Neural mechanisms of auditory sensory processing in children with high intelligence

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To investigate the differences in event-related potential parameters related to children's intelligence, 18 intellectually gifted children and 18 average children participated in this study. The electroencephalograms were recorded the auditory sensory memory that elicited the mismatch negativity (MMN) and late discriminative negativity (LDN), as well as involuntary attention switch that elicited the P3a and early MMN were analyzed. The results indicated that children with high intelligence had comparatively larger MMN, LDN, early MMN, P3a amplitudes, and earlier peak latency in LDN than average children. The enhanced neural function of the intellectually gifted children might be due to more spatially and temporally coordinated neural network, faster neural processing speed and more efficient neural activation functions. *NeuroReport* 18:1571–1575 © 2007 Wolters Kluwer Health | Lippincott Williams & Wilkins.

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Introduction

Highly intelligent individuals are always regarded as the ones who have fast brains, and they use much less time to finish cognitive tasks with much better performances than normal individuals [1]. Previous studies suggested that intellectually gifted individuals had much better attention focusing and memory abilities [2,3], but it is yet unknown which stages of information processing are enhanced in the individuals with high intelligence when they performed cognitive tasks. It is proposed that preattention processing and involuntary attention switch might play a role in the whole cognitive processing.

In auditory event-related potentials (ERPs), mismatch negativity (MMN) is one of the most important and sensitive indices to investigate neural processing [4]. MMN is elicited by a perceptually deviant stimulus or an absolutely different novel stimulus in a sequence of identical sound stimuli, and it reflects the brain's preattention processing ability [5]. It is also found that there is a late discriminative negativity (LDN) after MMN in children, and this component might also represent the discrimination ability of neural system [6]. In addition, when individuals make their involuntary attention switch to novel sound stimuli, an early ERP component MMN (we used 'eMMN' in our paper) and another ERP component named P3a are elicited. Studies show that unattended P3a is elicited immediately after the novel sounds [7], and the P3a that gets its large positive deflection peaking at 200–300 ms reflects an involuntary attention switch toward distinct sound stimuli changes [7]. P3a is also regarded as a sensitive tool to explore the basic biological foundation of high intelligence [8].

This study was carried out to detect whether highly intelligent children had different auditory sensory memory and attention functions compared with their normal peers, such as preattention processing and assessment of novelty. To this end, we measured auditory ERPs in children with high and average intelligence, and these auditory ERPs were supposed to be elicited by sound sequences in which a frequent sound (/ka/) was randomly replaced by either an infrequent deviant (/ta/) sound or novel sounds. Deviant sounds were expected to elicit the MMN and LDN responses, and novel sounds were expected to elicit the eMMN and P3a responses.

Materials and methods

Participants

Thirty-six participants were selected for this study. The entire sample consisted of two groups. (i) An intellectually gifted group [n=18, ten boys and eight girls; ages ranged from 11.4 to 12.4 years (mean age 11.8)]. The highly intelligent children were recruited from an experimental gifted class of a middle school in Beijing, and they were identified and selected from about 1500 candidates by using multiple criteria and multiple methods. Children's intelligence test scores and achievement scores (mainly for Chinese, English, and mathematics) were above the 95th percentile. Identification of these gifted children consisted of several steps: application, primary screening test [Standford–Binet Intelligence Test (revised) and Wechsler Preschool and Primary Scale of Intelligence (revised) were used], retest (five main criteria were considered: cognition, creativity, learning ability, special talent, personality traits), further confirmation (more information about the children's personality traits and physical conditions were gathered), identifying through practice [further identification through practice (student's learning process) was emphasized in this step. To educate them under equal conditions and environment and investigate their potential and actual performance levels was the continuation of the identification procedure]. (ii) An intellectually average group [n=18, nine boys and nine girls; age ranged from 11.2 to 12.2 years (mean age 11.7)]. The children in this group were from among those who responded to an advertisement placed in a primary school in Beijing.

Before the electroencephalogram (EEG) being recorded, all participants were tested by Cattell's Culture Fair Test (children's edition) [9] and Test of Nonverbal Intelligence (TONI-2, a language-free measure of cognitive ability, picture book form A) [10]. The mean IQs of the highly intelligent and average groups were 122.1 and 98.6, respectively. All children had no neurological or psychiatric problems. Their visions were normal or corrected to normal, and all were right-handed and were naive to electrophysiological procedures. Informed consent was obtained from the teachers and parents of the participants.

Stimuli and procedure

We revised the research paradigm of Lepistö *et al.* [11], and the stimuli were Chinese consonant–vowel syllables /ka/ and /ta/. In addition, 120 different novel sounds were used during the experiment, and they ranged from pure and complex tones to natural vowels. The syllables were presented for 100 ms (including 5 ms rise and fall times) with the intensity of 59 dB SPL (sound pressure level), and the intensity of novel sounds ranged from 55 to 79 dB SPL (mean 61.9 dB SPL). Three stimulus blocks of 400 stimuli using a 1000 ms interstimulus interval were present. The probabilities for standard syllable/ka/, deviant syllable /ta/ and the novel sounds were 0.8, 0.1, 0.1, respectively. Each stimulus block began with at least four standard sounds, and at least two standard syllables preceded each deviant syllable or novel sound. The stimuli were presented to the ears through insert earphones at a level of 75 dB SPL.

During the electrophysiologic acquisition period, participants sat comfortably in a reclining chair within an electrically shielded, sound-attenuated booth and watched self-chosen soundless videos. All participants were instructed to ignore the sounds and to sit as quietly as possible. None of the participants experienced difficulty complying with this instruction. The duration of the test session was approximately 35 min.

Event-related potential recording and data analysis

Nose-referenced EEG (amplified by SynAmps 2 online bandpass filtering: 0.05–100 Hz, sampling rate 1000 Hz) was recorded with Ag–AgCl electrodes, and recording sites F3-Fz-F4, FC3-FCz-F4, C3-Cz-C4, CP3-CPz-CP4, P3-Pz-P4, and O1-Oz-O2 according to the international 10–20 system [12] were chosen. The vertical electro-oculogram was recorded with electrodes placed above and below the left eye, and two active electrodes were placed at the right and left mastoids. EEG epochs of 900 ms, including 100 ms of prestimulus time, were offline-averaged separately for each stimulus class. Epochs with artifacts exceeding 100 μV at any electrode were omitted from further analysis.

The MMN and LDN were measured from the deviant-minus-standard ERP-difference waveforms, and the eMMN and P3a were from the novel-minus-standard ERP-difference waveforms. The MMN amplitude was calculated at the negative maximum between 200 and 400 ms for both groups. For the LDN, the corresponding latency window was at the negative maximum 400–700 ms for both groups. The eMMN was measured at the negative maximum between 50 and 250 ms for both groups. The P3a was defined at the largest negative peak between 250 and 450 ms.

The statistical presence of each component was tested by comparing their amplitudes with 0 μV. The between-group differences in the amplitudes, latencies, and electrode sites of the ERP components were analyzed with three-way analysis of variance: Group (children with high intelligence vs. normal children) × anterior–posterior electrode sites (anterior, posterior) × laterality (left, central, right).

Results

Mean peak latencies and amplitudes of MMN and LDN to deviant stimuli and the eMMN and P3a to novel stimuli in both groups are summarized in Table 1. The ERPs elicited by the standard, deviant, and novel sounds in both children groups are presented in Fig. 1. The deviant-minus-standard difference waves are in Fig. 2, and the novel-minus-standard difference waves in Fig. 3.

Responses to deviant sounds

For children with high intelligence, LDN peaked significantly earlier than those with normal intelligence [main effect of group $F(1,34)=23.37$, $P=0.002<0.005$]. Highly intelligent children had larger MMN [main effect of group $F(1,34)=21.98$, $P=0.002<0.005$] and LDN [main effect of group $F(1,34)=9.34$, $P=0.018<0.03$] amplitudes than normal children. For LDN peak amplitude, there were significant interactions between group effect and anterior–posterior electrode sites effect [$F(1,34)=7.17$, $P=0.028<0.03$]: highly intelligent group had larger peak amplitudes in anterior sites than that in posterior sites, whereas normal group had the reverse situation. For MMN, posterior sites had significant larger mean amplitudes

Table 1 Mean peak latency (ms) and amplitude (μV) of the MMN and LDN to deviant stimuli and the eMMN and P3a to novel stimuli in both groups

Group	MMN		LDN		eMMN		P3a	
	Latency	Amplitude	Latency	Amplitude	Latency	Amplitude	Latency	Amplitude
Highly intelligent	311.5 (49.02)	−3.79 (1.7)	480.22 (39.51)	−3.96 (1.77)	168.09 (18.87)	−4.28 (1.77)	329.65 (27.94)	3.57 (2.58)
Normal	298.57 (41.04)	−3.25 (1.48)	507.65 (62.31)	−3.62 (1.5)	171.3 (25.19)	−3.82 (1.27)	338.75 (26.82)	2.94 (1.88)

LDN, late discriminative negativity; eMMN, early mismatch negativity.

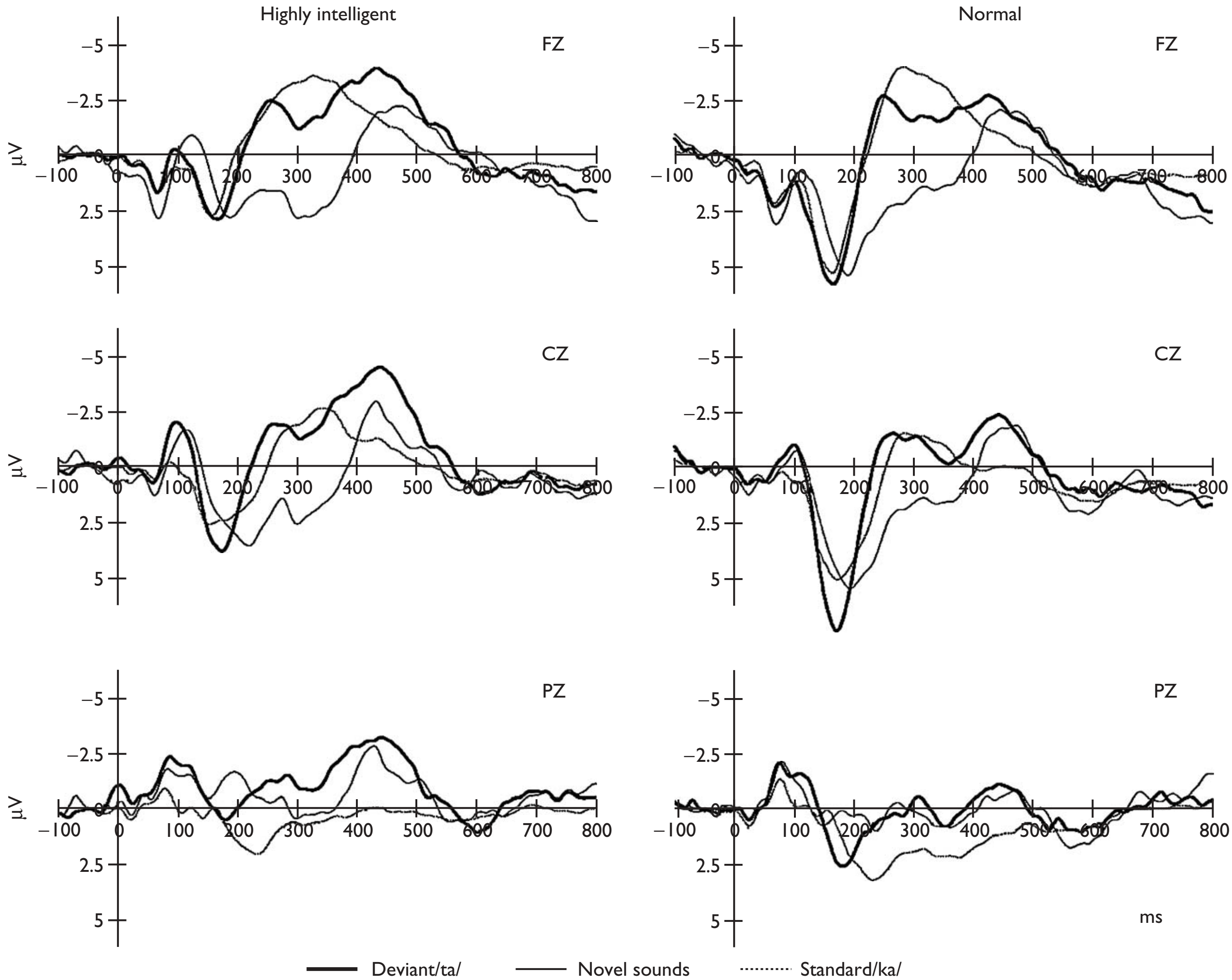

Fig. 1 The ERPs elicited by the standard, deviant, and novel sounds are presented for both groups. ERP, event-related potential.

than anterior sites in both groups [$F(1,34)=153.07$, $P=0.000<0.001$].

Responses to novel sounds

In both groups, novel sounds elicited a prominent P3a potential, after the eMMN. Main effects of Group [$F(1,34)=13.24$, $P=0.008<0.01$], anterior–posterior electrode sites [$F(1,34)=16.68$, $P=0.005<0.01$] and laterality [$F(1,34)=9.32$, $P=0.011<0.03$] were all significant for eMMN peak amplitude. Main effects of anterior–posterior electrode sites [$F(1,34)=384.01$, $P=0.000<0.001$] and laterality [$F(1,34)=14.8$, $P=0.003<0.005$] were significant for eMMN peak latency, but there was no Group effect difference. Main effect of anterior–posterior electrode sites for P3a peak latency was significant [$F(1,34)=35.48$, $P=0.001$], and there were significant interactions between group effect and anterior–posterior electrode sites effect [$F(1,34)=16.03$, $P=0.004<0.01$]: in anterior sites, the intellectually gifted had longer P3a latency than normal children; whereas in posterior sites, they had shorter P3a latency than their normal peers. In addition, main effects of group [$F(1,34)=5.81$, $P=0.047<0.05$], anterior–posterior electrode sites [$F(1,34)=293.7$, $P=0.000<0.001$] and laterality [$F(1,34)=10.29$, $P=0.008<0.01$] for P3a peak amplitude were all significant.

Discussion

From the results of deviant sound ERPs, highly intelligent children had larger MMN and LDN amplitudes than their normal peers, and they had much shorter LDN peak latencies than normal children. The present results might support that intellectually gifted children had much better preattention processing ability. From the results of novel sound ERPs, highly intelligent children had larger peak amplitudes in eMMN and P3a than those of normal children. These results suggested that highly intelligent children had higher involuntary attention switch toward distinct sound stimuli changes. The present results also considered that MMN distribution was in temporal area [13] and P3a was generated by mechanisms depending on frontal lobe functions [14].

The relationship between development and ERPs components is far from understanding fully, while it is even difficult to understand the relationship between intelligence and ERP [15]. Previous EEG studies confirmed that EEG band parameters had strong relationships with human's

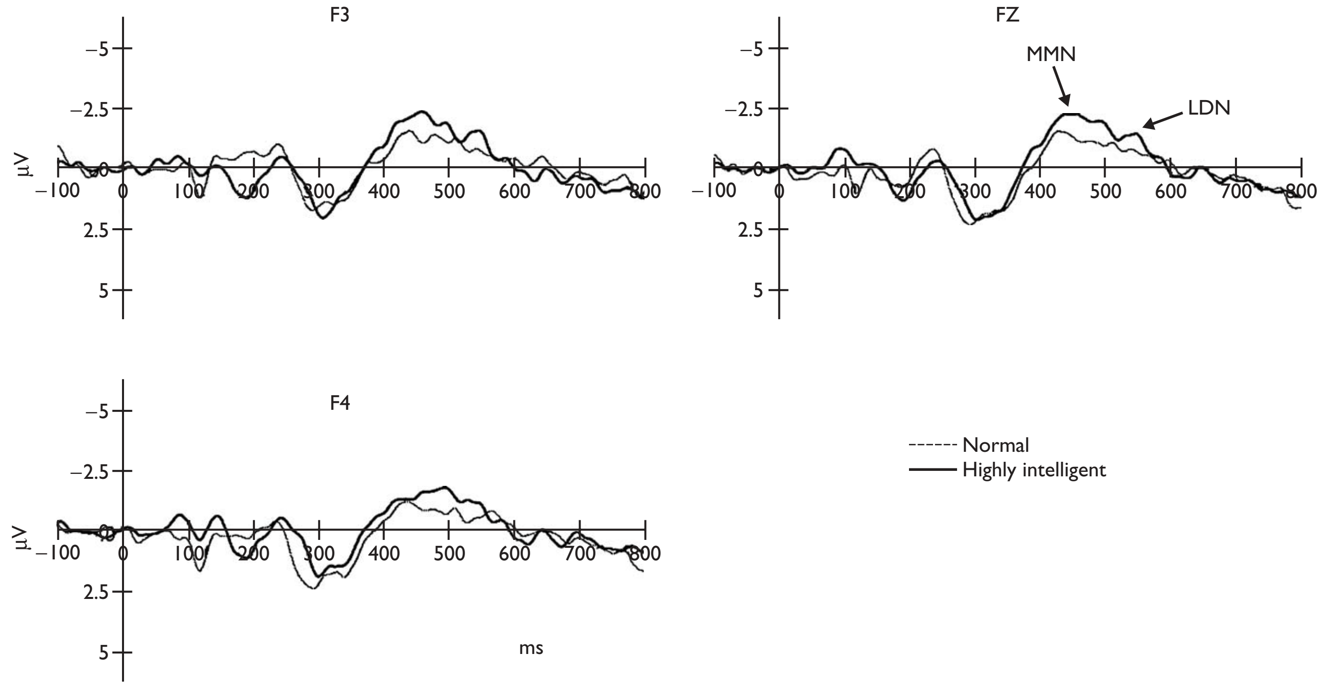

Fig. 2 The nose-referenced deviant-minus-standard difference waves for the two groups.

intelligence [16]. Jaušovec [17] studied the relationship between intelligence and EEG coherence and power measures in the lower and upper α-band, and the results indicated that highly intelligent individuals showed higher α power and more cooperation between brain areas when solving closed problems than that in a normal individual. Schmid *et al.* [18] further investigated the correlation between intelligence test variables and spectral EEG parameters in children, and they indicated that EEG recording could reliably reflect children's intellectual abilities. As the degree of EEG maturation is based on the active number of synapses and the maturation of the neuronal controlling system, it is deduced that intelligence might be determined by the degree of EEG maturation. Thus, these earlier EEG studies made good base for further exploration on the relationship between intelligence and neural cognitive processing.

Jaušovec and Jaušovec [3], using oddball tasks to investigate the relationship between event-related brain activity and intelligence found that intellectually gifted individuals showed more regular ERP waveforms than normal individuals. They also found that intellectually gifted individuals showed increased P3 amplitude and reduced latency under the attended conditions. Our present study further found that highly intelligent children also showed similar reduced latency and increased amplitude under the preattention conditions, and our findings further supported the neural efficiency hypothesis of intelligence [19], that is highly intelligent individuals have faster neural processing speed and more efficient neural activation functions. The neural efficiency hypothesis of intelligence states that highly intelligent individuals use fewer neurons and specific neuronal circuits in performing a specific task as compared with less intelligent individuals. Increased amplitudes of highly intelligent children during our auditory sensory processing task might be due to a more specific and focused use of neurons and neural circuits involved with a similar mechanism [20]. In addition, although the functional significance of LDN has not been widely established yet, it is elicited under the same condition as the MMN with a later onsetting, and might reflect some more complex aspects of auditory change processing [6]. The present results of LDN latency decrementing with increasing IQ scores might be regarded to be an evidence of the speed intelligence hypothesis or the saying 'faster brains have higher IQs' as suggested by Chalke and Ertl [1].

Our study also supported that P3a latency and amplitude were closely related to intelligence [8]. It is widely accepted that P3 latency is a measure of the duration of the stimulus evaluation process [21], or the time for allocating resources to update memory [22]. Our present findings showed that highly intelligent children could make faster detection of novel changes, and it meant that intellectually gifted children might have a better manifestation of central nervous system activity. From our results of P3a latency, highly intelligent children used more time and sources to complete involuntary attention processing to novel stimuli in brain's anterior sites than normal children, and this finding supported that intellectually gifted individuals had better and more efficient frontal functions than average individuals [23].

Conclusion

This study confirmed significant correlations between auditory sensory processing and intelligence in children. Children with high intelligence had larger peak amplitudes in all the LDN, MMN, eMMN, and P3a waveforms than their normal peers, and they had significant shorter latency in LDN waveforms. Enhanced frontal functions might help highly intelligent children to a large extent when they discriminated novel stimuli from the standard stimuli. Our findings on neural preattention processing and involuntary

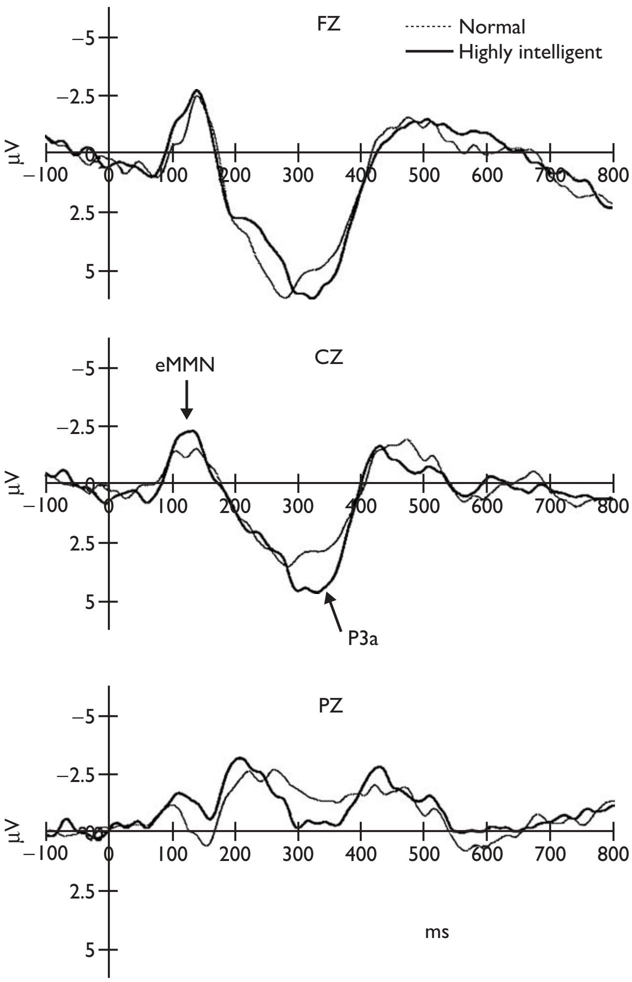

Fig. 3 The nose-referenced novel-minus-standard difference waves for the two groups.

attention switch supported the neural efficiency hypothesis and the speed intelligence hypothesis. Furthermore, these findings also obtained new insights that neural processing had much influence on neural substrates of intelligence.

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