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## Mismatch negativity in school-age children to speech stimuli that are just perceptibly different \*

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**Summary** The mismatch negativity event-related potential (MMN) was elicited in normal school-age children in response to just perceptibly different variants of the speech phoneme /da/. A significant MMN was measured in each subject tested. Child and adult MMNs were similar with respect to peak latency and duration. Measures of MMN magnitude (peak-to-peak amplitude and area) were significantly larger in children than in adults. The results of the present study indicate that the MMN can be elicited in response to minimal acoustic stimulus differences in complex speech signals in school-age children. The results support the feasibility of using the MMN as a tool in the study of deficient auditory perception in children.

**Key words:** Mismatch negativity; MMN; Speech; Auditory evoked potentials; Event-related potentials; Speech perception

Auditory evoked potentials are widely applied to the clinical assessment of auditory *detection*. A current challenge lies in the application of cortical, event-related potentials to the assessment of stimulus *discrimination*.

The MMN is elicited by a deviant, or rarely occurring, stimulus that is presented within a series of homogeneous, or standard, stimuli (Näätänen et al. 1978). It originates primarily in the auditory cortex (Csépe et al. 1987; Näätänen and Picton 1987; Kaukoranta et al. 1989) and reflects the brain's response to stimulus differences. Typically in recording the MMN, the subject's attention is occupied by another task, usually employing another sensory modality (such as reading a book or watching a television screen), so that the auditory stimuli are ignored (Näätänen et al. 1980; Picton and Hillyard 1988). The MMN does not require conscious attention to the stimuli (Näätänen 1991) and thus may provide an objective measure of the discrimination of stimulus differences.

In adults, the MMN has been shown to reflect the processing of acoustic stimulus differences, particularly to tonal stimuli. It has been obtained in response to minimal changes in acoustic parameters such as frequency, intensity, location and duration (Sams et al. 1985; Näätänen et al. 1987, 1989; Kaukoranta et al. 1989; Paavilainen et al. 1989; Novak et al. 1990) and can occur when the acoustic difference is quite small, even when the difference between the standard and deviant stimuli is near psychophysical threshold (Sams et al. 1985). Thus, the MMN appears to be a neurophysiologic index of fine discrimination of acoustic features.

### *MMN to speech stimuli*

A neurophysiologic measure that reflects the processing of speech stimuli that differ in minimal and well specified acoustic features has obvious theoretical and practical applications. An MMN can be elicited by speech stimuli at the ends of a phonetic continuum (Aaltonen et al. 1987). Investigations in this laboratory (Sharma et al. 1993) have revealed that, in adults, an MMN can be elicited by speech stimuli that are difficult to discriminate psychophysically, and consistent with Sams et al. (1990), the MMN was obtained to stimuli that lie within as well as across phonetic category boundaries. In the present study, the MMN to speech stimuli that are acoustically very similar and

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that are perceived as the same phoneme was examined in school-age children.

### MMN in children

The MMN has been well documented and described in adults. However, little information exists about the MMN in children. Alho et al. (1990) reported that the MMN could be elicited in infants. Previous studies (Kraus et al. 1991, 1992) revealed that the MMN in school-age children to the speech stimulus pair /da/-/ga/ was similar in latency and larger in amplitude to the MMN elicited by the same stimuli in adults. In behavioral studies, discrimination of fine-grained differences in speech stimuli has been shown to be better in adults than in children (Elliott and Hammer 1988). The MMN could provide a neurophysiological basis for this observation. In addition, deficits in auditory perception of speech have been linked to certain auditory-based learning problems (Tallal et al. 1980, 1985; Elliott et al. 1989). If the MMN can be elicited by minimal acoustic differences in speech stimuli, this information could provide a basis for the application of the MMN to the study of subtypes of auditory processing disorders in children.

The questions addressed in the current study were: (1) Can the MMN be obtained in children to speech stimuli that are just perceptibly different? (2) How does the MMN in children compare to the adult response?

## Methods

### Subjects

Data were collected from 10 children (7–11 years), 7 males and 3 females. All subjects were healthy and had normal hearing thresholds (< 15 dB HL) from 500 to 8000 Hz. Also reviewed here (for comparison with the child data) are data from 11 adults who formed part of a study reported elsewhere (Sharma et al. 1993).

### Stimuli

Speech stimuli were used to elicit the MMN. The stimuli were variants of the voiced stop consonant /da/. Acoustically, the two stimuli differ in the onset frequency of the second and third formant transitions. Stimuli were synthesized using a Klatt (1980) digital speech synthesizer.

The specific characteristics of the speech stimuli used in the MMN experiments were based on behavioral data. Children (7–11 years old) and adults with normal hearing were asked to identify stimuli along a 9-item continuum in which the second and third formants were varied systematically from /da/ to /ga/ (Walley and Carrell 1983). Subjects classified each stimulus as /da/ or /ga/ by pressing a corresponding

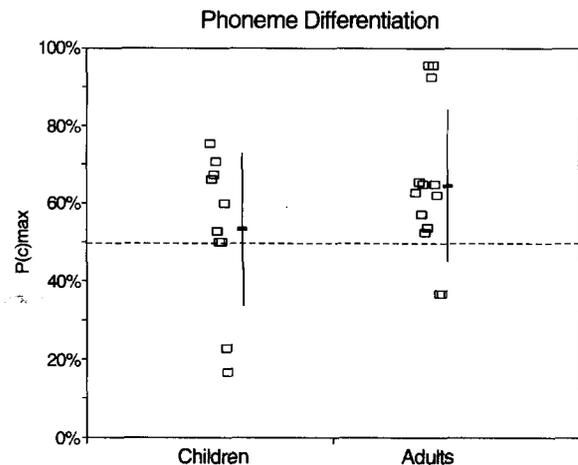


Fig. 1. P(c)max values obtained for adults and children in the behavioral discrimination of the two variants of /da/ used to elicit MMNs.

button. As expected, those experiments showed that the perception of the stimuli was categorical (Lieberman et al. 1967). The standard and deviant stimuli used in electrophysiologic testing were both identified as the phoneme /da/.

Neither adults nor children could easily distinguish between these stimuli when presented as same/different pairs. Performance in a same/difference task was near chance. Behavioral discrimination results for these stimuli are shown in Fig. 1 for individual adults and children, indicating better than chance discrimination for most of the adults and children. P(c)max is a measure of behavioral discrimination that combines signal detection measures of  $d'$  and  $\beta$  to create an unbiased measure of discriminability (Green and Swets 1974). A P(c)max of 50% indicates chance discrimination. The P(c)max for children using these stimuli was 53.2% (19.7 S.D.), and for adults, the P(c)max was 64.6% (19.5 S.D.).

Characteristics of the stimuli are shown schematically in spectrographic format in Fig. 2. The stimuli differed in the starting frequencies of the second and third formants (i.e., stimuli differed by 15 Hz for  $F_2$  and 175 Hz for  $F_3$ ). Standard and deviant stimuli were identical with respect to total duration, amplitude of voicing, fundamental frequency, steady-state vowel (duration and center frequencies of  $F_1$ ,  $F_2$  and  $F_3$ ) and consonant portion (starting frequency of  $F_1$  transition, transition duration for  $F_2$  and  $F_3$  and the steady-state formants  $F_4$  and  $F_5$ ). The transition durations were 40 msec for  $F_2$  and  $F_3$ . The  $F_2$  and  $F_3$  transitions were linear. The duration of each stimulus was 90 msec. The duration of voicing was constant for 80 msec and amplitude was decreased linearly to 0 in the last 10 msec of the stimuli. The fundamental frequency began at 103 Hz, increased linearly to 125 Hz in 35 msec, and

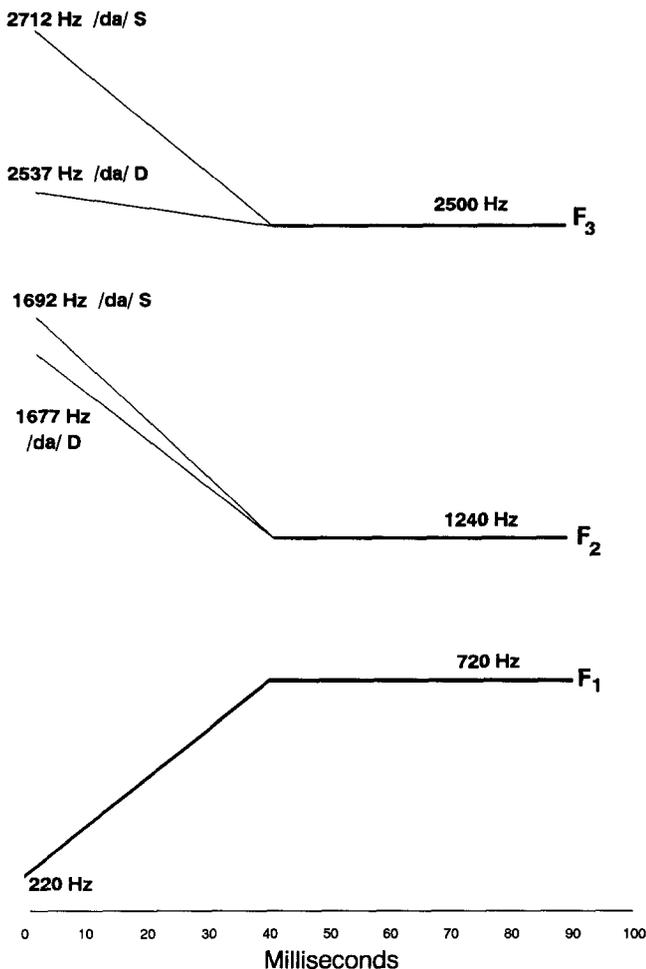


Fig. 2. Spectrographic representation of stimuli /da/S and /da/D. Characteristics common to both stimuli are indicated with thick, solid lines.

then decreased to 83 Hz in 55 msec. The peak amplitudes of the stimuli were within 0.5 dB of each other.

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. It also triggered the PC-based evoked potential averaging system for stimulus onset and indicated whether the trial contained a standard or deviant stimulus.

Speech stimuli were presented to the right ear at 75 dB SPL through insert earphones. The interstimulus interval was 1 sec. An oddball paradigm was used in which a deviant stimulus /da/D (probability of occurrence = 15%) was presented randomly in a series of standard stimuli /da/S (probability of occurrence = 85%). The averaged responses were elicited in blocks of 25 deviant stimuli and approximately 140 standard stimuli. That is, a trial block consisted of the average of 25 responses to deviant stimuli, while a standard "record" consisted of the average of approximately 140

responses to standard stimuli. Eight such blocks, totaling 1200 responses to standard and 200 responses to deviant stimuli, were obtained per subject. Stimuli were presented in a pseudorandom sequence with at least 3 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 stimulus average. Evoked responses elicited by standard stimuli and those elicited by deviant stimuli were averaged separately.

As a control, responses also were measured to 200 stimulus presentations of the /da/D stimulus in a "/da/D-alone" condition, presented in blocks of 25 stimuli. The MMN should occur only when the auditory system makes a discrimination in a sequence of standard and deviant stimuli. Therefore, the ERP obtained to /da/D presented in the oddball paradigm should be different from the response to the same stimulus when it is presented alone.

#### *Electrophysiologic measures*

To control for level of arousal and to minimize the subject's attention to the test stimuli, previous experiments have required subjects to read or to attend to auditory stimuli in the non-test ear (Näätänen et al. 1978; Näätänen 1990). For each experimental condition in the present study, subjects were instructed to watch videotaped movies or cartoons and to ignore the test stimuli, a more practical procedure for school-age children. The videotape audio levels were kept below 40 dB SPL (A-weighted). Although the MMN can be affected by attention (Woldorff et al. 1991; Alho et al. 1992; Woods et al. 1992), it is unlikely that subjects attended to stimuli in the present study because (1) the children barely discriminated the stimuli in a focused behavioral experiment, so it is not likely that these differences would have been consciously perceived while listening to the soundtrack of a video, (2) following the test session, each child responded appropriately to questions about the content of the video, (3) one must assume that the video soundtrack is more inherently interesting than the test stimuli and in fact, each child chose his own video, and (4) the acoustic differences between the stimuli were frequency differences, reported not to produce attention-related changes in the MMN (Näätänen 1991).

The ERPs were recorded from Fz/A2 with the forehead as ground. Eye movements were monitored with a supraorbital electrode referenced to the contralateral mastoid or a bipolar electrode montage (supraorbital-to-lateral canthus) which yielded similar wave form morphology to the supraorbital-to-mastoid montage. Prior to data collection, subjects were instructed to blink and move their eyes while amplifier settings were adjusted to ensure detection of eye move-

ments. Averaging was automatically suspended when the eye channel registered movement.

The recording window included a 50 msec pre-stimulus period and 500 msec of post-stimulus time. Evoked responses were analog bandpass filtered on-line from 0.1 to 100 Hz (12 dB/octave). Responses were digitally low-pass filtered with a Blackman filter at 40 Hz off-line.

#### Data analysis

**Individual subject data.** For each subject, a total of 8 trial blocks of /da/S and /da/D in the oddball paradigm and 8 blocks of /da/D-alone condition were used in the analysis. An individual grand average of those 8 trial blocks was computed. Thus the individual grand average consisted of a total of 1200 responses to standard (/da/S) stimuli and 200 responses to the deviant (/da/D) and /da/D-alone conditions.

Because the MMN is, by definition, elicited only by the deviant stimulus, a difference wave was computed by subtracting the individual grand average response to the standard stimulus from the response to the deviant stimulus. Likewise, a difference wave was computed by subtracting the response to the /da/D-alone stimulus from the response to the deviant stimulus when it occurred in the oddball paradigm.

The patterns of the standard, deviant, /da/D-alone, and difference (deviant minus standard, deviant minus /da/D-alone) wave forms were examined. The MMN was identified visually as a relative negativity following the N1. The MMN was apparent in the deviant and the difference wave forms, while the N1 was apparent in the standard, deviant and /da/D-alone wave forms.

Statistical tests were performed on the individual responses to ascertain that the MMN identified visually was indeed a significant negative deflection. Using each subject's grand average wave forms, a latency (in msec) was determined for the onset, offset, and point of maximum negativity (peak) of the MMN. Utilizing the contributing subtraction waves, *t* tests were performed (on the amplitudes) comparing 5 msec periods flanking the 3 marked latencies (onset, peak, offset). Likewise, *t* tests were performed on the individual deviant (oddball paradigm) minus /da/D-alone difference wave forms comparing the amplitudes at the same 3 latency points identified above. An MMN was considered to be present for that subject if the amplitude at the peak latency was significantly different from the amplitude at the onset or offset of the MMN in both the deviant minus standard and deviant minus /da/D-alone conditions.

**Group data analysis.** The MMN data also were analyzed for the subjects as a group. A grand average of the difference wave form was calculated. A point-by-point *t* test of the values of the contributing wave forms determined the latency period over which the

grand averages were significantly different from zero (i.e., a significant difference between the contributing standard and deviant wave forms). A significant negativity (seen in the grand average difference wave) following the N1 (seen in the grand average standard and deviant wave forms) was defined as the group MMN.

A similar analysis was performed comparing the deviant (oddball paradigm) and /da/D-alone responses. The MMN should occur in response to the deviant stimulus only when it is presented in the oddball paradigm and not when the deviant stimulus is presented alone.

The group data analysis included comparisons of MMN peak latencies and MMN duration, with duration being defined as the offset minus the onset latency for each subject. The MMN magnitude was measured on the individual grand averages in the following ways: (1) by measuring the amplitude from the preceding peak to the midpoint of the MMN (onset to peak) and from the midpoint to the end of the MMN wave form (peak to offset) and (2) by measuring the area of the MMN wave form. To measure the area of the MMN a line was drawn between the onset and offset of the MMN in the difference wave. The enclosed area of the difference wave form was measured in msec  $\times$   $\mu$ V. *T* tests were used to compare differences between adults and children for latency and magnitude measures.

## Results

Fig. 3 shows the grand average responses to the standard stimulus /da/S, the deviant stimulus /da/D,

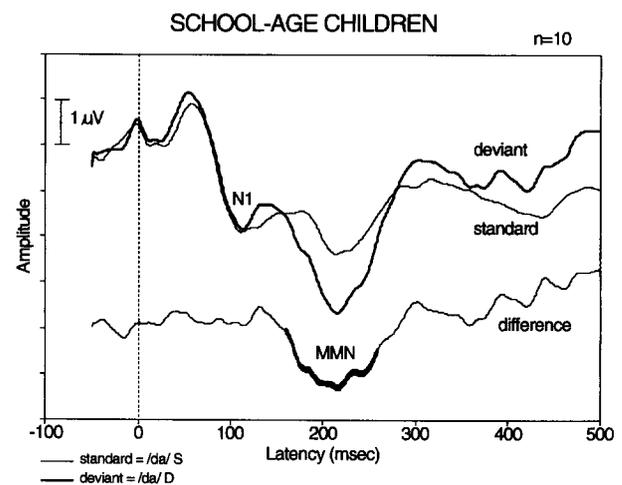


Fig. 3. Grand average event-related potentials obtained in response to the standard stimulus /da/S (top) and to the deviant stimulus /da/D (bottom). The grand average difference wave was obtained by subtracting the ERP to the standard stimulus from the response to the deviant stimulus. The thick portion of the difference wave indicates the range during which the difference between the standard and deviant wave forms were significantly different from zero. ( $|t| > 1.83$ ;  $df = 9$ ;  $P < 0.05$ ). Positive is up.

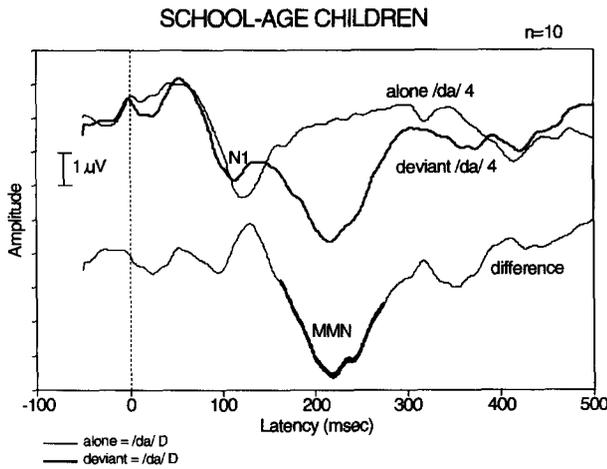


Fig. 4. The grand average response to the stimulus /da/D is compared in two conditions. The top trace is the ERP obtained to /da/D presented alone. The ERP obtained to /da/D when it was the deviant stimulus in the oddball paradigm is shown in the middle trace. The difference wave was obtained by subtracting the response to /da/D-alone from /da/D when it was the deviant stimulus in the oddball paradigm. Notice that the MMN occurs only in response to /da/D in the latter condition. ( $|t| > 1.83$ ;  $df = 9$ ;  $P < 0.05$ ).

and the difference wave. The MMN is evident in the response to the deviant stimulus and is seen clearly around the 200 msec region in the difference wave form. Also evident in the response to both standard and deviant stimuli is the N1 wave at about 100 msec.

Fig. 4 shows the grand average response to the /da/D stimulus when it was presented alone (top) and when it was the deviant stimulus in the oddball paradigm (bottom). Subtraction of these wave forms results in a negativity in the latency region similar to the MMN of Fig. 3.

**Detectability**

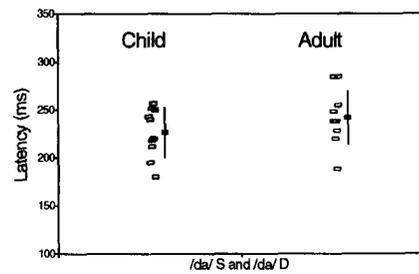
Intra-subject statistical testing indicated that an MMN was present in each of the 10 children. This is shown in Table I. By the criteria specified above, the MMN was present in each child, in the deviant minus

TABLE I

Analysis of MMN significance in individual subjects.

Subj.	Deviant-standard				Deviant rare-deviant alone			
	Onset/peak		Peak/offset		Onset/peak		Peak/offset	
	Amp	t	Amp	t	Amp	t	Amp	t
CM	1.41	1.62	2.38	3.05 **	2.35	2.01 *	4.66	3.49 **
CS	1.57	2.88 **	2.11	2.80 **	4.75	6.11 **	1.82	1.78
EB	3.23	2.83 **	6.01	5.17 **	6.58	4.55 **	7.90	6.11 **
EG	2.07	2.61 *	3.78	5.03 **	2.88	2.87 **	5.94	5.54 **
JF	4.26	5.14 **	6.42	11.03 **	4.44	5.17 **	6.52	10.04 **
JH	2.02	2.36 *	1.98	2.37 *	4.56	4.58 **	4.04	4.15 **
MB	4.58	6.37 **	4.39	4.98 **	8.98	8.01 **	6.61	6.54 **
SG	4.08	3.93 **	1.06	1.13	3.08	3.77 **	1.86	2.73 **
SM	3.80	4.83 **	1.63	2.70 **	5.25	4.64 **	3.28	2.75 **
YA	0.62	0.90	2.61	3.65 **	1.96	2.10 *	4.79	4.38 **

**MMN Peak Latency**



**MMN Duration**

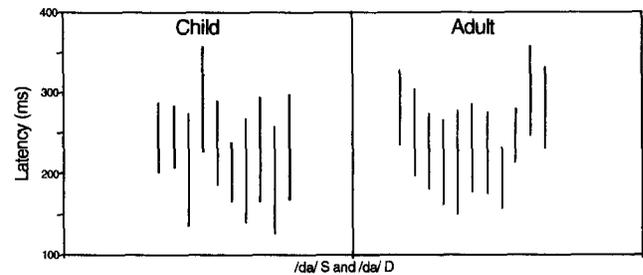


Fig. 5. MMN peak latency ( $\pm 1$  S.D.) and latency duration are shown for individual subjects and are compared in adults and children. Each vertical line = 1 subject.

standard condition as well as in the corresponding control deviant minus /da/D-alone condition.

**Latency**

The MMN latency values for each child and adult are shown in Fig. 5. Mean latency ( $\pm 1$  S.D.) is depicted by the vertical bars in the figure (top). Duration measurements, indicating the beginning and ending of the MMN response, are shown at the bottom of Fig. 5 for each child and are compared to the adult response.

Statistical measures of latency are listed in Table II. There were no significant latency differences, either in

TABLE II  
MMN /da/D-/da/S.

	Children		Adults		<i>t</i>
	Avg	S.D.	Avg	S.D.	
<b>Latency</b>					
Onset (msec)	171.8	33.2	192.9	33.6	1.45
Peak (msec)	226.2	26.1	242.9	27.4	1.42
Offset (msec)	285.4	31.3	292.2	35.4	0.46
<b>Magnitude</b>					
Onset/peak amp. ( $\mu\text{V}$ )	2.558	1.378	2.21	0.77	0.71
Offset/peak amp. ( $\mu\text{V}$ )	3.081	1.518	1.71	0.52	2.83 $P < 0.02$
Area ( $\mu\text{V} \times \text{msec}$ )	256.60	122.97	126.83	45.71	3.27 $P < 0.01$

peak latency or duration measures, between the MMN obtained in adults and children.

**Amplitude**

Individual amplitude values (onset-to-peak and peak-to-offset) for each child and adult are shown in Fig. 6. Mean amplitude ( $\pm 1$  S.D.) is also depicted by the vertical bars in the top of the figure. MMN area measures are shown for the children and adults at the bottom of the figure.

Statistical comparisons of amplitude are listed in Table II. The MMN amplitude (onset-to-peak) was not significantly different in adults and children. However peak-to-offset amplitudes were significantly larger in

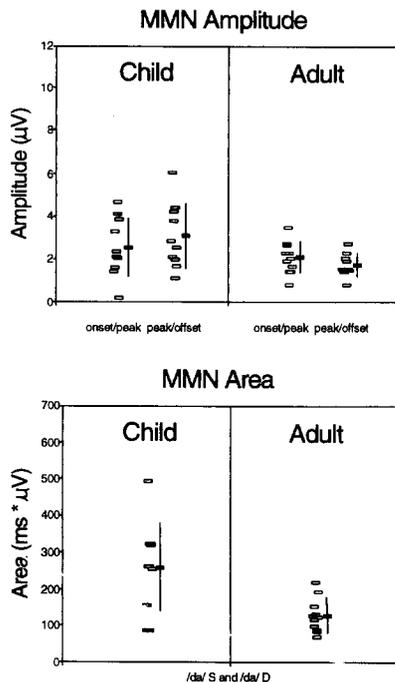


Fig. 6. MMN magnitude (amplitude and area) is shown for individual children and adults. Solid lines indicate  $\pm 1$  S.D.

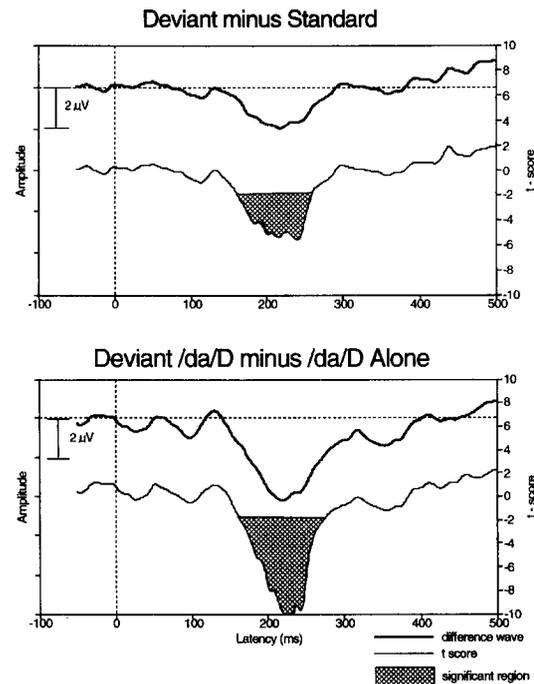


Fig. 7. Top: the bolder trace represents the grand average wave form obtained by subtracting the response to the standard stimulus /da/S from the response to the deviant stimulus /da/D. The bottom trace shows the *t* scores and the significant MMN range ( $|t| > 1.83$ ;  $df = 9$ ;  $P < 0.05$ ) is stippled. Bottom: the bolder trace represents the grand average wave form obtained by subtracting the response to /da/D when it was presented alone from the response to the same /da/D stimulus when it occurred as the deviant stimulus in the oddball paradigm. The lower trace shows the *t* scores and the significant MMN range ( $|t| > 1.83$ ;  $df = 9$ ;  $P < 0.05$ ) is stippled.

the children as compared to the adults ( $P < 0.02$ ). As seen in Fig. 6, MMN area measures were larger for the children than the adults ( $P < 0.01$ ).

Fig. 7 (top) shows the grand average MMN difference wave for all 10 children. The cross-hatched area denotes the portion of the difference wave which was statistically significant different from zero ( $|t| > 1.83$ ;  $df = 9$ ;  $P < 0.05$ ). The analysis clearly shows a significant difference in the latency region of the MMN, which occurs around 180–240 msec.

A similar analysis was done to compare the response to /da/D when it was the deviant stimulus in the oddball paradigm and when /da/D was presented alone (Fig. 7, bottom). Subtraction of the two responses yields a negativity at the latency of the MMN, reflecting the response to /da/D when it was the deviant stimulus in the oddball paradigm ( $|t| > 1.83$ ;  $df = 9$ ;  $P < 0.05$ ). These results indicate that the negativity seen in the difference wave form in the oddball paradigm truly represents a neurophysiologic mismatch response to stimulus differences and is not merely a response to the individual speech stimuli.

## Discussion

The results of the present study indicate that the MMN is an extremely sensitive neurophysiologic response to physical stimulus differences in complex speech signals. The MMN was obtained to speech stimuli that were just perceptibly different, thus demonstrating in children what has been already shown in adults (Sams et al. 1990; Sharma et al. 1993), that the MMN can be obtained to stimuli which are classified as the same phoneme. This study confirms earlier reports (Kraus et al. 1992) that the MMN can be elicited in response to speech stimuli in school-age children. In both studies, the MMN in children was similar to the adult response in latency and morphology and larger in magnitude in children than adults. The larger amplitude in peak-to-offset response may be partially related to an early developing "P3a-like" component described by Courchesne (1990). Recent data indicate that in response to tonal stimuli, the MMN in children is also of equal latency and larger amplitude as compared to adults (Csépe et al. 1992). Thus it appears that the MMN is a robust phenomenon in school-age children.

In the MMN literature, emphasis has been on group rather than individual data. Most investigations show averages across subjects or grand mean data. In this study, the MMN was shown to be present in each child tested. Thus it is possible to begin to consider the MMN as a potential measure for assessing central auditory function in children. From a practical standpoint, if clinical applications are to be envisioned for the MMN, this study forms part of the necessary groundwork for establishing its characteristics in school-age children. While previous reports (Elliott and Hammer 1988) have shown that behaviorally, children do not discriminate fine acoustic differences in speech stimuli, the robust MMN in children is an indication that certain fine stimulus differences are processed neurophysiologically.

A major portion of the MMN appears to originate in supratemporal auditory cortex and could serve as a measure to assess and investigate central auditory system function (Hari et al. 1984; Alho et al. 1986; Csépe et al. 1987, 1988; Näätänen and Picton 1987; Kaukoranta et al. 1989; Giard et al. 1990; Sams et al. 1991). Deficient auditory perception has been associated with certain auditory-based learning problems (Tallal et al. 1985; Elliott and Hammer 1988). The MMN reflects auditory sensory processing and, by inference, may be linked to auditory comprehension problems in school-age children (Korpilahti et al. 1992). Cochlear implant users are another group for whom an objective measure of central auditory function is of interest (Kraus et al. 1993). The specific relationship between the MMN

and behavioral auditory sensory processing is yet to be determined.

The characteristics of the MMN suggest its potential clinical use with patients for whom communication is difficult or compromised and for whom auditory discrimination and memory are in question (e.g., at-risk infants, children with language or learning disorders, cochlear implant users, adults with dementia or aphasia). The MMN does not require conscious attention to the stimuli and therefore provides an objective measure of the discrimination of stimulus differences. Consequently, it may permit an objective analysis of sensory processing and discrimination in patients who cannot consistently attend to stimuli.

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