Brain activity index of distractibility in normal school-age children

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Abstract

Children’s attention is easily diverted from a current activity to a new event in the environment. This was indexed in school-age children by diminished performance speed and accuracy in a visual discrimination task caused by task-irrelevant novel sounds. Event-related brain potentials (ERPs) elicited by these distracting sounds showed a prominent positive deflection that was generated by brain processes associated with involuntary switching of attention to novel sounds. Recordings of the magnetoencephalographic (MEG) counterpart of this brain activity revealed a major bilateral generator source in the superior temporal cortex. However, ERP scalp distributions indicated also overlapping brain activity generated in other brain areas involved in involuntary attention switching. Moreover, differences in ERP amplitudes and in their correlations with the reaction times between younger (7–10 years) and older (11–13 years) children indicated developmental changes in attentional brain functions.

Keywords: Auditory event-related potentials; Distraction; Involuntary attention; P3a; Cognitive development
that capacity-allocation deficits play an important role in their attentional problems [11].

The relation of the P3a to novel sounds and the distraction caused by such sounds has not been systematically studied in children however, although such information would be needed to validate the use of the P3a as a developmental measure of attention. Therefore, the present study addressed this issue by recording ERPs to novel sounds and by determining the effects of these sounds on visual task performance in two age groups of healthy children. The children were presented with stimulus pairs (one pair in 1.7 s) consisting of a task-irrelevant sound that was either a tone of 600 Hz ($P = 0.8$) or a complex, ‘novel’ sound ($P = 0.2$) followed by an image delivered 300 ms later (Fig. 1A). Each sound had duration of 200 ms and was binaurally presented through headphones at 50 dB above the subjective hearing threshold of subject. Each novel sound, such as those produced by hammer, rain or telephone, occurred only once during the experiment. The visual stimuli were 32 different white-line drawings (16 animals and 16 non-animals) extending 9 cm horizontally and 9 cm vertically, each presented for 300 ms in a random order in the center of the child’s visual field at the center of a black computer screen located approximately 130 cm from the subject’s eyes. Children were instructed to ignore the sounds, to focus their gaze on a fixation cross (1×1 cm) in the middle of a computer screen, and to press one response button with their right thumb when an animal image appeared on the screen and another button with their left thumb to a non-animal image. All children reached a correct-response rate of 70% or more during the experiment. Their motivation to perform the experimental task was indicated by their genuine interest to the results of their performance that were reported to them after each block in the 1–2 min breaks.

Children were divided into groups: younger ($M = 9$ years 8 months; $SD = 1$ year 5 months; three girls, seven boys) and older ($M = 12$ years 5 months; $SD = 7$ months, four girls, six boys). All had normal or corrected to normal visual acuity and no known auditory deficits. Informed consent was obtained from them and their parents.

The electroencephalogram (EEG; 0.1–100 Hz; sampling rate 500 Hz) was recorded from frontal (Fp1, Fp2, F7, F3, Fz, F4, and F8 according to the international 10–20 system), central (C3, Cz, C4), temporal (T3, T4, T5, T6), parietal (P3, Pz, P4), and occipital (O1, O2) scalp sites and the left and right mastoids (LM, RM). Voltage changes caused by eye movements and blinks were monitored with recordings from the forehead sites (Fp1, Fp2) and the left and right canthi. The reference electrode was placed on the tip of the nose. ERPs were obtained by averaging EEG epochs of 1200 ms beginning 100 ms before each sound onset. EEG epochs with eye movements and blinks were recorded with recordings from the forehead sites (Fp1, Fp2) and the left and right canthi. The reference electrode was placed on the tip of the nose. ERPs were obtained by averaging EEG epochs of 1200 ms beginning 100 ms before each sound onset. EEG epochs with eye movements, blinks, muscle activity, or other artifacts causing voltage changes higher than $\pm 100 \mu V$ at any channel were rejected from averaging, as well as the epochs for the first four stimuli of each block and the epochs for any tone occurring right after a novel sound. For each child, ERPs averaged separately for the tones and novel sounds consisted, after artifact rejections, of at least 400 and 120 acceptable EEG epochs, respectively. Averaged ERPs were filtered with a passband of 1–30 Hz. The mean ERP amplitude differences were statistically compared within-groups and between-groups ANOVAs including the factors Age, Phase, Frontality and Laterality. The Greenhouse–Geisser corrections were applied when

![Fig. 1. (A) An illustration of the auditory-visual distraction paradigm. (B) Electrical brain responses to novel sounds. The grand average of the difference waves obtained by subtracting the ERPs to repetitive tones from ERPs to novel sounds. The P3a response followed by the late negativity (LN), is composed of two phases: early (P3aE) and late (P3aL). The circles on the schematic scalp show the electrode locations. The solid connections indicate the 3 electrode lines from front to back (Frontality) and the dotted connections the 5 electrode lines from the left to right (Laterality). (C) Scalp distributions of the ERP difference-wave amplitudes (only for the electrodes that are depicted by circles and included in the ANOVAs). Interpolation between the electrodes was made by a cubic spline-fitting method.](image-url)
appropriate. The scalp distributions were statistically analyzed after voltage normalization.

The magnetoencephalographic (MEG) was recorded (0.03–100 Hz; sampling rate 300 Hz) in two of the children with a 122-channel whole-head magnetometer [1]. The experimental paradigm and the averaging of brain responses were similar to those in the EEG experiment and the MEG data acquisition and analysis were similar to those applied in a previous MEG study [1].

Involuntary attention to novel sounds resulted in significantly longer RTs ($F(1, 18) = 9.99, P < 0.006$), lower number of correct responses ($F(1, 18) = 14.94, P < 0.001$), and higher number of wrong responses ($F(1, 18) = 16.50, P < 0.0007$) to visual stimuli preceded by a novel sound (mean ± SD for RT was 605 ± 89 ms, for hits 90 ± 9%, for wrong responses 6 ± 7%) than to those preceded by a tone (mean ± SD was for RT 589 ± 96 ms, hits 92 ± 8%, wrong responses 8 ± 7%) there being no significant differences between the younger and older children. However, the children of the younger group showed more prolongation of RT to the visual stimuli preceded by a novel sound than those in the older group (617 ± 103 vs. 593 ± 76 ms, respectively).

ERPs to novel sounds showed a prominent P3a response (Fig. 1B). In accordance with adult data [5], this P3a had a biphasic waveform with an earlier peak at around 200 ms (peak latency at the central midline site in the younger group: 201 ± 36 ms; in the older group: 213 ± 41 ms) and a later peak at around 300 ms (303 ± 32 ms, 328 ± 47 ms, respectively) from sound onset. The P3a was followed by a broad fronto-centrally maximal late negative deflection (called below the LN) at latencies longer than 400 ms.

In both groups, the early phase of the P3a (mean amplitude measured over 150–250 ms) was largest over the central scalp with positive amplitudes over the frontal scalp and inverted, negative amplitudes over the inferior temporal and posterior scalp (over left and right mastoids; T5, T6), whereas the later phase of the P3a (250–350 ms) showed a significantly different distribution (Phase × Frontality interaction, $F(2, 36) = 25.49, P < 0.001$). In the 11–13-year-olds, the late phase of the P3a was anteriorly distributed to that in the 7–10-year-olds (Age × Phase × Frontality $F(2, 36) = 6.24, P < 0.005$) (Fig. 1B,C). This finding supports the results of previous studies indicating that in older children, the P3a response to novel sounds has a scalp focus anterior to that in the younger children [4].

The polarity inversion of the P3a over the inferior temporal and posterior scalp is consistent with generator sources in the auditory cortices [5]. This was supported by MEG recordings indicating that like in adults [1], bilateral sources in the superior temporal cortex contribute to the early phase of the P3a (Fig. 2). However, the later phase of the P3a did not invert its polarity over the inferior temporal and posterior scalp sites. Therefore, it appears to get overlapping contributions from P3a sources located in other brain regions that do not markedly contribute to the MEG responses, possibly because in these areas, the primary currents of pyramidal neurons generating the magnetic fields are not tangential to the skull [1].

The LN (measured as a mean voltage over 450–550 and 600–700 ms) was larger (more negative) in the younger children than in the older ones (main effect of Age $F(1, 18) = 6.28, P < 0.02$). The MEG data suggested that the LN might get a contribution from the temporal lobes. Moreover, the LN might correspond to the so-called reorienting negativity observed in similar studies in adults after P3a to distracting sounds and suggested to be associated with re-directing attention to the distracted task [6,16].

The younger group showed a significant positive correlation (Spearman $r = 0.75, P < 0.01$) between the prolonging effect of a preceding novel sound on the visual RT and the amplitude of the early phase of P3a over the central midline electrode site. This positive correlation supports the involvement of the P3a generator processes in the orienting of attention away from the visual task to the distracting novel sound.

In the older children, the ability to control attention with prefrontal executive control processes [13] might be indicated by shorter RTs after a novel sound and by the more frontally distributed late P3a than in the younger children. This ability might be achieved during childhood as a conse-

Fig. 2. Magnetic brain responses to the novel sounds. Equivalent current dipoles (ECDs) that optimally (in the least-squares sense) explained the measured magnetic P3am field corresponding to the electric P3a were separately determined for each hemisphere in a spherical head model by using MEG responses in a set of 44 channels centered at the approximate location of the auditory cortex [1]. The ECDs for the magnetic counterpart of LN (LNm) were determined by using 32 channels centered over the frontal area of each hemisphere. The arrows indicate the locations (the middle point of the arrow) and orientations of the estimated sources modeled with ECDs that best explained the measured magnetic fields over each hemisphere. In case an ECD had a goodness of fit (between the measured magnetic field and the one that would be produced by this ECD) lower than 70%, the dipole was regarded as being not reliably determined.
quence of the maturation of the prefrontal brain areas [3,15]. The larger LN in the younger children than in the older children, in turn, might be associated with more effortful redi-
trecting of attention back to the visual task after distraction.

The present results give hope that this new line of research might result in the development of an objective method for the pediatric, neuropsychological, and education-
tal assessment of children’s normal and abnormal distractibility and the related brain functions and dysfunc-
tions, respectively.

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[3] Courchesne, E., Chronology of postnatal human brain develop-
ment: event-related potential, positron emission tomogra-
phy, myelination, and synaptogenesis studies, Event-


[16] Schröger, E. and Wolff, C., Attentional orienting and reorien-
ting is indicated by human event-related brain poten-

