Auditory selective attention and processing in children with attention-deficit/hyperactivity disorder

Hilary Gomes [a,b,d,*], Martin Duff [a,b], Miguel Ramos [a], Sophie Molholm [a,b,c], John J. Foxe [a,b,c,d], Jeffrey Halperin [b,d]

[a] Cognitive Neuroscience Program, City College of New York, CUNY, New York, NY 10031, USA
[b] The Graduate Center of CUNY, New York, NY 10031, USA
[c] Departments of Pediatrics, Neuroscience, and Children's Evaluation and Rehabilitation Center (CERC), Albert Einstein College of Medicine, New York, NY 10031, USA
[d] Neuropsychology Program, Queens College, New York, NY 10031, USA

ARTICLE INFO

HIGHLIGHTS

- Children with ADHD exhibited almost no effect of attention on Nd, whereas an effect was elicited from children with TD.
- Children with ADHD exhibited larger P3bs for attended than unattended targets suggesting adequate inhibition of distracters.
- Reduced Tas were found for children with ADHD which may reflect limited sensory information.

ABSTRACT

Objective: This study sought to better characterize the contributions of deficits in attention allocation and distracter inhibition to the poor performance on attention tasks often seen in children with ADHD.
Methods: Electrophysiological (Nd, P3b) and behavioral measures (speed and accuracy) were examined during an auditory selective attention task in children with ADHD, children with typical development (TD), and adults. Thirty children (15 ADHD; 13 females) between the ages of 7 and 13 and 16 adults (8 females) participated.
Results: Nd waveforms were elicited from adults and children with TD, but not from children with ADHD. Further, those with ADHD exhibited significantly smaller auditory responses at 100 ms (Ta). P3bs were elicited in all three groups by targets but not by unattended deviants. Performance was significantly poorer in children with ADHD than TD and RTs were more variable.
Conclusions: Children with ADHD evidenced poorer attention allocation, as measured by Nd and hits, but were not more distracted by unattended deviants, as measured by P3b and false alarms, than children with TD.
Significance: Findings for Nd, P3b, and Ta considered together suggest that deficits in auditory selective attention in children with ADHD may be attributable to reduced information early in the processing stream.

1. Introduction

Attention-deficit/hyperactivity disorder (ADHD) is a common and impairing neuropsychiatric disorder of early onset that is characterized by age-inappropriate hyperactivity, inattentiveness, and impulsivity (Durston, 2003). Children with ADHD tend to do poorly in school and are at risk for school failure (Barkley, 2006). They generally have difficulties allocating their attention efficiently and, in at least some situations, are more vulnerable to distraction (Kenemans et al., 2005; Van der Stelt et al., 2001; Van Mourik et al., 2007). In school the abilities to selectively attend to the teacher, sustain that attention through a lesson, and inhibit processing of the distracters in the classroom, are critical for learning and school success.

Recordings of the electrical activity of the brain provide a noninvasive means of assaying the processes underlying selective attention. These have been well-characterized in the literature for both

* Corresponding author. Address: Psychology Department, NAC 7/120, City College of New York, 137th and Convent Avenue, New York, NY 10031, USA. Tel.: +1 212 650 5720.
E-mail address: hilary.gomes@gmail.com (H. Gomes).

adults and children, and provide objective metrics of selective attention. The high temporal resolution of EEG recordings also allows assessment of the integrity of the basic sensory processing that necessarily precedes selective attention. To assess selective attention processes, the response to a given stimulus when it is in an attended channel is compared to the response to the same stimulus when it occurs in an unattended channel. Successful selective attention should lead to a so-called negative-difference wave (Nd), the timing and amplitude of which are informative with regard to specific selective attention processes (for reviews see Hillyard et al., 1995; Näätänen, 1992; Näätänen et al., 2001). Nd onset-latency increases as the physical separation between the attended and unattended stimuli decreases, suggesting that Nd onset reflects the time required to determine whether a stimulus belongs to the unattended or the attended channel (i.e., whether or not it should receive extended processing). Whilst developmental studies reveal that Nd onset decreases into the teen years and beyond (Gomes et al., 2007), Nd responses are clearly apparent in pediatric populations and can serve as a useful metric of the integrity of brain processes involved in selective attention in clinical groups of children.

A handful of studies have compared Nds in children with and without ADHD (Loiselle et al., 1980; Rothenberger et al., 2000; Satterfield et al., 1990; Zambelli et al., 1977; for a review see Jonkman et al., 1997). Findings have been somewhat variable across studies. Some have found smaller Nds and poorer performance in children with ADHD (Jonkman et al., 1997; Loiselle et al., 1980; Satterfield et al., 1990; Zambelli et al., 1977). In contrast, others have demonstrated comparable Nds and performance between groups (Rothenberger et al., 2000; also see Satterfield et al., 1990).

We sought to resolve some of the ambiguity around electrophysiological measures of selective attention in ADHD. Several measures were taken to ensure a strong test of auditory selective attention. Selective attention is challenging for younger children when just one feature separates the attended and unattended channels. Therefore two channel cues were provided: ear and frequency, to facilitate channel separation. Targets, on the other hand, were selected for intermediate levels of difficulty to maximize the likelihood that selective attention to the specified channel would be necessary for successful task performance. Since selective attention processes in those with and without ADHD may employ different underlying neural circuitry we sampled from a relatively large number of electrodes allowing us to fully characterize selective attention processes. Finally, we used a highly standardized paradigm that has yielded well-characterized responses in the literature, and we collected a large number of trials for each stimulus condition to ensure a high signal-to-noise ratio. We hypothesized that children with ADHD would exhibit smaller Nds of later onset and peak-latency, reflecting their difficulties with sustaining attentional focus and allocating their attention efficiently in response to task demands (Halperin et al., 2008).

To examine the extent to which target stimuli were processed in the "unattended" channel, and thus the degree to which children with ADHD were unnecessarily processing distractors, we also measured the P3b response to targets in the attended and unattended channels (Ridderinkhof and Van der Stelt, 2000). The P3b is a positive-going response that is maximal at the midline parietal sites and is usually elicited by rare, unpredictable stimuli which the participant is actively trying to discriminate (for reviews see Johnson, 1989; Näätänen, 1992). P3b peak latency and amplitude are sensitive to a variety of task and stimulus parameters, mainly to the extent that these influence target detection (Reinvang, 1998). Developmental studies of the P3b have found that peak latency decreases with age but that the morphology of the component does not seem to change (Friedman, 1991; Johnson, 1989). Some studies report that P3bs elicited by target stimuli are smaller in children

with ADHD than in children with TD (Jonkman et al., 1997; Loiselle et al., 1980; Satterfield et al., 1990) but others report that they are equivalent (Rothenberger et al., 2000). It has been suggested that this difference might be attributable to accuracy and reflect the inclusion of responses to all targets, as opposed to only correct targets in most of these studies (Jonkman et al., 1997). P3b to unattended deviants has not generally been examined, but Satterfield et al. (1990) reported no difference between the groups in the amplitude of the waveform in the time window of the P3b in the ERP elicited by the unattended deviants (also see Loiselle et al., 1980). We expected P3b would be elicited by the attended targets from participants in all three groups. Further we expected P3b to be elicited by the unattended deviants in at least some of the children with ADHD reflecting difficulties maintaining their attentional focus on the stimuli in the attended channel.

2. Method

2.1. Participants

Participants were 16 adults (8 females), 15 typically developing children (8 females), and 15 children with ADHD (5 females). The adults ranged from 18 to 45 years of age ($M = 25.0$ y, $SD = 8.1$ y). Self-reported ethnicity for the adults was as follows: 8 Hispanic, 1 African American, 4 Caucasian and 3 Asian. One of the adults was left-handed.

Children were excluded from the study if they had a chronic medical or neurological illness; a history of neurological problems; were taking systemic medication (other than stimulant medication); had been diagnosed with schizophrenia, major affective disorder, autism, pervasive developmental disorder, or a chronic tic disorder; or were not attending school. Two children in the ADHD group who were taking stimulant medication were asked not to take it on the day of the experiment. Child participants also had to achieve a Full Scale IQ score of 80 or better on the Wechsler Abbreviated Scale of Intelligence (WASI; Psychological Corporation, 1999) and pass a bilateral hearing screening test (hearing threshold of 25 dB HL or better for 500–4000 Hz) on the day of testing.

The children with ADHD ranged in age from 7.3 to 12.5 years of age ($M = 9.7$ y, $SD = 1.8$ y). All were referred for participation in the study by teachers, parents, or clinicians, and had either behavioral and/or reading problems. Eight had been previously diagnosed with ADHD and five with language or learning issues. Parent-reported ethnicity was as follows: 9 Hispanic, 5 African American, and 1 Asian. Seven of the children came from bilingual households. Two were left-handed.

Children were categorized as having ADHD using parent, teacher, and examiner DSM-IV ADHD rating scales (DuPaul et al., 1998). Children needed to evidence six or more symptoms of either inattention or hyperactivity/impulsivity in one setting and at least four or more in a second setting to be considered for the ADHD group. Further, parents had to indicate that the symptoms were present by 7 years of age. A licensed pediatric neuropsychologist reviewed the child's file to determine if a different diagnosis was more appropriate (based on this review, four additional children were excluded).

The TD children ranged in age from 7.5 to 13.5 years of age ($M = 10.2$ y, $SD = 1.5$ y) and were recruited from the same local community as the ADHD group. All were in the age appropriate grade in school with no history of special education services. Age appropriate abilities were confirmed by normal range scores on standardized tests of cognition. In addition, TD children needed to have fewer than four symptoms of both inattention and hyperactivity/impulsivity rated as present by their parent on the ADHD rating scale. Parent-reported ethnicity for the children was as follows: 8 Hispanic, 3 African American, 2 Caucasian, and 3 Asian.

Table 1
Demographic, rating scale, and standardized test performance data for the two groups of children.

	ADHD	Typically Developing
Number	15 (5 females)	15 (8 females)
Age	9.7 y (1.8 y)	10.2 y (1.5 y)
Range	7.3–12.5 y	7.5–13.5 y
Parent DSM: Number of Inattentive symptoms	5.87 (2.5)[*]	1.47 (2.1)
Parent DSM: Number of Impulsive/Hyperactive symptoms	3.53 (2.4)[*]	0.73 (1.3)
Teacher/Examiner DSM: Number of Inattentive symptoms[a]	6.73 (2.2)	
Teacher/Examiner DSM: Number of Impulsive/Hyperactive symptoms[a]	5.07 (3.0)	
WASI: Verbal IQ	95.9 (10.9)[*]	108.7 (9.5)
WASI: Performance IQ	96.1 (9.2)[*]	108.9 (13.8)
WASI: Full Scale IQ	95.7 (9.7)[*]	109.8 (11.6)

[a] Teacher rating scales were returned for 13 of the 15 children. Examiner rating scales were substituted for the two missing scales.
[*] Significantly different from the typically developing children.

Nine of the children were from bilingual households and one child was left-handed.

Children were administered a battery of tests including the WASI. As shown in Table 1, the groups did not differ in age or gender (chi squared = 1.22, p = 0.269). Children in the ADHD group received significantly higher ratings from their parents for inattentive and impulsive/hyperactive symptoms [$t(28)$ = 5.2, p < 0.001; $t(28)$ = 3.9, p < 0.005, respectively] as expected given the criteria for group assignment. The TD children exhibited significantly higher scores on the cognitive tests administered [VIQ: $t(28)$ = 3.4, p < 0.005; PIQ: $t(28)$ = 3.0, p < 0.01; FSIQ: $t(28)$ = 3.6, p < 0.005]. It is common for children with ADHD to perform more poorly than their TD peers on standardized tests (Halperin et al., 2008). However, recent papers have argued against using IQ as a covariate in studies with a clinical sample, such as ours, as it is invalid to assume that IQ is independent of the disorder (Dennis et al., 2009).

Prior to testing, all children signed assent forms and parents and adult participants signed consent forms. The protocol for the study was reviewed and approved by the City College of New York Institutional Review Board and the New York City Department of Education.

Parents were paid $50 and parents of clinically referred children were provided with a written report. Adult participants were paid $10 per hour for their participation.

2.2. Stimuli

Four types of stimuli were presented to each participant, two standards [1000 Hz (low channel) and 2000 Hz (high channel) tones], an intensity target, and a duration target. Tones were presented monaurally through insert earphones. They were delivered at 82 dB SPL and were of 100 ms duration (including 10 ms rise and fall times), except for intensity and duration targets. Target stimuli deviated from standards by an amount that was adjusted individually according to detection performance of participants during a same-different pretest in which five levels of difference from the standard were presented for each of the target types in the ear and frequency channels to be used in the actual experiment. This was done to control for potential individual differences in discrimination. The target duration tones ranged between 25 and 85 ms (as compared to the 100 ms standard) and the intensity target tones were between 67 and 79 dB (as compared to the 82 dB standard). The children with ADHD received targets which on average showed a greater physical difference from the standards than those received by children with TD and the adults.

The ear to which the high versus low frequency stimuli were presented was counterbalanced across subjects, as was the ear to which a given target type (duration or intensity) was presented. Stimulus order was pseudo-randomized with the high and low standards each occurring 40% of the time and each of the targets

occurring 10% of the time. Stimulus onset asynchrony (SOA) varied randomly from 850 to 1150 ms with a mean SOA of 1 s to make stimulus onsets less predictable.

2.3. Procedure

Participants were presented with two streams ("channels") of stimuli differentiated by ear and frequency (1000 Hz, low and 2000 Hz, high channels). In one condition they attended to the high frequency channel and in the other to the low frequency channel. Participants were instructed to respond to infrequent targets within the attended channel via button press, while ignoring tones presented to the other ear. Stimuli were presented in runs of approximately 5 min, with 300 stimuli presented within a block. Altogether, a total of four "attend the high frequency channel" blocks and four "attend the low frequency channel" blocks were presented. All participants first attended to the tones presented to the right ear.

An adult sat with each child during the experiment to monitor attention and minimize movement. Further, if the child missed more than two targets in a row, they were gently reminded to listen to the appropriate ear for the target. Short breaks, in which the children remained seated, and long breaks, in which they were disconnected from the recording apparatus and allowed to walk around, were given as needed. Total experiment time was approximately 3 h, including approximately 45 min of electrode application, 1 and 1/2 h of testing with breaks, and 45 min of electrode removal and debriefing.

2.4. Electrode placement and recording techniques

The EEG was recorded from 32 Ag/AgCl electrodes mounted in an elastic cap with the amplifier bandpass set to 0.5–70 Hz (−6 dB points) and a sampling rate of 500 Hz. The scalp sites recorded were frontal/central: Fp1, Fp2, Fz, F3, F4, F7, F8, FCz, FC3, FC4; frontal/temporal/central: FT7, FT8, T3, T4, T5, T6, Cz, C3, C4; central/parietal: CPz, CP3, CP4; temporal/parietal/occipital: Tp7, Tp8, Pz, P3, P4, Oz, O1, O2; and left (A1) and right (A2) mastoid electrodes. The vertical electrooculogram (VEOG) was recorded from electrodes placed above and below the left eye. The horizontal electrooculogram (HEOG) was recorded via electrodes attached to the outer canthi of each eye. All of these sites were referenced to an electrode placed on the tip of the nose. Impedances at the beginning of the experiment were maintained at below 10 kΩ.

2.5. Data analysis

Adults were included in this study as adult data using comparable experimental parameters were not available and it was deemed important to establish that Nds would be elicited in adults, using

this paradigm. However, the primary comparisons are between the two child groups, with a focus on the responses to the attended versus the unattended standards (for which the signal to noise ratio was the best).

2.5.1. Behavioral data

RT and accuracy measures (hits and false alarms; FA) were recorded for each participant for each type of target and signal detection measures were calculated (d-prime and C). The window for behavioral responses was 200–1200 ms following stimulus onset. This response window slightly overlapped the presentation of the subsequent stimulus.

2.5.2. Electrophysiological data

Individual participant EEG data was sorted into 1100 ms epochs (including a prestimulus interval of 100 ms) as a function of stimulus and attention conditions. Each epoch was baseline corrected across the entire sweep before artifact rejecting and averaging. Artifact reject levels were set at +/− 100 μV for all electrodes to exclude blinks and movement artifacts. The averages for each condition were rebaselined to the average amplitude of the prestimulus portion of the epoch.

The mean number of sweeps included in the attended and unattended standard averages for the adults were 370.6, for the children with TD were 313.1, and for the children with ADHD were 221.8. An ANOVA comparing the number of sweeps across the two child groups found that the children with ADHD had significantly fewer than the children with TD [$F(1, 28) = 12.92$, $p < 0.01$, $\eta_p^2 = 0.32$]. It is likely that this difference reflects higher rates of movement related artifact rejection in the children with ADHD. Nonetheless, the number of acceptable ERP trials elicited in each group is substantial and yielded clear waveforms for most participants. Grand mean averages for each age-group and stimulus-type were obtained for purposes of display and examination of topographic distributions. Grand mean difference waveforms were obtained by subtracting the ERPs elicited by the standards when they were unattended from the ERPs elicited by the same standards when they were attended.

The windows chosen for average Nd amplitude measurements were the 50 ms surrounding the Nd peak latency (25 ms on each side of the peak) at FCz in the group grand averages. Grand mean peak latencies for the adults and children with TD respectively were as follows: intensity – 233 and 314 ms and duration – 233 and 310 ms. Nds were not as apparent in the children with ADHD, although a small, possible Nd was seen in the waveforms elicited in the intensity condition peaking at 340. This peak was used for

measurement purposes in both conditions for the children with ADHD. For each participant the Nd was rated as present, absent or questionable by examining the raw and difference waveforms at FCz. Onset and peak latencies of the Nds rated as present and questionable were determined by two raters. Rare differences were discussed until agreement was reached.

Latency windows for amplitude measurements of Ta and P1 were chosen by identifying the peak latencies in the grand mean waveforms. The peak latency for P1 was 70 ms and for Ta was 114 ms for both child groups (TD or ADHD) regardless of deviant condition or attention instruction. The windows chosen for average amplitude measurements were the 20 ms surrounding the peak latency (10 ms on each side of the peak).

An alpha level of 0.05 was used for all statistical tests. Greenhouse-Geisser corrections were used in reporting p values when appropriate.

3. Results

3.1. Behavioral

The behavioral data (see Table 2) were examined using a repeated measures MANOVA to explore differences in speed (RT), accuracy (hits and FA), and efficiency (RT variability) of target detection between the children with ADHD and those with TD. Significant multivariate effects were found for group [Wilks' Lambda; $F(4, 25) = 6.63$, $p < 0.005$, $\eta_p^2 = 0.52$] and target type [Wilks' Lambda; $F(4, 25) = 9.32$, $p < 0.0005$, $\eta_p^2 = 0.60$].

3.2. Target type

Participants detected the duration targets significantly more often [$F(1, 28) = 8.65$, $p < 0.01$, $\eta_p^2 = 0.24$] than the intensity targets but their RTs were significantly more variable for the duration than for the intensity targets [$F(1, 28) = 6.59$, $p < 0.05$, $\eta_p^2 = 0.19$].

3.3. Group

Children with ADHD were significantly less accurate than children with TD; detecting fewer targets [$F(1, 28) = 18.94$, $p < 0.0005$, $\eta_p^2 = 0.40$] and making more FA [$F(1, 28) = 5.35$, $p < 0.05$, $\eta_p^2 = 0.16$]. The RTs of the children with ADHD were also significantly more variable than those of children with TD [$F(1, 28) = 11.20$, $p < 0.005$, $\eta_p^2 = 0.29$].

Table 2
Behavioral data for each group for intensity and duration targets. Standard deviations are in parentheses.

	Age group					
	ADHD		Typically developing		Adults	
	Intensity	Duration	Intensity	Duration	Intensity	Duration
Percent hits	38.8 (14.6)	51.2 (15.0)	67.7 (18.4)	71.1 (19.5)	86.0 (11.7)	91.6 (9.3)
Median RT (ms)	588 (98)	559 (60)	557 (55)	538 (63)	487 (78)	464 (59)
RT SD (ms)	170 (41)	197 (37)	143 (26)	158 (35)	110 (26)	136 (33)
Total number of False alarms (FA)	25.2 (26.9)	29.5 (31.5)	13.0 (9.0)	10.0 (5.9)	2.8 (3.2)	3.3 (3.1)
Proportion of FA to unattended Deviants to Total FA	0.28 (0.18)	0.16 (0.15)	0.25 (0.29)	0.27 (0.26)	0.09 (0.27)	0.15 (0.20)
d-prime (sensitivity)	1.82 (.51)	2.15 (.71)	2.86 (.67)	3.11 (.83)	4.18 (.70)	4.52 (.92)
C (bias)	1.20 (.27)	1.04 (.26)	0.92 (.26)	0.88 (.32)	0.86 (.34)	0.58 (.34)
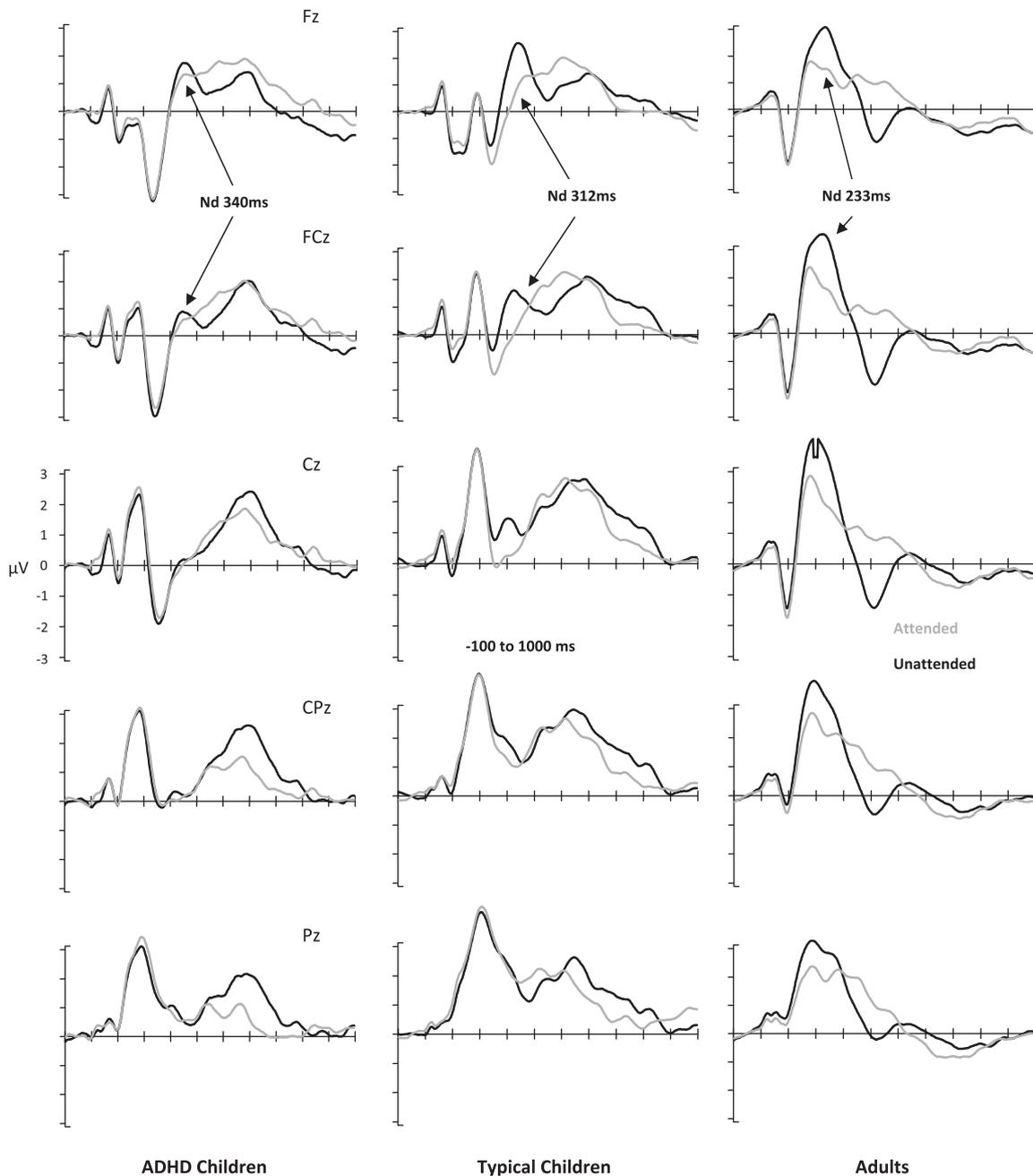
Fig. 1. Grand mean ERPs elicited from participants in the three groups at Fz, FCz, Cz, CPz, and Pz. The gray lines are the ERPs elicited by the standard tones when they were in the attended channel and the black lines are the ERPs elicited by the standard tones when they were in the unattended channel. In this and all subsequent figures, stimuli were presented at time zero, positive is up, and waveform were smoothed for display.

To further examine differential effects of target type between the child groups signal detection measures were calculated. Significant multivariate effects were again found for group [Wilks' Lambda; $F(2, 27) = 10.13$, $p < 0.005$, $\eta_p^2 = 0.43$] and target type [Wilks' Lambda; $F(2, 27) = 4.68$, $p < 0.05$, $\eta_p^2 = 0.26$] and were significant for both d-prime and C; however, the interaction was not significant.

To examine the efficiency of channel selection between the two child groups, the proportion of FA to unattended deviants as a function of total FA were compared with a two (ADHD and TD) by two (target type) ANOVA. A proportion was used to control for the more impulsive responding seen in the children with ADHD as evidenced by their statistically higher total FAs and more liberal response bias. No significant effects or interactions were found.

In summary, the children with ADHD missed more targets, made more FA, and exhibited more variable RTs than children with TD. However, responses to unattended deviants were comparable between the two groups when the proportions of FA to unattended deviants relative to total FA were examined.

3.4. ERPs

Fig. 1 displays the grand mean waveforms elicited by the standard tones when they were in the attended (gray line) and unattended channels (black line) at selected midline recording sites (Fz, FCz, Cz, CPz, Pz) from children with ADHD, children with TD, and adults. ERPs elicited in the duration and intensity conditions have been collapsed for this figure. Developmental changes in
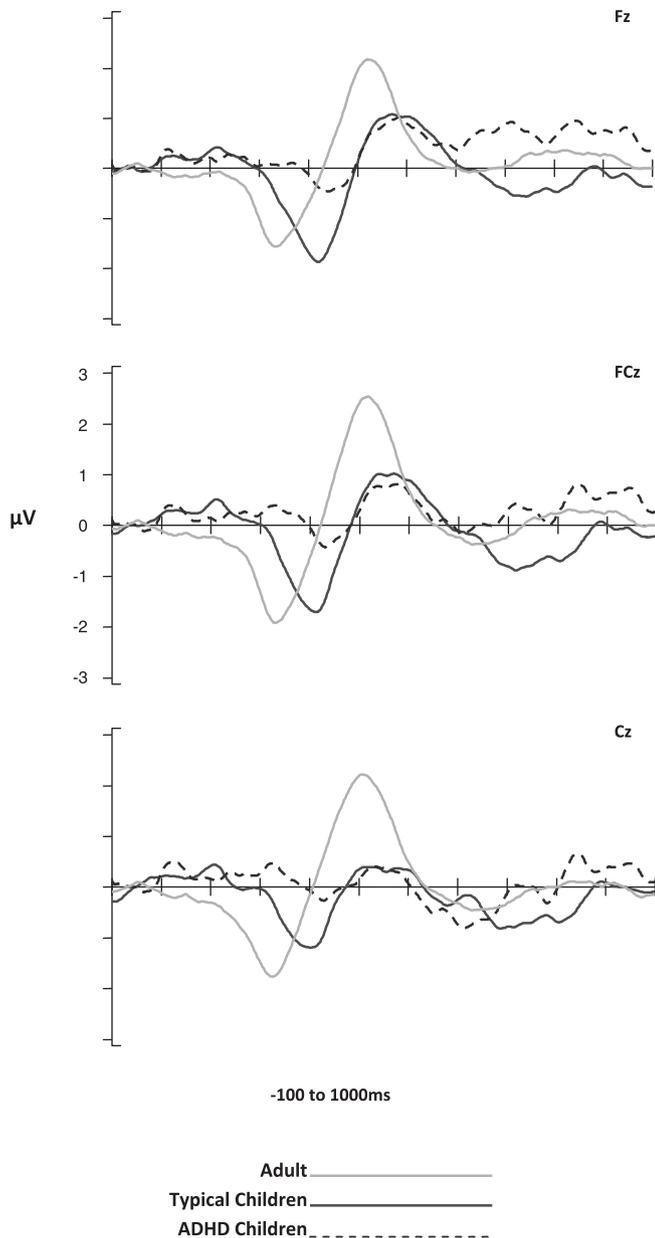
Fig. 2. Grand mean difference waveforms (Nd) elicited from participants in all three groups obtained by subtracting the ERPs elicited by the standard tones when they were unattended from the ERPs elicited by the standard tones when they were attended at selected electrode sites (Fz, FCz, Cz). The gray, black, and dotted lines are the waveforms elicited from the adult, children with TD and children with ADHD, respectively.

Table 3

Mean amplitudes in μV of the Nds in intensity and duration conditions by group and electrode. Standard deviations are in parentheses.

	Group					
	ADHD		Typically Developing		Adults	
	Intensity	Duration	Intensity	Duration	Intensity	Duration
Fz	−0.41	−0.54	−1.57[*]	−2.07[**]	−1.43[**]	−1.70[**]
	(3.16)	(2.18)	(2.35)	(2.58)	(1.41)	(1.83)
FC3	0.39	−0.02	−0.55	−1.22[**]	−1.17[**]	−1.65[**]
	(3.27)	(1.79)	(2.04)	(1.55)	(1.37)	(1.64)
FCz	−0.46	−0.33	−1.30[*]	−2.12[**]	−1.72[**]	−2.11[**]
	(3.96)	(2.26)	(2.36)	(2.37)	(1.67)	(1.96)
FC4	0.30	−0.02	−0.36	−1.79[**]	−1.47[**]	−1.55[**]
	(3.18)	(2.46)	(2.04)	(2.39)	(1.42)	(1.73)
C3	0.64	−0.10	−0.11	−1.14[*]	−1.07[**]	−1.49[**]
	(3.53)	(2.51)	(2.03)	(1.77)	(1.36)	(1.50)
Cz	−0.25	−0.18	−0.75	−1.59[**]	−1.55[**]	−1.91[**]
	(4.07)	(2.90)	(2.27)	(1.79)	(1.71)	(1.77)
C4	0.56	−0.07	−0.27	−1.61[*]	−1.13[**]	−1.50[**]
	(3.33)	(2.77)	(2.30)	(2.68)	(1.44)	(1.58)

[*] $p < .05$.
[**] $p < .01$.

the morphology of the waveforms are clearly evident. ERPs elicited from the child groups are characterized by a P1 peaking at approximately 70 ms, a N1 peaking at about 115 ms, and a P2 peaking at about 190 ms. P1s are larger in the children than in the adults, but N1s and P2s are smaller. However, the most notable developmental difference is the presence of an additional negative going wave followed by a positive going wave in the children (Gomes et al., 2007).

3.4.1. Nd amplitude analyses

Nd is identified as the separation between the waveforms elicited by the attended and unattended standards. It begins on the upward slope of the P2 component for the adults and somewhat later in the children (see Fig. 1). As can be seen in the difference

waves in Fig. 2, Nds are much smaller for the children with ADHD than for the adults and children with TD. Consistent with the literature Nd is largest in the fronto-central region and peaks at approximately 230 ms for the adults. The Nd is followed by a positive going wave which peaks at approximately 410 ms in the adults and is largest over centrally located electrodes.

Analysis of the amplitude data occurred in two stages. First, to establish that the amplitude of the waveform elicited by the standards when they were in the attended channel was significantly different from the amplitude of the waveform elicited by the standards when they were in the unattended channel in the Nd latency window, three way ANOVAs with factors of target type (intensity, duration), attention (attended, unattended), and electrode (Fz, FCz, Cz, FC3, FC4, C3, C4) were conducted for each group. Main effects of attention were found for the adults and children with TD but not for the children with ADHD [adult: $F(1, 15) = 32.45$, $p < 0.0005$, $\eta_p^2 = 0.68$; TD: $F(1, 14) = 10.57$, $p < 0.01$, $\eta_p^2 = 0.43$; ADHD: $F(1, 14) = 0.00$, NS]. In order to explore the consistency of these findings, the Nd amplitudes for seven electrode sites used in these analyses were compared using post hoc t-tests (see Table 3). The attention effect was significant at all electrode sites for the adults in both conditions and the children with TD in the duration condition. In the intensity condition, the effect of attention was significant only centrally at Fz and FCz for children with TD. For the children with ADHD there were no significant differences at any electrode site in either condition.

Second, to examine amplitude differences between groups a three way ANOVA was conducted comparing the amplitude of the Nd across target type, electrode (Fz, FCz, Cz, FC3, FC4, C3, C4), and the two child groups. A main effect for group [$F(1, 28) = 4.65$, $p < 0.05$, $\eta_p^2 = 0.14$] was found reflecting the larger Nds elicited from the children with TD than from the children with ADHD. There was also a main effect of electrode [$F(6, 168) = 7.84$, $p < 0.0005$, $\eta_p^2 = 0.22$]. No other main effects or interactions were significant.

### 3.4.2. Individual ratings of Nd

Nds were identified in the grand means of 87.5% of the adults (14 in each condition), 73.3% of the children with TD (13 in duration and 9 in intensity), and 56.6% of the children with ADHD (8 in duration and 9 in intensity). For the children with ADHD an additional analysis was done to determine if significant Nds were
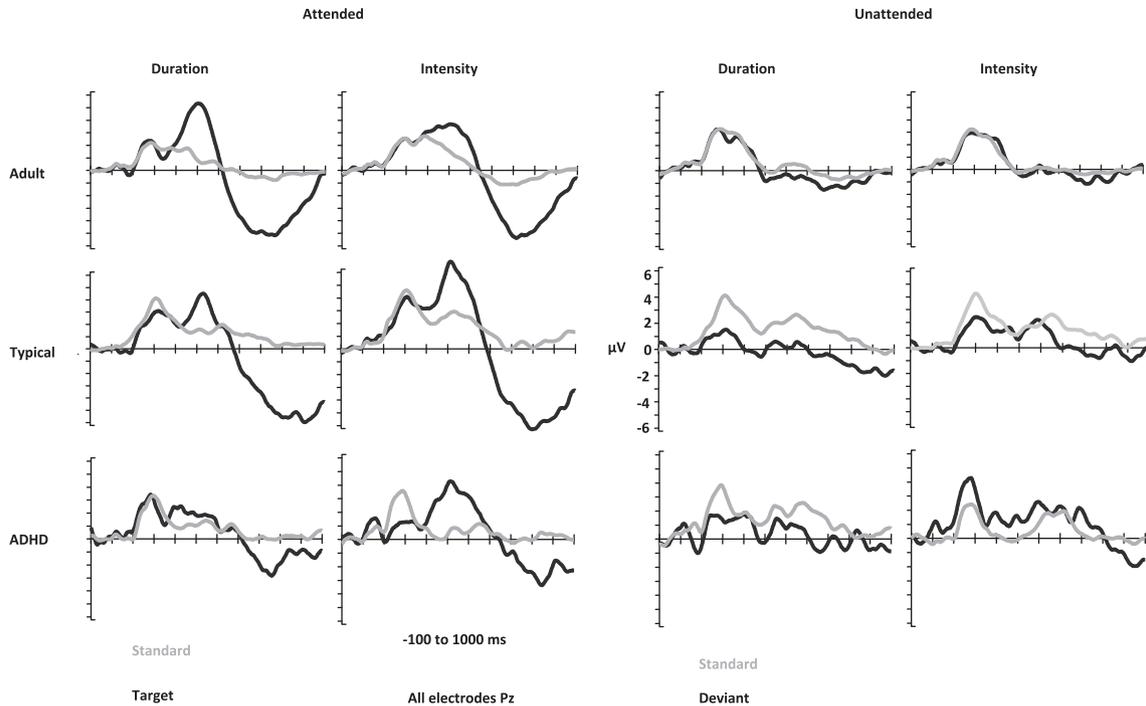
Fig. 3. Grand mean ERPs (P3b) elicited by the correctly detected attended targets and unattended deviants compared to the relevant standards in both the duration and intensity conditions for all three groups at Pz. The black lines are the ERPs elicited by the target/deviant tones and the gray lines are the ERPs elicited by the standard tones.

elicited from the children rated as having present or questionable Nd. The 2 (attention) X 7 (electrode) ANOVA conducted for the intensity condition found a main effect of attention [$F(1, 8)$ = 8.72, $p < 0.05$, $\eta_p^2 = 0.52$]. However, no attention effect was found for the duration condition [$F(1, 7)$ = 0.94, NS]. This finding supports

the observation of a small Nd in the intensity condition for the children with ADHD and suggests individual differences in selective attention. An examination of the demographic and performance data failed to reveal any obvious differences between the children with ADHD evidencing Nd in the intensity condition and
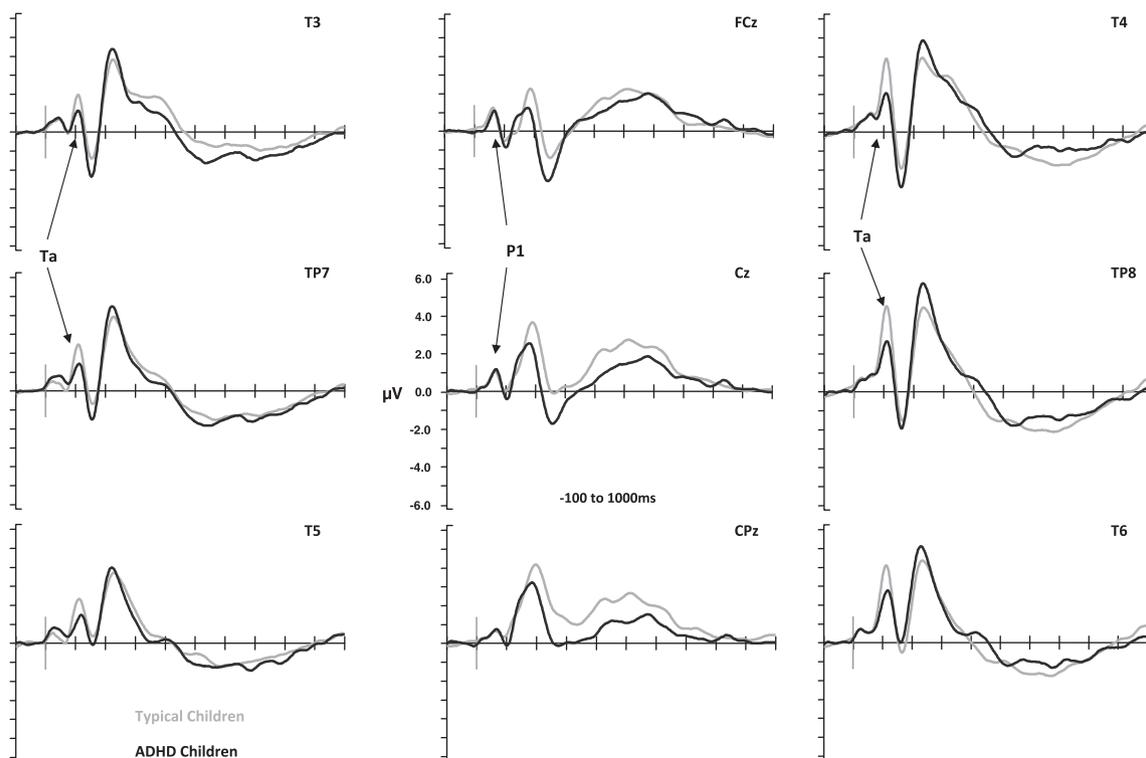
Fig. 4. Ta and P1 evidenced in the grand mean ERPs elicited from participants in the two child groups at FCz, Cz, CPz, T3, T4, TP7, TP8, T5, and T6. The black lines are the ERPs to the attended standards elicited from the children with ADHD and the gray lines are the ERPs elicited from the children with TD.

Table 4
Mean amplitudes in μV of the Ta and P1 by group, electrode and attention collapsed over deviant type.

	ADHD Attended	ADHD Unattended	Typical Attended	Typical Unattended
Ta (lateral)				
T3	1.50 (1.50)	1.72 (1.36)	2.62 (2.16)	2.40 (1.93)
T4	2.55 (1.41)**	2.45 (1.42)**	4.80 (2.45)	4.35 (2.23)
TP7	1.73 (1.91)*	1.98 (2.17)	3.08 (2.25)	2.90 (1.96)
TP8	3.16 (1.27)***	2.81 (1.05)***	5.45 (1.85)	4.93 (1.63)
T5	1.49 (1.39)**	1.52 (2.02)	2.81 (1.50)	2.54 (1.35)
T6	3.04 (1.46)**	2.42 (1.28)***	4.81 (1.67)	4.30 (1.26)
P1 (central)				
FCz	1.49 (1.43)	1.55 (1.44)	1.34 (1.51)	1.36 (1.45)
FC3	1.39 (1.31)	1.38 (1.55)	1.58 (1.64)	1.35 (1.28)
FC4	1.60 (1.52)	1.58 (1.38)	1.80 (1.53)	1.38 (1.39)
Cz	1.41 (1.35)	1.54 (1.82)	1.02 (1.52)	1.16 (1.32)
C3	1.45 (1.46)	1.37 (1.60)	1.34 (1.73)	1.16 (1.27)
C4	1.34 (1.54)	1.35 (1.58)	1.42 (1.67)	0.96 (1.53)

* $p < .05$.
** $p < .01$.
*** $p < .001$ when comparing the amplitude of the Ta and P1 components elicited from the children with ADHD and those with TD.

those who did not. It should be noted that only five children with ADHD evidenced Nds in both conditions, seven evidenced them in one condition but not the other and three did not evidence Nds in either condition.

3.4.3. Latency analyses

Onset and peak latencies for Nds rated as present and questionable were compared using repeated measures MANOVAs with the factors of group (adult, TD, and ADHD) and target type (duration, intensity). Missing data was replaced with means for the appropriate group and condition for the omnibus test but not for the post hoc *t*-tests. There was a main effect of group which was significant for both onset and peak measures [Wilks' Lambda; $F(4, 74) = 13.64$, $p < 0.0005$, $\eta_p^2 = 0.42$; onset: $F(2, 38) = 27.48$, $p < 0.0005$, $\eta_p^2 = 0.59$; peak: $F(2, 38) = 28.12$, $p < 0.0005$, $\eta_p^2 = 0.60$]. The two child groups did not differ on any of the latency measures but all latency measures were found to decrease with age when adults and children with TD were compared [duration onset ($t(25) = 5.37$, $p < 0.0005$), duration peak ($t(25) = 5.27$, $p < 0.0005$), intensity onset ($t(21) = 6.44$, $p < 0.0005$) and intensity peak ($t(21) = 5.85$, $p < 0.0005$)].

3.4.4. P3b

The allocation of attention can also be assessed by comparing the ERP correlates of target detection for stimuli in the attended and unattended channels. Targets in the unattended channel will be referred to as "deviants". Fig. 3 presents the P3bs for the correctly detected attended targets and the unattended deviants. P3bs were elicited from participants in all three groups in both target conditions by the attended targets but were not elicited by the unattended deviants suggesting that participants in all three groups were able to follow the task instructions and maintain their attentional focus on the specified channel. The attention effects on P3b were confirmed for the children using a repeated measures ANOVAs with the factors of target type (duration, intensity), attention (attended, unattended), and group (TD, and ADHD) [$F(1, 28) = 21.38$, $p < 0.0005$, $\eta_p^2 = 0.43$]. No other main effects or interactions were significant.

3.4.5. Ta analyses

An examination of the obligatory components elicited by the standards reveals a smaller positivity in the 100 ms range at the lateral electrode sites for the children with ADHD than for the children with TD (see Fig. 4). This component is thought to be Ta because of its latency and scalp distribution. An ANOVA with the factors of group, deviant type, attention instruction, and electrode (T3, T4, TP7, TP8, T5, T6) comparing the amplitude of Ta at the lateral electrode sites found a main effect of group [$F(1, 28) = 11.66$, $p < 0.005$, $\eta_p^2 = 0.29$]. None of the interactions with group were significant. Follow-up *t*-tests demonstrated that the group difference was significant at $p < 0.05$ or better at most lateral electrode sites examined for both the attended and unattended standards (see Table 4). A similar analysis comparing the amplitude of a central positivity, P1, using six central electrodes (FCz, Cz, FC3, FC4, C3, C4) found no main effect [$F(1, 28) = 0.08$, NS] or significant interactions of group.

In summary, significant group Nds were elicited from the adults and children with TD but not from the children with ADHD. However, some of the children with ADHD did appear to evidence Nds (based on experimenter ratings) and when the waveforms from only those children were examined a significant Nd was present in the intensity condition but not in the duration condition. An early lateral positivity, Ta, elicited by attended and unattended standards was found to be smaller in the children with ADHD than in those with TD. P3s were elicited by correctly detected targets in all three groups but not by unattended deviants.

4. Discussion

This study examined attention allocation, maintenance, and distracter inhibition in children with ADHD, children with TD, and adults during an auditory selective attention task. In what follows we consider the implications of the resulting behavioral and electrophysiological data, both for TD children and for children diagnosed with ADHD.

4.1. Selective attention in children with TD and adults

Children with TD and adults were able to selectively attend to the designated channel in this paradigm, as reflected in clear Nds, a well-established electrophysiological metric of auditory selective attention, and the pattern of behavioral measures (adequate hits and a low rate of false alarms). Nd onset and peak latencies were earlier for the adults than for the children, replicating Gomes et al. (2007) and suggesting developmental improvements in the speed and efficiency of attention allocation (Ridderinkhof and Van der Stelt, 2000). Further, the effectiveness of channel selection and the inhibition of distracter processing for both the adults and children with TD was evidenced by the elicitation of P3bs to detected targets but not to unattended deviants.

The use of two cues for channel identification, tone frequency and location, was expected to positively impact performance and electrophysiological measures (Hansen and Hillyard, 1980) relative to Gomes et al. (2007) where channel was identified by frequency alone. Evidence for this was not, however, at all apparent in our data. We were particularly surprised that improvement was not apparent for the children where selective attention processes are still developing and one might expect that multiple cues would be particularly helpful. Future work using a within subject manipulation of number of cues for channel selection will be better suited to assess the benefits to children and clinical groups of channel cue redundancies in selectively attending to task relevant inputs.

4.2. Selective attention in ADHD

Notably, despite pretesting in which the difference levels were set to achieve a moderately high level of accuracy, performance was quite weak for the children with ADHD once these stimuli were placed in the context of a selective attention task. Children

with ADHD showed significantly poorer target detection than their age matched controls, and Nds were not significant in the group electrophysiological data. An examination of the individual waveforms suggested that Nds were evident in some of the children. However, the effect was inconsistent. In these children, an Nd was usually only identified in one condition and not the other, and many of the Nds were rated as questionably present. Nonetheless when only the children rated as having present or questionable Nds were examined there was evidence of a significant Nd in the intensity condition but not the duration condition.

Although somewhat weaker performance and smaller Nds were expected from the children with ADHD when compared to those with TD, the absence of a significant Nd and the extremely poor performance of the children with ADHD at the group level were not anticipated. However, our current findings are generally consistent with Jonkman et al. (1997), Loiselle et al. (1980), and Zambelli et al. (1977), all of whom found smaller Nds and poorer performance in the children with ADHD than in their control children. Further, as in the current study, Zambelli et al. (1977) directly compared the amplitude of the waveforms elicited in the attended and unattended conditions and found no significant attention effect in their participants with ADHD. In contrast, Rothenberger et al. (2000) found no evidence of group differences in Nd between the children with ADHD and TD. There are two critical differences between the Rothenberger study and ours. First, in the Rothenberger study the target stimuli were very frequent. In their study, 40% of the stimuli in the attended channel were targets which required button press responses, in contrast to 20% of attended stimuli in the current study. Second, the targets in the Rothenberger study were easy to discriminate (frequency target of 1500 Hz with a standard of 1000 Hz), while our targets were individually selected to be moderately challenging to detect. These factors may have increased the alertness of the participants in the Rothenberger study resulting in exceptionally good compliance and very strong performance. The results of the Rothenberger study might provide clues to optimizing performance in children with ADHD; however, they do not explain why these children have general difficulties with attention allocation in the first place.

So why is the allocation of attention particularly challenging for children with ADHD? We will consider a number of possible explanations for our findings. First, perhaps the children with ADHD were attending to all of the stimuli and consequently did not show electrophysiological selective attention effects or behavioral benefits associated with focusing on the critical channel. Although possible, this explanation seems unlikely given that there are no indications that the unattended deviants were processed as targets (unattended deviants did not elicit P3bs or a proportional increase in FA) as would be expected if the children were actively attending to all of the stimuli. Alternatively, perhaps these children had trouble attending to any of the stimuli. Again, although possible, this explanation also seems unlikely given that the targets in the attended channel were processed differently than deviants in the unattended channel (as indexed by measures of P3). Trouble attending to the task would be expected to result in similar sized, and probably small, P3bs to both attended targets and unattended deviants.

Another possibility is suggested by the significantly smaller Tas elicited by both the attended and unattended standards from the children with ADHD as compared to those from the children with TD. Perhaps the children with ADHD were trying to comply with the task demands but were inefficiently attending to (Bekker et al., 2005) or processing the sensory information making the task more difficult. As such they were engaged in the task but were less consistent and effective in their performance due to limited information about the stimuli. This interpretation of our data is consistent with cascade models of information processing in which restricted early information has cascading implications for later processing (McClelland, 1979). In our paradigm, limited information about the stimuli would impact the attention related ERPs in two ways. First, it would obviously impact the representation of the current stimulus, but it might also reduce the quality of the memory of the standard (referred to as the attentional trace; Näätänen, 1992; Näätänen et al., 2001) making it harder to make judgments about the current stimulus. Unfortunately, it is not possible to determine if similar group differences in the Ta were seen in other selective attention studies as none of them presented data from lateral electrodes and most only recorded from midline sites. However, a similar component has been shown to have reduced amplitude and increased latency in children with severe language impairments (but normal hearing) when compared to children with TD (Tonnquist-Uhlen, 1996).

Ta, one of the components of the auditory T-complex (Ponton et al., 2002; Tonnquist-Uhlen et al., 2003), has not been extensively studied, but appears to reach mature amplitude and latency relatively early (Tonnquist-Uhlen et al., 2003) and to be best represented in dipole source models by radial dipoles located in parabelt area of secondary auditory cortex (Ponton et al., 2002). As the Ta component matures early and is relatively insensitive to attention, at least in our study, it may reflect basic, stimulus processing. The reduced amplitude Ta seen in the children with ADHD may reflect a dampening of information available to this system, more limited activation, or immature/incomplete neural synchronization (Gilley et al., 2005). All of these explanations would suggest that the information available for making decisions about channel membership and target identity is impoverished. Further, it is possible that the reduced Ta reflects aberrant processing earlier in the auditory system. Studies examining brain-stem auditory evoked potentials (BAEP) in children with attention deficit disorder as compared to children with typical development have found transmission delays; specifically longer latencies for waves III and V, and transmission times between waves I-III and III-V (Lahat et al., 1995; Puente et al., 2002). As wave III is generated in the pons and wave V in the midbrain (Näätänen, 1992), the delays in these waves and the increased transmission times suggest possible brainstem dysfunction in ADHD. Such a processing delay at the level of the brainstem could result in impoverished cortical representations and poor performance, especially in challenging situations. Notably, if confirmed, such findings might be consistent with the notion that ADHD is not due to a primary deficit in higher cortical executive/prefrontal functioning (Barkley et al., 1997; Pennington and Ozonoff, 1996), but rather that differences in earlier-developing subcortical regions have a significant impact on the development and functioning of these more rostral brain structures (Halperin and Schulz, 2006; Sergeant, 2000).

These findings must be viewed within the context of several limitations. The lateral Ta group differences, while intriguing, were post hoc and thus, should be considered cautiously until replicated. Second, we did not systematically assess psychiatric disorders other than ADHD, although parents were queried about previous diagnoses, and only two children were reported to have been diagnosed with another psychiatric disorder, conduct disorder in both cases. Consequently, we are unable to determine with certainty the degree to which the results might be affected by other possible comorbidities.

5. Summary

This study confirms that children with ADHD have difficulty selectively attending to competing channels of auditory information, with much poorer target detection performance compared to their typically developing peers, and the virtual absence of an electrophysiological index of selective attention (the Nd). Examination

of the sensory evoked responses suggests a possible contributing factor to these processing difficulties. Namely, an impoverished representation of the auditory signal (as suggested by a diminished Ta) might have cascading effects on later discrimination, especially in the face of a complex auditory environment. Future work will follow up on the notion that basic sensory processing is impaired in children with ADHD.

Acknowledgement

References

Barkley RA. Attention-deficit hyperactivity disorder: a handbook for diagnosis and treatment. 3rd ed. New York: Guilford; 2006.

Barkley RA. Behavioral inhibition, sustained attention, and executive function: constructing a unified theory of ADHD. Psychol Bull 1997;121:65–94.

Bekker EM, Kenemans JL, Hoeksma MR, Talsma D, Verbaten MN. The pure electrophysiology of stopping. Int J Psychophysiol 2005;55:191–8.

Dennis M, Francis DJ, Cirino PT, Schachar R, Barnes MA, Fletcher JM. Why IQ is not a covariate in cognitive studies of neurodevelopmental disorders. J Int Neuropsychol Soc 2009;15:331–43.

Dupaul GJ, Power TJ, Anastopoulos AD, Reid R. ADHD rating scale – IV: checklists, norms, and clinical interpretation. New York: Guilford; 1998.

Durston S. A review of the biological bases of ADHD: what have we learned from imaging studies? Ment Retard Dev Disabil Res Rev 2003;9:184–95.

Friedman D. The endogenous scalp-recorded brain potentials and their relationship to cognitive development. In: Jennings JR, Coles M, editors. Handbook of cognitive psychophysiology: central and autonomic nervous system approaches. New York: John Wiley & Sons; 1991. p. 621–56.

Gilley PM, Sharma A, Dorman M, Martin K. Developmental changes in the refractoriness of the cortical auditory evoked potential. Clin Neurophysiol 2005;116:648–57.

Gomes H, Duff M, Barnhardt J, Barrett S, Ritter W. Development of auditory selective attention: event-related potential measures of channel selection and target detection. Psychophysiology 2007;44:711–27.

Halperin JM, Marks DJ, Schultz KP. Neuropsychological perspectives on ADHD. In: Morgan JE, Ricker JH, editors. Textbook of clinical neuropsychology. New York: Taylor and Francis; 2008. p. 333–45.

Halperin JM, Schulz KP. Revisiting the role of the prefrontal cortex in the pathophysiology of attention-deficit/hyperactivity disorder. Psychol Bull 2006;132:560–81.

Hansen JC, Hillyard SA. Endogenous brain potentials associated with selective auditory attention. Electroenceph Clin Neurophysiol 1980;49:277–90.

Hillyard SA, Mangun GR, Woldorff MG, Luck SJ. Neural systems mediating selective attention. In: Gazzaniga MS, editor. The cognitive neurosciences. Cambridge: MIT; 1995. p. 665–81.

Johnson R. Developmental evidence for modality-dependent P300 generators: a normative study. Psychophysiology 1989;26:651–67.

Jonkman LM, Kemner C, Verbaten MK, Koelega HS, Camfferman G, vd Gaag RJ, et al. Event-related potentials and performance of attention-deficit hyperactivity disorder: children and normal controls in auditory and visual selective attention tasks. Biol Psychiatry 1997;41:595–611.

Kenemans JJ, Bekker EM, Lijffijt M, Overtoom CCF, Jonkman LM, Verbaten MN. Attention deficit and impulsivity: selecting, shifting, and stopping. Int J Psychophysiol 2005;58:59–70.

Lahat E, Avital E, Barr J, Berkovitch M, Ariazoroff A, Aladjem M. BAEP studies in children with attention deficit disorder. Dev Med Child Neurol 1995;37:119–23.

Loiselle DL, Stamm JS, Maitinsky S, Whipple SC. Evoked potential and behavioral signs of attention dysfunction in hyperactive boys. Psychophysiology 1980;17:193–201.

McClelland JL. On the time relations of mental processes: an examination of systems of processes in cascade. Psychol Rev 1979;86:287–330.

Näätänen R. Attention and brain function. Hillsdale, NJ: Lawrence Erlbaum; 1992.

Näätänen R, Alho K, Schröger E. Electrophysiology of attention. In: Pashler H, editor. Steven's handbook of experimental psychology, vol. 4. 3rd ed. New York: John Wiley & Sons; 2001. p. 601–53.

Pennington BF, Ozonoff S. Executive functions and developmental psychopathology. J Child Psychol Psychiatry 1996;37:51–87.

Ponton C, Eggermont JJ, Khosla D, Kwong B, Don M. Maturation of human central auditory system activity: separating auditory evoked potentials by dipole source modeling. Clin Neurophysiol 2002;113:407–20.

Psychological Corporation. Wechsler abbreviated scale of intelligence. San Antonio, TX: Psychological Corporation; 1999.

Puente A, Ysunza A, Pamplona M, Silva-Rojas A, Lara C. Short latency and long latency auditory evoked responses in children with attention deficit disorder. Int J Pediatr Otorhinolaryngol 2002;62:45–51.

Reinvang I. Validation of reaction time in continuous performance tasks as an index of attention by electrophysiological measures. J Clin Exp Neuropsychol 1998;20:885–97.

Ridderinkhof KR, Van der Stelt O. Attention and selection in the growing child: views derived from developmental psychology. Biol Psychol 2000;54:55–106.

Rothenberger A, Banaschewski T, Heinrich H, Moll GH, Schmidt MH, van't Klooster B. Comorbidity in ADHD-children: effects of coexisting conduct disorder or tic disorder on event-related brain potentials in an auditory selective-attention task. Eur Arch Psychiatry Clin Neurosci 2000;250:101–10.

Sergeant J. The cognitive-energetic model: an empirical approach to attention-deficit hyperactivity disorder. Neurosci Biobehav Rev 2000;24:7–12.

Satterfield JH, Schell AM, Nicholas TW, Satterfield BT, Freese TE. Ontogeny of selective attention effects on event related potentials in attention-deficit hyperactivity disorder and normal boys. Biol Psychiatry 1990;28:879–903.

Tonnquist-Uhlen I. Topography of auditory evoked cortical potentials in children with severe language impairment. Scand Audiol Suppl 1996;44:1–40.

Tonnquist-Uhlen I, Ponton C, Eggermont JJ, Kwong B, Don M. Maturation of human central auditory system activity: the T-complex. Clin Neurophysiol 2003;114:685–701.

Van der Stelt O, van der Molen M, Gunning WB, Kok A. Neuroelectrical signs of selective attention to color in boys with attention-deficit hyperactivity disorder. Brain Res Cogn Brain Res 2001;12:245–64.

Van Mourik R, Oosterlaan J, Heslenfeld DJ, Konig CE, Sergeant JA. When distraction is not distracting: A behavioral and ERP study on distraction in ADHD. Clin Neurophysiol 2007;118:1855–65.

Zambelli AJ, Stamm JS, Maitinsky S, Loiselle DL. Auditory evoked potentials and selective attention in formerly hyperactive adolescent boys. Am J Psychiatry 1977;134:742–7.