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Automatic Processing of Duration in Children with Attention-Deficit/Hyperactivity Disorder

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Abstract

Individuals with attention-deficit/hyperactivity disorder (ADHD) often exhibit deficits in processing information about time. Most studies, however, have required participants to perform active tasks and consequently it is unclear if performance deficits are due to impaired processing of temporal information, attentional deficits, or to impairments at a later stage of decision-making. This study used mismatch negativity (MMN) to examine automatic processing of temporal information in children with ADHD. The sample consisted of 11 children with typical development (8 boys; mean age/*SD* = 9.3/0.6 years) and 12 with ADHD (10 boys; mean age/*SD* = 8.9/0.8 years). Using the MMN paradigm, responses to standards and four deviants (hard/easy frequency, hard/easy duration) were elicited during the same sequence. The children's ability to actively discriminate each deviant was also assessed. Both groups exhibited MMNs to all deviants suggesting successful automatic discrimination. Furthermore, amplitude and latency measures were roughly comparable across groups. No group differences were seen on the active discrimination task, but performance was worse for duration than for frequency deviants. These results suggest that children with ADHD are able to automatically process temporal information, so deficits reported in active discrimination paradigms are likely due to deficits in subjective perception or usage of temporal information. (*JINS*, 2013, *19*, 686–694)

Keywords: ADHD, Temporal discrimination, Automatic processing, MMN, Mismatch negativity, ERP

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 (APA, 2000). Children with ADHD generally have difficulties allocating their attention efficiently and are often more vulnerable to distraction. One explanation for some of these deficits is that early processing of information, which generally occurs automatically and outside of our conscious awareness, is impaired in ADHD resulting in difficulties with attention allocation and modulation of distracting information. Inefficient processing of temporal information, a critical auditory processing skill (ASHA, 2005), suggests itself as a possible candidate as (1) individuals with ADHD often exhibit deficits in processing information about time (Barkley, 2006); (2) brain areas shown to be active during duration discrimination tasks (Rao, Mayer, & Harrington, 2001), specifically the basal ganglia, have been identified as being dysfunctional in individuals with ADHD (Durston, van Belle, & de Zeeuw, 2011; Halperin & Schulz, 2006); (3) studies in individuals with cerebellar damage, another brain area implicated in ADHD (Castellanos et al., 2002), show deficits in temporal perception (Mangels, Ivry, & Shimizu, 1998); and (4) manipulations of synaptic availability of dopamine, a neurotransmitter implicated in ADHD, can alter performance on time tasks (Coull, Cheng, & Meck, 2011; Rammsayer, 1999). Notably, some recent studies have led investigators to propose discrimination of brief intervals as a possible endophenotype of ADHD (Himpel et al., 2009; Huang et al., 2012).

Deficits on tasks requiring temporal processing of information have been frequently found in individuals with ADHD (for a review see Toplak, Dockstader, & Tannock, 2006). A variety of behavioral tasks have been used to investigate temporal processing, including discrimination, estimation, production, reproduction, and anticipation. In general, studies using these tasks have found that individuals with ADHD make larger timing errors and that their errors increase with longer durations (Plummer & Humphrey, 2009). This second finding

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of poorer performance at longer durations has been interpreted as reflecting weaknesses in working memory and sustained attention in addition to or instead of deficits in "pure" temporal processing (Toplak et al., 2006). In addition to working memory, sustained attention and temporal processing, these tasks also require decision making, memory, and behavioral output (i.e., verbal labeling or motor responding) all of which could contribute to performance deficits in individuals with ADHD. Duration discrimination tasks are somewhat less confounded by other functions, but continue to require working memory, attention, and active decision making and have been criticized as being a less reliable and accurate measure of time perception due to their forced choice nature (Plummer & Humphreys, 2009). Most studies using discrimination have found that individuals with ADHD are generally less accurate and exhibit larger duration discrimination thresholds for both brief (i.e., less than 1 s) and longer intervals (i.e., up to 5 s; Gooch, Snowling, & Hulme, 2011; Himpel et al., 2009; Huang et al., 2012; Toplak et al., 2006).

Although behavioral measures suggest deficits at some stage of temporal processing in individuals with ADHD, the accuracy of "pure" temporal perception has not been directly addressed as most prior studies have required active responding. An event related electrophysiological measure (i.e., event related potentials or ERPs) of automatic processing, the mismatch negativity (MMN), allows for the assessment of discriminative processes without requiring active responding or focused attention (for review, see Näätänen, Paavilainen, Rinne, & Alho, 2007). In fact, in most MMN studies participants are engaged in some other activity and are told to ignore the stimuli. MMN reflects an automatic neuronal response to a change in auditory input and is traditionally elicited by a deviant auditory stimulus in a train of repetitive, homogeneous stimuli (termed standards). A comparison of the waveforms elicited by the standard and deviant stimuli reveals a potential that is larger for the deviant stimuli, and is negative at the midline and often positive at the mastoids when the nose is used as the reference. It is argued that the central auditory system forms and stores a representation of the standard stimulus which lasts for a few seconds. Each new stimulus is compared to this model or to a prediction based on this model and a MMN is elicited if the auditory system detects a difference (Grimm and Schröger, 2007). The accuracy of the neural representation of the standard stimulus or the prediction based on that model, as well as the neural representation of the current sensory input are hypothesized to impact the stability of the MMN.

MMNs have been elicited by changes in duration, as well as a variety of other auditory features and by changes in auditory patterns in adults and children (for a review, see Näätänen et al., 2007). However, at least in adults, MMNs are generally elicited only by differences that the participant can also behaviorally discriminate (e.g., Kraus et al., 1995; Näätänen, Schröger, Karakas, Tervaniemi, & Paavilainen, 1993) and the amplitude and the latency of MMNs are usually related to the size of the deviance with easier to discriminate stimuli eliciting larger, earlier MMNs (Näätänen et al., 2007). The main sources for MMN have been located bilaterally in the supratemporal plane of the auditory cortex with distinct neural networks responsible for generating MMNs elicited by different acoustic features (Näätänen et al., 2007). The vertical orientation of these sources in the supratemporal plane results in the MMN being largest in the fronto-central region, very small across the sides of the head and inverted in polarity at the mastoids. Frontal- and parietal-lobe contributions have also been identified. Furthermore, cerebellar activation has been reported in paradigms with duration deviants (Schall, Johnson, Tood, Ward, & Michie, 2003), and patients with cerebellar degeneration exhibit delayed MMNs to duration deviants (Moberget et al., 2008).

Among individuals with ADHD, MMNs have been elicited by speech and frequency deviants, although the amplitude and latency effects relative to controls have been inconsistent (Barry, Johnstone, & Clarke, 2003; Kemner et al., 1996; Oades, Dittmann-Balcar, Schepker, Eggers, & Zerbin, 1996; Rothenberger et al., 2000; Sawada et al., 2010; Winsberg, Javitt, & Shanahan-Silipo, 1997). Only one study, that of Huttunen, Halonen, Kaartinen, and Lyytinen (2007), has examined duration MMNs in individuals with ADHD. In this study, clear MMNs were elicited from children with ADHD by two duration deviants and there were no statistical differences in MMN peak latency or amplitude between the children with ADHD and controls. A reanalysis of the same data separating children with both ADHD and a reading disability found earlier frontal MMN peak latencies in children with ADHD alone to the easier duration deviants as compared to typically developing children (Huttunen-Scott, Kaartinen, Tolvanen, & Lyytinen, 2008). However, the deviant durations used in this study were brief (30 and 50 ms) and consequently may have been perceived as different from the standards in both duration and intensity due to temporal integration (Cowan, 1984).

This study evaluated duration discrimination for small and large changes in duration in children with typical development (TD) and in children with ADHD using MMN. Based on the behavioral literature, we hypothesized that the small, harder to discriminate duration change would elicit larger and earlier MMNs from children with TD relative to those with ADHD. In contrast, we expected the large change in duration to elicit MMNs of similar amplitude and latency from both groups in that such a difference would be clearly evident to all children. Small and large frequency deviants were also presented as a control condition.

METHOD

Participants

Ten children with TD and 12 with ADHD were recruited *via* letters sent to participants in an ongoing longitudinal study of children identified as TD or at risk for ADHD when they were 3 to 4 years old (see Healey, Miller, Castelli, Marks, & Halperin, 2008, for a description of the recruitment strategy, exclusion criteria, and sample characteristics of the longitudinal study). Data from three additional children were excluded for various reasons (one took stimulant medication on the testing day and two failed to meet criteria for the TD group). One additional TD child was recruited from outside of the project. To be eligible for this study, children had to be between the ages of 7–10 years.

Children were accepted into the ADHD group for this study only if they currently met criteria for a diagnosis of ADHD based upon parent and teacher ratings using the ADHD-RS-IV (DuPaul, Power, Anastopoulos, & Reid, 1998) and an interview with the parent using the Kiddie-SADS-PL (K-SADS; Kaufman et al., 1997). Eight children met criteria for ADHD-Combined Type and four for ADHD-Inattentive Type. Eight children with ADHD also met criteria for one or more comorbid diagnosis (five with a disruptive behavior disorder, two with nocturnal enuresis, three with an anxiety/mood disorder, two with phobias, and one with a tic disorder). Six of the children with ADHD were being treated with stimulant medication and were asked not to take it on the day of the experiment. One child took asthma medication on the day of the study, and another took clonidine the night before.

Children in the TD group were in the age appropriate grade in school with no history of special education services and were required to have fewer than four of the nine Diagnostic and Statistical Manual of Mental Disorders, Fourth Revision (DSM-IV) symptoms for ADHD in both the Inattentive and Hyperactive/Impulsive domains on the rating scale and interview measures. Three of the TD children met criteria for one or more psychiatric diagnosis other than ADHD; two for nocturnal enuresis and two for phobias. All children also had to pass a bilateral hearing screen on the day of testing to be eligible to participate.

As shown in Table 1, the groups did not differ in age, gender, or socioeconomic status (SES). The sample was racially and ethnically diverse, with 14 Caucasians (61%), 3 Asians (13%), and 6 of mixed ancestry (26%); 8 (35%) children had at least one parent of Hispanic descent. The sample was predominantly of middle class SES (Nakao & Treas, 1994), although a wide range was represented. Significantly more inattentive and hyperactive/impulsive symptoms were endorsed by parents on the K-SADS for the children with ADHD than TD. The groups did not differ on most academic skills assessed by the Wechsler Individual Achievement Test, Third Edition (WIAT) at the most recent annual reevaluation for the longitudinal study; however, reading comprehension was stronger for children with TD than ADHD. It should be noted that children in the current study did not differ in SES, overall intelligence, gender or ethnicity from those in the longitudinal sample and that children with ADHD in the current study did not differ from those with ADHD in the longitudinal study at the 8-year-old evaluation in scores on WIAT reading subtests, K-SADS, parent and teacher ADHD-RS-IV ratings, or on the measures mentioned above.

Before testing, all children agreed to participate following an assent process and parents signed informed consent forms. The protocol for the study was reviewed and approved by the Queens College/CUNY Institutional Review Board. Parents were compensated $50 for their time and expenses, and children were given a book.

Stimuli

Five types of stimuli were presented to each participant, one standard [1000 Hz, 250 ms duration], two duration deviants [1000 Hz tones, 450 ms (easy) and 350 ms (hard)] and two frequency deviants [250 ms tones, 1400 Hz (easy) and 1200 Hz (hard)]. Stimulus durations were chosen to be longer than 200 ms as up to approximately 200 ms, longer stimuli of equal physical intensity are judged to be louder due to temporal integration (Cowan, 1984). All tones were created with 25 ms rise/fall times and were presented binaurally through insert earphones at 75 dB SPL. Stimulus order was pseudo-randomized with standards occurring 60% of the time and each deviant occurring 10% of the time with the restriction that deviants of the same type had to be separated by at least two stimuli of different types. Stimulus onset asynchrony (SOA) was 800 ms, except for during the response condition (see below) when it was 1600 ms to allow the children time to respond.

Table 1. Demographic, rating, and standardized test data for children with ADHD and TD

	ADHD	TD	T	P
Number	12 (2 females)	11 (3 females)		
Age	8.9 y (0.8 y)	9.3 y (0.6 y)	1.29	.21
SES	58 (15.0)	70 (17.6)[1]	1.73	.10
K-SADS: no. of DSM Inattentive symptoms	7.4 (1.2)	0.1 (0.3)[1]	18.1	<.0005
K-SADS: no. of DSM Impulsive/Hyperactive symptoms	5.6 (2.2)	0.5 (1.0)[1]	6.8	<.0005
WIAT – Word Reading	116 (10.1)	120 (7.6)[1]	1.06	.30
WIAT – Reading Comprehension	108 (9.5)[1]	117 (7.5)[1]	2.31	.03
WIAT – Pseudoword Decoding	113 (9.8)	117 (7.9)[1]	1.14	.27
WIAT – Spelling	115 (13.9)	121 (15.1)[1]	0.92	.37

[1] Data missing from 1 child.

ADHD = attention-deficit/hyperactivity disorder; TD = typically developing; SES = socioeconomic status; K-SADS = Kiddie-SADS-PL; DSM = Diagnostic and Statistical Manual of Mental Disorders; WIAT = Wechsler Individual Achievement Test, Third Edition.

Procedure

Ten experimental runs were presented, each lasting approximately five minutes and containing 310 stimuli for a total of 300 possible deviants of each type. During these runs children were given a hand held video game to play. In a final run, children were instructed to respond to all deviants *via* a single button press. During this brief discrimination task, each of the deviants was presented 15 times and the standard was presented 100 times.

An adult sat with each child during the experiment to minimize movement. Breaks were given as needed and total experiment time was approximately 3 hr.

Electrode Placement and Recording Techniques

The electroencephalogram (EEG) was recorded from 32 Ag/AgCl electrodes mounted in an elastic cap with the amplifier bandpass set to 0.1–70 Hz and a sampling rate of 500 Hz. 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 (LM) and right (RM) mastoids. The vertical electrooculogram was recorded from electrodes placed above and below the left eye and the horizontal electrooculogram *via* electrodes attached to the outer canthi. All sites were referenced to an electrode placed on the tip of the nose. Impedances were kept below 10 kΩ.

Individual participant EEG data were sorted into 700-ms epochs (including a prestimulus interval of 100 ms) as a function of stimulus conditions. Each epoch was baseline corrected across the entire sweep before artifact rejecting and averaging. Artifact reject levels were set at ± 100 μV to exclude blinks and movement artifacts. The averages for each condition were rebaselined to the average amplitude of the prestimulus portion of the epoch. Grand mean averages for each group and stimulus-type were obtained for purposes of display and examination of topographic distributions. Grand mean difference waveforms were obtained by subtracting the waveforms elicited by the standards from those elicited by the deviants. ERP recording and analysis procedures used here have been used before with children by the authors (e.g., Dunn, Gomes, & Gravel, 2008; Molholm, Gomes, & Ritter, 2001) and are consistent with those used in the field (for review see Luck, 2005).

RESULTS

Behavioral Data

Behavioral data were only obtained during the final run. The number of hits for each deviant type and the number of false alarms (FA) to the standards were calculated for each child. As can be seen in Table 2, the children had substantial difficulty identifying the deviants, particularly the duration deviants, a pattern confirmed by the main effect of deviant feature ($F(1,20) = 72.9$; $p < .0005$; $\eta_p^2 = .78$) in a three-way analysis of variance (ANOVA) comparing hits across group, deviant feature (frequency, duration), and discriminability (easy, hard). There was also a main effect of discriminability ($F(1,20) = 25.4$; $p < .0005$; $\eta_p^2 = .56$) reflecting the better identification of the easy-to-discriminate deviants than the hard. However, there was no significant main effect of group or interaction including group. In contrast to the poor identification of targets, the children made few FA but again no significant group differences were found.

Table 2. Percent hits for deviants and number of false alarms for standards

	ADHD	TD[1]	Partial eta squared
Duration – Easy	21.7 (25.4)	30.0 (18.7)	.036
Duration – Hard	11.7 (16.4)	15.3 (13.4)	.016
Frequency – Easy	66.7 (20.1)	66.7 (16.6)	.000
Frequency – Hard	61.1 (20.0)	57.3 (17.8)	.011
Standards – FA	6.1 (8.8)	1.9 (2.7)	.095

Note. Standard deviations are in parentheses.
[1] Data missing from 1 child.
ADHD = attention-deficit/hyperactivity disorder; TD = typically developing.

Electrophysiological Data

Figure 1 displays the grand mean waveforms elicited by the standard tones at selected recording sites from children with ADHD and TD. Midline waveforms are characterized by a P1 peaking at approximately 90 ms, a prominent negativity peaking at approximately 250 ms, and a positive going wave peaking at approximately 340 ms. This wave configuration is

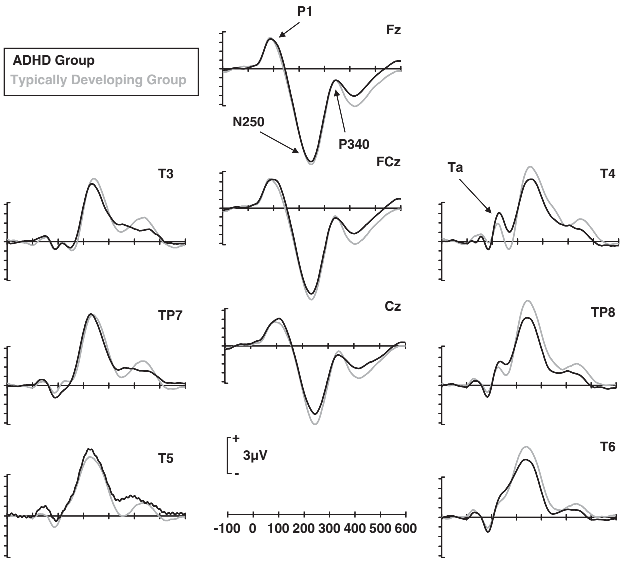

Fig. 1. Grand mean waveforms elicited by standard tones from children with ADHD (black line) and TD (gray line). In this and all figures, time line is −100 to 600 ms, stimuli were presented at time zero, positive is up, and waveforms were smoothed for display.

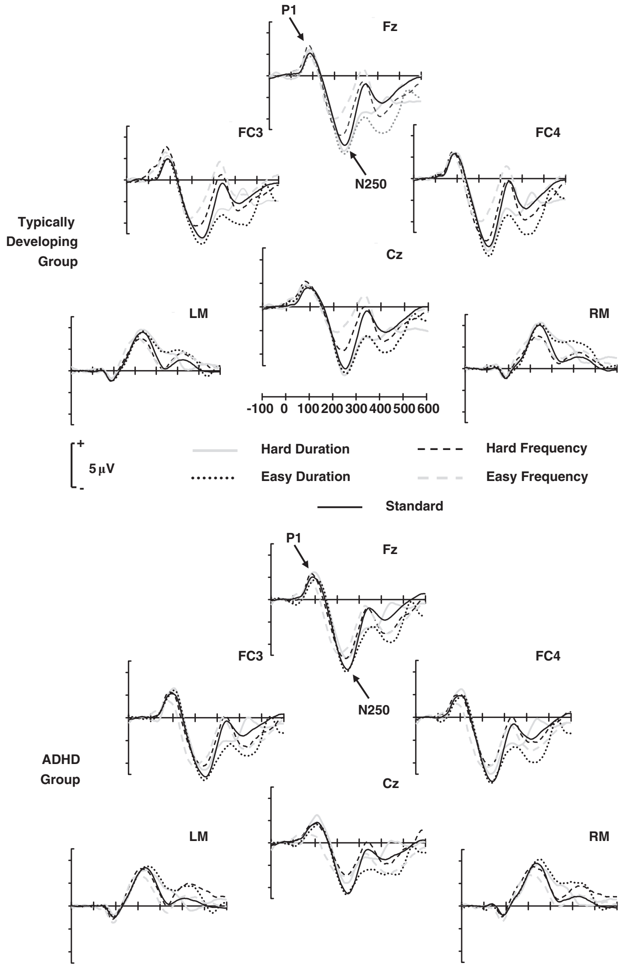

Fig. 2. Unsubtracted grand mean waveforms to standards, hard- and easy-to-discriminate frequency and duration deviants elicited from children with ADHD and TD.

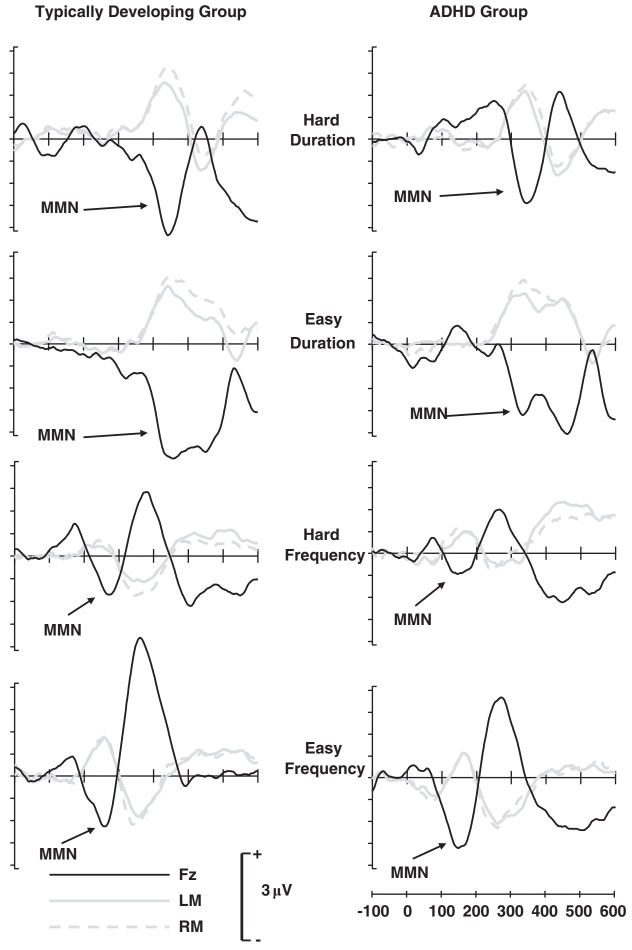

Fig. 3. Grand mean MMN (deviant minus standard) waveforms for children with ADHD and TD to hard- and easy-to-discriminate frequency and duration tones. Fz (black line) and right and left mastoids (gray lines) show the MMN polarity reversal.

consistent with other developmental studies that have used relatively short SOAs (Čeponienė, Cheour, & Näätänen, 1998; Gomes et al., 1999).

MMN is identified as the separation between the waveforms elicited by the standards and the deviants occurring approximately 100 ms after the onset of deviance. For the frequency deviants, which are detectable near the onset of the sound, the separation begins near the peak of the P1 and is larger for the more easily discriminable tone. For the duration deviants the separation begins after the standard would have stopped, on the up-slope of the N250 (see Figure 2). Consistent with the literature, MMN is largest in the fronto-central region, very small across the sides of the head and inverted in polarity at the mastoids, as can be seen in the difference waves in Figure 3. It appears that the easy duration deviants might elicit two MMNs; one peaking at approximately 340 ms associated with standard and one at 450 ms associated with the difficult to discriminate duration deviant.

Analysis of the MMN amplitude data occurred in two stages. First, it was established that the amplitude of the waveform elicited by the deviants was significantly different from the amplitude of the waveform elicited by the standards in the deviant specific MMN latency windows (TD: $F(1,10) = 18.70$; $p < .005$; $\eta_p^2 = .65$; ADHD: $F(1,11) = 6.25.4$; $p < .05$; $\eta_p^2 = .36$). These analyses were calculated using separate four-way ANOVAs for each group with factors of stimulus type (standard, deviant), deviant feature (frequency, duration), discriminability (easy, hard), and electrode (Fz, Cz, FC3, FC4, LM, RM). These electrode sites were chosen *a priori* based on the literature to reflect the maximal MMN activity in the fronto-central region (Fz, Cz, FC3, FC4) and the MMN inversion at the left and right mastoids (LM, RM). Greenhouse-Geisser corrections were used when appropriate. The windows chosen for average MMN amplitude measurements were the 50 ms surrounding the MMN peak latency at Fz in the group grand mean difference waveforms. Grand mean peak latencies for the children with TD and ADHD, respectively, were as follows: easy frequency—166 and 150 ms, hard frequency 168 and 148 ms, easy duration—336 and 334 ms, and hard duration 350 and 344 ms. Because the time windows differed for each of the deviants, separate average amplitude measures were

Table 3. Mean amplitudes in μV of the MMNs in the duration and frequency conditions by group and electrode

	ADHD	ADHD	TD	TD
	Easy	Hard	Easy	Hard
Duration				
Fz	−2.40 (1.86)*	−2.22 (2.50)*	−3.74 (2.70)*	−3.23 (1.34)*
LM	1.75 (1.82)*	1.51 (1.34)*	1.89 (2.22)*	1.80 (1.53)*
RM	2.16 (3.10)*	1.80 (2.39)*	2.17 (1.92)*	2.43 (1.63)*
Frequency				
Fz	−2.42 (2.41)*	−0.75 (2.72)	−1.56 (2.40)*	−1.24 (1.92)*
LM	0.67 (1.03)*	0.56 (1.38)	1.13 (1.36)*	0.20 (1.24)
RM	0.67 (1.20)*	0.82 (1.25)*	1.24 (1.39)*	0.41 (1.25)

Note. Standard deviations are in parentheses.
*$p < .05$, deviant amplitude versus standard.
MMN = mismatch negativity; ADHD = attention-deficit/hyperactivity disorder; TD = typically developing; LM = left mastoid; RM = right mastoid.

taken from the standard waveform for each of the deviants. This is necessary so that for each deviant the difference between the waveform elicited by the deviant and the standard in that particular time window can be compared. To explore the consistency of these findings, the MMN amplitudes were compared using planned *t* tests (see Table 3). The MMN was significant across electrode sites for the duration and easy frequency deviants but not for the hard frequency deviants.

Second, the MMN amplitudes were compared across groups using an omnibus four-factor ANOVA (deviant feature, discriminability, electrode, and group). In addition, because potential group differences might be small, a measure of the MMN amplitude between Fz and the mastoids (Fz − [LM + RM]/2; "total MMN") was also examined. This is comparable to using linked mastoids as the reference, instead of the nose (Tervaniemi, Ilvonen, Karma, Alho, & Näätänen, 1997). The only significant main effect or interaction of the omnibus analysis included the factor of electrode, partially reflecting the reversal in polarity between the fronto-central electrodes and the mastoids. However, there were trends toward main effects of deviant feature and discriminability which became significant when the measure of total MMN amplitude was examined (deviant feature: $F(1,21) = 22.17$, $p < .0005$; $\eta_p^2 = .51$; discriminability: $F(1,21) = 9.68$; $p < .005$; $\eta_p^2 = .31$). These effects reflect the larger MMNs elicited by the duration than frequency deviants and the larger MMNs elicited by the easier to detect than the more challenging deviants (see Table 3 and Figure 3). There was no significant main effect of group or interaction with group in either analysis. Most importantly for our hypothesis is the interaction of group × deviant feature × discriminability: $F(1,21) = .10$, $p = .754$, $\eta_p^2 = .005$, for the total MMN. Although our small sample limited the power of the group comparison, it should be noted that the effect size is quite small.

Average MMN peak latency measures were examined by identifying the latency of the most negative peak in the individual subtraction waveforms at Fz in the 100 ms surrounding the grand mean peak latencies for each condition. Two-way ANOVAs with factors of discriminability and group were conducted separately for the frequency and duration deviants due to the large expected differences in MMN peak latency. MMN average peak latencies did not differ across group or discriminability.

DISCUSSION

This study examined duration discrimination in a well characterized group of children with ADHD. Deficits on behavioral tasks requiring temporal processing are found so frequently in the literature that discrimination of brief durations has been suggested by some as a possible endophenotype of ADHD (Himpel et al., 2009; Huang et al., 2012). Nonetheless, most of these tasks have required a behavioral response, as well as working memory, attention, and decision making. This study used a MMN paradigm to assess automatic duration discrimination of ignored stimuli. It was hypothesized that children with ADHD would exhibit smaller amplitude MMNs with later peak latencies than TD children in response to hard-to-discriminate duration deviants; however, this was not the case. Both groups of children exhibited robust and roughly equivalent MMNs to easy and hard-to-discriminate duration deviants, as well as to frequency deviants. Furthermore, both groups were very poor at identifying the duration deviants, although they were able to identify the frequency deviants. These findings strongly suggest that the behavioral deficits seen on temporal processing tasks in individuals with ADHD are not due to "pure" temporal processing and discrimination but to the subjective perception of duration (Gautier & Droit-Volet, 2002) or the task specific usage of temporal information (Radonovich & Mostofsky, 2004).

Our findings, as well as much of the behavioral literature on temporal processing in individuals with ADHD (Toplak et al., 2006), are consistent with a model of separate but parallel automatic and cognitively mediated neural timing systems for intervals in the millisecond to minute range (Lewis & Miall, 2003). The automatic or perceptual timing system has been proposed to be important for millisecond timing and the duration MMN most likely reflects processing in this system. MMNs are elicited when stimuli are presented at a relatively rapid pace, but not when presentation rate is slowed to approximately 1 stimulus every 10 s (Näätänen et al., 2007). In addition, elicitation of a MMN, although generally correlated with behavior, does not always predict the ability to actively discriminate a deviant (Molholm et al., 2001).

The automatic timing system is thought to involve the motor and premotor frontal circuits, the cerebellum, the basal ganglia (Coull et al., 2011), and perhaps the temporal cortex, especially for auditory stimuli. Timing in this range may be an emergent property of the neural processing of these stimuli and as such may be distributed and modality specific. The cerebellum may be particularly critical to this system. Studies have found that damage to the cerebellum results in impaired temporal processing and MMNs with longer onset latencies (Mangels et al., 1998; Moberget et al., 2008). Models of cerebellum functioning suggest that it may be involved in generating predictions about upcoming stimuli which prepare sensory systems and consequently reduce the needed processing resources (Ito, 2005; Koziol, Budding, & Chidekel, 2012). Recent conceptualizations of the MMN also propose that the MMN system generates a concrete prediction of the upcoming stimulus and that the comparison occurs between the current stimulus and predicted stimulus (Grimm & Schröger, 2007). Our findings of robust, roughly comparable MMNs elicited by difficult to discriminate changes in duration in individuals with ADHD and TD suggest that the automatic/perceptual system is most likely intact in individuals with ADHD.

In contrast, impairment or inefficiency in the second system, the attention-dependent, cognitively controlled timing system may be responsible for the behavioral deficits individuals with ADHD evidence on temporal processing tasks in the literature. This system is proposed to be particularly important for processing longer intervals where attention allocation and management, as well as processes related to memory and active discrimination, can impact processing and decision making. In addition, this system may be involved to some degree in the temporal processing of brief stimuli when tasks require active responding, although the children's extremely poor performance (on average only 2 of 15 correct for the hard duration deviants) in the current study resulted in a floor effect which obscured any group differences. This second timing system is thought to be modality independent and to depend on right prefrontal cortex, supplementary motor areas, the basal ganglia, and perhaps parietal regions (Coull et al., 2011). Although findings related to the basal ganglia have been ambiguous (Rao et al., 2001), some have suggested that the basal ganglia might be important for maintaining temporal information until it is needed for decision making (Coull et al., 2011).

An examination of the results of duration discrimination studies with non-temporal control conditions in individuals with ADHD (Radonovich & Mostofsky, 2004; Toplak, Rucklidge, Hetherington, John, & Tannock, 2003) suggest that general processes associated with comparing stimuli, decision making, and motor responding are unlikely to be responsible for the group differences seen on duration tasks. In contrast, the performance deficits might be due to inefficiencies in processes specific to duration, perhaps those associated with sequentially processing and maintaining in memory representations of temporal intervals or processes which disrupt the maintenance of these memories. Consistent with this suggestion, the accuracy of temporal judgments of longer, supra-second range stimuli have been shown to be influenced by attention allocation and task demands (Droit-Volet, Meck, & Penney, 2007), as well as by task irrelevant information when it is processed instead of ignored (Barkley, Koplowitz, Anderson, & McMurray, 1997). Consequently, performance deficits seen in individuals with ADHD may very well be due to poor allocation, maintenance, and control of attentional resources to both task related stimuli and to irrelevant environmental or internal stimuli, all of which may impact the subjective perception of duration and the efficient usage of temporal information.

Limitations

Although these findings are robust and strongly suggest that "pure" temporal perception and automatic discrimination are intact in school age children with ADHD, our ability to generalize these results is limited in several ways. First, our study used a relatively small sample of children with ADHD which raises concerns about the generalizability of our findings. These concerns are heightened by the facts that the children with ADHD in our sample evidenced strong academic skills, were primarily boys, and performed comparably to the TD children on a brief discrimination task, as well as by the general heterogeneity of ADHD. Although these limitations are real and can only be completely addressed by replicating the findings, these children were drawn from a well characterized prospective longitudinal sample in which their ADHD status is regularly assessed and they do not differ in demographic, intelligence, or academic skills from the children with ADHD in the larger group. Their strong academic skills likely reflect their on average middle class status, as well as perhaps their early identification as at risk for ADHD. The gender differential reflects the higher prevalence of the disorder in boys than in girls and a floor effect on the brief discrimination task impedes demonstrating group differences.

Second, the children in our study were between the ages of 7 and 10. It is possible that smaller, later MMNs to hard-to-discriminate duration deviants would be seen in younger children with ADHD than in their TD peers. MMN elicitation and amplitude, can be enhanced through discrimination training (Näätänen et al., 2007), so it is plausible that there is a point in development at which children with ADHD exhibit deficits in automatic duration discrimination. However, even if that is true, it does not explain why school age children with ADHD continue to exhibit deficits on active temporal judgment tasks. Finally, perhaps the duration discriminations used in this study were too easy and group differences would have been seen if smaller differences between the standard and duration deviants were used. However, this is unlikely as even the TD children had significant difficulty identifying the duration deviants in context.

The small sample size also limited our ability to compare the MMN amplitude between the children with TD and ADHD making it possible that there are small group differences which we can not detect. Nonetheless, the clear MMNs elicited from children with ADHD suggest intact automatic processing. Finally, the briefness of the behavioral task and the difficulty of the duration discriminations must be considered limitations of this study. Because of a floor effect, we were unable to show the expected group difference in active temporal processing or to provide support for the role of an attention-dependent, cognitively controlled timing system in these group differences. The behavioral task could have been made easier by presenting each of the deviants in separate runs, but this would have significantly increased the length of the behavioral task and would not have matched the electrophysiological paradigm.

Summary

Automatic discrimination of brief auditory temporal information, assessed with MMN, was robust in children with ADHD and was roughly comparable in amplitude and latency to children with TD. Consequently behavioral deficits reported in the literature are unlikely to be due to deficits in “pure” temporal processing or discrimination and it is improbable that discrimination of brief intervals is an endophenotype of ADHD. Reported behavioral deficits are likely due to errors in the subjective perception of duration or inefficiencies in the usage of temporal information. Finally, this study also provides further support for a model of separate automatic and cognitively mediated neural timing systems for brief intervals (Lewis & Miall, 2003).

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