (lower thick line). The boxes below the difference waves indicate the latency range over which a significant mismatch response occurred.

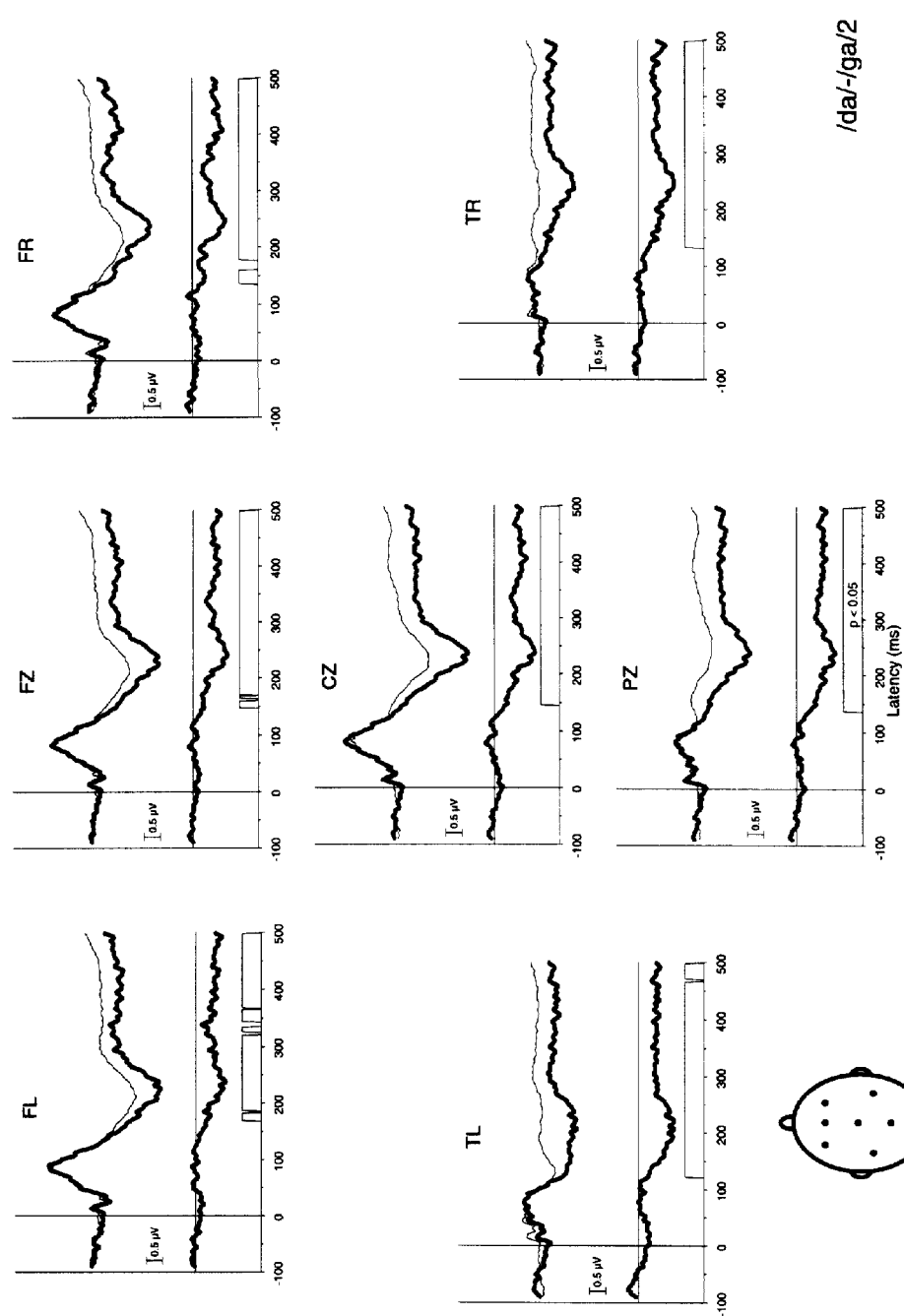


Table 2. Percentage of subjects with MMNs using three identification criteria.

Criteria	MMN condition				
	/da-ga/ ₁	/da-ga/ ₂	/ba-wa/ ₁	/ba-wa/ ₂	/ba-wa/ ₃
Visual Identification	94.4%	100.0%	92.6%	96.3%	97.5%
Area > 100 $\mu\text{V} \times \text{ms}$, Duration > 100 ms	83.1%	93.0%	84.0%	91.4%	92.6%
Area > 225 $\mu\text{V} \times \text{ms}$, Duration > 175 ms	66.2%	83.1%	50.6%	66.7%	75.3%

Note. An increasing number of subjects showed an MMN as the stimulus pairs became easier to discriminate.

for three identification criteria. The first criterion consisted of visually identifying, in the difference wave, a relative negativity following the N1 occurring between 100 and 500 ms. The second set of criteria required the negativity to have an area of greater than 100 $\mu\text{V} \times \text{ms}$ and a duration exceeding 100 ms. Finally, a stringent third set of criteria required the MMN area to be greater than 225 $\mu\text{V} \times \text{ms}$ and the duration to be greater than 175 ms. False-alarm rates for MMN response detection are low when these strict criteria are used (McGee, Kraus, & Nicol, 1997; McGee, Nicol, & Kraus, 1997).

Interestingly, in spite of the range of behavioral discrimination difficulty, neurophysiologic responses (MMN) were evidenced by most children for all of the experimental contrasts. Behaviorally, the /da-ga/₁ and /da-ga/₂ stimuli were discriminated by 61% and 100% of all children, and /ba-wa/₁, /ba-wa/₂, and /ba-wa/₃ were discriminated by 7%, 36%, and 96% of the children, respectively.

Area, duration, onset latency, amplitude, and peak latency were examined in order to determine if age effects were present. Overall, MMN appears to be stable during the school-age years. No changes in morphology were noted. Scatterplots of MMN area (Figure 4) indicate little change with age for all stimulus contrasts. Regression analyses revealed no significant changes in morphology, duration, onset latency, or peak latency with age. MMN area did not change with age for 4 of the 5 /da-ga/ and /ba-wa/ contrasts. MMN area did change significantly with age for /ba-wa/₃ at Fz ($r = -.24$, $p = .04$). (Data from 6 children with no responses were not used in the analyses.) MMN amplitude also was attenuated inconsistently with age, reaching significance for /ba-wa/₁ at Fz ($r = -.26$, $p = .03$) and for /da-ga/₁ at Fz ($r = -.28$, $p = 0.22$), FL ($r = -.34$, $p = .01$), and FR ($r = -.3$, $p = .02$). Similar results were obtained when the data were analyzed according to the three identification criteria described above.

For additional analyses, children were divided into the same age groups as for the behavioral data analysis: younger than 8.5 years, between 8.5 and 11.5 years, and older than 11.5 years. No significant main effects of age (ANOVA) were found for any MMN parameter for the /da-ga/ contrasts [duration $F(2, 65) = .3$, $p = .7$; area

$F(2, 65) = .4$, $p = .7$; onset latency $F(2, 57) = .6$, $p = .5$; amplitude $F(2, 65) = 1.0$, $p = .4$]. For /ba-wa/, no significant age effects were found when the subjects with absent MMNs were excluded [duration $F(2, 63) = .2$, $p = .9$; area $F(2, 63) = .6$, $p = .6$; onset latency $F(2, 63) = 0.0$, $p = 1.0$; amplitude $F(2, 63) = .8$, $p = .5$]. However, including these subjects resulted in a significant effect of age for MMN area only [$F(2, 75) = 3.2$, $p = .05$]. Post hoc testing revealed no significant differences between the two younger groups. MMN was significantly smaller in area in the oldest group compared with the youngest and middle groups for the /ba-wa/ stimulus (Scheffé $F' = 49.1$, $p < .05$ and Scheffé $F' = 15.2$, $p < .01$, respectively). Additional analyses of variance indicated no other significant age effects, irrespective of other MMN identification criteria for either contrast. Figure 5 shows means and standard deviations for /da-ga/ MMN area and duration for the three groups of children and the adults.

Because the MMN essentially does not change across the school-age years, data from all of the children were combined to provide normative values. Response characteristics for all MMN parameters (onset latency, duration, and area) are shown in Table 3. Means and standard deviations are reported from electrodes Fz, Cz, FR, FL, TR, and TL for the /da-ga/ stimulus pairs and from Fz for the /ba-wa/ contrast.

Effect of Sex

Responses from 37 age-matched boys and girls were compared for the /da-ga/ contrasts and from 52 age-matched boys and girls for the /ba-wa/ contrasts. These comparisons yielded no significant differences between males and females for any of the MMN parameters.

Hemispheric Symmetry

First, it was of interest to determine whether response symmetry changed with age. Symmetry was assessed at frontal and temporal sites by computing $(\text{FL} - \text{FR})/(\text{FL} + \text{FR})$ and $(\text{TL} - \text{TR})/(\text{TL} + \text{TR})$, respectively. Analysis of variance indicated no significant hemispheric differences among the young, middle, and older groups, with or without the adult data for either /da-ga/ contrast [temporal electrodes: area $F(3, 54) = .5$, $p = .7$,

Figure 4. MMN area as a function of age. MMN area and best-fit line for all children tested with both /da-ga/ contrasts (Fz and Cz) and the three /ba-wa/ (Fz) contrasts.

There was no significant change in duration with age.

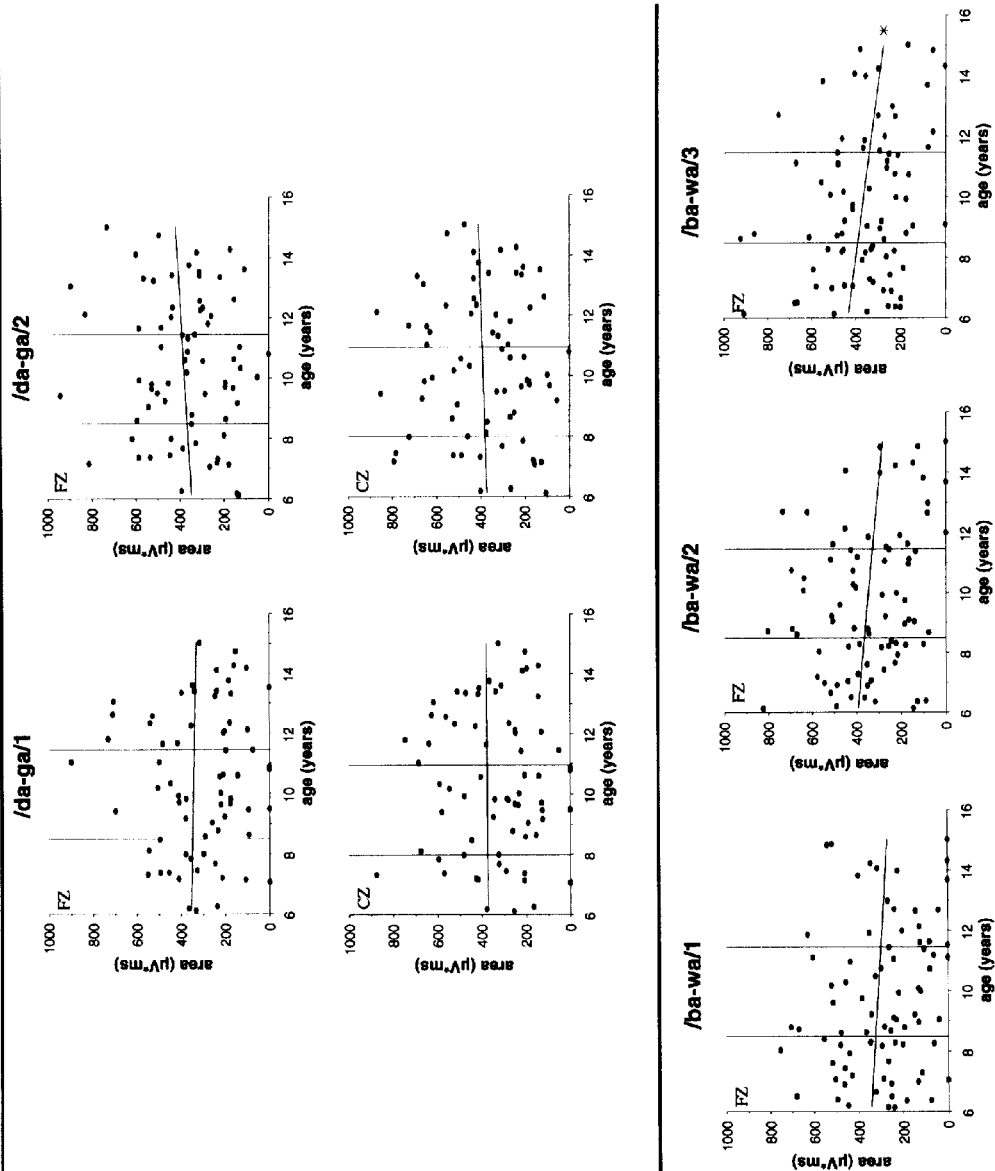
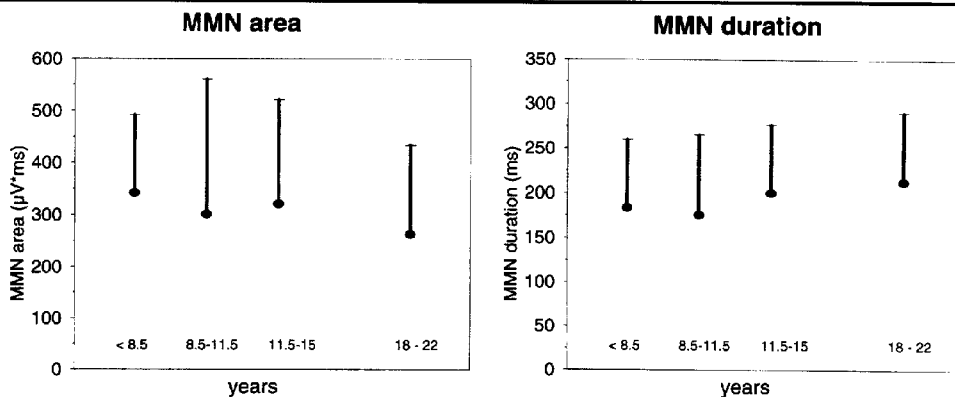


Figure 5. Means and standard deviations for MMN amplitude and duration for four age groups to /da/. The bars represent one standard deviation.



duration $F(3, 54) = .8, p = .5$; frontal electrodes: area $F(2, 65) = .1, p = .9$, duration $F(2, 65) = .8, p = .5$). Thus, MMN symmetry remained consistent throughout the school-age years and into adulthood.

Response symmetry was assessed by comparing MMN responses from the right versus left frontal and temporal electrode sites (FL vs. FR and TL vs. TR). Mismatch responses were symmetrical between the two hemispheres, despite the fact that stimulation was monaural. No significant hemispheric differences were evident for MMN duration and area at either frontal or temporal electrode sites.

Stimulus Differences

For both /da-ga/ and /ba-wa/ contrasts, the MMN became larger as the acoustic difference between the stimuli was increased. Onset latency did not change significantly. Figure 6 (top) shows grand average alone, deviant, and difference waves for the three /ba-wa/ contrasts. The region of significance increased systematically as the stimuli became easier to discriminate. The bottom of Figure 6 shows the data plotted in a different way. The response to the /wa/ stimulus presented alone is shown along with the response to the same /wa/ stimulus when it signaled an acoustic change in a sequence of /ba/ stimuli and in a sequence of /ba/ stimuli. The differences between the alone trace and the other two traces characterize the MMN response and show that its magnitude (duration and area) is greater when the acoustic contrast is greater. Correspondingly, analysis of variance supported the observation that magnitude measures increased significantly as the stimulus pairs became easier to discriminate. As shown in Table 4, the MMN was significantly larger for increased stimulus differences for both stimulus continua.

Discussion Summary

Overall, both behavioral and neurophysiologic data indicate that speech-sound discrimination is developed by age 6 and that no sex differences exist. Nonetheless, there are some developmental trends that bear mention. For example, in the /ba-wa/ perceptual data, the JNDs for the 6- to 8-year-olds were larger than the JNDs for the older children. This effect might have occurred because this contrast was always tested first (see Method); in other words, a familiarization, practice, or training effect may have occurred. This explanation is consistent with the observation that there were no JND developmental differences for the /da-ga/ contrast, which was tested last. Furthermore, the /ba-wa/ JNDs of some young children were as small as those of the older children. Again, this observation is consistent with an interpretation that age-related changes in the /ba-wa/ JNDs may not be actual perceptual differences but simply a result of variability in attention or motivation. There were no developmental changes for either contrast between ages 8 and 15. Moreover, JNDs measured from a group of young adults (Koch et al., 1999) did not differ from JNDs obtained in the children, further suggesting that the ability to discriminate these contrasts behaviorally is mature by school age (see Figure 2).

Many investigators have acknowledged that it is difficult to separate the physiologic limits of the central auditory system from other developmental variables that mature with age (see, e.g., Allen et al., 1989). However, the neurophysiologic responses measured in the present experiments made it possible to assess the brain's processing of small acoustic differences independent of the

Table 3. Normative MMN parameters for the /da-ga/ and /ba-wa/ stimuli.

		MMN parameter		
Electrode		Area ($\mu\text{V} \times \text{ms}$)	Duration (ms)	Onset latency (ms)
/da-ga/ ₁				
Fz (n = 64)	M	345.9	202.7	187.2
	SD	204.4	65.4	57.8
Cz (n = 65)	M	383.6	212.5	187.0
	SD	221.7	70.2	60.1
FL (n = 63)	M	347.5	196.8	197.5
	SD	201.3	63.5	61.0
FR (n = 65)	M	357.7	200.9	193.9
	SD	206.9	67.5	54.1
TL (n = 64)	M	319.3	192.5	197.9
	SD	223.5	71.7	62.8
TR (n = 64)	M	328.6	192.5	195.9
	SD	253.3	68.3	65.2
/da-ga/ ₂				
Fz (n = 68)	M	385.4	230.4	192.5
	SD	195.8	64.2	53.5
Cz (n = 69)	M	393.5	218.4	195.2
	SD	205.8	63.7	54.7
FL (n = 69)	M	401.3	221.3	192.6
	SD	231.5	65.6	53.7
FR (n = 69)	M	412.5	217.0	203.5
	SD	221.8	65.3	59.0
TL (n = 69)	M	302.9	196.8	210.1
	SD	158.1	66.5	63.5
TR (n = 70)	M	285.3	194.8	216.1
	SD	154.5	59.1	61.9
/ba-wa/ ₁				
Fz (n = 75)	M	315.0	208.4	187.5
	SD	175.8	63.4	49.3
/ba-wa/ ₂				
Fz (n = 78)	M	357.6	225.5	182.8
	SD	183.9	56.8	47.4
/ba-wa/ ₃				
Fz (n = 79)	M	378.6	239.5	178.7
	SD	183.3	54.0	54.4

Note. For the two /da-ga/ conditions, means and standard deviations are listed for MMN parameters measured at Fz, Cz, FR, FL, TR, and TL. For the three /ba-wa/ conditions, means and standard deviations are listed for MMN parameters measured at Fz.

confounding effects of attention and behavioral development. Moreover, because an MMN can be measured to stimulus differences that are not consciously perceived (Tremblay et al., 1998), assessment of preconscious ability was possible.

The present data showed no developmental changes in latency and morphology for school-age children (although smaller MMN magnitude was observed in children older than 11.5 years). Thus, these neurophysiologic responses provide a metric against which children with suspected abnormal auditory function can be compared. The fact that the MMN response is stable throughout the school-age years simplifies its research and clinical application in this population, at least for these stimulus contrasts. However, using the MMN clinically necessitates a method for determining the validity of the response in individual subjects. Various methods have been proposed that are promising for routine clinical use (McGee et al., 1997a, 1997b; Ponton, Don, Eggermont, & Kwong, 1997).

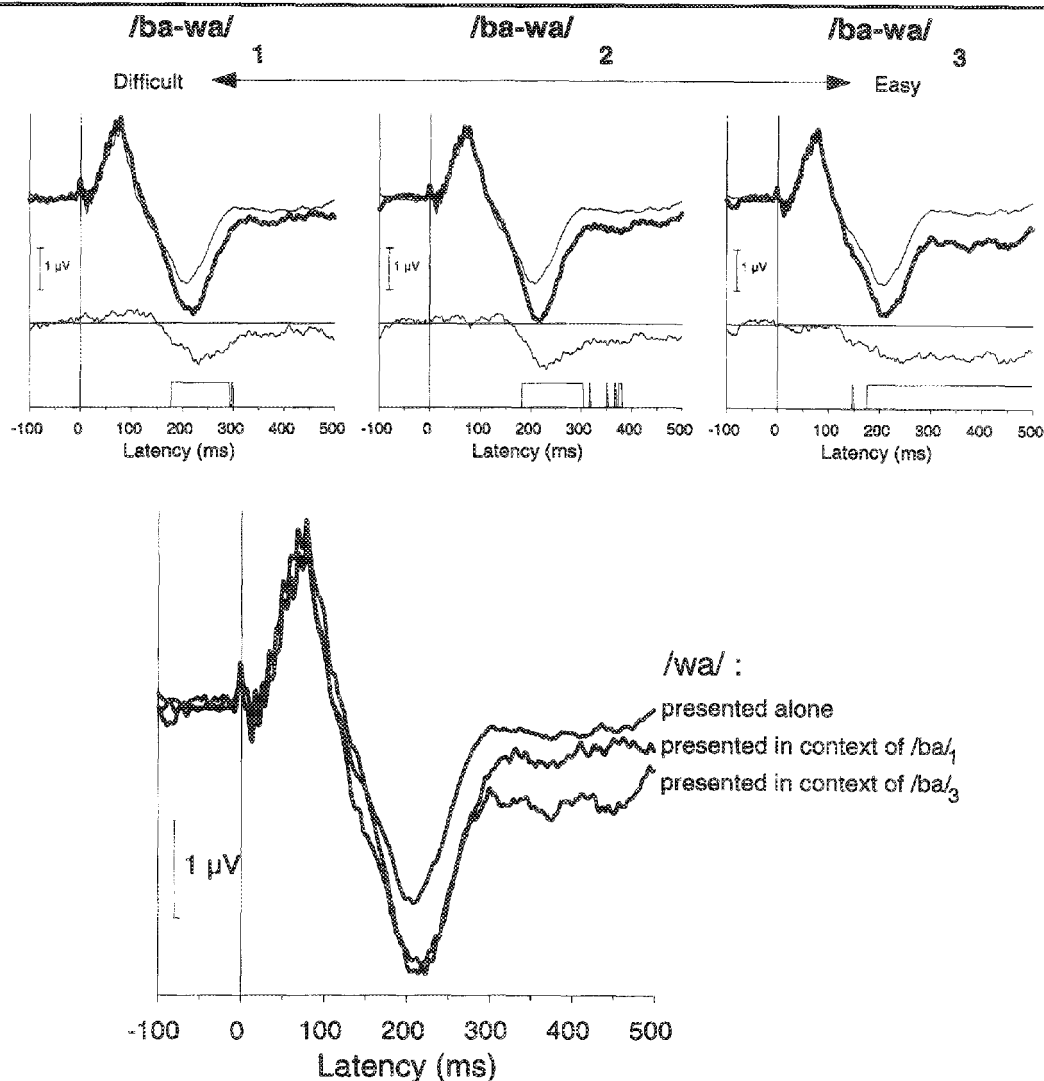
Development of Auditory/Speech Perception

Many studies suggest that fundamental auditory abilities continue to change and improve during the first decade of life (Elliott, 1979; Litovsky, 1997; Marshall, Brandt, Marston, & Ruder, 1979; Palva & Jokinen, 1975; Werner & Marean, 1996 for review). Although speech-sound awareness and language-specific abilities are evident in the first year of life (Jusczyk, 1993; Kuhl, 1993), many basic auditory abilities continue to change as children approach school age. For example, developmental effects have been reported in pure-tone sensitivity (Bargones et al., 1995; Schneider et al., 1989), frequency selectivity (Allen et al., 1989; Olsho, 1985; Schneider et al., 1990; Veloso et al., 1990), and temporal resolution (Jensen & Neff, 1993; Trehub et al., 1995; Wightman et al., 1989).

The ability to classify and identify vowels and consonants can be adultlike by school age (Nitttrouer, 1992; Nitttrouer & Studdert-Kennedy, 1987; Ohde et al., 1996; Walley & Carrell, 1983), and children can make use of many acoustic cues to make those identifications (Bertoncini et al., 1987; Nitttrouer, 1996; Walley et al., 1984). Nonetheless, speech-perception skills change with auditory experience. Studies suggest that older preschool children have poorer sensitivity to stop consonant and vowel place of articulation than adults (e.g., Elliott et al., 1981; Ohde et al., 1996; Sussman, 1993; Sussman & Carney, 1989). Other reports indicate that the ability to identify talkers uniquely does not mature until the teenage years and that age affects the ability to acquire an accent-free second language (Oyama, 1976; Tahta et al., 1981; Yamada, 1995).

This study shows that behavioral discrimination and neurophysiologic representation of fine acoustic differences in speech sounds are developed by age 6 and do not change between ages 8 and 15. Therefore, the

Figure 6. Grand average MMN responses elicited by the three /ba-wa/ contrasts. The top panels show the response to /wa/ presented alone (deviant-alone condition, upper thin line), the response to /wa/ when it signaled an acoustic change in an ongoing sequence of homogeneous stimuli (upper thick line), and the resulting difference wave (lower thin line). The area of significance (boxes) increases as the stimulus contrast becomes easier to discriminate. The bottom panel shows the response to the /wa/ presented alone (deviant-alone condition), the response to /wa/ when it was the deviant stimulus in the /ba-wa/₁ condition, and the response to /wa/ when it was the deviant stimulus in the /ba-wa/₃ condition. Again, the response magnitude to the same stimulus increases as the stimulus contrast becomes easier to discriminate.



physiologic mechanisms for representing fine speech differences and their behavioral counterparts appear stable in school-age children. Nonetheless, these data do not imply that the auditory system is static. Mature

listeners can show both behavioral learning and neurophysiologic plasticity in response to novel speech contrasts (Bradlow et al., 1997; Cheour et al., 1998; Kraus et al., 1995; Näätänen et al., 1997; Tremblay et al., 1997,

Table 4. Effect of stimulus difference on MMN parameters.

<i>/da-ga/</i> ₁ vs. <i>/da-ga/</i> ₂		
Electrode	<i>t</i>	<i>p</i>
Area		
Fz	1.80	.076
Cz	0.87	.386
FL	2.23	.029 ^a
FR	2.32	.023 ^a
TL	0.08	.940
TR	0.66	.514
Duration		
Fz	3.44	.001 ^a
Cz	1.45	.153
FL	3.62	.001 ^a
FR	2.49	.015 ^a
TL	1.52	.134
TR	1.44	.154
<i>/ba-wa/</i> ₁ vs. <i>/ba-wa/</i> ₂ vs. <i>/ba-wa/</i> ₃		
Electrode	<i>F</i> (2, 72)	<i>p</i>
Area		
Fz	3.86	.023 ^b
Duration		
Fz	9.25	.000 ^b

Note. MMN was larger as the stimulus pairs became easier to discriminate.

^aDenotes response to */da-ga/*₂ was larger than the response to */da-ga/*₁. ^bDenotes that the response to */ba-wa/*₃ was larger than the response to */ba-wa/*₁.

1998). It remains to be determined whether the time course of training is shorter or otherwise different in children as compared to adults or whether developmental learning and trained learning are different processes.

Development of Thalamo-Cortical Electrophysiologic Responses

Auditory perception and associated neurophysiologic responses change from birth through the school-age years. Development of the auditory periphery and brainstem are already mature by age 2 (Hecox & Galambos, 1974). Middle latency and various cortical potentials continue to develop through puberty (Kraus & McGee, 1995; Steinschneider et al., 1992, review). The P1/N1 cortical potentials show morphological changes through the second decade (Courchesne, 1990; Cunningham et al., 1997; Eggermont, 1989; Ponton et al., 1996; Sharma et al., 1997).

In contrast to the developmental changes observed in these auditory evoked responses, the characteristics of the MMN are remarkably stable, representing similar

cortical processes from infancy to adulthood. Specifically, an MMN-like response to stimulus differences is evident even in babies (Alho, Saino, Sajaniemi, Reinikainen, & Näätänen, 1990; Cheour et al., 1998; Cheour et al., 1995; Csépe, 1995; Kurtzberg, Vaughan, Kreuzer, & Fliegler, 1995), and by school age MMN responses to tones, speech syllables, and synthetic speech are mature—with response magnitude even exceeding the responses of adults (Kraus et al., 1993; Csépe, 1995; Csépe, Dieckmann, Hoke, & Ross, 1992).

Nonetheless, there are some reports of MMN changes during the school-age years. For example, significant decreases in MMN peak latency have been reported during the school-age years in response to pure-tone contrasts differing in frequency and duration (Korpilahti & Lang, 1994; Kurtzberg et al., 1995). However, we have found that MMN peak latency is a variable measure because the MMN can be broad and its peak difficult to define. Onset latency and MMN duration prove more useful because they are less variable and easier to identify. We have found no developmental changes in onset, peak latency, or duration for speech stimuli. However, we did observe decreases in MMN amplitude in our oldest children. This decrease may reflect the decrease in N1 amplitude that occurs during the school-age years. This interpretation is supported by the observation that MMN duration did not change with age.

Differences among studies also may be attributed to the differing neural generating systems involved, depending on the acoustic characteristics of the stimuli used to elicit the response. Differences in recording procedures (stimuli, repetition rate, deviant stimulus probability, stimulus sequence) and response analysis methods may also play a role. For these reasons, it is important to establish normative data for a specified set of stimulus and recording procedures, which then can be used as a metric for comparison.

The data reported here indicate that the speech-elicited MMN is present and largely developed by age 6 and does not change in latency or morphology throughout the school-age years. Thus, this neurophysiologic reflection of sensitivity to fine acoustic changes is developed early in life. The early maturation of the MMN is important from a clinical standpoint because use of the measure does not require the application of different norms across the age-span.

Sex Differences

In the auditory system, anatomic differences between males and females have been found in the planum temporale of humans (Kulynych, Vladar, Jones, & Weinberger, 1994) and forebrain structures in songbirds (Nottebohm & Arnold, 1976). Both behavioral (Cohen,

Levy, & McShane, 1989; McGuinness & Pribram, 1979; Rosenthal, Archer, Dimatteo, Koivumaki, & Rogers, 1974) and physiologic auditory pathway asymmetries are known to exist in humans and animals (Ehret, 1987; Fitch, Brown, O'Conner, & Tallal, 1993; King, Nicol, McGee, & Kraus, 1999). In response to vowel stimuli, MMN latency (onset and peak) was found to be 20 ms earlier in males than females, although no sex differences were found for amplitude (Aaltonen, Eerola, Lang, Uusipaikka, & Tuomainen, 1994). In contrast, this study did not find differences between male and female children in their fine-grained discrimination abilities nor in the neurophysiologic representation of speech-sound changes.

Hemispheric Symmetry

The results of this study indicate that speech-sound elicited MMN is symmetric in school-age children and that response symmetry is maintained from age 6 to age 15. Symmetric responses also were reported to speech stimuli in adults (Aaltonen et al., 1994; Tremblay et al. 1997). That symmetry was not found in children or adults when the stimuli were tonal (Giard, Perrin, Pernier, & Bouchet, 1990; Korpilahti & Lang, 1994; Paavilainen, Alho, Reinikainen, Sams, & Näätänen 1991). The MMN elicited by tones was larger over the right hemisphere, irrespective of the ear stimulated.

Other studies in adults have shown that speech-elicited MMNs can be asymmetric. For example, the MMN elicited by the syllable /da/ was larger over the left hemisphere when /da/ signaled a phonetic change but was symmetric when the same /da/ signaled a pitch change (Sharma & Kraus, 1995). Näätänen et al. (1997) also found left-hemisphere enhancement to phonetically relevant native language prototypes. Similarly, in a study of training and plasticity, MMNs elicited by non-native speech syllables were initially symmetric. However, training-associated changes were significantly larger over the left than over the right hemisphere (Tremblay et al., 1997). It may be that the linguistic or phonetic relevance of speech stimuli influences the hemisphere more active in discriminating stimulus change.

Clinical Implications

An interesting finding in this study is that neurophysiologic responses were observed for stimulus contrasts with acoustic differences less than the child's JND. It may be that the MMN reflects the brain's encoding of a stimulus difference that is not taken advantage of by some children or that some stimulus differences are too small to be consciously detected. One could envision a clinical protocol that assessed behavioral JNDs first. If a child had an unusually poor JND, than

an electrophysiologic evaluation would aid in determining whether the brain represented that contrast or whether neural representation of the relevant acoustic difference was absent. The resulting pattern of behavioral and physiologic results would help target rehabilitation efforts.

Thus the early maturation of the MMN—and its task and attention independence—make it a tool for evaluating central auditory function in school-age children. It can be used—even in young children—to evaluate the central sensory representation of acoustic differences important for speech perception without the confounding factors of attention, language development, and cognitive ability.

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