The development of the length of the temporal window of integration for rapidly presented auditory information as indexed by MMN

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Abstract

Objective: The length of the temporal window integrating successive auditory stimuli into unitary percepts has been estimated to be less than 200 ms in adults. The aim of the study was to investigate the development of the integrating window in children to determine whether it is similar to young adults.

Methods: A modified auditory oddball paradigm was presented at a rapid (150–400 ms) onset-to-onset pace during recording of electroencephalogram in two groups of children (aged 5–8 and 9–11 years) and one group of adults. Latencies and amplitudes of the P1, N1, and the mismatch negativity (MMN) components of event-related brain potentials (ERPs) were measured.

Results: The length of the temporal window of integration (TWI) was shorter in adults (<200 ms) than older children (<300 ms in 9–11-year-olds) and younger children (<350 ms in the 5–8-year-olds). In addition, age-related changes were found in the latency and amplitude of the ERP components.

Conclusions: The results demonstrate a general maturational development of the auditory evoked potentials and also a specific maturational process for temporal encoding of information in auditory cortex.

Significance: Rapid stimulus presentation rates can be successfully used in school-aged children to study neural mechanisms of auditory processes.

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Keywords: Temporal window of integration; Development; Auditory evoked potentials; P1; N1; Mismatch negativity (MMN)

1. Introduction

The human auditory system relies on various acoustic cues to process and organize sensory information in the daily environment. These cues include the physical characteristics of the sounds (e.g. intensity, frequency, spatial location) as well as the temporal relationships between the sounds. Temporal processing of auditory information enables us to make meaning of the spectro-temporal changes in sounds needed to understand speech or to appreciate melody in music. To identify distinct auditory events, mechanisms that integrate and segregate sound elements within individual sound streams are needed.

Temporal integration is one such processing mechanism in auditory event formation that is responsible for cohering the basic ongoing units. Acoustic elements that occur in close temporal proximity (e.g. within less than 200 ms) are often integrated and processed as a single unit, whereas if the same elements occurred outside the 200 ms period (outside the temporal window of integration or TWI) then the same elements would be processed as separate units (Ross et al., 2002; Sussman et al., 1999; Winkler et al., 1998; Yabe et al., 1997, 1998; Zwislocki, 1960).

Behavioral studies of auditory temporal resolution demonstrate that infants have a higher gap detection threshold than young children (5-year-olds; Trehub et al., 1995) and young adults (Trehub et al., 1995; Werner et al., 1992), while younger children (6- to 7-year-old) have a higher threshold than older children (8- to 13-year-olds).
2. Experiment 1

Experiment 1 tests the length of temporal window of integration in young adults; the results will provide the basis for comparison with the two child groups.

2.1. Methods

2.1.1. Subjects

Six healthy adults (5 males) between the ages of 23–39 years (M=32.3 years, SD=6.4 years) were paid to participate in the study. All participants passed a hearing screening before the experiment was conducted. Informed consent from the participants was obtained following a detailed explanation of the experimental procedures. Human subjects treatment was in accordance with the guidelines of the committee for clinical investigation at the Albert Einstein College of Medicine where the study was conducted.

2.1.2. Stimuli

Three sinusoidal tones (50 ms duration, 7.5 ms rising/falling time) were calibrated with a Bruel & Kjaer sound level meter (type 1613) and presented bilaterally through insert earphones (E-A-RTONE® 3A). Frequent tones (standards) were presented 85% of the time at 440 Hz and 80 dB SPL. Frequency deviants (494 Hz, 80 dB SPL) comprised 7.5% of the stimuli and intensity deviants (440 Hz, 65 dB SPL) comprised the remaining 7.5% of the stimuli. The frequency deviants were randomly presented in the sequence but intensity deviants were not. Every time a frequency deviant occurred an intensity deviant followed it (see Fig. 1). A total of 4000 stimuli were presented for each condition (3400 standards, 300 frequency and 300 intensity deviants).

![Stimulus Paradigm](image-url)
2.1.3. Procedures

Participants sat in a comfortable chair in front of a TV monitor during the experiment and were instructed to watch a silent video and to disregard the sounds. Four experimental conditions that differed only in SOA were presented (150, 200, 250, and 300 ms). The order of the conditions was randomized across participants. There was at least one break during the testing session, in which the participants were able to get up, walk around and have a snack. The session was 1.5 h in duration, which included electrode cap placement and break.

2.1.4. Data recording

Electroencephalogram (EEG) was recorded with an electrode cap from the following 9 electrode sites: Fz, F3, F4, Cz, C3, C4, Pz (10–20 system) and the left and right mastoids (LM and RM). F7 and F8 were used to monitor horizontal electrooculogram (HEOG). FP1 and electrode placed below left eye were used to monitor the vertical EOG (VEOG). The tip of the nose was used as reference. The EEG and EOG were digitized (Neuroscan Synamps amplifier) at 500 Hz (0.05–100 Hz bandpass) and digitally filtered off-line between 1.5 and 20 Hz. Epochs were 700 ms, starting 100 ms before stimulus onset, to be able to see the responses to the double deviants within the epochs. Artifact rejection criterion was set at ±75 μV to exclude epochs that contained excessive motor or eye movement. ERPs were averaged separately for the standards and the frequency deviants in each condition. Difference waves were obtained by subtracting standard ERPs from deviant ERPs.

2.1.5. Data analysis

Peak latency for grand means of P1 (first positive peak) and N1 (first negative peak after P1) were measured in the ERP response elicited by standards. Amplitudes of the ERP responses were measured with reference to the mean amplitude in the 100 ms pre-stimulus period (subtracted from each point of the averaged ERP responses). Mean amplitude of P1 was measured from a 40 ms window centered on the peak of the component from the grand-averaged waveform at Fz. Because the grand-averaged waveforms were often above baseline, measuring the mean voltage at the negative peak would not reflect the full amplitude of the ERP waveform. Therefore, we measured the amplitude of the N1 from the first positive peak to the first negative peak (peak-to-trough; Ponton et al., 2000).

ERPs were measured separately for the standard stimuli and the frequency-followed-by-intensity deviants in each condition. MMN was delineated by subtracting the standard ERP from the deviant ERP. MMN peak latency was measured from the grand mean deviant—standard difference waveforms at Fz, the site of greatest signal to noise ratio. The epoch was chosen to include the ERP response to successive deviant stimuli. Thus, MMN amplitudes were measured from a 40 ms window (centered on the grand mean peak) in two ranges. Range 1 was chosen where the first MMN was elicited. Range 2 was chosen as the visible negative peak closest to the expected latency of the intensity MMN according to the stimulus presentation rate. In the 150 ms SOA condition, Range 1 was between 134 and 174 ms (peak, 154 ms) and Range 2 was between 260 and 300 ms (peak, 280 ms). In the 200 SOA conditions, Range 1 was between 114 and 154 ms (peak, 134 ms) and Range 2 was between 314 and 354 ms (peak, 334 ms). In the 250 ms SOA condition, Range 1 was between 132 and 172 ms (peak, 152 ms) and Range 2 was between 352 and 392 ms (peak, 372 ms). In the 300 ms SOA conditions, Range 1 was between 144 and 184 ms (peak, 164 ms) and Range 2 was between 414 and 454 ms (peak, 434 ms).

One-tailed, one-sample t tests were used to determine the presence of MMN. Repeated-measures analysis of variance (ANOVA) was used to compare the amplitude and latency of P1, N1, and MMN across conditions. Greenhouse–Geisser corrections for sphericity were applied and the P values reported. Tukey HSD post hoc analyses were calculated.

2.2. Results and discussion

2.2.1. ERPs

A clear positive peak (P1) followed by a clear negative peak (N1) can be seen in all conditions evoked by the standard and deviant stimuli (see Fig. 2).

2.2.1.1. P1 component. Average amplitudes and latencies of the P1 component for all conditions are summarized in Table 1. ERPs are displayed in Fig. 2 (left column). P1 amplitude and latency was compared across SOA conditions. A main effect of condition was found for amplitude ($F(3, 15) = 8.13, P < 0.05$) but not for latency ($F(3, 15) = 1.70, P = 0.24$). Post hoc analyses indicated that P1 amplitude was larger in the longer SOA conditions (250 and 300 ms SOA) than in the shorter SOA conditions (150 and 200 ms SOA).

2.2.1.2. N1 component. The average amplitude N1 (peak to trough) and latency of N1 were also compared across conditions (see Table 1 and Fig. 2). There was no effect of SOA condition for latency ($F(3, 15) = 1.10, P = 0.36$) or for amplitude ($F(3, 15) = 1.23, P = 0.33$).

2.2.2. Difference waveforms

One MMN was elicited by the successive deviants in the 150 ms SOA condition ($t_{(6)} = -2.98, P < 0.05$; see Fig. 2). No significant difference from zero was found for the difference waveforms in Range 2 in this condition ($t_{(6)} = -1.14, P = 0.15$). Two separate MMNs were elicited in the 200, 250 and 300 ms SOA conditions (200 ms: $t_{(6)} = -2.62, P < 0.05$; $t_{(6)} = -3.37, P = 0.01$; 250 ms: $t_{(6)} = -3.72, P < 0.01$; $t_{(6)} = -2.95, P < 0.05$; 300 ms: $t_{(6)} = -3.52, P < 0.01$; $t_{(6)} = -3.11, P < 0.05$, respectively). There was no difference in the latency
3. Experiment 2

The purpose of Experiment 2 was to determine whether the integrating window is similar in 9–11-year-old children as that of adults. It has been found that by approximately 9 years of age, frequency discrimination for brief tones reaches adult-like characteristics (Thompson et al., 1999). If temporal integration processes are also similar in 9–11-year-olds as adults, then one MMN should be elicited by double deviants only at interstimulus intervals less than 200 ms.

3.1. Methods

3.1.1. Subjects

Nine children (6 boys) between the ages of 9 and 11 years ($M=10.8$ years, $SD=9.6$ months) with reported normal language development were paid to participate in the study. All participants passed a hearing screening before the experiment was conducted. Informed consent from the child’s guardian and informed assent from the participants were obtained following a detailed explanation.
of the experimental procedures. Human subjects treatment was in accordance with the guidelines of the committee for clinical investigation at the Albert Einstein College of Medicine where the study was conducted.

3.1.2. Stimuli and procedures

The stimuli and procedures used in Experiment 2 were identical to those used in Experiment 1.

3.1.3. Data recording

Electroencephalogram (EEG) was recorded with an electrode cap from the following 9 electrode sites: Fz, F3, F4, Cz, C3, C4, Pz (10–20 system) and the left and right mastoids (LM and RM). F7 and F8 were used to monitor horizontal electrooculogram (HEOG). FP1 and electrode placed below left eye were used to monitor the vertical EOG (VEOG). The tip of the nose was used as reference. The EEG and EOG were digitized (Nicolet amplifier) at 250 Hz (0.05–100 Hz bandpass) and digitally filtered off-line between 1.5 and 20 Hz. Epochs were 700 ms starting 100 ms before stimulus onset to be able to see the responses to the double deviants within the epochs. Artifact rejection criterion was set at $\pm 100 \mu V$ to exclude epochs that contained excessive motor or eye movement. ERPs were averaged separately for the standards and the frequency deviants in each condition. Difference waves were obtained by subtracting standard ERPs from deviant ERPs.

3.1.4. Data analysis

The data analysis procedures were identical to Experiment 1. The amplitudes of the difference waveforms measured in the 150 ms SOA condition were for Range 1 between 220 and 260 ms (peak, 240 ms) and Range 2 between 320 and 360 ms (peak, 340 ms). In the 200 ms SOA condition, Range 1 was between 212 and 252 ms (peak, 232 ms) and Range 2 was between 364 and 404 ms (peak, 384 ms). In the 250 ms SOA conditions, Range 1 was between 196 and 236 ms (peak, 216 ms) and Range 2 was between 400 and 440 ms.

Table 1

<table>
<thead>
<tr>
<th>Group</th>
<th>Condition (SOA) (ms)</th>
<th>Amplitude</th>
<th>Latency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>P1</td>
<td>N1</td>
</tr>
<tr>
<td>Adults</td>
<td>150</td>
<td>0.45 (0.19)</td>
<td>−0.54 (0.58)</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>1.22 (0.37)</td>
<td>−1.01 (0.43)</td>
</tr>
<tr>
<td></td>
<td>9–11-year-olds</td>
<td>1.14 (0.44)</td>
<td>−2.37 (1.13)</td>
</tr>
<tr>
<td></td>
<td>5–8-year-olds</td>
<td>1.38 (0.98)</td>
<td>−3.32 (1.29)</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Group</th>
<th>Condition (SOA) (ms)</th>
<th>Range 1 Latency</th>
<th>Range 2 Latency</th>
<th>Range 1 Amplitude</th>
<th>Range 2 Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adults</td>
<td>150</td>
<td>157 (17)</td>
<td>157 (17)</td>
<td>−1.07 (0.88)*</td>
<td>281 (03)</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>162 (25)</td>
<td>162 (25)</td>
<td>−1.13 (1.05)*</td>
<td>503 (17)</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>148 (23)</td>
<td>148 (23)</td>
<td>−1.02 (0.67)**</td>
<td>281 (03)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>−0.94 (0.66)**</td>
<td>237 (03)</td>
<td>−0.90 (0.75)**</td>
<td>501 (14)</td>
</tr>
</tbody>
</table>

Results of the one-sample, one-tailed Student $t$ tests: *$P<0.05$, **$P<0.01$. 

- - Dotted line indicates a significant difference among SOA conditions. Conditions below the dotted line have significantly larger values than those above the line. Where there is no line there was no difference across SOA conditions.
(peak, 420 ms). In the 300 ms SOA condition, Range 1 was between 180 and 220 ms (peak, 200 ms) and Range 2 was between 444 and 484 ms (peak, 464 ms).

One-tailed, one-sample t tests were used to determine the presence of MMN. Repeated-measures ANOVA was used to compare the amplitudes and latencies of P1, N1, and MMN across conditions. Mixed design ANOVA was used to compare the amplitude and latency of P1, N1, and MMN between the adults and the 9–11-year-olds. Greenhouse–Geisser corrections for sphericity were applied and the P values reported. Tukey HSD post hoc analyses were calculated.

3.2. Results and discussion

3.2.1. ERPs

A large and clear positive peak (P1) followed by a large and clear negative peak (N1) can be seen in all conditions evoked by the standard and deviant stimuli (see Fig. 3). This P1–N1 pattern has been similarly reported in 9–11-year-old children (Albrecht et al., 2000; Čeponienė et al., 1998, 2002; Courchesne, 1990; Gomes et al., 1999; Johnstone et al., 1996; Korpilahti and Lang, 1994; Kurtzberg et al., 1995).

3.2.1.1. P1 component. Average amplitudes and latencies of the P1 component for all conditions are summarized in Table 1. The average amplitude and latency of the P1 component were compared across conditions. A main effect of condition was found for amplitude ($F(3, 24) = 55.22$, $P < 0.01$) but was not quite significant for latency ($F(3, 24) = 2.99$, $P = 0.07$). Post hoc analyses indicated that amplitude of P1 peak was larger in the longer SOA conditions (250 and 300 ms SOA) than in the shorter SOA conditions (150 and 200 ms SOA). However, the amplitude of P1 in the 300 ms condition was significantly larger than that in 250 ms condition as well.

![Grand mean ERPs](image-url)

Fig. 3. Grand mean ERPs (left column) are displayed for the 9–11-year-old group. ERPs elicited by the deviant (dotted line) are overlain with the ERPs elicited by the standard (solid line). Recordings from the Fz, Cz, and Pz electrodes are shown for each SOA condition separately to show the topography of the ERP components. Thick solid arrows (in the Cz column) show the timing of the onset of the successive frequency and intensity deviant stimuli. The P1 and N1 components are labeled for each condition. Note the increase in amplitude of P1 and N1 with increasing SOA. Grand-mean standard—deviant difference waveforms (right column) are displayed for the frontal (Fz) electrode site for each condition separately. Arrows point to the MMN components. Note that two MMNs were elicited only in the 300 ms conditions.
3.2.1.2. N1 component. The average amplitude (peak to trough) and latency of N1 were also compared across SOA conditions (see Table 1 and Fig. 3). A main effect of condition was found for both amplitude ($F(3, 24)=44.66$, $P<0.01$) and latency ($F(3, 24)=13.01$, $P<0.01$). Post hoc analysis showed that the N1 peak-to-trough amplitudes were larger in the longer SOA conditions (250 and 300 ms SOA) compared to the shorter SOA conditions (150 and 200 ms SOA). The N1 peak latency was shorter in the 150 ms SOA condition (185 ms) than the rest of the conditions (210–230 ms; see Table 1).

3.2.2. Difference waveforms

One MMN was elicited by the successive frequency and intensity deviants in the 150, 200 and 250 ms SOA conditions ($t_{(8)}=-2.99$, $P<0.01$; $t_{(8)}=-2.34$, $P<0.05$; $t_{(8)}=2.99$, $P<0.01$, respectively). No significant difference from zero was found for the difference waveforms in Range 2 of these conditions. Two separate MMNs were elicited, one by each of the deviant stimuli, only when the two successive deviants were separated by 300 ms (Range 1: $t_{(8)}=-3.29$, $P<0.01$; Range 2: $t_{(8)}=-2.10$, $P<0.05$). There was no difference in the latency ($F(3, 24)=0.85$, $P=0.45$) or amplitude ($F(3, 24)=0.40$, $P=0.67$) of the Range 1 MMNs. (For details of amplitudes and latency see Table 2). An ANOVA with factors of Condition (4 levels of SOA)× Laterality (left, middle, and right)× Position (frontal vs. central) revealed a main effect of laterality ($F(2, 16)=5.34$, $P<0.05$) and a main effect of position ($F(1, 8)=7.83$, $P<0.05$) on the mean amplitude of the Range 1 MMNs with no interactions. Post hoc analysis showed that MMN amplitude was larger at the lateral electrodes (left and right scalp sites) than the middle sites. MMN amplitude was larger at frontal sites, consistent with typical MMN topography (Alho, 1995).

These results demonstrate that the length of the integrating window for 9–11-year-old children is longer than the integrating window for adults (less than 300 ms vs. less than 200 ms, respectively).

3.2.3. Comparison between adults and 9–11-year-olds

3.2.3.1. P1 component. Separate ANOVAs with factors of Condition (4 levels of SOA)×Group (adults and children) were conducted to test the amplitudes and latencies of P1 between the two groups. A main effect of group was found for latency ($F(1, 13)=6.30$, $P<0.05$). P1 latency was earlier in adults than 9–11-year-olds. An interaction between condition and group was found for amplitude ($F(3, 39)=20.67$, $P<0.01$). Post hoc analysis revealed that the children had larger P1 amplitudes than adults only at the longer SOA conditions (250 and 300 ms).

3.2.3.2. N1 component. Separate ANOVAs with factors of Condition (4 levels of SOA)×Group (adults and children) were conducted to test the amplitudes and latencies of N1 between the two groups. An interaction between condition and group was found for N1 amplitude ($F(3, 39)=20.45$, $P<0.01$). Post hoc analysis revealed that the children had larger N1 amplitude than adults in all SOA conditions except 150 ms. Overall, the latency of N1 was earlier in adults than in children, shown by a main effect of group on latency ($F(1, 13)=66.32$, $P<0.01$).

3.2.3.3. MMN component. Separate ANOVAs with factors of Condition (4 levels of SOA)× Group (adults and children) were conducted to test the amplitudes and latencies of MMN between the two groups. No group difference in amplitude ($F(1, 13)=0.03$, $P=0.87$) was found but the latency of Range 1 MMN was significantly earlier for adults ($F(1, 13)=24.96$, $P<0.01$) than those for children.

4. Experiment 3

The results of Experiment 2 indicated that 9–11-year-old children have a longer temporal window of integration than adults. The purpose for Experiment 3 was to test whether the integrating window would be similar in younger children ages 5–8 years as that of the 9–11-year-olds to determine if there is a development of this integration process.

4.1. Methods

4.1.1. Subjects

Eleven (4 boys) 5–8-year-old ($M=6.6$ years, SD=10.8 months) children with reported normal language development were paid to participate in the study. All participants included in the experiment passed a hearing screening. Informed consent from the guardians and informed assent from the children were obtained after a detailed explanation of the experimental procedures was provided. Human subjects treatment was in accordance with the guidelines of the committee for clinical investigation at the Albert Einstein College of Medicine where the study was conducted.

4.1.2. Stimuli and procedures

The stimuli used in Experiment 3 were identical to those used in Experiment 1. A pilot study conducted prior to the experiment showed that the successive double deviants elicited only one MMN in the 300 ms SOA condition for the 5–8-year-old children. This determined that longer SOA conditions were needed for the younger children to be able to demonstrate the length of the integrating window. Therefore, we used the following three conditions of SOA: 300, 350, and 400 ms (onset-to-onset). In order to keep the duration of the session no longer than 1.5 h for younger children while using longer
SOAs than Experiment 2, we reduced total number of stimuli in current experiment. A total of 3000 stimuli were presented in each condition (2550 standards, 225 frequency and 225 intensity deviants). The order of conditions was counterbalanced across participants. Children took at least two longer breaks (approx. 10 min) during the testing session and additional shorter breaks (approx. 2 min) as needed. The total duration of the session was 1.5 h, which included electrode cap placement and breaks. All remaining experimental procedures were identical to Experiment 1.

4.1.3. Data recording

Data recording procedures were identical to Experiment 2, with the exception of the epoch length used. Epoch length was increased to 800 ms post-stimulus onset (and starting 100 ms before stimulus onset) to accommodate the longer SOA needed to observe the ERP responses to the successive deviants in the longest condition of SOA.

4.1.4. Data analysis

The data analysis procedures were identical to Experiment 2. The amplitudes of the difference waveforms measured in the 300 ms SOA condition were between 252 and 292 ms (peak, 272 ms) for Range 1 and between 600 and 640 ms (peak, 620 ms) for Range 2. In the 350 ms SOA condition, Range 1 was between 224 and 264 ms (peak, 244 ms) and Range 2 was between 536 and 576 ms (peak, 556 ms). In the 400 ms SOA condition, Range 1 was between 192 and 232 ms (peak, 212 ms) and Range 2 was between 572 and 612 ms (peak, 592 ms).

One-tailed, one-sample t tests were used to determine the presence of MMN. Repeated-measures ANOVA was used to compare the amplitudes and latencies of P1, N1, and MMN across conditions. One-way ANOVA was used to compare the amplitude and latency of P1, N1, and MMN among the adults and two groups of children for the 300 SOA condition. Greenhouse–Geisser corrections for sphericity were applied and the P values reported. Tukey HSD post hoc analyses were calculated.

4.2. Results and discussion

4.2.1. ERPs

A large and clear positive peak (P1) followed by a large and clear negative peak (N1) can be seen in all conditions evoked by the standard and deviant stimuli (see Fig. 4).
4.2.1. P1 component. Table 1 summarizes the amplitude and latency of the P1 elicited in the three conditions of SOA. In contrast with P1 elicited in the 9–11-year-old age group, there was no significant difference in amplitude \((F(2, 20)=1.75, P=0.21)\) or latency \((F(2, 20)=1.31, P=0.28)\) across conditions. The latency of P1 increased as the SOA increased (see Table 1), however, this difference was not significant. This may be due to greater individual variability in younger children compared to the older children.

4.2.1.1. P1 component. Table 1 summarizes the amplitude and latency of the P1 elicited in the three conditions of SOA. In contrast with P1 elicited in the 9–11-year-old age group, there was no significant difference in amplitude \((F(2, 20)=1.75, P=0.21)\) or latency \((F(2, 20)=1.31, P=0.28)\) across conditions. The latency of P1 increased as the SOA increased (see Table 1), however, this difference was not significant. This may be due to greater individual variability in younger children compared to the older children.

4.2.1.2. N1 component. Table 1 summarizes the amplitude and latency of the N1 elicited in the three conditions of SOA. No difference in amplitude \((F(2, 20)=1.00, P=0.37)\) or latency of N1 \((F(2, 20)=3.62, P=0.67)\) was found. Similar to the P1, the latency value of N1 increased as the SOA increased (see Table 1), however, this difference was not significant. This may be due to greater individual variability in younger children compared to the older children.

4.2.2. Difference waveforms

Fig. 4 (right column) displays the difference waveforms. One MMN was elicited by the successive deviants in the 300 ms conditions \((t_{1(10)}=-2.67, P<0.05)\), whereas two MMNs were elicited by the successive deviants in the 350 ms \((t_{1(10)}=-1.93, P<0.05; t_{1(10)}=-2.06, P<0.05, respectively)\) and in the 400 ms conditions \((t_{1(10)}=4.11, P<0.01; t_{1(10)}=-2.60, P<0.05, respectively)\). The amplitude of Range 1 MMNs did not change across conditions \((F(2, 20)=0.38, P=0.68)\; see Table 2\). Although, the latency value of Range 1 MMN was shorter with increasing SOA, this decrease did not quite reach significance \((F(2, 20)=3.18, P=0.09)\; see Table 2\). A three-way repeated measures ANOVA with factors of Condition (4 levels of SOA), Laterality (left, middle, and right), and Position (frontal vs. central) revealed no main effects \((F(2, 20)=1.44, P=0.26; F(2, 10)=0.10, P=0.81; F(1, 10)=3.52, P=0.09, respectively)\) and no interaction on the amplitude of Range 1 MMNs. There was a trend towards significance for position (the MMN amplitude was larger at frontal electrode sites), however, the difference was not quite significant. These MMN results demonstrate that the length of the integrating window in 5–8-year-old children is less than 350 ms, which is longer than that observed in both 9–11-year-olds and adults (see Table 3).

4.2.2. Difference waveforms

Fig. 4 (right column) displays the difference waveforms. One MMN was elicited by the successive deviants in the 300 ms conditions \((t_{1(10)}=-2.67, P<0.05)\), whereas two MMNs were elicited by the successive deviants in the 350 ms \((t_{1(10)}=-1.93, P<0.05; t_{1(10)}=-2.06, P<0.05, respectively)\) and in the 400 ms conditions \((t_{1(10)}=4.11, P<0.01; t_{1(10)}=-2.60, P<0.05, respectively)\). The amplitude of Range 1 MMNs did not change across conditions \((F(2, 20)=0.38, P=0.68)\; see Table 2\). Although, the latency value of Range 1 MMN was shorter with increasing SOA, this decrease did not quite reach significance \((F(2, 20)=3.18, P=0.09)\; see Table 2\). A three-way repeated measures ANOVA with factors of Condition (4 levels of SOA), Laterality (left, middle, and right), and Position (frontal vs. central) revealed no main effects \((F(2, 20)=1.44, P=0.26; F(2, 10)=0.10, P=0.81; F(1, 10)=3.52, P=0.09, respectively)\) and no interaction on the amplitude of Range 1 MMNs. There was a trend towards significance for position (the MMN amplitude was larger at frontal electrode sites), however, the difference was not quite significant. These MMN results demonstrate that the length of the integrating window in 5–8-year-old children is less than 350 ms, which is longer than that observed in both 9–11-year-olds and adults (see Table 3).

4.2.3. Comparison among three groups in the 300 ms SOA condition

4.2.3.1. P1 component. There was a main effect of group on P1 amplitude \((F(2, 23)=6.63, P=0.05)\) and latency \((F(2, 23)=8.74, P<0.01)\). Post hoc analyses showed that the older children had larger P1 amplitudes than adults but not larger than the younger children. In addition, the younger children had a longer P1 latency than both the older children and adults but there was no difference in latency between older children and adults.

4.2.3.2. N1 component. There was a main effect of group on the N1 amplitude \((F(2, 23)=14.44, P<0.01)\) and latency \((F(2, 23)=24.66, P<0.001)\). Post hoc analyses showed that the group difference was between the adults and the children. Adults had smaller N1 amplitudes and earlier N1 latency than both groups of children but the two groups of children did not differ from each other.

4.2.3.3. MMN component. There was a main effect of group on latency for the Range 1 MMN \((F(2, 23)=17.40, P<0.01)\) but no main effect of group on amplitude \((F(2, 23)=0.35, P=0.71)\). Post hoc analysis showed that the younger children had longer (Range 1 MMN) latency than the older children, whereas older children had longer (Range 1 MMN) latency than adults. The MMN latency appears to decrease with increasing age.

5. General discussion

The main purpose of the current study was to determine whether the length of the auditory TWI was similar in two groups of school-aged children (5–8 and 9–11-year-olds) and young adults. In the younger group of children (5–8 years), successive elements were integrated with a 300 ms onset-to-onset pace (shown by one MMN elicited by the double deviants); whereas in the older group of children (9–11 years), successive elements were integrated with a 250 ms onset-to-onset pace. In adults, successive elements were integrated with a 150 ms onset-to-onset pace. This demonstrates a decreasing TWI with increasing age.

Feature discrimination was found to show adult-like behavioral characteristics at age 9 (Thompson, et al., 1999),
whereas in the current study, the integration window for age 9–11-year-old children was longer than has been found for adults. This indicates that the development of the integration process of successive elements to perceptual units may have a different time course than the development of feature discrimination in the human brain.

5.1. ERPs

5.1.1. P1 component

In the 9–11-year-old children, the latency of P1 did not change as a function of SOA (it was stable at around 110 ms) but the amplitude of P1 did. P1 amplitude significantly increased with increasing SOA from roughly 1 μV at 150 ms SOA to over 5 μV at 300 ms SOA (this pattern of results was similar for the adults). In contrast, there was no difference in latency or amplitude of P1 for the younger children, which may, in part, be due to greater variability in general among younger children.

Our findings differ from some other ERP studies with children (e.g., Čeponienė et al., 1998, 2002). Whereas we found an increase in P1 amplitude with increasing SOA from 150 to 400 ms, Čeponienė et al. (1998) found that the amplitude of P1 decreased in 7- to 9-year-old children as SOA increased from 450 to 1500 ms. Čeponienė et al.’s results may differ due to the use of longer SOAs. As interstimulus interval has been shown to have an effect on the amplitude of obligatory responses in adults (Naätänen and Picton, 1987), it may be in children that when the silence between sounds is greater than 400 ms, the amplitude of the P1 does not increase any further.

5.1.2. N1 component

Unlike P1, the amplitude and latency of N1 was affected by SOA for both groups of children. Both the latency and the amplitude (measured peak to trough) of N1 increased with increasing SOA. These results demonstrate that SOA influences the latency and amplitude of the auditory evoked potentials when the sounds are presented rapidly (between 150 and 400 ms onset-to-onset). This result differs from previous studies that have shown no effect of SOA on the latency and amplitude of N1 component in children (Čeponienė et al., 1998, 2002; Takeda et al., 2002). However, no previous studies tested ERP responses to sounds with the rapid SOAs used in the current study (between 150 and 400 ms). The fastest presentation rate used in other studies was 450 ms, with increasing onset-to-onset times to 7800 ms. Therefore, the different results found between laboratories may be due to the rate of presentation.

In sum, in the current study, using rapid SOAs (less than 450 ms), the results demonstrate that the amplitude of the obligatory responses (P1 and N1) in both groups of children increased as SOA increased. In the 9–11-year-old group, latency of the N1 changed as a function of SOA but the latency of P1 did not. For the 5–8-year-old group, latency of the obligatory responses did not significantly change with SOA, even though the values consistently increased with increasing SOA for both P1 and N1.

5.2. Difference waveforms

Elicitation of two MMNs to successive deviants revealed a decrease in the length of the temporal window with increasing age. Two MMNs were elicited at 200 ms SOA in adults, at 300 ms in 9–11-year-olds, and at 350 ms in 5–8-year-olds.

MMN latency and amplitude (for Range 1) did not change significantly across SOA conditions (found within each age group separately). This result differs from one other study we are aware of (Čeponienė et al., 1998) that reported MMN results across different SOA conditions (measured in the same subjects) using an oddball-type paradigm with children of similar ages. Čeponienė et al. found that latency of the MMN increased with increasing SOA (from 450 to 1500 ms in three conditions), although MMN amplitude did not change significantly. It is possible that the increase in MMN latency was the consequence of longer onset-to-onset intervals used in their paradigm compared to our paradigm.

5.3. Development

5.3.1. Development of ERP components

Overall, the obligatory ERP components (P1 and N1) were larger in amplitude for children than adults. This result is consistent with previous studies (Čeponienė et al., 2002; Johnstone et al., 1996; Shafer et al., 2000; Takeda et al., 2002). The overall comparison of the ERPs between the older children and adults (recorded with identical SOA conditions) showed an inverse relationship between the amplitude of the obligatory responses and age: amplitude of P1 and N1 decreased as age increased. Interestingly, this difference in amplitude was not reflected in the MMN amplitude: there was no difference in MMN amplitude as a function of age. This suggests that the underlying mechanisms eliciting MMN differ from those associated with the obligatory ERP responses.

When comparing the three groups at the same SOA condition (300 ms), the latency of P1, N1 and Range 1 MMN decreased as age increased. This finding was consistent with that of previous ERP and MEG studies (Čeponienė et al., 2002; Gomes et al, 1999; Gomot et al., 2000; Korpihaati and Lang, 1994; McArthur and Bishop, 2002; Paetau et al., 1995; Ponton et al., 1996, 2000; Shafer et al., 2000; Sharma et al., 1997). The age-related decrease in latency suggests that there is a maturational process in the neuronal transmission velocity, possibly resulting from increased axonal diameter, development of myelin sheath,
and faster perceptual processing speed (Albrecht et al., 2000).

5.3.2. Development of auditory processing

The length of the TWI was longer in 5–8-year-old children (less than 350 ms) than in 9–11-year-old children (less than 300 ms) and both age groups had longer integrating windows than found for adults (less than 200 ms). Taken together, these results show a developmental trend in the temporal window of integration. This finding of a decrease in integrating functions of the auditory system is consistent with other studies of temporal resolution; for example, gap detection threshold decreases as a function of increasing age (Hautus et al., 2003; Trehub et al., 1995; Werner et al., 1992). Taken together, these results demonstrate a maturational process for integrating temporal information to unified sound percepts in the human auditory system.

6. Conclusion

Our results demonstrate a general maturational development of the auditory evoked potentials as well as a specific maturational process for temporal encoding of information in auditory cortex. Additionally, of importance when considering the development of ERP components in children, the presentation rate of stimuli (i.e. the length of SOA) has to be taken into account. This study provides evidence that short SOAs can be used successfully to study neural mechanisms of auditory processing in school-aged children.

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References

Alho K. Cerebral generators of mismatch negativity (MMN) and its magnetic counterpart (MMNm) elicited by sound changes. Ear Hear 1995;16:38–51.


