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RESEARCH ARTICLE

Transcranial Doppler sonography reveals sustained attention deficits in young adults diagnosed with ADHD

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Abstract

The National Institute of Mental Health has recently launched the Research Domain Criteria framework that seeks to inform clinical classification schemes by elevating the status of neuroscience research in the diagnosis of mental disorders. The current research seeks to contribute to that initiative by using a neurophysiological measure, transcranial Doppler sonography that has been shown to be sensitive to decrements in sustained attention and may provide an additional biomarker of executive dysfunction in ADHD. Twenty-seven participants performed a 12-min vigilance task while cerebral blood flow velocity (CBFV) was recorded. Thirteen participants were included in an ADHD condition if they had been formally diagnosed with ADHD. The remaining 14 participants who had never been formally diagnosed with ADHD were included in the control condition. Participants that had been diagnosed with ADHD demonstrated a steeper decrement in performance accuracy, a steeper decrement in perceptual sensitivity, and employed a more liberal response bias over time as compared to the control participants. Critically, the decrement in CBFV was steeper for participants previously diagnosed with ADHD than those who were not. Moreover, CBFV was found to better predict decreases in sensitivity and hit rate, as well as increases in liberal responding above and beyond self-reported ADHD symptoms. Results suggest that CBFV can be used to index failures of executive control in ADHD and can predict response strategy, and that the measure may provide an additional index of the sustained attention deficits associated with ADHD compared to traditional diagnostic methods.

Keywords ADHD · Transcranial Doppler · TCD · Vigilance · Sustained attention

Introduction

The current consensus is that the prevalence of attention deficit hyperactivity disorder (ADHD) is roughly 2–5% in adults (American Psychiatric Association 2013), and that these prevalence rates are relatively similar across cultures (Fayyad et al. 2007). Although there are three predominant subtypes of ADHD (i.e., hyperactivity, inattention, and combined type), the inattentive type is the most common diagnosis in adult ADHD (Boonstra et al. 2005; Hervey et al. 2004; Roth and Saykin 2004; Woods et al. 2002). There is some controversy surrounding the diagnosis of ADHD (e.g., Frick and Nigg 2012), with one of the larger sources of discussion being that the diagnostic criteria for ADHD does not appropriately emphasize the importance of executive dysfunction (Barkley 2014; Boonstra et al. 2005; Kessler et al. 2010). A widely used diagnostic assessment technique for ADHD, the Conners continuous performance test (CPT), is a measure of one's ability to sustain attention. The main diagnostic feature of the CPT is errors of omission over time in which salient stimuli are not identified by the participant (Conners 1994). Criticisms of the CPT as a diagnostic instrument are that the CPT as a stand-alone measure cannot reliably distinguish ADHD from other deficits (McGee et al. 2000), and that the specific CPT parameters are not associated with specific ADHD symptomatology (e.g., is inattention related to omission errors; Epstein et al. 2003).

The purpose of this study is to determine if cerebral blood flow velocity (CBFV), assessed using transcranial Doppler sonography (TCD), is sensitive to sustained attention deficits in young adults who have been diagnosed with ADHD. Some of the controversy related to the diagnosis of ADHD may be alleviated if researchers identify critical differences for those with and without ADHD in underlying brain structure and function. Importantly, this view is consistent with

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the newly refined NIH Research Domain Criteria framework that seeks to elevate the status of neuroscience findings in future classification schemes of mental disorders (Insel et al. 2010). To that end, a recent meta-analysis of 16 studies that used functional magnetic resonance imaging (fMRI) indicated that skill deficits associated with ADHD can be isolated to the fronto-parietal system (Cole et al. 2014; Cortese et al. 2012), a network that is involved in attentional control (Scolari et al. 2015). However, fMRI may not be an ideal source of supplementary diagnostic information for the diagnosis of ADHD, as it is simply too expensive and invasive to be used in day-to-day clinical settings. For example, the fMRI scanning procedure requires participants to remain almost motionless for lengthy periods of time while engaged in a sustained attention task, but studies have shown that individuals engaged in sustained attention tasks become restless and "fidgety" (e.g., Galinsky et al. 1993). Additionally, there are ecological abnormalities associated with the use of fMRI, such as the requirement for supine posture, head restraint, and an alteration of brain hydrostatics (Raz et al. 2005).

The limitations and restrictions associated with fMRI can be overcome by employing TCD, a relatively inexpensive and non-invasive ultrasound procedure that allows for continuous monitoring of cerebral blood flow velocity (CBFV) in the mainstem intracranial arteries (Duscheck and Schandry 2003; Stroobant and Vingerhoets 2000). TCD is often used as a research tool, but is also used clinically to diagnose cerebrovascular disease (Babikan and Wechsler 1999; Caplan et al. 1990). The logic underlying TCD is that when a particular area of the brain becomes metabolically active during the performance of mental tasks, the body increases the speed at which blood flows to that region to remove carbon dioxide (Aaslid 1986). TCD measures this increase in speed in arterial blood flow, and therefore measures the amount of work being performed by the brain areas being supplied by that artery. Although TCD does not have the degree of localization of fMRI, cross-validation studies have shown that TCD provides similar results in terms of hemispheric lateralization (Schmidt et al. 1999), and that the temporal resolution is comparable or superior to other imaging methods that examine cerebral hemodynamics (Parasuraman and Rizzo 2007; Duscheck and Schandry 2003). Further, the areas that mediate complex perceptual and cognitive processes are anatomically interconnected and linked together functionally (Posner and Raichle 1993). Therefore, TCD is a reasonable methodology for studying brain systems in clinical and applied settings.

Studies that have examined the relation between CBFV and vigilance (i.e., sustained attention) have revealed a consistent pattern of results. The absolute level of blood flow velocity is related to increases in task difficulty (Hitchcock et al. 2003; Shaw et al. 2010a, b, 2012; Warm et al. 2009). Furthermore, a near-universal finding is that as vigilance performance decreases (often quickly), this decrease is accompanied by a temporal decline in cerebral hemovelocity (Schnittger et al. 1997; Shaw et al. 2009). In addition, the CBFV effects are lateralized to the right cerebral hemisphere, consistent with fMRI studies that point to a right-hemispheric system in the functional control of vigilance performance (Parasuraman et al. 1998). Finally, several studies have shown that the temporal decline in CBFV only occurs when participants are actively engaged in the task—participants who are exposed to an identical vigilance task without a work imperative show no decrement in CBFV (Hitchcock et al. 2003; Shaw et al. 2009, 2012). These findings have been interpreted as neurophysiological evidence of a cognitive resource model of vigilance. In that model, the need for continuous attention results in an increased depletion of information-processing resources (Norman and Bobrow 1975) that are not replenished during task performance (Johnson and Proctor 2004; Langner et al. 2011; Parasuraman 1979; Parasuraman et al. 1987; Proctor and Vu 2012; Shaw et al. 2009, 2012, 2016; Warm et al. 2008; Wiggins 2011).

In addition to the broader findings relating CBFV to vigilance, CBFV has been shown to be sensitive to a wide range of individual differences that are linked to vigilance. Individual differences have a long history in sustained attention research, and several researchers have argued that it is important to consider the link between these individual differences and neurophysiological measures, as they provide insight into resource allocation during vigilance (Matthews et al. 2011, 2014; Shaw et al. 2010a, b; Parasuraman 2009; Shingledecker et al. 2010). These individual differences include personality characteristics such as extraversion (Shaw et al. 2010a, b, 2016), neuroticism (Mandel et al. 2015), and impulsivity (Shaw et al. 2010a, b), as well as the effects of practice and experience (Shaw et al. 2013). In addition, CBFV has been shown to be sensitive to performance deficits associated with cognitive ageing (Harwood et al. 2017).

ADHD is linked to vigilance because difficulties in maintaining attention and vulnerability to distraction likely accelerate the rate of loss of attentional resources. For example, Willcutt et al. (2005) conducted a meta-analysis of 83 studies that confirmed a moderate effect size for impaired vigilance task performance in children with ADHD. The key finding from that meta-analysis is that the primary deficit is in executive functions (importantly, the differences in executive functioning could not be explained by group differences in general intelligence). Young (2004) has developed a psychometrically sound scale of adult ADHD symptomatology that includes items for symptoms such as inattention, impulsivity, and restlessness. A factor analysis differentiated an ADHD factor

from other elements of personality functioning including emotional problems, delinquency, and social functioning. A subsequent study (Young and Gudjonsson 2005) confirmed that a group of adults meeting criteria for ADHD obtained higher scores on the Young scale, and also performed poorly on the CPT. Furthermore, the Young ADHD scale correlated with frequency of errors of omission on a sustained attention task.

In this study, we used TCD to measure CBFV in young adults with ADHD and compared them with healthy controls during a continuous performance (i.e., vigilance) task. Based on the well-established evidence of executive dysfunction in ADHD, it was hypothesized that individuals diagnosed with ADHD would perform more poorly on the vigilance task on all metrics of performance when compared to controls. Given that CBFV has been shown to be sensitive to the allocation of attentional resources, and people with ADHD have more difficulty sustaining attention, we hypothesized that there would be a steeper decrement in CBFV in participants with ADHD compared to control participants. We also sought to determine the extent to which a decrement in CBFV would be correlated with behavioral performance decrements, and whether hemovelocity would predict performance decrements above and beyond self-reported ADHD symptom severity.

Method

Participants

Participants consisted of 27 students (14 women) from George Mason University (mean age = 22.51 years, SD = 4.10). All participants were right-handed and had normal or corrected-to-normal vision. Participants who reported having been diagnosed with ADHD constituted the ADHD group (n = 13, 8 women). Participants who had no history of an ADHD diagnosis were placed in the control group (n = 14, 6 women). Also, participants in the ADHD group self-reported that they were not currently taking any medication in the past year to manage their ADHD symptoms. Importantly, there was a significant difference in the ADHD symptomatology scale of the Young ADHD Questionnaire-Self Report scale (described below) between the ADHD group (M = 174.54, SD = 37.20) and the control group (M = 96.93, SD = 47.84), t (25) = 4.68, $p < .05$ supporting the notion that reports of ADHD were accurate. Participants provided written consent prior to completing the study, and all study procedures and methods were reviewed and approved by the George Mason University Institutional Review Board.

Apparatus

ADHD Questionnaire

The primary questionnaire used in the study was the Young ADHD Questionnaire-Self Report scale (YAQ-Young 2004). The YAQ-S is a 112 item self-report questionnaire that was used to assess symptoms of attention deficit/hyperactivity. The YAQ-S questionnaire comprised four scales: (1) ADHD symptomatology relating to underlying core symptoms of attention, hyperactivity, and impulsivity; (2) emotional problems relating to feelings of anxiety, depression, anger, and the impact of mood on social relationships; (3) delinquency relating to aggressive behaviors, damage or theft of property, police contact, and substance misuse; and (4) social functioning relating to the ability to engage positively and socialize with others. Although the scale was administered in its entirety, only the ADHD symptomatology subscale was analyzed; it consists of 45 items (Cronbach's alpha = 0.97) and is rated on an eight-point Likert scale from "not at all" to "most of the time". For example, one item is "Have you jumped from task to task without finishing the first?"

Abbreviated vigilance task

Participants completed an abbreviated 12-min vigilance task. Participants viewed the repetitive presentation of 8 mm × 6 mm capital letters on a 17-inch CRT monitor. The letters, which consisted of an 'O', 'D', and a 'backwards D' were light grey and were constructed in 24-point Arial Font. Each letter was centered on the computer screen and was presented for 40 ms. The letters were presented against a visual mask that covered the entire visual field and consisted of unfilled circles on a white background. The unfilled circles of the mask measured 1 mm in diameter and were outlined by black lines which were 0.25 mm thick. The mask elements were separated by 3 mm along the horizontal and vertical directions and 2.5 mm along the diagonal axis. The letter stimuli appeared to be positioned behind this mask. An illustration of the display is presented in Fig. 1. In both conditions, stimuli were presented at a rate of 57.5/min. Critical

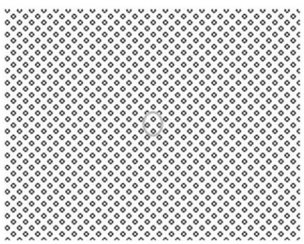

Fig. 1 Screenshot of the display. Depicted is the critical event "O" and the visual mask

events were the letter "O" and neutral events included both the forward and backward-facing capital "D." Twenty-four critical events appeared in each 2-min watchkeeping period (critical signal probability = 20%). The schedule of critical and neutral events was randomized for each participant. Participants signified their detection of critical signals by pressing the spacebar on a computer keyboard. Responses occurring within 1000 ms after the onset of a critical signal were considered to be correct detections. All other responses were considered false alarms. Stimulus presentation and response recordings were orchestrated via a Dell desktop computer. The abbreviated vigilance task used in this study has been used extensively in research and has been found to produce effects similar to longer vigilance tasks (Becker et al. 2015; Mandell et al. 2015; Temple et al. 2000).

Cerebral blood flow velocity

Hemovelocity measures were taken bilaterally from the right and left middle cerebral arteries (MCA) by means of a Spencer TCD unit equipped with two 2-MHz ultrasound transducers. The MCAs were measured because they have the largest perfusion territory and provide a global index of processing within each cerebral hemisphere (Duschek and Schandry 2003). It is particularly important to measure an artery with a large perfusion territory, as studies using PET and fMRI have revealed a highly dispersed network of cortical regions that support vigilance (see Parasuraman et al. 1998 for a review). The transducers, embedded in a plastic bracket, were secured to the participant's head by an adjustable plastic strap and located dorsal and immediately proximal to the zygomatic arch along the temporal bone. A small amount of Aquasonic-100 brand ultrasound transmission gel was placed on the transducers to ensure transmission of the ultrasound signal. The distance between the transducer face and the sample volume was adjusted at 2 mm increments to isolate the MCA, which was monitored at depths of 45–55 mm (Aaslid 1986). The participant was connected to the TCD unit for the entire duration of a baseline period, a practice period, and the abbreviated vigilance task.

Procedure

Participants first completed a biographical questionnaire to gather demographic information and screen for ADHD medication. All participants self-reported that they were not currently taking medication. Participants then completed a computerized version of the pre-task Dundee Stress State Questionnaire (DSSQ). The DSSQ stems from the idea that stress is a multidimensional construct that may involve several domains, including affective, cognitive, and motivational factors (Hockey 1997; Matthews et al. 1999, 2002). The DSSQ was not central to the research question for this study and was therefore not analyzed. Following the completion of the pre-task DSSQ, the TCD headset and transducers were applied to the participants. After clear CBFV readings were secured, a 5-min baseline CBFV measurement was recorded while the participant was not presented with any stimuli. The participant then read self-paced instructions and completed a 2-min practice on the computer. The conditions in the practice session were identical to those in the experimental trial. Participants were required to detect 80% of the critical events with no more than 10% false alarms during the practice in order to move onto the experimental task. If a participant failed to meet criteria in the first practice, a second practice was administered. After completing the practice, participants completed the 12-min vigilance task. After completion of the vigilance task, the headset was removed and participants completed a computerized version of the post task-DSSQ and the YAQ-S. The entire experiment lasted approximately 90 min.

Results

Data manipulation

Of primary interest in our experiment was whether there were performance and CBFV-related differences between ADHD and control participants. We characterized performance in a number of ways. First, we assessed participants' response accuracy during the experimental session for both correct detections ('hits') and false alarms. Second, we combined these metrics into a single sensitivity (d') value, calculated by subtracting the normalized false alarm rate from the normalized hit rate (Macmillan and Creelman 2004). This metric represents the perceptual ability of participants to separate 'signal' from 'noise'. Third, we calculated response bias (β), which represents an index of how 'liberal' or 'conservative' the participant was in their responding. Although neither a liberal nor a conservative response bias is necessarily ideal, an unchanging response bias in the face of unchanging risks and rewards (i.e., signal probability) should be considered optimal. In all analyses, performance over time was characterized as 12 min or 720 s.

With regard to CBFV, velocity scores during the trial were expressed as a proportion of the participant's final 60 s of the 5-min baseline. This is consistent practice in studies employing TCD (e.g., Aaslid 1987; Shaw et al. 2009), and is done to account for baseline differences in CBFV (see Stroobant and Vingerhoets 2000 for a review of individual differences associated with baseline CBFV).

All analyses were completed using linear mixed-effects models in R and *lme4* (Bates et al. 2012; R Core Team 2013). Compared to more traditional analyses (e.g., ANOVA, OLS regression), mixed-effects models better account for

potential non-independence in measurement, particularly for repeated measures designs (Baayen et al. 2008). Random effect terms were selected using nested model comparisons (Pinheiro and Bates 2000). The random effect for trial time in the overall accuracy regression was the only variable to significantly improve model fit and therefore was the only term to be retained; all other regressions contained fixed effects only. Satterthwaite (1946) approximations were used to determine denominator degrees of freedom for t and p values.

Response accuracy

We hypothesized that participants with ADHD would show poorer performance on all of our performance metrics, which include a lower hit rate, a greater false alarm rate, greater losses in sensitivity, and a more variable response bias throughout the experiment. We first used a logistic regression model to accommodate the binary accuracy outcome, with group (ADHD, control), time (1–720 s), and signal type (critical, neutral), as well as all two- and three-way interaction terms as predictors. This analysis yielded a significant main effect of group, Exp (B) = 0.376, 95% CI [0.153, 0.922], p = .0326, whereby, at any given time, the odds of providing an incorrect response were 62% greater for participants in the ADHD group as compared to the control group. There was also a main effect of signal type, Exp (B) = 0.0871, 95% CI [0.0686, 0.111], p < .001, such that the odds of providing an incorrect response for critical events were 91% greater than those for neutral events. The effect of signal type was qualified by an interaction with time, Exp (B) = 0.692, 95% CI [0.545, 0.877], p = .00237, whereby participants' accuracy decreased for critical events over time, but their performance with neutral events remained relatively invariant (and high) throughout the task. Lastly, there was a significant interaction between group and signal type Exp (B) = 1.40, 95% CI [1.03, 1.89], p = .0317. In addition to being more likely to provide an incorrect answer overall, participants with ADHD were particularly likely to err when faced with critical events. The odds of participants in the ADHD group providing an incorrect response were 40% greater during critical events compared to neutral events. Thus, our hypotheses regarding group differences in participant accuracy were supported (see Fig. 2) and consistent with current use of continuous performance tasks by clinicians.

Perceptual sensitivity (d')

Perceptual sensitivity (d') was calculated using 30-s intervals, because the formula for perceptual sensitivity requires multiple time points. Therefore, time was replaced by block number (1–24) as a predictor. Group (ADHD, control) and the interaction between group and block were also included as predictors. We observed a significant effect of block, $B = -0.0303$ SE = 0.009, $p < .001$, $d = -0.27$, with all participants exhibiting decreasing sensitivity levels over time. The interaction between block and group approached significance, $B = -0.0211$, SE = 0.0128, p = .0992, d = 0.13, such that participants with ADHD experienced a somewhat steeper sensitivity decrement throughout the course of their vigil compared to controls. The lack of a significant main effect by group may have been driven by lesser differences in false alarm responding (responding affirmatively during neutral events), which factors into the calculation of sensitivity. Our hypothesis in this regard was therefore only partially supported (Fig. 3).

Response bias (β)

Response bias was also calculated using 30-s intervals, and was predicted by block (1–24), group (ADHD, control), and the interaction between the two. Overall, we found no effect of block, $B = -0.0021$, SE = 0.004,

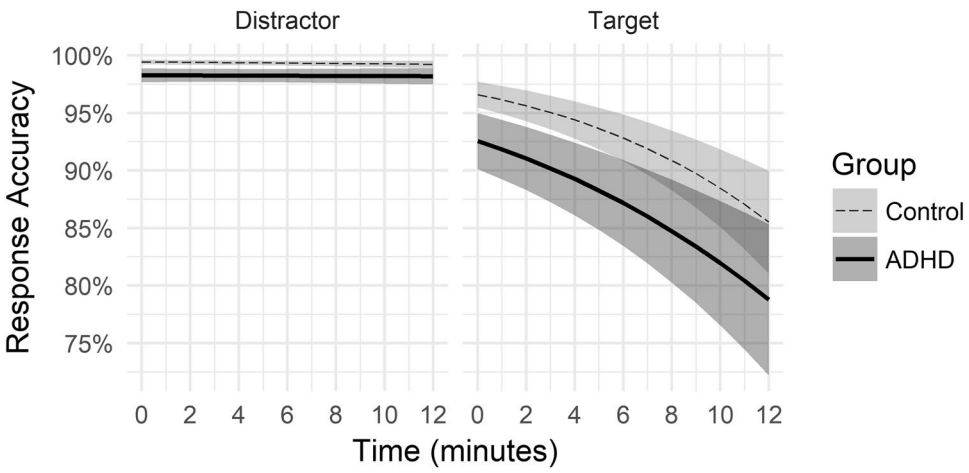

Fig. 2 Participant accuracy over time in response to critical and neutral events by group

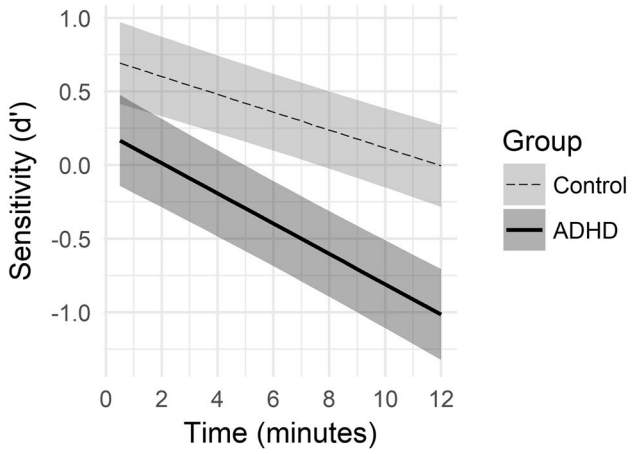

Fig. 3 Participant perceptual sensitivity (d') over time by group

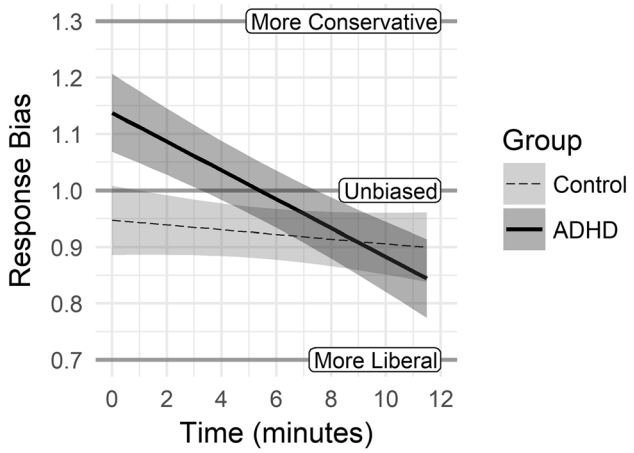

Fig. 4 Participant response bias (β) over time by group

$p = .57$. However, we did find a significant effect of group, $B = 0.201$, SE = 0.0962, $p = .0393$, $d = 0.43$, and the interaction between group and block approached significance, $B = -0.0106$, SE = 0.005, $p = .0536$, $d = 0.15$ (Fig. 4). Participants with ADHD employed an overall more conservative response style (i.e., tended to favor misses to false alarms), and also exhibited greater variability in that response style throughout the experiment. Specifically, participants with ADHD became significantly more liberal by the conclusion of the experiment, representing a riskier response strategy with time. Our hypothesis regarding response bias was therefore supported.

Cerebral hemovelocity

The focus of the present study was on the possibility of hemovelocity differences by group, whereby we hypothesized participants with ADHD would experience a greater velocity decrement than controls. We further hypothesized that this decrement would be correlated with behavioral performance decrements, and that hemovelocity would predict performance decrements above and beyond self-reported ADHD symptom severity. To test these hypotheses, we predicted cerebral hemovelocity using time (1–720), group (ADHD, control), hemisphere (right, left), and all resultant two- and three-way interactions. First, we found a main effect of time, $B = -0.154$, SE = 0.0087, $p < .001$, $d = -0.18$, whereby participants' hemovelocity decreased over time, from approximately 3% over baseline to approximately 1% under baseline. We also found a main effect of hemisphere, $B = 0.411$, SE = 0.012, $p < .001$, $d = 0.17$, with faster overall blood flow in the right compared to the left hemisphere. Although there was no main effect of group, there was an interaction between group and hemisphere, $B = -0.253$, SE = 0.0178, $p < .001$, $d = -0.05$: participants in the ADHD group exhibited slower overall blood flow compared to participants in the control group, but this difference was only apparent in the right cerebral hemisphere. There was also a three-way interaction between group, hemisphere, and time, $B = -0.0552$, SE = 0.0178, $p < .001$, $d = -0.05$, whereby the ADHD group exhibited a greater decline in cerebral hemovelocity in the right hemisphere compared to participants in the control group (see Fig. 5). This decline occurred in the hypothesized direction, and importantly, there were no group differences in CBFV during the first minute of the vigilance task, $B = -0.0106$, SE = 0.0123, $p = .397$.

Self-reported ADHD symptom severity and nested model comparisons

Our last set of analyses was intended to demonstrate the utility of cerebral hemovelocity measurement in predicting vigilance performance above and beyond self-reported ADHD symptoms. Substantial range differences in the scales used to measure symptom severity and blood flow velocity required us to rescale the predictors using z-transformation. All variables were transformed using grand means and standard deviations, and CBFV relative to baseline was standardized rather than the raw velocity values. For this reason, the regression weights reported in this section can be interpreted as standardized weights.

We first predicted overall accuracy, sensitivity, and response bias with self-reported symptoms alone. Symptom severity was a marginally significant predictor of overall accuracy, $B = -0.02$, SE = 0.01, $t(16) = -2.10$, $p = .052$, and a significant predictor of sensitivity, $B = -0.32$, SE = 0.15, $t(16) = -2.12$, $p = .049$. In both cases, greater symptoms were associated with poorer performance. Symptoms were not associated with response bias, $B = -0.07$, SE = 0.10, $t(16) = 0.65$, $p = .52$.

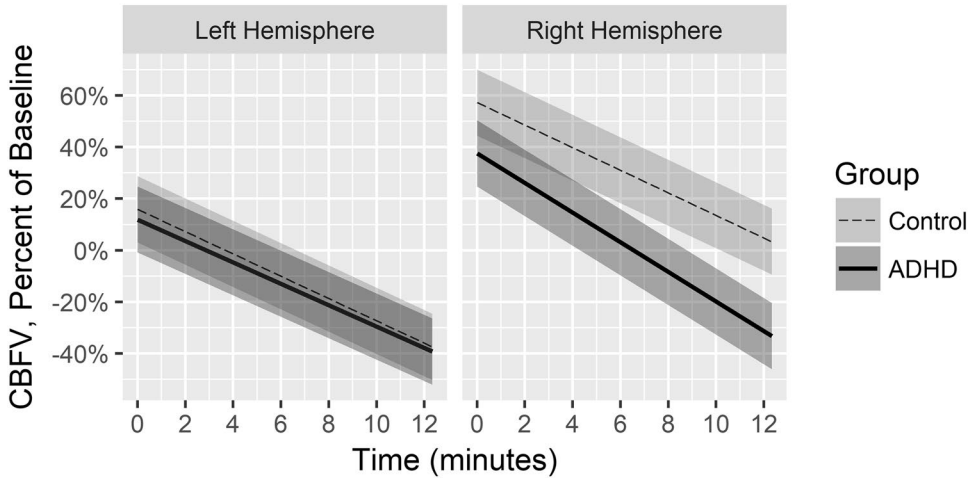

Fig. 5 Cerebral hemovelocity over time by group and hemisphere

We then added blood flow velocity to the regression models and evaluated its added predictive utility using nested model comparisons. For both sensitivity and response bias, including blood flow velocity in the prediction model contributed significantly to model fit: χ^2 (3, N = 29) = 27.53, $p < .001$ and χ^2 (3, N = 29) = 12.15, $p = .007$, respectively, with greater bloodflow predicting less sensitive and more liberal responding. Blood flow was not predictive of overall accuracy, $B = -0.001$, SE = 0.002, $p = .62$, nor did it improve model fit, χ^2 (3, N = 29) = 0.35, $p = .950$. Overall accuracy may be more difficult to predict due to the relative rarity of critical events requiring a response. Indeed, omitting the large number of neutral events that required no response from the participants and were largely met with correct inaction yielded a significant main effect of blood flow velocity, $B = 0.038$, SE = 0.007, $p < .001$, and a significant improvement in model fit above symptoms as a sole predictor, χ^2 (3, N = 29) = 68.96, $p < .001$.

Discussion

The purpose of the current investigation was to examine the extent to which a relatively new and inexpensive neurophysiological measure was sensitive to differences in vigilance between young adults with ADHD and those without. The performance results revealed that, as predicted, correct detections and perceptual sensitivity both declined at a steeper rate for the ADHD group as compared to the control group. Moreover, the analysis of response bias (beta) indicated that the ADHD group started out at a much more liberal rate of responding. The decline in perceptual sensitivity and increase in response bias are consistent with the idea that individuals with ADHD have a more impulsive style of responding. These results are also in line with the empirical findings in the CPT literature (Conners 1994; Epstein et al. 2003; Losier et al. 1996; Riccio et al. 2001).

The results pertaining to the CBFV measure are also consistent with predictions. We observed a significant overall CBFV decrement, and that decrement was modulated by cerebral hemisphere. While there was no main effect of group, the effects of the group variable were apparent in a 3-way interaction between group, time, and cerebral hemisphere. Specifically, while CBFV was initially elevated for both groups in the right hemisphere, CBFV declined more steeply in the ADHD group as compared to the control group. A finding of this sort is important for two reasons. First, it is consistent with a plethora of evidence that suggests that most vigilance effects will be restricted to the right hemisphere (Hitchcock et al. 2003; Tulving et al. 1994; Warm et al. 2009). In addition to supporting the view of a right-hemispheric system in the control of vigilance, the laterality effect in this study challenges a major criticism that could be leveled against any TDC/vigilance experiment. Based upon findings that blood flow velocity is sensitive to changes in blood pressure and cardiac output (Caplan et al. 1990), and that changes in heart rate variability are correlated with vigilance performance (Parasuraman 1984), one could argue that TCD-derived performance/hemovelocity associations do not reflect information processing per se, but instead reflect gross changes in systemic vascular activity that co-vary with blood flow. However, such gross changes in vascular activity are not likely to be hemisphere dependent.

Perhaps more importantly, the CBFV results show differentiation between the ADHD group and the control group. CBFV declined for the ADHD group more steeply than for the control group. Generally, a finding of this sort is interpreted in terms of the resource model of vigilance, in which there is a consumption of information-processing resources that are not replenished with continuous task performance. It should be noted, though, that whether the CBFV measure reflects a drainage of information-processing resources or resource allocation policies remains an open question. Recent evidence examining CBFV across a wide range of

individual differences show that it may be more reflective of resource allocation (e.g., Becker et al. 2015; Shaw et al. 2013, 2016), but earlier evidence that has examined task factors suggest that CBFV reflects a resource depletion process (Hitchcock et al. 2003; Schnittger et al. 1997; Shaw et al. 2009, 2012). Nevertheless, the findings of a steeper decline in CBFV is consistent with the resource model, and is supportive of the findings in ADHD that failures in executive functioning, most notably attention, are the primary drivers of the decrement (e.g., Willcutt et al. 2005). These findings are also consistent with the neuroimaging evidence that exists—the cortical network implicated in ADHD, the fronto-parietal network, is the same network implicated in the functional control vigilance (e.g., Lim et al. 2010; Parasuraman et al. 1998). This is strong evidence that the CBFV measure is sensitive to ADHD.

The results from the nested model comparisons suggest that ADHD symptomatology, as measured by the YAQ-S Adult ADHD scale, was predictive of observers' perceptual sensitivity, which replicates previous findings (e.g., Young and Gudjonsson 2005). More compelling are the results pertaining to CBFV. It was found that adding CBFV to the model that included symptomatology from the YAQ-S scale enhanced model fit when predicting perceptual sensitivity and response bias. This means that CBFV can index failures of attention, as indicated by predicting perceptual sensitivity, but may also be able to predict response strategy, as indicated by response bias. Previous research has indicated that a liberal response strategy is associated with impulsivity (Helton 2009), which is a trait that is often associated with ADHD. This finding is promising, as it suggests that CBFV is sensitive to both of the primary symptoms associated with ADHD, inattention and impulsivity (Toplak et al. 2009).

The authors would be remiss if we did not acknowledge the potential limitations of the current research. First, and perhaps most glaringly, is with regard to the criteria that we used to select participants into the ADHD group. Our criteria were that participants had to be formally diagnosed and that they were not taking any ADHD medications. Hence, it is unknown how long these young adults have been diagnosed, which could have implications on the severity of their ADHD symptomatology. Moreover, it is also not known if these individuals had ever been prescribed medicine once they were diagnosed, which could also have implications for the severity of their symptoms. Also, future research should consider the different subtypes of ADHD to determine it the attentional impairment has similar manifestations across all ADHD subtypes. We also failed to consider correlates, such as anxiety and depression, which can often be comorbid with ADHD and thus affect performance. Additionally, the CPT is the more clinically oriented assessment, and although it is considered a vigilance tasks by many authors, it takes on a more "go, no-go" response strategy unlike the "no-go, go" strategy used in the current study. There has been some research that has suggested that the two task types may have qualitative differences (e.g., Helton et al. 2009). Future research should examine the extent to which the findings of the current study generalize to different vigilance task types. This information would help clinicians and practitioners identify those tasks that would be most useful in diagnosis.

The inability to sustain attention is a critical element associated with the symptomatology of young adults with ADHD. Thus, in addition to the theoretical implications of our results, it is worthwhile to consider the potential applied application. It may be possible to add CBFV, or a measure akin to CBFV (e.g., cerebral oxygenation) to the existing methods of diagnosing ADHD. As stated in the introduction to this report, there is a growing concern that neuroscience findings are not given sufficient consideration in the diagnosis of mental disorders (Cuthbert 2014; Cuthbert and Insel 2013; Insel et al. 2010; Kapur et al. 2012). The finding that CBFV has predictive utility above and beyond self-reported symptomology is a testament to the importance of examining neurophysiological biomarkers in diagnosis. Moreover, the inclusion of neuroimaging techniques as possible biomarkers for mental disorders has the potential to guide treatment selection and improve clinical outcomes (McGrath et al. 2013). We are not suggesting that existing methods of diagnosing ADHD be replaced by neurophysiological measures, but rather that the measure could be considered as a supplementary assessment. Future research should consider the incremental validity that the CBFV adds above and beyond existing diagnostic measures.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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