



Accommodative response and cortical activity during sustained attention

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ARTICLE INFO

Article history:

Received 10 March 2011

Received in revised form 3 April 2012

Available online 2 May 2012

Keywords:

Accommodation

Attention

ADHD

WAM-5500

EEG

Conners' CPT

ABSTRACT

Greater accommodative lag and vergence deficits have been linked to attentional deficits similar to those observed in Attention Deficit Hyperactivity Disorder (ADHD). The purpose of the present study was to assess the effect of accommodative–vergence stress on a measure of sustained attention (Conners CPT) used in the diagnosis of ADHD. Twenty-seven normal non-ADHD adults completed the Conners CPT twice: wearing -2.00 D lenses and normally (without the -2.00 D lenses) in a counterbalanced order with at least 24 h between the sessions. Simultaneous recording of participants' dynamic accommodative responses was performed from the right eye using the Grand Seiko WAM-5500 auto-refractor and electroencephalographic activity (EEG) in the left prefrontal region using the Neurosky Mindset headset. The results demonstrated a significantly greater accommodative lag in the -2.00 D stress condition and a significantly poorer performance on the Conners CPT as indexed by slower reaction time, greater standard error of hit reaction time, greater response variability, poorer stimulus detectability and a greater number of perseverations. No differences were observed on measures of EEG in the theta (4–7 Hz), alpha (8–12 Hz), and beta (12–20 Hz) bands. Moreover, when directly juxtaposed with each EEG band in multiple linear regression analyses, greater accommodative lag in the stress condition was significantly associated with a greater probability of clinical classification on the Conners CPT, and was also marginally predictive of the number of omissions recorded in the stress condition. The results demonstrated that sustained attention can be influenced by such factors as accommodative–vergence stress and suggest that bottom-up processes can contribute to and potentially exacerbate attentional problems in individuals with ADHD. The study also showed that cortical dysfunction (while sufficient) may not be a necessary condition for attentional deficits.

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1. Introduction

1.1. Neurophysiology of ADHD

Theories of the etiology of Attention Deficit Hyperactivity Disorder (ADHD) have traditionally incorporated the notions of dysfunctional arousal, activation and alertness systems in the brain. More recent theoretical advances propose a top-down model that includes an executive control network located in the frontal cortico-striatal pathway that regulates the level of arousal and alertness (Sergeant, 2000, 2005). There is evidence that individuals with ADHD have increased dopamine transporter (DAT) in the striatum, which decreases the availability of extracellular dopamine (DA; Dougherty et al., 1999). Consequently, these individuals exhibit overactivation of the prefrontal cortex (PFC; Sheridan, Hinshaw, & D'Esposito, 2010) and this increased firing could result in irrelevant

shifts of attention or irrelevant updating in working memory and produce distractible behavior (Volkow et al., 2005). The function of stimulant medication, according to this model, would be to decrease the 'noise' in the PFC by increasing extracellular DA in the striatal region. Indeed, in a recent study by Sheridan, Hinshaw, and D'Esposito (2010) stimulant medication in the form of methylphenidate reduced PFC activity in children with ADHD and improved their performance on a delayed match-to-sample task using letter stimuli.

Similarly, Loo et al. (2009) examined patterns of cortical arousal and activation as a function of adult ADHD diagnosis during completion of a sustained attention task that has repeatedly been shown to differentiate ADHD from normal groups (Epstein et al., 2003). On this 14-min Continuous Performance Test (CPT) by Conners participants are asked to press the space bar in response to every stimulus letter except the target letter "X". Electroencephalographic (EEG) recordings measured during CPT testing showed that the pattern of cortical activation in ADHD adults was markedly different from that of the controls especially in the frontal regions. The most robust finding was a significantly greater attenuation of 8–10 Hz alpha band power in the ADHD group compared

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to controls. Alpha power is negatively associated with arousal again suggesting that the ADHD group experienced a significantly greater level of cortical arousal in the frontal regions than controls.

At the same time, using conservative estimates pharmacotherapy (includes both stimulant and non-stimulant medication) has been found ineffective for at least 10% of pediatric and adult patients diagnosed with ADHD even after controlling for psychiatric comorbidity, drug intolerance and a history of stimulant misuse (Wigal, 2009). While overdiagnosis can never be ruled out, Scituito and Eisenberg (2007) concluded that it does not appear there is sufficient evidence to support the notion that ADHD is currently systematically being overdiagnosed. There is, therefore, a possibility that in a small percentage of ADHD patients cognitive/attentive deficits may be primarily related to a non-cortical bottom-up mechanism that is not affected by ADHD medication.

1.2. Accommodative–vergence stress and visual discomfort

One such mechanism may involve a dysfunction in the oculomotor system. When a young person with normal binocular vision engages in the act of viewing a near target, there is an oculomotor response of the eyes known as the ‘near triad’ that includes pupil miosis (constriction), binocular convergence and increased accommodation. Although both accommodation and vergence will respond independently to proximal stimulation, a cross-linked reciprocal interaction exists between accommodation–convergence (AC), defined as a reflexive change in convergence driven by changes in accommodation, and of convergence–accommodation (CA), defined as a reflexive change in accommodation driven by a change in vergence, such that accommodation and convergence will be held in relative synchrony with each other.

Under optimal circumstances where the accommodative and vergence responses are closely matched, young persons will typically show a mild under-accommodation to a distance target. When viewing near targets, a mild amount of under-accommodation or accommodative lag can be expected. The amount of accommodative lag is not constant for everyone, but is different from one person to another. On average, the amount of accommodative lag behind the target plane is between 0.25 D and 0.50 D (Fincham & Walton, 1957; Iwasaki, Tawara, & Miyake, 2006). If introduced with a concurrent mental task while viewing near targets, such as reading, subjects will generally show an additional 0.25–0.75 accommodative shift toward far, presumably due to the activation of the sympathetic nervous system (Bullimore & Gilmartin, 1988).

Usually, the accommodative–vergence system is able to cope for short periods of time with some degree of conflict. Thus, a mild dissociation between accommodation and vergence reflected by an accommodative lag or a fixation disparity may not cause visual discomfort for a person engaged in a near visual task because the system is sufficiently flexible. In studies of asthenopia associated with stereoscopic displays, there is evidence that as the conflict between the vergence distance and accommodative distance increases or if such dissociated viewing becomes prolonged, symptoms of fatigue and discomfort are more likely to ensue as the viewer attempts to counteract the accommodation–vergence mismatch (Emoto, Niida, & Okano, 2005; Hoffman et al., 2008; Yano et al., 2002).

Accommodative–vergence stress can also be experimentally induced by artificially decoupling the normal accommodative–vergence mechanism using -2.00 D lenses or using base-in (BI) prism (Bharadwaj & Candy, 2009; Maddox, 1886). In the former condition, an accommodative stimulus demand is created that is in excess of the vergence stimulus demand. In the case of BI prism, a reduced fusional vergence stimulus demand is created relative to a fixed accommodative stimulus demand.

Clinical investigations have shown that young subjects vary in the degree to which they can view through minus lenses or BI

prisms before the stimulus is excessive and they experience blur and then diplopia (Chin & Breinin, 1967; Parks, 1958; von Noorden & Avilla, 1990). This individual range of accommodation–vergence stress that can be induced without any blur or diplopia in either direction is referred to as *the zone of clear, single binocular vision* (Howard & Rogers, 2002; Morgan, 1944). Within this zone exists a smaller theoretical zone of comfort known as *Percival's area of comfort*, which is the middle third of the *zone of clear, single binocular vision* (Howard & Rogers, 2002; Morgan, 1944). Relative accommodative–vergence stress can be endured by many individuals when performing near tasks without the stimulus target being seen as “blurred” or “double”. The possibility that one will experience discomfort will depend on whether or not the accommodative–vergence response resides inside or outside *Percival's area of comfort*.

Howarth and Clemes (2006) used -2.00 D lenses in a within-subject design in which participants were asked to complete a task on a visual display unit (VDU) under conditions of normal/corrected-to-normal vision and near-point binocular stress induced with -2.00 D lenses. In the stress condition participants reported significantly greater visual discomfort. Additionally their near-point accommodation and convergence were significantly worse after completing the VDU task in the stress condition compared to the non-stress condition (mean near points receded by over 1 cm).

Earlier research also showed that accommodative–vergence near-point stress induced with BI prism or -2.00 D lenses resulted in significant deterioration of reading comprehension and reading speed (Garzia et al., 1989; Ludlam & Ludlam, 1988).

1.3. ADHD, accommodation and convergence

Many of the adverse symptoms expressed by individuals with accommodative and vergence problems have also been reported for individuals diagnosed with attention problems. Borsting, Rouse, and Chu (2005) found that school-aged children with symptomatic accommodative dysfunction and or convergence insufficiency (CI; a condition where the vergence plane tends to dissociate behind the accommodative plane of a viewed near target) appear to have a higher frequency of ADHD-like behaviors as measured by the Conner's Parent Rating Scale-Revised Short Form (CPRS-R:S). Granet et al. (2005) also reported a three times greater incidence of Attention-Deficit Hyperactivity Disorder (ADHD) among patients with convergence insufficiency (CI) when compared to the general population and, conversely, a threefold greater incidence of CI in the ADHD population. Moreover, Granet et al. (2005) went further to suggest that medications used to treat ADHD may actually aggravate CI as some of the drugs are associated with side effects of blurred vision and difficulties of accommodation.

Finally, Gronlund et al. (2007) reported a number of ocular and visual abnormalities in children and adolescents with ADHD. Specifically, the authors found that overall 76% of the ADHD subjects had abnormal ophthalmologic findings including subnormal visual acuity, strabismus, reduced stereo-vision, absent or subnormal near point convergence, refractive errors, small optic discs and/or signs of cognitive visual problems. Importantly, administration of stimulant medication did not significantly improve visual function in the ADHD group.

1.4. Current study

In the present study we used an open field autorefractor to continuously measure accommodative lag along with prefrontal EEG activity in normal non-ADHD subjects as they performed a continuous performance task with and without -2.00 lenses designed to induce accommodative–vergence stress. The term accommodative–vergence stress is defined in this study as the stimulus

demand mismatch that was induced rather than the subjective feeling of asthenopia that may have been experienced by the subject. We hypothesized that the disruption of visual processing alone may be sufficient to account for symptoms of inattentiveness in the absence of changes in cortical activity.

2. Method

2.1. Materials

2.1.1. Participants

Twenty-seven college students 18–26 years of age (8 males and 19 females) participated in the study for course credit. The study was approved by the Institutional Review Board of the University of North Dakota. All participants were required to provide informed written consent prior to their participation. The participants were screened for normal or corrected to normal visual acuity (20/20 or better in each eye) at distance and near. Uncorrected refractive errors and corrected over-refractions of the right eye all had spherical equivalent (SE, sphere + 0.5 X cyl.) between -0.50 sph. and $+0.50$ sph. and showed astigmatism <-0.75 sph. All participants demonstrated at least 9 D of accommodative amplitudes monocularly and binocularly and were non-strabismic, with heterophorias measuring between 2 prism diopters esophoria and 6 prism diopters exophoria, which is considered to fall within a normal range (Casillas & Rosenfield, 2006). Those with strabismus, uncorrected astigmatism $>$ or equal to 0.75 and anisometropia, as well as significant ocular pathology (excluding color deficiencies) and head trauma were excluded. Additional exclusionary criteria included presence of a learning disability, ADHD, or a psychiatric condition such as depression and/or concomitant use of stimulant medication, antidepressants, or anxiolytic drugs.

2.1.2. Static and dynamic accommodation

Static push-up accommodative amplitudes were measured for each subject monocularly and binocularly using an RAF rule according to Donder's clinical method (Donders, 1864).

Steady-state accommodative responses were measured dynamically from the right eye using the Grand Seiko WAM-5500 autorefractor (Grand Seiko Co. Ltd., Hiroshima, Japan) in HI-SPEED mode. The left eye was not covered during the experiment as all subjects viewed the near target stimulus binocularly, thus insuring a closed vergence loop. The Grand Seiko WAM-5500 is a binocular open-field autorefractor and keratometer that also permits dynamic recording of refraction and pupil size by connection to an external PC via an RS-232 port. The instrument can measure refraction in the range of ± 22 D sphere and ± 10 D cylinder in increments of 0.01, 0.12 or 0.25 D for power, and 1° for cylinder axis. In the present study the WAM-5500 software was set for the maximal resolution of 0.01 D.

Measurement data are displayed on an internal 5.6 in. color monitor, which permits visualization of the pupil to enable alignment of the instrument with the subject's visual axis. In high-speed mode, mean spherical refractive error (MSE; equalo spherical component + cylindrical power/2) and pupil diameter can be recorded at a rate of 5 Hz by interfacing with a PC running the WAM communication system (WCS-1) software, allowing objective measurement of a subject's dynamic accommodative response to a target. A number of research studies have recently showed that the WAM-5500 produces reliable and accurate measurements of dynamic accommodation (Chase et al., 2009; Sheppard & Davies, 2010; Tosha et al., 2009).

In the present study spherical accommodative response was sampled every 200 ms during a 15-min Continuous Performance Test presented on a laptop computer screen at a distance of 40 cm from the observer. Participants viewed a series of 2.5 cm

high-contrast white letters on a black computer screen at a central point of fixation, yielding an approximate near Snellen equivalent letter size of 20/858 (angular subtense at the eye is inverse tangent of $2.5/40$ or 3.57°). During recording of dynamic accommodation focus of the corneal reflections on the WAM-5500 monitor was continuously maintained using a joystick.

Accommodative lag was determined by subtracting the subject's mean point of focus during testing (WAM-5500 dynamic refraction value 'REF_mean_dynamic') from the target distance (2.5 D) and adjusting for the baseline static refraction value ('REF_mean_static'). In the stress condition an additional adjustment was made for the -2.0 D lens.

Formula 1 (non-stress): Accommodative lag (D) = $-2.5 - \text{REF_mean_dynamic}_{\text{nonstress}} - \text{REF_mean_static}$

Formula 2 (-2.0 D stress): Accommodative lag (D) = $-4.5 - \text{REF_mean_dynamic}_{\text{stress}} - \text{REF_mean_static}$

2.1.3. EEG recording

EEG recording was carried out using Neurosky's Mindset headset. The headset incorporates a single active pea-sized electrode (10 mm diameter) that is placed in the left forehead area approximately 2 cm above the left eyebrow. This roughly corresponds to area Fp1 using the International 10–20 System of electrode placement. The reference electrode is integrated into the earpiece of the headset and measures electrical potential from two points on the left earlobe. The electrical potential is supplied directly to the embedded chipset for analog filtering with band pass and notch filters and 128 kHz digital sampling every second. Analogue data is then automatically converted into digital format and analyzed by Fast Fourier Transform (FFT) in the headset circuit board. FFT produces power values for each 1-s epoch and each frequency bin that are transmitted via Bluetooth to the Mindset Research Tools data acquisition software installed on a Mac Book Pro laptop. The extracted data represent the electrical potential difference between active and reference electrodes, and analyses of the power ratio of the frequency components to total power have reliably and accurately shown which frequency range is dominant at the time the data are taken (Yasui, 2009). Power values for each frequency component were then grouped into 3 frequency bands: theta (4–7 Hz), alpha (8–12 Hz) and beta (12–20 Hz). Similar bands were used in the study by Loo et al. (2009), in which frontal and parietal cortical activity was correlated with performance on Conners CPT.

2.1.4. Conners Continuous Performance Test

The Conners' Continuous Performance Test (CPT) is a neuropsychological task of sustained attention that has repeatedly been shown to differentiate ADHD from normal groups (Epstein et al., 2003). The test takes 14 min to complete and requires participants to make a response (mouse click) as quickly as possible to any letter displayed in the center of a laptop computer screen except the letter "X" (probability of occurrence = 0.10). Each letter (~ 2.5 cm, white on a black screen) is displayed for 250 ms over 18 blocks of 20 trials on a Sony lap-top computer screen (screen resolution 1024×768) with high contrast (95.1%). The signal in each block is presented at one of the three interval rates, i.e. 1, 2, or 4 s in a counterbalanced order. Dependent measures include hit reaction time, accuracy (errors of omission and commission), signal detection parameters of d' (sensitivity) and beta (response bias) as well as response variability between and within the blocks (the standard error estimate of hit reaction time).

2.2. Procedure

Upon arrival at the lab each participant read and signed the informed consent form and completed two questionnaires. The first

questionnaire concerned demographic information and medical history. The second instrument was the Convergence Insufficiency Symptom Survey (CISS), a 15-item questionnaire assessing symptoms related to reading, including fatigue, headaches, reading performance and perceptual distortions. A score of 22 or higher on the CISS has been shown to differentiate between adults with convergence insufficiency (CI) from those with normal binocular vision (Rouse et al., 2003). The CISS is useful in identifying children with other binocular vision and accommodative disorders that have symptoms that are similar to those found with convergence insufficiency (Borsting et al., 1999, 2003).

Next participants underwent a brief optometric examination that included distance and near monocular and binocular acuities, monocular and binocular accommodative pushup amplitudes, near Maddox Rod dissociated phoria testing and static WAM-5500 baseline autorefractometry measurements of the right eye taken three times while subjects binocularly viewed a distant target at 6 m. Lastly, a probe of accommodative-vergence flexibility was given whereby each subject was asked to read aloud a 20/20 reduced Snellen line of letters binocularly at 40 cm. while -2.00 lenses were held before the subject's eyes or habitual correction. All subjects were able to successfully resolve the acuity letters without diplopia. This momentary ability to have accommodation stimulated while the vergence is held constant is known as relative accommodation and indicates a capacity of our subjects to fall within a normal range of clinically established positive relative accommodation values for adults (Fry, 1983; Morgan, 1968).

Following the exam, participants were asked to completely uncover their ears from any hair as well as to remove any earrings. Next the Neurosky Mindset headset was placed over their ears with the active electrode positioned in firm contact with the forehead area approximately 2 cm above the left brow. The subjects then placed their chin in the chin support of the WAM-5500 and were given instructions how to complete Conners CPT by clicking on the corded mouse extending from the laptop. All participants first completed a 3-min practice session before beginning the experimental blocks. Dynamic accommodation and pupil diameter of the right eye as well frontal EEG activity were recorded throughout the duration of the CPT.

Testing took place between 9:00 am and 3:00 pm and was comprised of two sessions (separated by at least 24 h) that were administered in a counterbalanced order. Thus each participant completed a non-stress CPT session, during which participants viewed the laptop screen binocularly using their habitual optical correction of contact lenses or glasses (if they had corrected vision). In the stress condition participants completed the CPT task while wearing -2 -D spherical lenses binocularly in a trial frame (if no glasses or contacts were worn) or wearing -2 -D trial lenses binocularly clipped over their glasses.

3. Results

3.1. Baseline data

The mean score on the Convergence Insufficiency Symptom Survey was 16 (SD = 7.13). On the accommodative pushup amplitude test the mean for the right eye was 10.50 D, for the left eye 10.55 D (SD = 4.42), and 13.26 D (SD = 4.82) on the binocular pushup amplitude measure. On the phoria test the mean finding was an exophoria of 4.31^{Δ} (SD = 5.53). Mean static refraction/over-refraction of the right eye at baseline was -0.02 D. Predictably, measures of accommodative pushup amplitude had significant high correlations with each other ($r = 0.86$). Additionally a significant moderate correlation was observed between phoria and the total score on the CISS ($r = 0.41$, $p = 0.045$) with higher phoria values associated with greater CISS scores.

3.2. Within-subject comparisons

Participants' accommodative lag, EEG activity, and performance on Conners CPT in the non-stress and stress conditions were compared with a series of paired-sample *t*-tests. The results showed that accommodative lag was significantly greater in the stress condition compared to the non-stress condition. Attentional performance significantly deteriorated in the stress condition increasing the probability of participants' clinical classification by 6%. Participants in the stress condition had a significantly slower reaction time, a significantly greater standard error of hit reaction time, showed greater response variability, significantly poorer stimulus detectability and a significantly greater number of perseverations. No significant differences were observed on measures of EEG activity for any of the frequency bands (theta, alpha, beta) or pupil diameter. These results are summarized in Table 1.

3.3. Regression modeling

Accommodative lag in the stress condition was then directly juxtaposed with frontal EEG activity in a series of multiple regression analyses predicting each of the attentional measures. Each EEG frequency band was tested in a separate regression model since they had very high (over 0.93) significant bivariate correlations with each other producing problems of multiple collinearity. Pupil diameter was the third continuously measured variable in the stress condition. This variable, however, was not included into the regression models as it did not show significant bivariate correlations with any of the attentional measures.

The results showed that the power of each of the three frequency bands was not significantly predictive of performance on any of the attentional measures. Greater accommodative lag, on the other hand, was associated with a significantly higher probability of clinical classification ($p < 0.05$) regardless of the bandwidth entered into the model. Each model accounted for 30–40% of variance in this attention measure (see Table 2 for details). Accommodative lag in the stress condition was also marginally predictive ($p = 0.06$) of the mean number of omissions recorded in the same condition.

There were no significant correlations between accommodative lag in the stress condition and the power of any of the frequency bands. Fig. 1 illustrates a fairly flat pattern of fluctuations of the three bands across the range of accommodative lag responses. On the other hand, significant bivariate correlations were observed

Table 1

Mean differences on measures of visual function, cortical activity and sustained attention (CPT).

Variable name	No stress		-2.0 D stress		<i>t</i>
	Mean	SD	Mean	SD	
Accommodative lag (D)	-1.02	0.79	-4.24	0.96	26.98**
Pupil diameter (mm)	5.57	0.87	5.34	1.01	1.73
EEG theta (4–7 Hz)	42.96	42.20	26.17	26.10	0.93
EEG alpha (8–12 Hz)	20.87	21.33	11.89	8.05	1.23
EEG beta (12–20 Hz)	13.26	19.10	8.15	9.40	0.70
Clinical probability	0.29	0.15	0.35	0.22	-2.01^{\dagger}
Omissions	1.30	1.86	5.04	13.47	-1.45
Commissions	11.37	6.74	12.44	6.33	-1.02
Hit reaction time (ms)	359.76	53.13	379.23	59.02	-3.54^{\dagger}
Hit reaction time SE	4.49	1.33	5.31	2.23	-2.47^{\dagger}
Variability	5.82	2.25	8.59	6.44	-2.36^{\dagger}
Detectability	0.95	0.47	0.74	0.36	2.74*
Response style	0.64	0.77	0.61	0.81	0.19
Perseverations	0.11	0.32	0.52	0.80	-3.05^{**}

* $p < 0.05$.

** $p < 0.01$.

Table 2

Regression analysis summary for accommodative lag and EEG frequency bands in the stress condition predicting probability of clinical classification on Conners CPT.

Model	Variable	B	SEB	β
1 ^a	Accommodative lag	0.19	0.08	0.63*
	Alpha (8–12 Hz) power	–0.12	0.01	–.42
2 ^b	Accommodative lag	0.19	0.08	0.67*
	Beta (12–20 Hz) power	–0.02	0.01	–0.48
3 ^c	Accommodative lag	0.19	0.08	0.65*
	Theta (4–7 Hz) power	–0.004	0.003	–0.34

^a Adjusted $R^2 = 0.38$ ($N = 27$, $p = 0.07$).

^b Adjusted $R^2 = 0.44$ ($N = 27$, $p = 0.05$).

^c Adjusted $R^2 = 0.30$ ($N = 27$, $p = 0.12$).

* $p < 0.05$.

between accommodative lag in the stress condition and probability of clinical classification ($r = 0.59$; $p = 0.04$), number of omissions ($r = 0.59$; $p = 0.04$) and hit reaction time ($r = 0.55$; $p = 0.05$).

Furthermore, a series of paired-sample t -tests showed that mean accommodative lag of subjects at each minute of the Conners CPT in the non-stress condition was significantly smaller than the mean accommodative lag for corresponding time points in the stress condition. Fig. 2 shows that the accommodative lag at each minute of the Conners CPT in the non-stress condition was fairly stable fluctuating around -1.00 D ($M = 1.01$, $SD = 0.05$). In the -2.0 D stress condition accommodative lag was also fairly stable vacillating near -4.0 D ($M = 4.2$, $SD = 0.13$).

4. Discussion

The results of this study showed that performance on a computerized test of sustained attention often used in diagnosis of ADHD can be compromised by adding a -2.00 D accommodative stimulus to the normal -2.50 D accommodative–vergence stimulus demand. Increasing the accommodative stimulus from -2.50 to

an absolute of demand of -4.50 D while retaining a fixed vergence stimulus at -2.50 D resulted in a larger accommodative lag and significantly poorer performance on the CPT reaction time, standard error of hit reaction time, response variability, stimulus detectability and the number of perseverations was found. There was no appreciable change in frontal lobe electrophysiological activity. Importantly, minus lens induced accommodative–vergence demand increased the likelihood of clinical diagnosis on the Conners CPT by 6%. Dynamic measure of accommodation during binocular viewing of the Conners CPT showed that greater accommodative lag in the stress condition was significantly correlated with the probability of clinical diagnosis, reaction time and number of omissions. What was particularly interesting was the finding that accommodative lag alone could account for a significant proportion of cases with a higher probability of clinical classification even after controlling for frontal EEG activity.

The Conners CPT letter stimulus occupied a vertical dimension of 2.5 cm on the computer screen with a 0.5 cm brush stroke. This is equivalent to a relatively large reduced Snellen acuity letter of 20/858 at 40 cm, approximating a relatively low spatial frequency target of 0.7 cpd. This sized target subtends the retina at 3.57° at a 40 cm. distance. Under the non-stressed CPT condition, subjects showed an average lag of accommodation of 1.02 D with sustained viewing of about 14 min. High contrast targets of low spatial frequency do not appear to require particularly accurate accommodation. Therefore, a greater lag of accommodation can be expected compared to higher frequency targets (Tucker & Charman, 1987; Ward, 1987).

Under the stressed CPT condition, an average accommodative lag of -4.24 D was recorded. The direction of this response agrees with Leat and Gargon (1996) who found that accommodative lag increases for increased demands. Under conditions where stimuli to accommodation and vergence conflict, it is known that accommodation is less accurate, yielding a larger accommodative lag than under non-conflicting binocular viewing conditions (e.g.

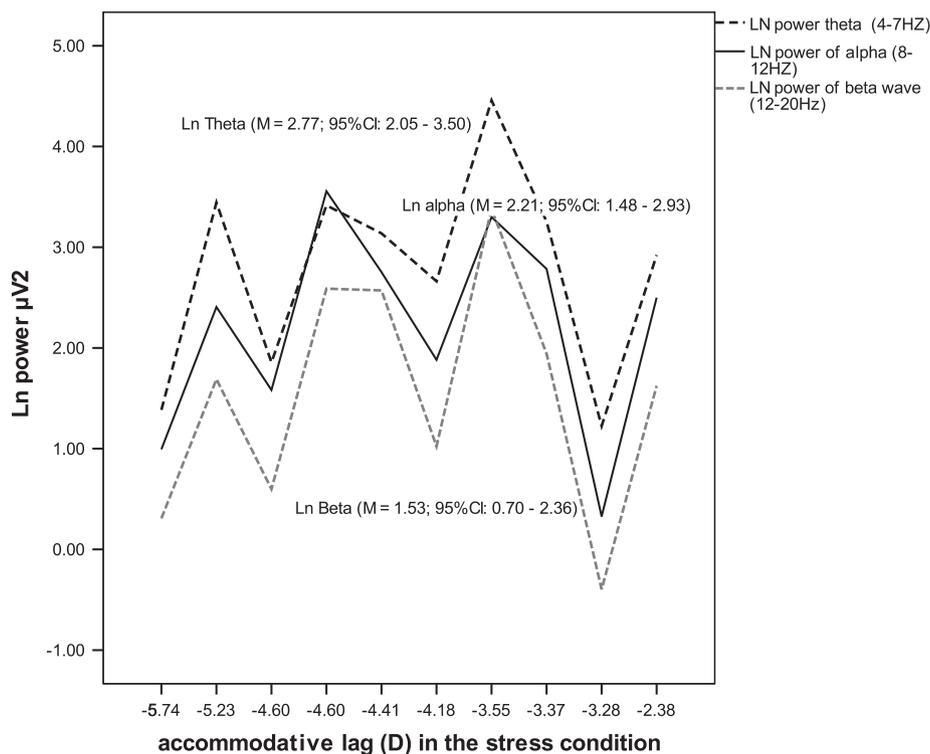


Fig. 1. Relationship between frontal EEG bands and accommodative lag during completion of Conners CPT in the stress condition.

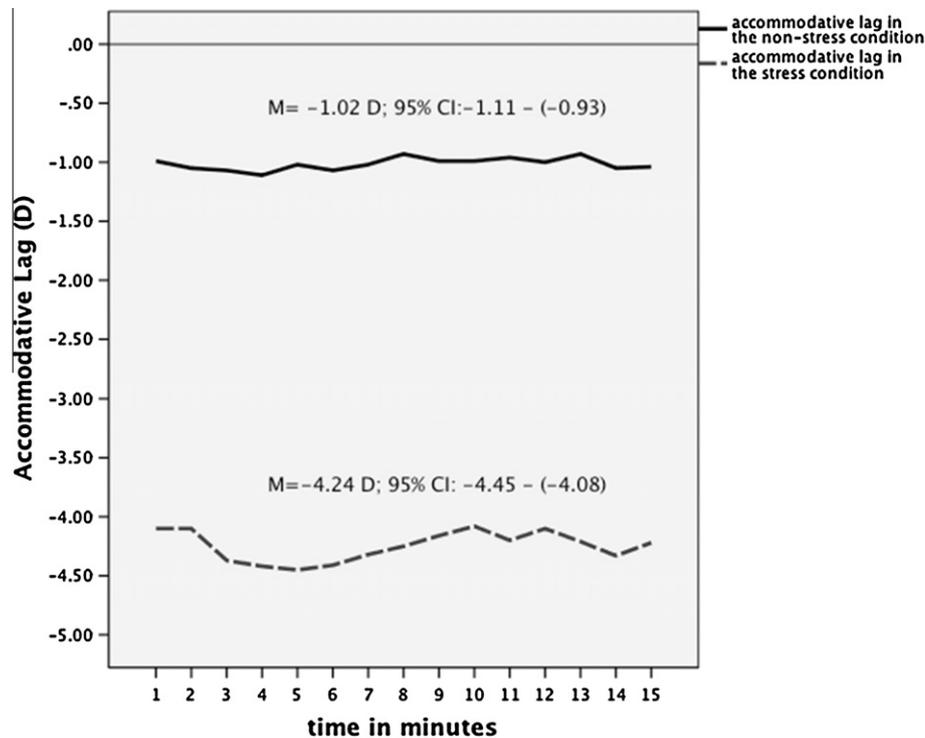


Fig. 2. Accommodative lag during completion of Conners CPT in non-stress and stress conditions ($n = 26$).

Hung & Ciuffreda, 1994; Jaschinski, 1997; Ramsdale & Charman, 1988).

The large accommodative lag means found under the stress CPT condition suggest that a significant retinal defocus beyond the eye's depth of focus (DOF) may have occurred. Depth-of-focus refers to the range of retinal defocus that can be tolerated without the perception of blur with accommodation held constant. Xu et al. (2009) reported that retinal defocus greater than 2 D would compromise task performance such as reading, whereas under more stringent and restrictive dynamic viewing conditions such as rapid serial visual presentation (RSVP) retinal defocus beyond a range of 1.0 and 1.5 D can deleteriously affect performance at near due to an exceeded "functional blur threshold".

In the present study the CPT task represented a temporally limiting and restricting condition (similar to RSVP), making CPT performance susceptible to retinal defocus with even low accommodative lag being potentially detrimental to performance. Our CPT target subtended a visual angle of 3.57° and with an average pupil diameter of 5.34 mm and accommodative lag of -4.24 D in the stress condition of the CPT, it is very likely that the subjects exceeded their DOF resulting in perception of blur. For example, Wang and Ciuffreda (2004) reported a foveal mean DOF of 0.89 D (range: 0.55–1.55 D) with an artificial 5 mm pupil placed in front of the cyclopleged and dilated right eye of the subject. At 8° of retinal eccentricity the total subjects' DOF in their study increased to 3.51 D (range: 3.16–3.86 D).

At the same time under specific viewing conditions, in which processing time is not an issue, target clarity may not be all that necessary for object recognition. For example, Tucker and Charman (1987) showed that a subject with normal vision and paralyzed accommodation could still read a letter of our size (20/858) when defocused by minus lenses of over -7 D. In combination with the dynamic timing limitations of the CPT, however, perceived blur in the presented study may have adversely affected the subjects' performance especially on measures of reaction time and stimulus detectability in the fastest interstimulus interval condition (1 s). In

the other two interstimulus interval conditions when the letters were presented at 2 and 4-s intervals, identification of targets may have been less compromised by retinal defocus but by other factors such as accommodative–vergence stress.

4.1. ADHD, accommodation, convergence and EEG

According to a model of homeostatic balance between accommodation and convergence in an individual wearing stress-inducing experimental lenses, accommodation will tend to lag further behind the plane of the target and convergence will localize closer than accommodation (Schor, 1983a, 1983b, 1985; Schor & Narayan, 1982; Semmlow & Heerema, 1979). Since convergence and accommodation do not localize nearly as close to the same target plane for visually stressed condition as they do for non-stressed persons, extra effort, consciously or unconsciously, must be directed toward the effector system mismatch. It is felt that this added effort may diminish one's information processing capacity, create asthenopia, disrupt attentional reserves, and decrease the efficiency of task performance (Skeffington, 1974).

Our EEG data also seems to be somewhat consistent with the above hypothesis. Specifically, non-significant attenuation of EEG power was observed in the stress condition for all measured EEG band frequencies including alpha power. Loo et al. (2009) also reported that the most robust finding in their study during completion of the Conners CPT was a significantly reduced alpha power in adults with ADHD compared to normal controls especially over the frontal and parietal regions. The researchers suggested that decreased alpha power may be an important neurophysiological marker in adults with ADHD representing increased cortical arousal necessary to comply with the experimental situation. In non-ADHD adults attenuation of 8–10 Hz alpha power has been observed during a variety of tasks and is thought to represent increased attentional demands (Klimesch, Sauseng, & Hanslmayr, 2007). Additionally reductions in alpha power have been linked to expectancy and preparation of the visual cortex to incoming

visual cortex (Gomez et al., 2004). It is thus possible that in our study increased accommodative–vergence demand in the -2.0 D stress condition required greater recruitment of attentional resources for accurate processing of the visual stimulus which was reflected in presumably greater cortical activation (indexed by attenuated alpha power) at least in the frontal region. For persons with accommodative–vergence conflicts, the struggle to keep accommodation and convergence within the *zone of clear, single binocular vision* may become a distracting event that can be detrimental to attentional and cognitive performance.

This concept supposes that there is a limited –capacity pool of attention available for processing and a fixed amount of overall energy consumption that is made available to the brain. For example, Laufs et al. (2006) reported an inverse relationship between alpha power and fMRI BOLD cortical response. Attention thus seems to optimize the use of the visual system's limited resources by enhancing the representation of objects appearing with relevant features or at relevant locations while diminishing the representation of objects appearing at less relevant locations or with less relevant aspects of our visual environment. With efficient binocular and accommodative function, the allocation of attention is not depleted by the need to exercise volitional control of accommodation and vergence to compensate for their dysfunction (LaBerge & Samuels, 1974; Peachey, 1991). If a person can reduce the amount of attention needed for a task, then more attention is available that can be devoted to a concurrent task (e.g. Schneider & Shiffrin, 1977).

4.2. Study limitations

The methodology of the study did not allow separation of accommodative/vergence stress from perceived blur. CPT testing under non-cyclopleged conditions with the use of incrementally increasing minus lens powers could have provided better information about the relative contribution of blur and accommodative/vergence stress factors on performance, especially if an objective method to measure fixation disparity, such as binocular eye movement recordings, and a self-report symptom questionnaire were also included. Likewise, CPT testing under cyclopleged conditions using incrementally decreasing plus lens powers and questionnaire could have provided better information about the contribution of blur factors on performance.

Other limitations include a relatively small sample size and the use of only one frontal EEG electrode. Although Loo et al. (2009) did report greatest differences in the alpha range between ADHD and non-ADHD adults in the frontal region, the researchers also found differences in the parietal region. It is, therefore, possible that there may have been shifts in the band activity in other brain regions under the condition of increased accommodative stress, but the measurements from these regions were not taken. Nevertheless, the Neurosky's Mindset headset has been validated by Yasui (2009) who used the system's EEG output to discriminate between REM/non-REM sleep, car driving, using a cell phone while driving a car as well as students' engagement in classroom activities and relaxation. The system's software also provided data on the signal quality. In the present study only 100% signal quality data was used making it highly unlikely that the observed EEG activity was spurious.

5. Conclusion

Overall the results of this study suggest that bottom-up processes such as accommodative stress (as indexed by a greater accommodative lag) and/or functional blur can influence sustained attention to visual stimuli and may potentially contribute to and

exacerbate the severity and clinical profile of attentional problems in individuals with ADHD. Whether anomalies of the oculomotor system can account for instances of drug-resistant forms of ADHD is not yet known, the present study is one of the first to suggest that a possible accommodative–vergence mismatch may be a sufficient condition for inattentiveness that is not necessarily correlated with the frontal cortical function (as measured by EEG).

Other populations whose performance on the Conners CPT may be compromised may include those who have errors of refraction (e.g. uncorrected hyperopia, uncorrected astigmatism, anisometropia), anomalies of binocularity (e.g. convergence excess; convergence insufficiency) and/or anomalies of accommodation (e.g. accommodative insufficiency, ill-sustained accommodation) and/or individuals who have normal clinical findings of accommodation and vergence, but are susceptible to a breakdown of this synchrony when doing near tasks under conditions that activate the sympathetic nervous system.

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