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Event-Related Potentials in Individuals with Attention-Deficit/Hyperactivity Disorder Performing the Attention Network Test[*]

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ABSTRACT

The current study investigated the neural basis of attention-deficit/hyperactivity disorder (ADHD) by examining the performance of individuals with ADHD on the Attention Network Test (ANT) by Fan, McCandliss, Sommer, Raz, and Posner (2002) while recording high-density electroencephalography (EEG) and utilizing event-related potential (ERP) methodology. Fifty-seven college students were divided into three groups: ADHD-inattentive subtype (ADHD-IA), ADHD-hyperactive/combined subtype (ADHD-HI), and control. The peak amplitude of the P300 waveform was analyzed for performance on each attention network measured by the ANT: the alerting network, the orienting network, and the executive control network. The peak P3 was significantly different between the control and ADHD-IA groups for the alerting and executive networks, and between the control and ADHD-HI groups for the orienting network. Behaviorally, participants in the control and ADHD-IA groups had faster reaction times than did participants in the ADHD-HI group, but all groups performed at a high level of accuracy.

KEY WORDS Attention; Attention Network Test; ADHD; ADHD Subtypes; Event-Related Potentials

Attention-deficit/hyperactivity disorder (ADHD) is one of the most common mental health problems, present in anywhere between 5% and 10% of the population (CDC 2022; Cortese et al. 2012; Iannaccone et al. 2015). Generally conceived of as having two dimensions—inattention and hyperactivity/impulsivity (Clarke et al. 2001; Johnstone, Barry, and Clarke 2012; Karalunas and Nigg 2019; Burns et al. 2001)—ADHD is divided in the *Diagnostic*

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and Statistical Manual of Mental Disorders, fifth edition (DSM-5) into three subtypes revolving around these dimensions: predominantly inattentive (ADHD-IA), predominantly hyperactive/impulsive (ADHD-HI), and combined inattentive and hyperactive/impulsive (ADHD-C; American Psychiatric Association 2013). The behavioral disturbances exhibited by children with ADHD are known to persist into adolescence and adulthood (Barkley 1998; Callahan and Plamondon 2018; CDC 2022; Kooij et al. 2016; Lazzaro et al. 1997; Luo, Halperin, and Li 2020; Silk et al. 2016; Torgalsbøen, Zeiner, and Øie 2019). Despite many years of research in this area, there are still questions and controversies surrounding ADHD and its treatment (Baeyens, Roeyers, and Walle 2006; Cortese et al. 2012; National Institutes of Health 2000). One current controversy revolves around the future of diagnosing subtypes of ADHD. Scientists have long debated the heterogeneity of ADHD in clinical presentations (Lee, Sibley, and Epstein 2016). Although clinical experience suggests that the subtypes of ADHD are so distinct that they should perhaps be categorized as different disorders, evidence also exists that subtypes do not show diagnostic stability over time (Nigg, Tannock, and Rohde 2010; Simon et al. 2009). One possible explanation for such diagnostic instability is based on long-term and age-related studies that have shown natural changes in attentional efficiency from childhood into adulthood due to neural development (Arias et al. 2016; Abundis-Gutierrez et al. 2014; Lee et al. 2016; Luo et al. 2020; van Dinteren et al. 2014). In concordance with recent neurodevelopmental research, the DSM-5 has introduced diagnostic criteria by which the severity of inattentive and hyperactive/impulsive symptoms are rated along a three-point spectrum: mild, moderate, or severe.

The complex nature of ADHD has been revealed in research because of the variability in behavioral presentations of the disorder. According to a 10-year event-related potential (ERP) review (Johnstone et al. 2012), individuals with ADHD demonstrate consistent performance deficits in experimental settings, including higher-than-average errors of omission and commission (e.g., Defrance et al. 1996; Jonkman et al. 1997; Satterfield, Schell, and Nicholas 1994), as well as hindered performance on tasks of persistence, sustained attention, and planning or organizational skills (Ahmadi et al. 2014; Lee et al. 2016; Miller, Kavcic, and Leslie 1996), during experimental settings; however, although some studies have found that individuals with ADHD had slower reaction times (RTs) than did controls (Jonkman et al. 1999; Liu et al. 2020; Samyn et al. 2014), other studies have found the opposite (Konrad et al. 2006; Perchet et al. 2001). As a result of numerous experiments utilizing a homogeneous ADHD group rather than a heterogeneous (various subtypes) group, research has revealed that these differences could be due to a higher prevalence of one subtype over the others in the heterogeneous samples. For instance, individuals with ADHD-IA typically display slower reaction times in attention-demanding tasks (Baeyens et al. 2006), whereas individuals with ADHD-HI and those with ADHD-C usually display faster reaction times in the same tasks (Rodriguez and Baylis 2007). The inconsistencies in behavioral as well as ERP outcomes have thus been attributed to variations in experimental factors such as task requirements, age groups, and ADHD subtype groups (Johnstone et al. 2012; Kratz et al. 2011; Samyn et al. 2014; Silk et al. 2016).

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This lack of experimental consistency has led researchers to focus on identifying more empirically valid methods for diagnosing ADHD. The current predominant method of ADHD diagnosis has been highly dependent on symptoms reported on questionnaires as well as on external observations (Konrad et al. 2006) rather than on physiological measurements (Karalunas et al. 2014); however, the pathophysiology of ADHD has been increasingly characterized by the dysfunction of neural processes underlying attentional networks (Cortese and Castellanos 2015; Iannaccone et al. 2015; Johnstone et al. 2012). Numerous studies suggest that a combination of neuroimaging techniques in addition to current clinical methods would provide a clearer understanding of the neural processes, allowing for a more objective means by which to diagnose and distinguish between ADHD subtypes (Cortese and Castellanos 2015; Iannaccone et al. 2015). Given the lack of consensus on diagnosing subtypes for ADHD (Kuntsi et al. 2014; Lee et al. 2016), the differential behavioral results in ADHD literature, and the need for further investigation of neural correlates underlying the disorder (Silk et al. 2016), it is crucial that the neural basis of ADHD be investigated with regard to the differences that can be observed in each subtype by implementing attention-demanding tasks along with cognitive neuroscience methods. The present study accomplished this by combining the Attention Network Test (ANT) by Fan, McCandliss, Sommer, Raz, and Posner (2002) with ERP methodology. Differences among the subtypes were analyzed based on their inattentive or hyperactive/impulsive symptoms listed in the DSM-5, while adhering to an argument made by Milich, Balentine, and Lynam (2001) and Riley and colleagues (2008) that ADHD-HI and ADHD-C are the same in adulthood. Alternatively, most research has focused on the differences between the ADHD-IA and ADHD-C subtypes, given the low rates of ADHD-HI diagnoses in children (Baeyens et al. 2006) and adults (Nikolas and Nigg 2013).

ATTENTION NETWORK TEST AND ADHD

Fan et al. (2002) designed the ANT to examine the independence of the attentional networks proposed by Posner and Petersen (1990). Posner and Petersen developed the hypothesis that the sources of attention form a specific system of anatomical areas. These areas are posited to comprise three networks, which are responsible for alerting, orienting, and executive control. *Alerting* consists of attaining and sustaining a vigilant state and is thought to be associated with the frontal and parietal regions of the right hemisphere (Fan et al. 2002; Markett et al. 2013). *Orienting* refers to the selection of pertinent information from sensory input and has been associated through event-related functional magnetic resonance imaging (fMRI) studies with superior parietal lobe activation (Fan et al. 2002). Finally, *executive* control is defined as resolving conflict among responses (Fan et al. 2002) and “the ability to maintain an appropriate problem-solving set for attainment of a future goal” (Welsh and Pennington 1988:201; Baeyens et al. 2006). The executive control aspect of attention can be studied through tasks that involve conflict among stimuli, such conflict activating the anterior cingulate cortex and the lateral prefrontal cortex (Fan et al. 2002). A follow-up fMRI study by Fan, McCandliss, Flombaum, and Posner (2003) on the attentional networks indicated that the alerting part of the ANT activated frontal-parietal areas along with the thalamus, the orienting aspect of the ANT activated the superior parietal lobes, and the conflict part of the ANT activated the anterior cingulate plus right and left frontal areas. The overall role of each network in attentional processing can be studied by comparing different trial conditions within the ANT paradigm; therefore, the ANT can potentially indicate which attentional network's dysfunction might contribute to the attention disorders in clinical patients, such as ADHD.

Several studies have examined ADHD participant performance on the ANT paradigm. Findings in the literature, including a recent meta-analysis of the literature on this clinical subset, indicate that ADHD participants show deficits in the alerting network measured by the ANT (Arora, Lawrence, and Klein 2020; Booth, Carlson, and Tucker 2007; Johnson et al. 2008; Mullane et al. 2010). Specifically, Mullane and colleagues found deficits in reaction time and accuracy for the alerting task, and Johnson and colleagues demonstrated elevated omission errors for the alerting task. Although neither of these studies observed differences between ADHD participants and controls in the orienting network, they did report decreased performance in the conflict, or executive function, task. Furthermore, Mullane and colleagues examined for but failed to find differences between ADHD subtypes in any of the three attentional networks. Results from Booth and colleagues' study demonstrated subtle differences between ADHD subtypes, such that participants diagnosed with ADHD-IA performed better for the alerting network task on the ANT than did participants diagnosed with ADHD-C. A study by Adólfsdóttir and colleagues (2008) found no differences between ADHD subtypes but did find that, overall, participants with ADHD had lower accuracy than did control participants for the entire ANT and showed larger standard errors on their reaction times than did control participants. The literature examining ANT performance by individuals with ADHD indicates that there are deficits in relation to the alerting network and possibly the executive function network but not the orienting network (Abramov et al. 2019; Arora et al. 2020; Booth et al. 2007; Johnson et al. 2008; Mullane et al. 2010); however, results are mixed regarding differences between ADHD subtypes. It would thus be useful to examine the brain processes underlying observed behavioral results in ADHD participants by recording ERPs during performance on the ANT.

EVENT-RELATED POTENTIALS

ERPs consist of EEG signals averaged over multiple trials and time-locked to stimulus or response production (van Dinteren et al. 2014). They are useful for examining the functional relationship between brain physiology and the cognitive operations underlying behavior (Barceló and Rubia 1998; Falkenstein, Hoormann, and Hohnsbein 1999; Johnstone et al. 2012; Li et al. 2015). ERPs comprise several waveforms, differentiated in terms of their polarity, amplitude, latency, and scalp distribution (van Dinteren et al. 2014). The earlier positive waveforms (P1 and P2) are thought to pertain to processing of the physical attributes of the stimulus. The early negative waveforms (N1 and N2) seem to reflect other aspects of stimulus processing, such as feature analysis.

The later positive waveforms reflect judgmental processes, independent of the physical aspects of the stimuli (Defrance et al. 1996; Sutton, Braren, and Zubin 1965). One such late positivity, termed P3, which occurs approximately 300 ms after stimulus onset (Fabiani,

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Gratton, and Coles 2000; Li et al. 2015; Neuhaus et al. 2010; van Dinteren et al. 2014), is associated with identification processes related to the detection of task-relevant stimuli (Kratz et al. 2011; Mangun and Hillyard 1995; Neuhaus et al. 2010) and the allocation of attentional resources when working memory is engaged (Donchin and Coles 1988; Li et al. 2015; Linden 2005; Neuhaus et al. 2010; Picton 1992). Wright, Geffen, and Geffen (1995) found that validly cued targets increased P3 amplitudes (Abundis-Gutierrez et al. 2014). P3 amplitude is thought to be a reflection of the effortfulness of the stimulus response and the intensity of processing (Neuhaus et al. 2010), whereas P3 latency is taken as a reflection of the speed/efficiency of information processing (Li et al. 2015).

The relation between P3 amplitude and the amount of effort put into a task is counterintuitive, with larger amplitudes observed in less cognitively demanding conditions (such as validly cued targets) and smaller amplitudes observed in more cognitively demanding conditions (such as invalidly cued targets); thus, an increase in mental effort appears to suppress P3 amplitude. One explanation for this could be that, because neural processes in the brain operate on automatic/unconscious levels in reaction to previously learned stimuli involving simpler processes, larger P3 waves are associated with less mental effort because the brain is carrying out these tasks "automatically" in response to the cues, resulting in less need for conscious effort. We see cognitive processes operating in this manner in many other daily tasks involving processing of simple and/or previously learned stimuli and tasks, including proprioception, visual processes, color processing, and the like. If, for example, an individual were to practice the more complex, cognitively demanding conditions, allowing for the brain to learn and familiarize itself with the process, we might see an increase in P3 amplitude on these tasks because the neural system would be responding to previously associated patterns or stimuli. Indeed, previous studies have shown that after practice, subjects can detect contours embedded in complex backgrounds with more ease, and as detection improves with contour length, the responses of neurons in the primary visual cortex (area V1) increase as well (Kandell et al. 2021).

The P3 wave represents a complex summation of interactions between neural systems involving the frontal and parietal lobes during cognitive processes of attention and working memory. Further, cognitive deficits due to mental or neurological diseases result in increases in P3 latency as well as decreases in P3 amplitude (Li et al. 2015). Children with a clinical diagnosis of ADHD have demonstrated reduced frontal and parietal P3 amplitudes to target stimuli in visual and auditory studies, in comparison with typically developing children, dyslexic children, and children diagnosed with autism spectrum disorder (Abramov et al. 2019; Jonkman et al. 1997; Kemner et al. 1996, 1998; Satterfield et al. 1990; Verbaten et al. 1994). van Dinteren and colleagues (2014) suggest that the suppressed P3 amplitude exhibited by individuals with ADHD is due to compensation mechanisms, more easily visible in neuroimaging techniques (Cortese et al. 2012), which recruit neural resources to maintain a steady level of behavioral performance. Results of a Go/NoGo ERP study by Rodriguez and Baylis (2007) revealed that ADHD participants demonstrated smaller P3 amplitudes than did control participants at frontal electrode sites, correlating to the anterior attentional system that includes the anterior cingulate cortex and basal ganglia, the anterior system being involved in executive functions, attentional recruitment, and control of brain areas performing complex cognitive tasks (Posner and Dehaene 1994).

Additionally, a lower P3 amplitude in ADHD participants at posterior parietal electrode sites was observed, indicating that portions of the parietal lobe were involved in covert orienting to visual stimuli. This posterior system is thought to comprise the superior parietal cortex, the pulvinar, and the superior colliculus. It is largely responsible for selecting one stimulus location out of many and for shifting between stimuli (Posner and Dehaene 1994). The differences between the controls and the attention-disordered groups remained consistent across the anterior and posterior attentional systems, indicating that individuals with ADHD demonstrated deficits in the processes involved in both alerting and orienting.

The present study used ERPs from channels surrounding and including Fz and Pz of a high-density EEG sensory net to investigate the electrophysiological differences between controls and ADHD-subtypes in the attention networks as elicited by the ANT. This study hypothesized that individuals with ADHD-IA would show suppressed ERP activity in the alerting network, whereas individuals with ADHD-C/HI would show suppressed ERP activity in the executive network. In accordance with the Rodriguez and Baylis (2007) study, it was hypothesized that reaction time differences would not be significant but that the ADHD subgroups would commit more errors than would controls. No predictions regarding the orienting network were made, as previous studies did not find significant effects in that network (Booth et al. 2007; Johnson et al. 2008; Mullane et al. 2010). It was expected that the present ERP study would follow the patterns of activation in electrodes that correlated with the areas found in the Fan et al. (2003) fMRI study.

METHOD

Participants

A total of 57 adult undergraduate students participated in this study (control group n = 22, ADHD-IA n = 15, and ADHD-C/HI n = 20). There were 24 males and 33 females (ratio of 1:1.38) with normal or corrected-to-normal vision. Their ages ranged from 18 to 34 (M = 21, SD = 3.74). Participants with ADHD were contacted through the university's Office of Disability Services. These students had to provide documentation of their ADHD diagnosis to the experimenter before being able to participate in the study. Students who reported that they were taking medication were asked upon scheduling not to take their medication for 24 to 48 hours prior to participation in this study.

All participants were given the DSM-5 checklist for ADHD symptoms. For the purposes of this study, a distinction was not made between the ADHD-HI and ADHD-C subtypes. This decision was based on the study by Milich and colleagues (2001), which suggested that in adulthood, individuals with ADHD-HI and ADHD-C show little differences in symptoms, whereas individuals with ADHD-IA continue to show differences from the other two groups. This study therefore included three groups: ADHD-IA, ADHD-C/HI (comprising both ADHD-HI and ADHD-C subgroups) and control. Each participant with ADHD was assigned to an ADHD subgroup according to their score on the DSM-5 checklist for ADHD symptoms.

Based on data from a normative pilot study collected from a sample of 1,400 undergraduate students, individuals scoring 11 or above in inattentive symptoms but below 13 in hyperactive/impulsive symptoms were assigned to the ADHD-IA group. Individuals scoring 13 or above on the hyperactive/impulsive symptoms were assigned to the ADHD-C/HI group, regardless of their score on the inattentive symptoms. Participants in the control group scored 6 or below on both inattentive and hyperactive/impulsive symptoms. Control participants were recruited through general psychology courses and completed the DSM-5 checklist for ADHD symptoms prior to participation. Potential control participants who scored above 6 on either scale were not included in this study, to eliminate any similarities in ADHD symptoms to those within the ADHD subgroups. Participants were either awarded a $25 monetary incentive or issued a 0.05% increase in class credit.

Materials

The DSM-5 checklist for ADHD symptoms consists of nine inattentive items and nine hyperactive/impulsive items. All inattentive and hyperactive/impulsive items are on a four-point scale (*not at all* = 0, *just a little* = 1, *pretty much* = 2, *very much* = 3). The inattentive items scale ranges from 0 (no ADHD-IA symptoms endorsed) to 27 (all ADHD-IA symptoms endorsed as *very much*). The hyperactive/impulsive items scale ranges from 0 (no ADHD-HI symptoms endorsed) to 27 (all ADHD-HI symptoms endorsed as *very much*).

All participants also completed a short questionnaire asking if they were taking any medication, when they had last taken said medication (if any), if they had any psychological or neurological disorders, if they had ever been diagnosed with a learning disability, and if they had ever been diagnosed with an attention disorder. Only participants reporting the absence of other psychological or neurological disorders participated in the present study. Participants who had taken medication fewer than 24 hours prior to the testing date were rescheduled.

The ANT (Fan et al. 2002) combines the cued reaction time (Posner 1980) and the flanker task (Eriksen and Eriksen 1974), requiring participants to indicate the direction of a horizontal arrow. Participants pressed the right key on a serial response box with their right thumb when the center arrow pointed right, and they pressed the left key with their left thumb when the center arrow pointed left. Flankers, which were either arrows (congruent or incongruent condition) or dashes (neutral condition), surrounded the target arrow, with two on each side. The target arrow and flankers all appeared in a straight line in the middle of the screen, either above or below a central fixation cross. The four flanker arrows pointed in the same direction, and they may or may not have coincided with the direction of the target arrow, resulting in congruent and incongruent conditions.

Warning asterisk cues did not always appear before target onset, but when they did, they signaled that target onset was upcoming. Warning cue conditions could be of four types: the absence of an asterisk cue (no cue condition); a single cue that replaced the fixation cross (center cue condition); two simultaneous cues, with one above and one below the fixation cross (double cue condition); or a single cue that validly predicted the location, either above or below the fixation cross, of the upcoming target (spatial cue condition). There were a total of 96 trials per block, and 3 blocks per session.

The trials for each cue type condition (no cue, center, double, and spatial) were collapsed regardless of flanker type, yielding 72 trials for each cue type condition. The trials for each flanker type condition (congruent, incongruent, and neutral) were collapsed regardless of cue type condition, yielding 96 trials for each flanker type condition. Participants were seated 73 cm from a 29” color video computer monitor (NEC Multisync XM29) displaying at 1280 horizontal and 1024 vertical pixels. This distance resulted in a visual angle of .55˚ for target arrows.

Fan et al. (2002) explained that the attentional networks are determined by comparing measurements of the behavioral responses influenced by the alerting cues, the spatial cues, and the flankers. For the alerting network, the no-cue condition was compared to the double cue condition (72 no-cue trials vs. 72 double-cue trials). For the orienting network, the center cue condition was compared to the spatial cue condition (72 center cue trials vs. 72 spatial cue trials), and for the executive network, the congruent condition was compared to the incongruent condition (96 congruent trials vs. 96 incongruent trials). Fan et al. found no differences between the congruent and neutral conditions and that either of the two could be compared to the incongruent condition for the executive network.

Procedure

Participants were assigned to one of the three group conditions: ADHD-IA, ADHD-C/HI, or control group, based on their diagnoses and symptoms (or lack thereof). They were then fitted to the electrode cap (described below) and given the instructions for the ANT. They had two minutes of practice followed by three blocks of trials that lasted six minutes each. Participants were allowed to relax and rest their eyes between blocks.

Electrophysiological Data Analysis

Scalp EEG was recorded through a sensor net, part of the Electrical Geodesics Incorporated High-Density EEG system (Tucker 1993; Tucker et al. 1994), with amplifiers capable of collecting 128 channels of EEG data and high-impedance “geodesic electrodes” as transducers for the EEG. The impedance threshold was set at 100 kΩ. An average reference served as the reference for the EEG signal, which was recorded at a sampling rate of 250 Hz (4 ms samples), and the common electrode was located at the nasion. After recording, data were segmented using a 100 ms prestimulus interval and a 600 ms poststimulus onset for correct trials only. Segments were then averaged using Netstation 3 analysis tools (Electrical Geodesics, Inc. 1999) to derive ERPs for each participant. Based on the EGI (Electrical Geodesics, Inc.) guidelines, trials containing more than 10% bad channels were eliminated, as were trials containing an eye blink during the 700 ms segment. The bad-channel algorithm detects bad channels by measuring the difference between fast and slow running averages of channel amplitude. Once these were detected, they were removed from the averaging procedure. Data were then filtered offline from 0.1 to 50 Hz.

ERP analysis consisted of only correct responses (left or right) to the target arrows. The P3 peak amplitude was measured at the frontal electrodes surrounding electrode 11, comparable to Fz on the Jasper 10-20 system (Jasper 1958; Luu and Ferree 2000) for the alerting and executive networks. The P3 peak amplitude was measured at the parietal electrodes surrounding electrode 62, comparable to Pz on the Jasper 10-20 system (Jasper 1958; Luu and Ferree 2000) for the orienting network. The late positive peak amplitude for each participant that occurred during these intervals was identified as the respective P3 used for the amplitude analysis. The latency for that peak was used for the latency analysis. These analyses were conducted using a mixed general linear model (GLM).

Behavioral Data Analysis

The number of correct responses, as well as the reaction times for those responses, was analyzed using mixed GLMs.

RESULTS

ERP Analysis

A mixed GLM consisted of the between-subjects factor group (three levels: control, ADHD-IA, and ADHD-C/HI) and the within-subjects factor condition (six levels: no cue, double cue, center cue, congruent, and incongruent). Where appropriate, follow-up contrasts were performed running a second mixed GLM of Group 2 by Condition 2 where only two groups at a time were compared (control vs. ADHD-IA, control vs. ADHD-C/HI, or ADHD-IA vs. ADHD-C/HI) on each attentional network as indicated by the levels of condition (no cue vs. double cue, center cue vs. spatial cue, or congruent vs. incongruent).

The first mixed GLM revealed no main effect of group, $F(2, 44) = .73$, $p = .49$, partial $\hat{\eta}^2 = .03$, power = .17. Controls, ADHD-IA, and ADHD-C/HI did not differ in their overall ERP activity to the ANT; however, group and condition interacted significantly, $F(10, 44) = 3.08$, $p = .001$, partial $\hat{\eta}^2 = .12$, power = .98. This interaction was explored further by running the second mixed GLM format for all three attentional networks. Each network was determined by comparing two of the six conditions. A significant P3 difference for a comparison—for example, no cue versus double cue—would indicate that target arrows were being processed differently based on the absence or presence of the signal (for the alerting network), the location of one cue (for the orienting network), and the direction of the flanker arrows (for the executive network). The first mixed GLM did not reveal which of the three groups engaged in differential processing for the two conditions compared in each network. The follow-up mixed GLMs provided the answers, with a significant interaction indicating which groups differed and in which networks.

Alerting Network

The alerting network was determined by comparing the no-cue condition to the double-cue condition during the 100–300 ms interval following the target. See Figures 1–3 for the alerting-network ERP waveforms for the control, ADHD-IA, and ADHD-C/HI groups. Results indicated that processing in the alerting network was different between the control and ADHD-IA groups ($F(1, 39) = 5.23$, $p = .03$, partial $\hat{\eta}^2 = .12$, power = .61) but not between the control and ADHD-C/HI groups ($F(1, 34) = .57$, $p = .46$, partial $\hat{\eta}^2 = .02$, power = .11), nor between the ADHD-IA and ADHD-C/HI groups, $F(1, 31) = 1.85$, $p = .18$, partial $\hat{\eta}^2 = .06$, power = .26. Overall, the mean P3 amplitude for the control and ADHD-C/HI groups was lower for the no-cue condition than for the double-cue condition, whereas the P3 amplitude for the ADHD-IA group was virtually the same in both conditions.

Figure 1. Alerting-Network ERP Waveform for the Control Group as Depicted by the No-Cue and Double-Cue Conditions

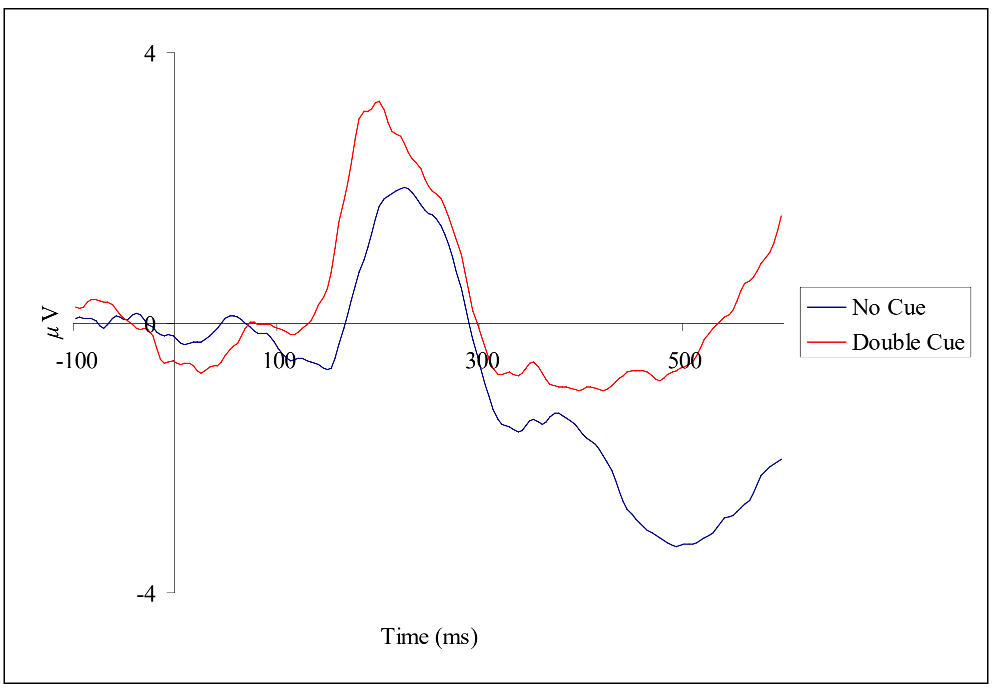

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Figure 2. Alerting-Network ERP Waveform for the ADHD-IA Group as Depicted by the No-Cue and Double-Cue Conditions

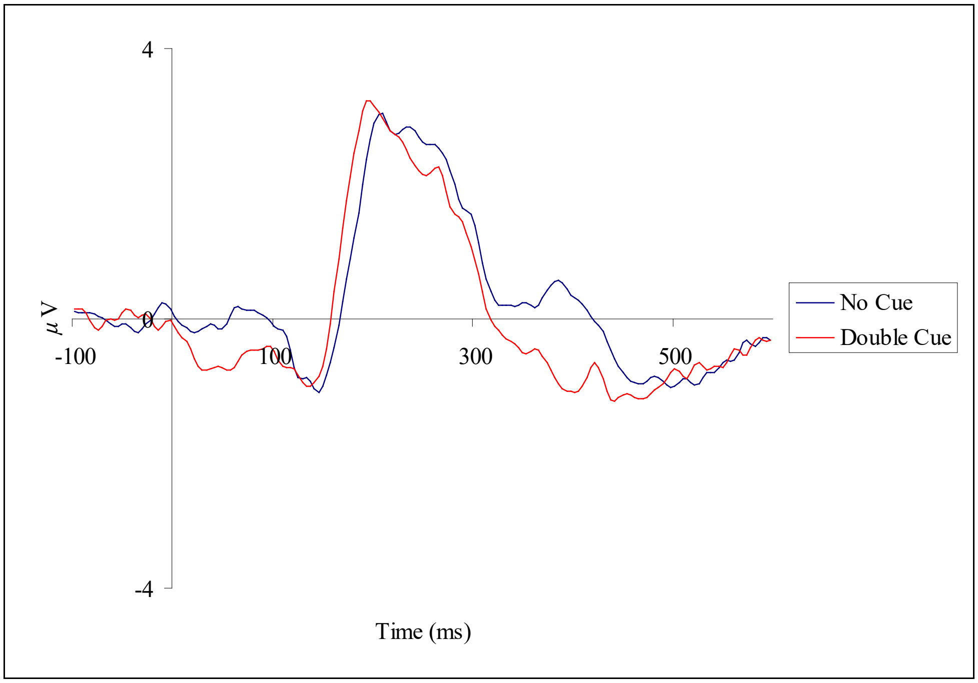
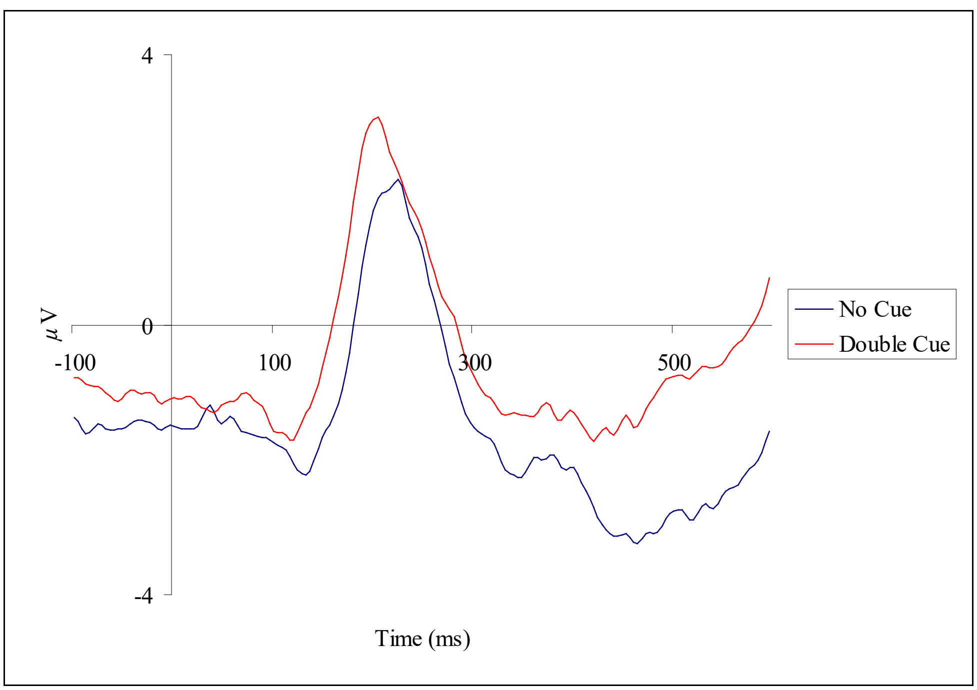


Figure 3. Alerting-Network ERP Waveform for the ADHD-C/HI Group as Depicted by the No-Cue and Double-Cue Conditions



Orienting Network

The orienting network was determined by comparing the center-cue condition to the spatial-cue condition during the 300–500 ms interval following the target. See Figures 4–6 for the orienting-network ERP waveforms for the control, ADHD-IA, and ADHD-C/HI groups. Results reveal that processing in the orienting network was different between the control and ADHD-C/HI groups ($F(1, 35) = 5.52$, $p = .03$, partial $\hat{\eta}^2 = .14$, power = .63) but not between the control and ADHD-IA groups ($F(1, 31) = .57$, $p = .46$, partial $\hat{\eta}^2 = .02$, power = .11) or between the ADHD-IA and ADHD-C/HI groups, $F(1, 30) = 2.37$, $p = .13$, partial $\hat{\eta}^2 = .07$, power = .32. The mean P3 amplitude for the control and ADHD-IA groups was much higher for the center-cue condition than for the spatial-cue condition in relation to the P3 amplitude for ADHD-C/HI, where the P3 amplitude for the center-cue condition was not much higher than for the spatial-cue condition.

Figure 4. Orienting-Network ERP Waveform for the Control Group as Depicted by the Center-Cue and Spatial-Cue Conditions

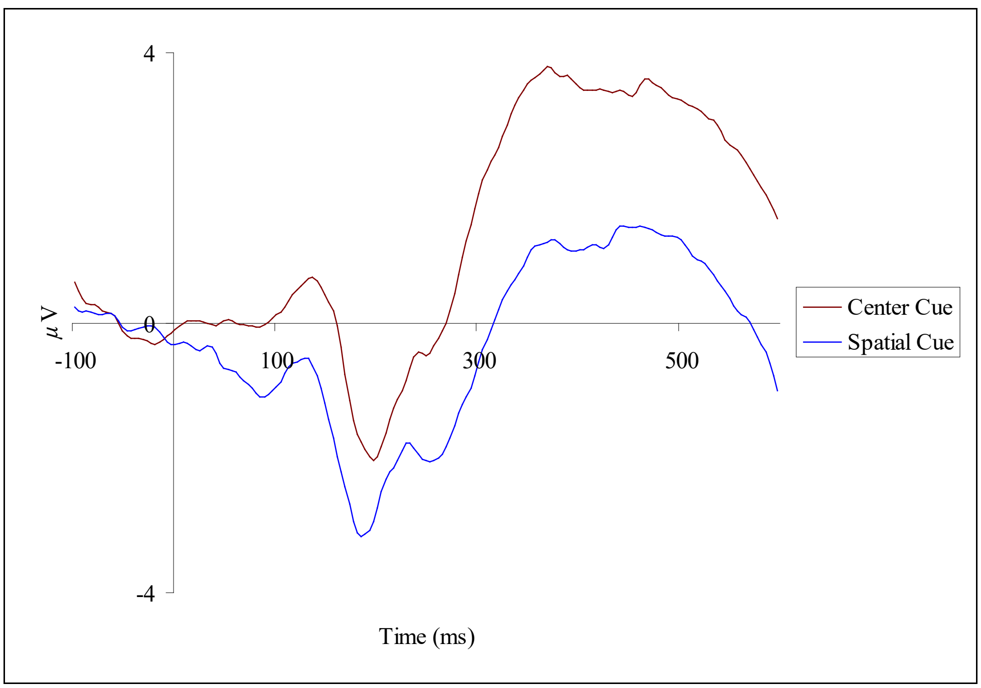


Figure 5. Orienting-Network ERP Waveform for the ADHD-IA Group as Depicted by the Center-Cue and Spatial-Cue Conditions

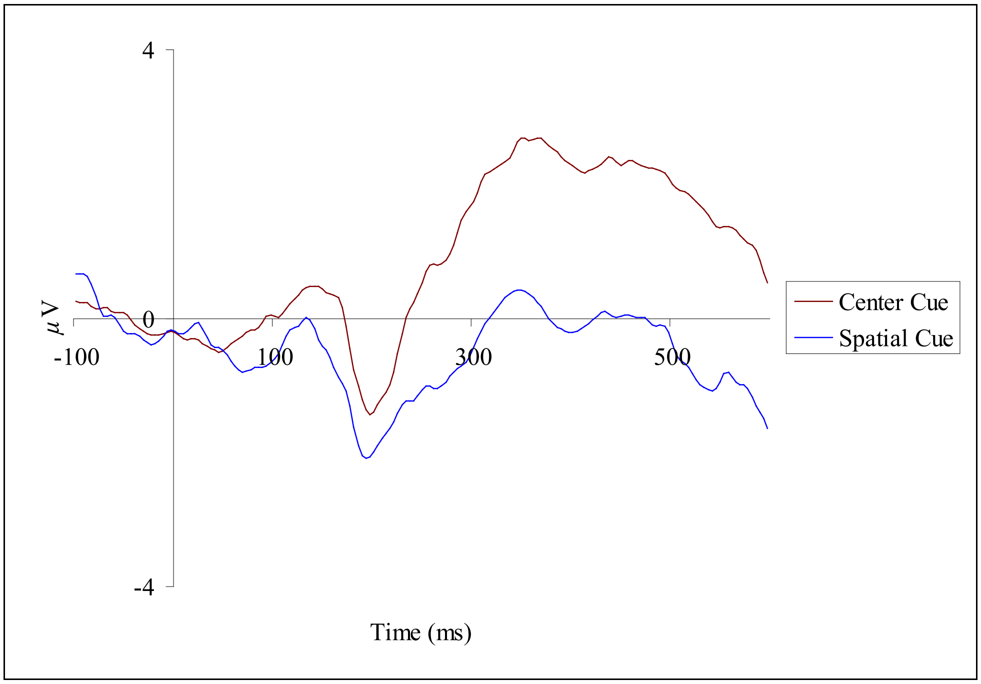
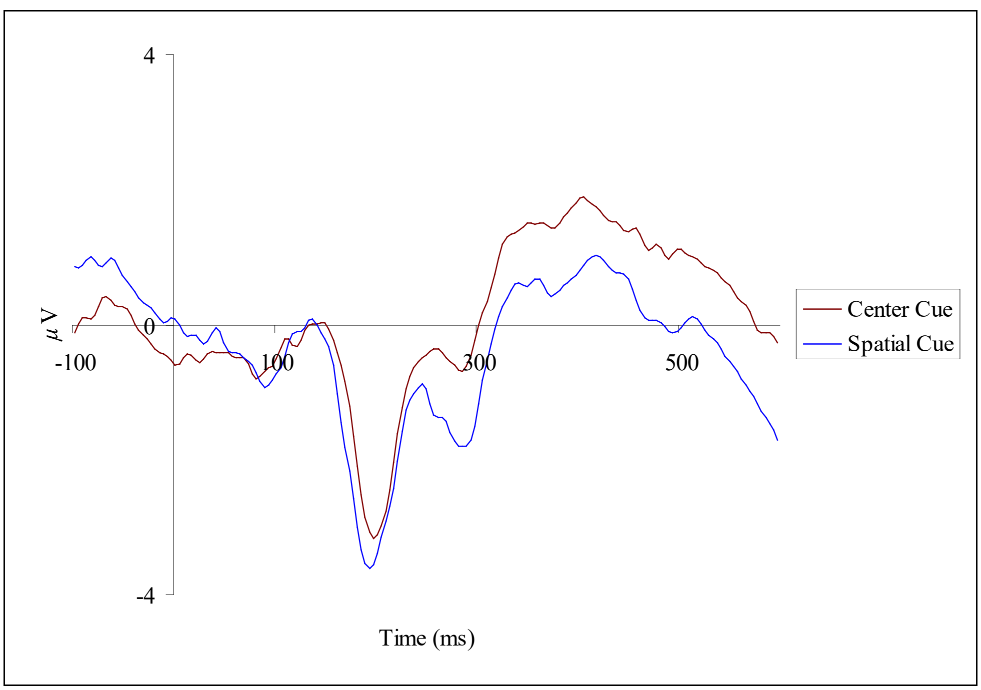


Figure 6. Orienting-Network ERP Waveform for the ADHD-C/HI Group as Depicted by the Center-Cue and Spatial-Cue Conditions



Executive Network

The executive network was determined by comparing the congruent condition to the incongruent condition during the 100–300 ms interval following the target. See Figures 7–9 for the executive-network ERP waveforms for the control, ADHD-IA, and ADHD-C/HI groups. Results indicated that processing in the executive network was different between the control and ADHD-IA groups ($F(1, 30) = 5.29$, $p = .03$, partial $\hat{\eta}^2 = .15$, power = .61) and the difference between the control and ADHD-C/HI groups was marginally significant ($F\ (1, 35) = 3.55$, $p = .07$, partial $\hat{\eta}^2 = .09$, power = .45) but the processing between the ADHD-IA and ADHD-C/HI groups was not significant, $F(1, 31) = .38$, $p = .54$, partial $\hat{\eta}^2 = .01$, power = .09. The overall pattern was for controls to have a higher mean P3 amplitude in the congruent condition than in the incongruent condition, whereas the P3 amplitude for ADHD-IA and ADHD-C/HI groups was virtually equal for both conditions.

Figure 7. Executive-Network ERP Waveform for the Control Group as Depicted by the Congruent and Incongruent Conditions

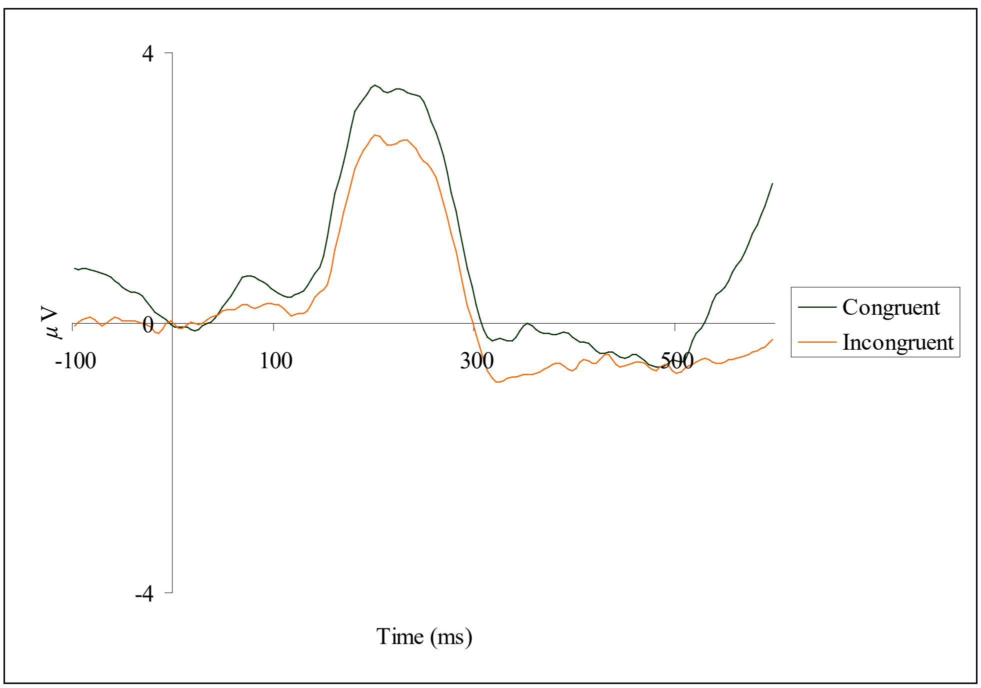


Figure 8. Executive-Network ERP Waveform for the ADHD-IA Group as Depicted by the Congruent and Incongruent Conditions

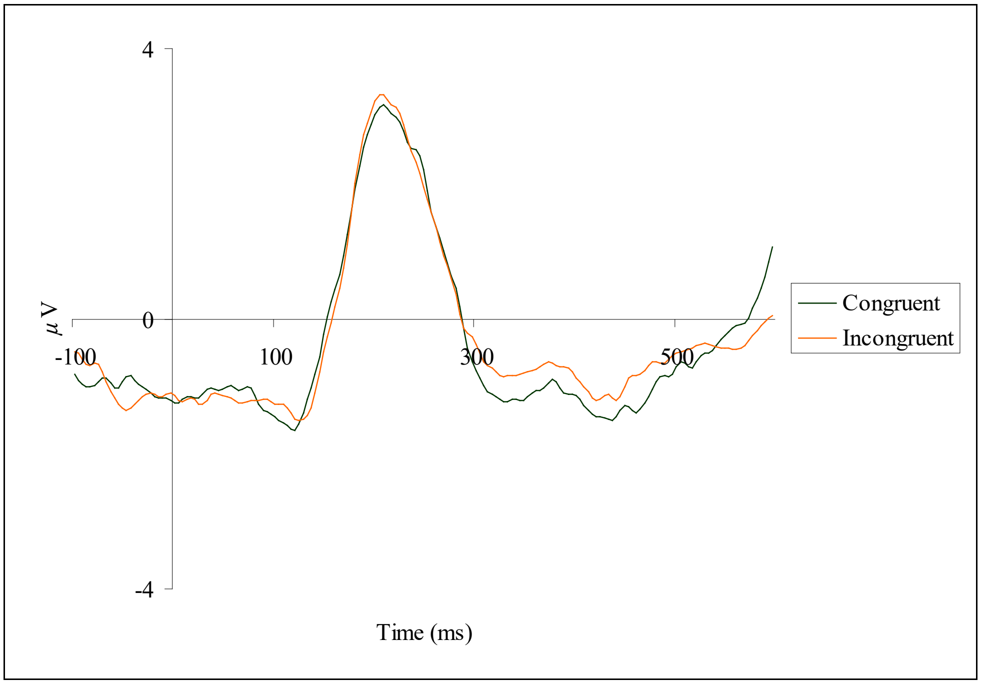
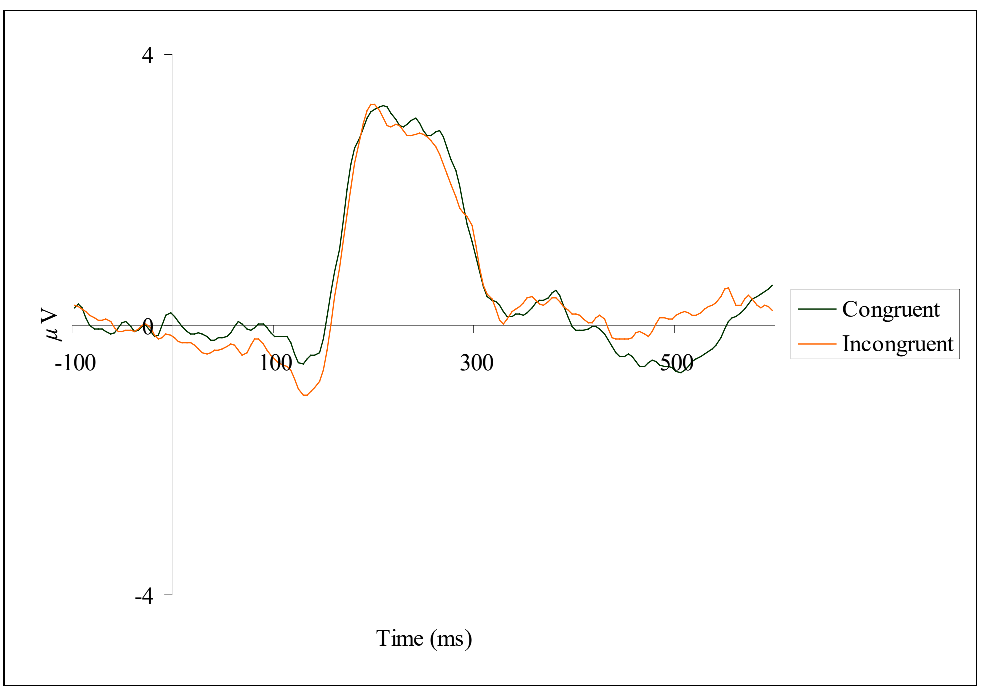


Figure 9. Executive-Network ERP Waveform for the ADHD-HI Group as Depicted by the Congruent and Incongruent Conditions



Latency

There were no latency effects for group or for the interaction between group and condition: $F(2, 44) = .98, p = .38$, partial $\hat{\eta}^2 = .04$, power = .21, and $F(10, 44) = 1.25, p = .26$, partial $\hat{\eta}^2 = .05$, power = .64, respectively. The latency for that peak was used for the latency analysis (see Table 1).

Table 1. Latency Range for P3 Analysis by Network

	Latency Range
Alerting network	100–300 ms
Orienting network	300–500 ms
Executive network	100–300 ms

Behavioral Data Analysis

Reaction times to correct responses were analyzed using a mixed 3 × 4 × 3 GLM, consisting of the between-subjects factor group (3) and two within-subjects factor conditions, cue type (no cue, double cue, center cue, and spatial cue), and flanker type (congruent, incongruent, and neutral). See Table 2 for RT means and standard deviations for each cue type and flanker type. Results indicated a significant effect of group ($F(2, 54) = .12.01, p = .0001$, partial $\hat{\eta}^2 = .31$, power = .99), cue type ($F(3, 162) = 198.25, p = .0001$, partial $\hat{\eta}^2 = .79$, power = 1.00), and flanker type ($F(2, 108) = 319.09, p = .0001$, partial $\hat{\eta}^2 = .86$, power = 1.00) separately. There were no interaction effects; however, the group × cue type × flanker type interaction was marginally significant, $F(12, 324) = 1.68, p = .07$, partial $\hat{\eta}^2 = .06$, power = .86.

Post hoc pairwise comparisons using the Tukey honestly significant difference (HSD) test revealed that the ADHD-C/HI group had slower RTs than did the control and ADHD-IA groups, while the control and ADHD-IA groups did not differ. Linear contrasts indicated that RTs were faster for target arrows preceded by a spatial cue (up or down) than for targets presented without a cue. As for flanker type, responses to targets in the incongruent condition were significantly slower than those in the congruent and neutral conditions. The cue-type and flanker-type findings coincided with Fan and colleagues' 2002 study. The marginally significant interaction effect of group x cue type x flanker type suggests a different RT pattern for ADHD-IA in the incongruent condition. RTs for the control and ADHD-C/HI groups in the incongruent condition were faster when the arrows were preceded by a double cue than when cues were not presented; however, for the ADHD-IA group, in the incongruent condition, the RT differences between no cue and double cue were minimal.

The three groups performed the task at a high level of accuracy and did not differ significantly in error rates, $F(2, 54) = 2.07, p = .14$, partial $\hat{\eta}^2 = .07$, power = .41. As shown in Table 3, the control group responded with 98.71% accuracy (SE = 1.92), the ADHD-IA group responded with 97.75% accuracy (SE = 2.02), and the ADHD-C/HI group with 96.74% accuracy (SE = 2.33).

Table 2. Reaction Times by Group and by Cue Type for Each Flanker Type

Cue Type	Flanker Type	Control ms (SE)	ADHD-IA ms (SE)	ADHD-C/HI ms (SE)
No cue	Congruent	541 (12)	575 (21)	681 (31)
	Incongruent	623 (19)	695 (31)	783 (31)
	Neutral	526 (13)	566 (20)	674 (34)
Double Cue	Congruent	486 (11)	524 (19)	629 (28)
	Incongruent	602 (19)	684 (34)	759 (32)
	Neutral	473 (10)	526 (22)	628 (31)
Center Cue	Congruent	498 (12)	561 (27)	646 (34)
	Incongruent	609 (17)	673 (32)	768 (30)
	Neutral	486 (12)	538 (20)	632 (30)
Spatial Cue	Congruent	453 (12)	511 (22)	591 (28)
	Incongruent	539 (16)	618 (36)	718 (36)
	Neutral	438 (10)	514 (22)	580 (30)

Table 3. Accuracy Rates by ADHD Group Collapsed across All Tasks

	Control	ADHD-IA	ADHD-HI
Percent correct	98.71	97.75	96.74
Standard error	1.92	2.02	2.33

DISCUSSION

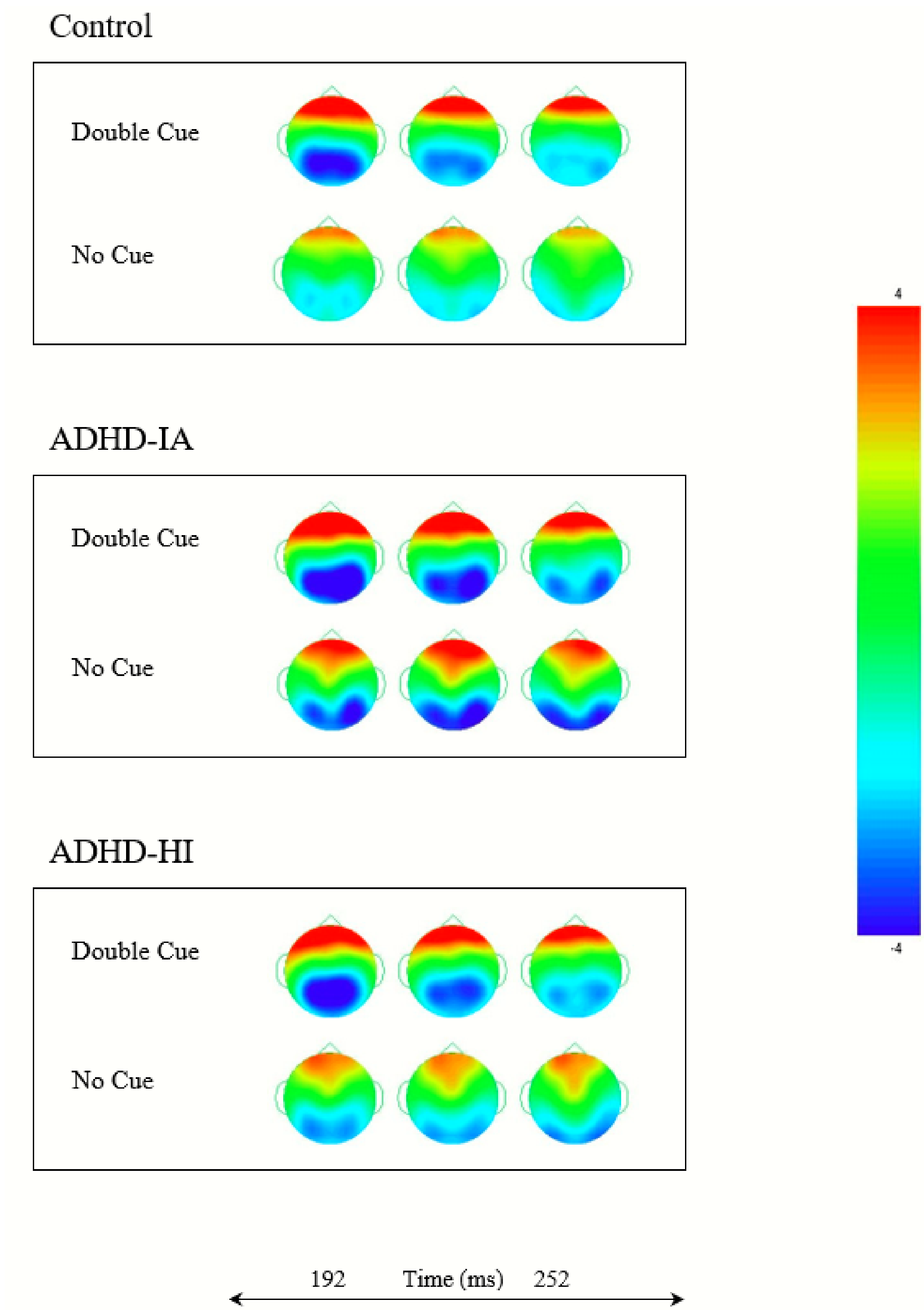
This study examined neurological and behavioral performance differences between the subtypes of ADHD and controls for the three attention networks proposed by Posner and Petersen (1990). The pattern was for controls to consistently elicit larger P3 peak amplitudes for one condition than the other for each attention network. This variation in amplitude of the controls was significantly different from those of the participants with ADHD-IA for the alerting and executive networks and of the participants with ADHD-C/HI for the orienting network. Behaviorally, the control and ADHD-IA participants had faster RTs than did ADHD-C/HI participants, and all groups performed at a high level of accuracy throughout.

Interpreting the results requires caution because the ANT does not directly measure the attention networks by tracking one specific component but rather relies on a subtraction technique of two conditions. Although individuals with ADHD usually have smaller P3 amplitudes to correctly detected targets (Brandeis et al. 2002), the present study did not focus on comparing P3 amplitudes of individual conditions between the ADHD groups and controls but focused on the amplitude difference between two conditions associated with a particular network; information on each network was derived by comparing two conditions at a time, following the Fan and colleagues' 2002 procedure. A significant difference between two conditions does not necessarily describe a network's operation; however, when we compared this difference to the difference between those same conditions across two groups (e.g., comparing the difference between the no-cue condition and the double-cue condition across the control and ADHD-IA groups), we were able to describe that network's operation for the first group in relation to the second group. For instance, controls exhibited a larger P3 amplitude for the double-cue condition than for the no-cue condition (alerting network), but the P3 amplitudes for these two conditions in the ADHD-IA group were equal. We conclude that participants in the control group (presumably representing the general population) were processing the two conditions differently, whereas participants in the ADHD-IA group were processing the two conditions equally. This indicates a difference of function in the alerting network for participants with ADHD-IA.

Alerting Network

The hypothesis for the alerting network stated that the ADHD-IA group would show suppressed ERP activity, indicating more effortful processing of the target. Results supported this hypothesis and revealed that for the alerting network, the control group generated a larger P3 peak amplitude in the double-cue condition than in the no-cue condition; this indicates that controls processed target arrows with less effort based on the presence of warning cues. There was no significant difference in the alerting network between the control and ADHD-C/HI groups nor between the ADHD-IA and ADHD-C/HI groups; however, although the control group processed the two conditions differently, the peak P3 amplitudes in both conditions were equal for the ADHD-IA group (see Figure 10). This difference between groups on the alerting network suggests that participants in the control group were better able to establish a vigilant state and to maintain readiness to react than were participants in the ADHD-IA group, presumably because of the latter's inattentive tendencies. Results here coincided in part with the conclusion of Sergeant, Oosterlann, and van der Meere (1999), who asserted that individuals with ADHD have difficulty controlling the activation state. Furthermore, the literature supports findings that individuals with ADHD show behavioral deficits in the alerting network as measured by the ANT (Booth et al. 2007; Johnson et al. 2008; Mullane et al. 2010). This once again aligns with previous studies and hypotheses that suggest the higher activation of the neural system is due to neurons responding to cues and previously learned stimuli, explaining the counterintuitive nature of higher P3 amplitudes resulting in less mental effort put forth (Kandell et al. 2021).

Figure 10. Topographical Maps for the Alerting Network



The differences between ADHD-IA and ADHD-C/HI in the alerting network were not significant; the only difference observed was between the control and ADHD-IA groups. The obvious question then becomes, Why were participants in the ADHD-C/HI group more similar to those in the control group than in the ADHD-IA group? After all, the ADHD-C/HI group used here scored higher on inattentive symptoms than did the ADHD-IA group. One could argue that different subgroups of ADHD may have different sources of their symptoms. Individuals in the ADHD-C/HI group could potentially experience inattentive symptoms due to their hyperactive/impulsive tendencies. Such behavioral problems cannot account for the ADHD-IA group's inattention, however. Their attention deficits may well be due to a dysfunction of the alerting system. Findings by Booth and colleagues (2007) indicated that participants with ADHD-IA performed better behaviorally on the alerting task than did participants in the control group. Our findings do not necessarily contradict those findings. Potentially, participants with ADHD-IA showed more effortful processing during the double-cue condition, indexed by the lack of a difference in the P3 amplitude between the double- and no-cue conditions, because they were having to compensate and focus more on the task; thus, the behavioral facilitation observed by Booth and colleagues may be an indicator of compensatory effort on the part of the participants in the ADHD-IA group.

Orienting Network

Results indicated that processing in the orienting network was significantly different between controls and ADHD-C/HI, but not ADHD-IA. Although both groups elicited a higher P3 peak amplitude in the center-cue condition than in the spatial-cue condition, the interaction effect reveals that the difference in P3 peak amplitude was larger for controls than for ADHD-C/HI. This suggests that for control-group participants, processing of the target arrows was influenced by the location of the warning signal to a greater extent than for participants in the ADHD-C/HI group, who processed the target arrows more similarly regardless of location. This finding is in agreement with results from a study by van Leeuwen and colleagues (1998), in which the researchers determined that children with ADHD differed from controls in preparatory processing attributed to the orienting network; however, that study did not differentiate among the subtypes of ADHD. In comparison, Berger and Posner (2000) stated that empirical support of the involvement of the orienting network in ADHD pathology is lacking. In support of this, significant behavioral differences in the orienting network for ADHD participants and controls has not been reported in the literature (Booth et al. 2007; Johnson et al. 2008; Mullane et al. 2010). The present study, however, detected a significant difference in the orienting network between participants in the control and ADHD-C/HI groups, indicating a difference in function of the orienting network (see Figure 11). This may be a subtle enough effect that it is more observable when examining neural correlates through such methods as ERPs than through behavior alone, a conclusion that is supported by Rodriguez and Baylis (2007), who found smaller, lower P3 amplitudes for ADHD participants with electrodes recording brain activity correlating to the orienting network. The ADHD-IA group did not differ from the control or ADHD-C/HI groups in P3 peak amplitude.

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Figure 11. Topographical Maps for the Orienting Network

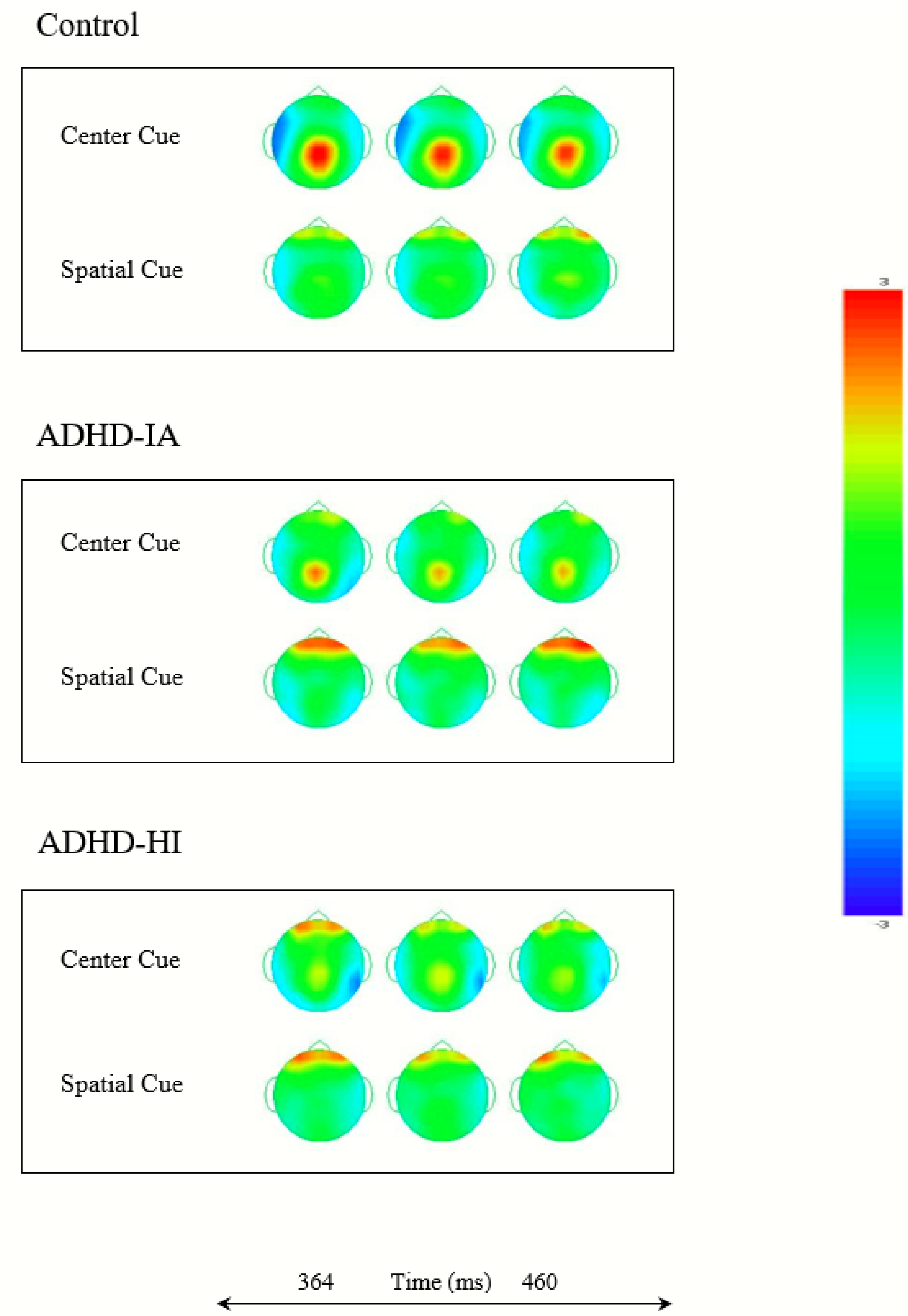
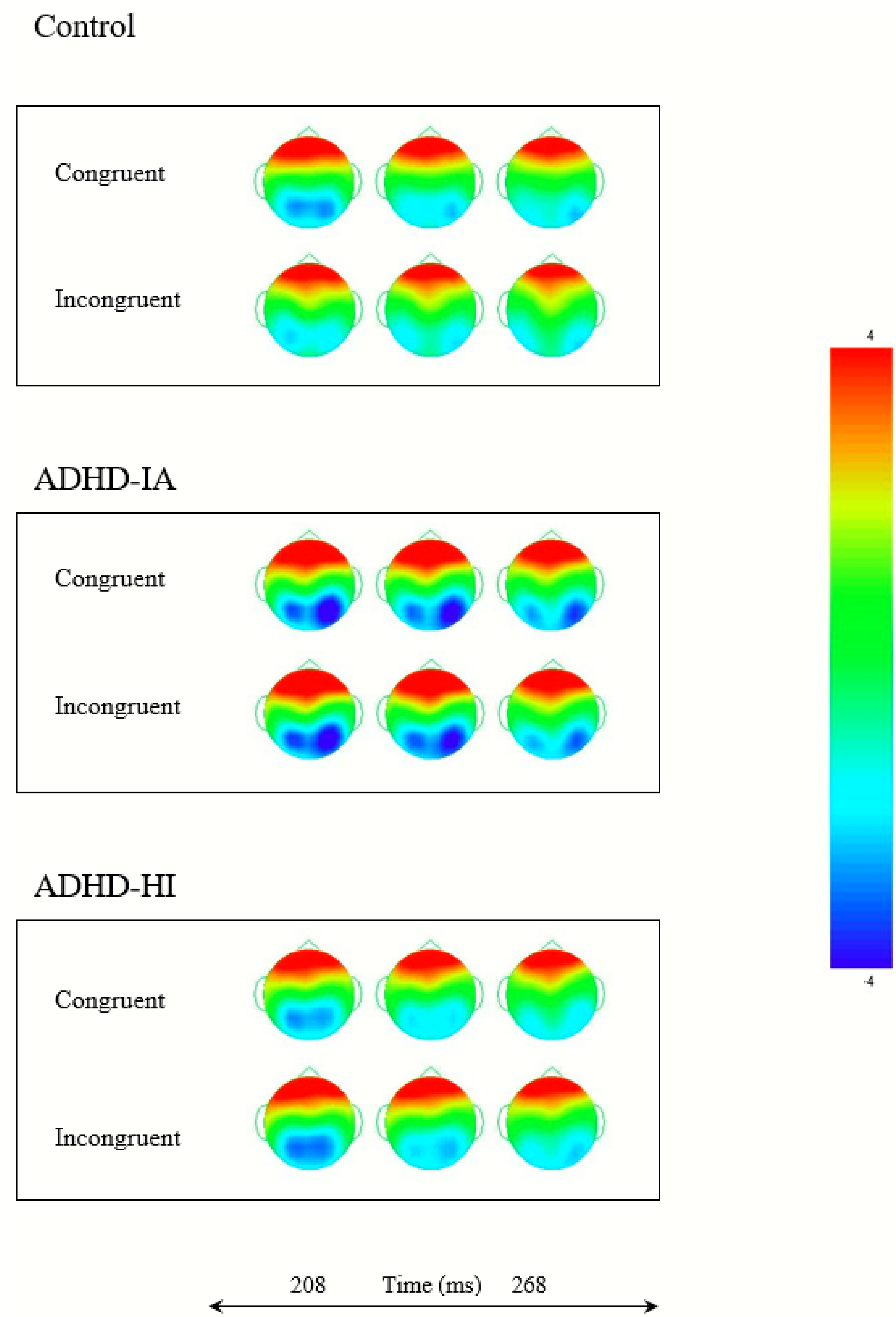


Figure 12. Topographical Maps for the Executive Network



Executive Network

The hypothesis for the executive network stated that the ADHD-C/HI group would show suppressed ERP activity. This hypothesis was partially supported. The P3 peak amplitude for the congruent condition was larger than for the incongruent condition only in the control group. The other two groups demonstrated no difference in processing congruent flankers and incongruent flankers (see Figure 12). According to the results, the executive network for the control group operated differently than for the ADHD-IA group, and the difference between the control and ADHD-C/HI groups was marginally significant. Both of these comparisons indicate a difference in function in the executive network for both of the ADHD subgroups. Barkley (1998) discussed the idea that ADHD is a deficit in executive control and that this deficit extends to cognitive processes. Berger and Posner (2000) also stated that the deficits seen in ADHD are due to executive function/effortful control dysfunctions. These findings are consistent with reports on the performance of ADHD participants on the ANT, which indicate behavioral deficits for the executive network (Booth et al. 2007; Johnson et al. 2008; Mullane et al. 2010). The two ADHD subgroups, however, did not differ from one another in the executive network.

Behavioral Measures

A review of the studies reveals that some research found slower RTs for the ADHD group than for controls (e.g., Jonkman et al. 1997). In contrast, other studies found faster RTs for the ADHD group (e.g., Perchet et al. 2001) and still others found no RT differences (e.g., van Leeuwen et al. 1998). The hypothesis for the present study predicted no RT differences between the groups. Results, however, revealed that participants in the ADHD-C/HI group had slower RTs than did participants in the control and ADHD-IA groups. These results are in line with findings by Booth and colleagues (2007), which demonstrated that ADHD-IA participants performed better than ADHD-C/HI participants for the alerting-network piece of the ANT. Other aforementioned studies did not differentiate among the subtypes of ADHD; therefore, it is likely that, because those samples consisted of all the subtypes together, the slower RT of the ADHD-C/HI group seen in the present study was canceled out by the faster RT of the ADHD-IA group. It is also possible that the ADHD-C/HI group participants, aware of their impulsive tendencies and knowing that the object of the task was to be accurate, were engaging in an accuracy/speed trade-off, for they were as accurate as the other groups' participants. In general, though, the patterns found in the present study, while not always significant, follow the same trend identified in the meta-analysis of Arora and colleagues (2020), which indicated that children with ADHD exhibit slower RTs on these types of tasks than do children in control groups.

We predicted that the ADHD groups would commit more errors than the control group. The higher-than-average errors committed by participants with ADHD reported in other studies (e.g., Defrance et al. 1996; Johnson et al. 2008; Jonkman et al. 1999; Satterfield et al. 1994) were not evident in this study, however. Participants with ADHD as well as participants in the control group performed the ANT at a high level of accuracy. This could also be sample-specific, for the participants in this study were college students who already performed at a relatively high level in order to be admitted to and remain in higher education. It is possible that the same study with a sample consisting of a lower-education tier of individuals with ADHD might reveal different levels of accuracy between them and controls. In fact, there is some support for this hypothesis. Adólfsdóttir and colleagues (2008) observed that when participants' full-scale intelligence quotient scores were included as a covariate in performance on the ANT, behavioral group differences were nonsignificant. Equal education level, as in the present study, may work as a similar control. A major strength of the present study consists of differentiating ERP activation in groups matched on overall performance. This study was able to measure processing differences in all three attention networks and that found ERP activity cannot be attributed to accuracy differences.

GENERAL CONCLUSIONS

When considering the ERP differences across the groups, one pattern was consistent across all three networks: The control group was always significantly different than at least one ADHD subgroup, but the two ADHD subgroups were never significantly different from each other. These findings partially support the idea of heterogeneous groups of ADHD. If individuals with ADHD comprised one homogeneous group, controls would display different attentional network ERP activity than both individuals with ADHD-IA and those with ADHD-C/HI. This is not the case here, where the control group is clearly different in ERP activity from the ADHD-IA group in the alerting network and from the ADHD-C/HI group in the orienting network. For the executive network, the control group processed information differently than did the ADHD-IA group, and the differences between the control and ADHD-C/HI groups were marginally significant. This last network is the only network for which one could potentially argue that ADHD-IA and ADHD-C/HI belong to a homogeneous group. The lack of significant differences in ERP activity between ADHD subtypes can be accounted for by looking at the behavioral measures. The vast majority of the literature draws the same conclusion: Individuals with ADHD perform more poorly than do controls on behavioral tasks (e.g., van Leewun et al. 1998). This conclusion is absent from the present study. Using a college sample accounts for this lack of agreement with the literature and is supported by findings from Adólfsdóttir and colleagues (2008). Participants in this study must perform at a certain level of success in order to enter and remain in higher education. These participants are either not afflicted by their attention disorder or are able of coping with the disorder through medication or other means; therefore, although their attention networks function differently than those of controls, these participants manage to perform behavioral tasks at levels equal to those of controls. Interestingly, though, the only behavioral difference between ADHD-IA and ADHD-C/HI comes in the RT data: Participants with ADHD-IA were faster than participants with ADHD-C/HI. The probable explanation is the speed/accuracy tradeoff referenced earlier.

The present study makes a strong case for heterogeneity in ADHD when it comes to the underlying neural systems compromised by the disorder. Specifically, in comparison to controls, individuals with ADHD-IA were found to have P3 deficits in the alerting

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network while individuals classified as having ADHD-C/HI were found to have P3 deficits in the orienting network. These deficits indicate that it took more effort for individuals with ADHD-IA than for individuals in the control group to perform the alerting aspect of the task, while individuals with ADHD-C/HI put more effort into the orienting aspect of the task. Future studies could use an ADHD sample consisting of individuals whose attention disorder prevents them from performing at optimal levels, with the goal of highlighting neurophysiological and behavioral differences based on the deficits differentially affecting underlying neural networks.

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