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Symptoms of convergence and accommodative insufficiency predict engagement and cognitive fatigue during complex task performance with and without automation

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A R T I C L E   I N F O

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A B S T R A C T

Deficits in the accommodative and/or vergence responses have been linked with inattentive behavioral symptoms. While using automated systems (e.g., self-driving cars, autopilot), operators (e.g., drivers, pilots, soldiers) visually monitor displays for critical changes, making deficits in the accommodative and/or vergence responses potentially hazardous for individuals remaining actively engaged in the task at hand. The purpose of this study was to determine if symptoms of accommodative-vergence deficits predict an individual's level of task engagement and cognitive fatigue while performing a flight simulation task with or without automation. Eighty-four participants performed a flight simulation task with or without automation. Prior to task completion, self-report accommodative-convergence deficit symptoms were assessed with the Convergence Insufficiency Symptom Survey (CISS). Before and after the flight simulation task participants rated their task engagement and cognitive fatigue. Electroencephalographic activity (EEG) was recorded concurrently during task performance. Results showed that higher scores on the CISS were related to increased feelings of fatigue and decreased ratings of task engagement. The CISS was also positively related to parietal-occipital fast alpha power during the last 10 min of the task for participants using automation, suggesting increased cortical idling. CISS scores did not predict performance. Results have implications for optimizing operator cognitive states over extended task performance.

1. Introduction

The visual system plays a vital role in an operator's ability to successfully perform tasks. For instance, pilots scan instruments during flight and drivers continuously integrate visual information from the road to safely maneuver an automobile. Two of the oculomotor responses critical for human operators are the accommodative and vergence responses. Accommodation occurs when the shape of the crystaline lens changes as an adaptation to near or far foveal (focused) vision as the ciliary muscles surrounding the lens of the eye relax or contract, thereby changing the tightness of the zonular fibers that attach to the lens and act as suspensory ligaments (Rehman et al., 2019). Vergence occurs when the eyes move inwards or outwards to maintain a fused, singular image on the retina. Accommodation and convergence are coupled physiologically. Through this coupling, when the eyes accommodate, they also converge and when the eyes converge, they also accommodate (American Optometric Association, 2011).

A significant amount of research and system design consideration has been given to reducing operator visual fatigue (asthenopia) to improve operator comfort and performance (Arvanitis et al., 2007; Blehm et al., 2005; Dillon and Emurian, 1996; Emoto et al., 2005; Rajabi-Vardanijani et al., 2014; Rempel et al., 2007; Sommerich et al., 2001; Wang and Huang, 2004). However, significantly less is known about how the visual system influences the cognitive states of operators. A review focusing on virtual image displays by Edgar (2007) asserted that high workload operational conditions tend to shift accommodation inwards and result in accommodative strain while operators use virtual image displays (e.g., heads-up-displays). Recent research has demonstrated that extended driving can modulate measures of the oculomotor system. Specifically, Vera et al. (2016) found that participant intraocular pressure decreased and accommodative lag (a measure of accommodative functioning) increased from pre to post after performing a 2 h simulated drive, indicating a decline in accommodation. Moreover, these changes in ocular parameters were accompanied by increased feelings of fatigue and reduced arousal. Because the oculomotor system plays a vital role in operator performance, deficits in oculomotor responses may result in

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suboptimal cognitive states that ultimately influence safety outcomes. Specifically, individuals with oculomotor deficits may be more susceptible to reductions in sustained attention over time.

1.1. Accommodative and convergence insufficiency and sustained attention

Previous research has shown that deficits in accommodative and/or vergence responses may mimic attentional difficulties and behavioral symptoms characteristic of Attention-Deficit/Hyperactivity Disorder (ADHD), such as poor concentration and missing details (Borsting et al., 2005; Poltavski et al., 2016). The most common disorders of the accommodative and vergence systems include accommodative insufficiency (AI) and convergence insufficiency (CI). AI is a sensory motor disorder characterized by an inability to focus or maintain focus at near, while CI is a sensory motor anomaly linked to deficits in the ability to attain and/or sustain accurate eye convergence at a near target (Marran et al., 2006). AI and CI often present with similar symptoms including image blur, headache, asthenopia, diplopia, and poor concentration while performing near work (American Optometric Association, 2011; Daum, 1983, 1984; Hinkley et al., 2016). In two retrospective studies by Daum (1983, 1984) of patients with AI ($n = 96$) and CI ($n = 110$), the comorbidity rate between the disorders was 65%. Borsting et al. (2003) provided a more quantitative analysis of the prevalence and severity of symptoms known to occur both in patients with AI and patients with CI. Using the Convergence Insufficiency Symptom Survey (CISS) of 16 questions and a 3-point scale ranking system for frequency of occurrence, Borsting et al. (2003) showed that the comorbidity of AI with CI that has all three classic clinical CI signs (exophoria at near, a remote near point of convergence, and decreased fusional amplitudes) was 79% in their sample of 392 school children aged 8–15 years. A modified 15-question version of CISS was also used to evaluate symptoms in adults age 19–30 years by comparing a group with symptomatic CI (all three clinical signs present) to those with normal binocular vision (Rouse et al., 2004). Excellent discrimination (sensitivity, 97.8%; specificity, 87%) was obtained using a cutoff score of $\geq$21 for adults, which the researchers recommended to use in 19–30 year olds for evaluation of symptoms of CI. The results of these studies suggest that the CISS is a valid and reliable instrument that can be used clinically or as an outcome measure for research studies for individuals with convergence and accommodative deficits.

Poltavski et al. (2012) provided experimental support for the link between accommodative-vergence deficits and sustained attention by decoupling the accommodative-vergence responses with -2.0 diopter (D) lenses in healthy adults. Poltavski and colleagues found that participants wearing -2.0 D lenses had significantly reduced performance on a sustained attention task (Conners' Continuous Performance Test) and greater accommodative lag, indicating a diminished accommodative response. Additionally, greater accommodative lag predicted an increased probability of clinical ADHD diagnosis according to the behavioral results of the sustained attention task. Similar findings have recently been reported by Daniel and Kapoula (2019), who showed that healthy participants under accommodation/vergence conflict had a greater interference effect on the Stroop test.

In their subsequent study, Poltavski et al. (2016) used a similar research design with college students grouped according to their CISS scores into the low and high CISS symptom groups. The results showed that the high CISS symptom group committed a significantly greater number of commissions, perseverations, and had worse target detectability on Conners' Continuous Performance Test than the low CISS symptom group across both stress (-2.0 D lens) and non-stress sessions (normal vision).

1.2. Oculomotor functioning, task engagement, and automation

The above findings indicate that accommodative and/or vergence deficits may compromise sustained attention. The construct of task engagement is highly relevant for tasks requiring sustained attention and vigilance (Matthews et al., 2002). Task engagement refers to a state in which the operator is actively orientated toward a task (Hockey et al., 2009) and uses cognitive resources to process task-related stimuli (Kamzanova et al., 2011). Task engagement includes aspects of energy, concentration, and motivation (Matthews et al., 2002). A loss of task engagement puts the operator at risk for distractibility and mind wandering (Matthews et al., 2013), while greater task engagement has been shown to positively relate to vigilance task performance (Matthews et al., 2017). Given the results of Poltavski et al. (2012, 2016) and Daniel and Kapoula (2019) relating oculomotor deficits and their CISS-based symptoms to compromised sustained attention performance, the oculomotor system may affect task engagement, an important construct for several operational environments (e.g., long-haul driving, unmanned aerial vehicle missions, baggage screeners).

One applied area in which task engagement plays an important role is the monitoring of automated systems. Researchers have shown that automated systems can result in reduced task engagement over time (Neubauer et al., 2012; Saxby et al., 2013) and may compromise vigilance performance (Matthews et al., 2010). Since a large portion of the information obtained by a human operator is in the visual domain, disruptions in visual functions vital for carrying out near work (i.e., convergence and/or accommodation) may play an important role in modulating task engagement and affect operator performance when automated systems are in use. Specifically, operators with accommodative-vergence deficits using automated systems may be prone to a greater loss of task engagement over time.

The underlying rationale for the link between oculomotor deficits and task engagement is based on the relationship between stressors, task engagement, and vigilance performance. Matthews et al. (2017) used structural equation modeling to test the causal paths between a stressor (i.e., the common cold), task engagement, and vigilance performance. Results indicated that task engagement directly impacted vigilance performance and mediated the effects of stressors on vigilance performance. The authors concluded that stressors reduce cognitive resource availability for operators to remain actively engaged in a task. By extension, stressors like disruptions in accommodation and/or convergence responses may act in a similar fashion to modulate task engagement by reducing cognitive resource availability through the continuous adjustment of image blur and/or disparity. Because automated environments typically reduce task engagement from the outset, accommodative-vergence deficits may further hamper task engagement and compromise safety when operators monitor automated systems.

1.3. EEG correlates of task engagement and visual functioning

Differences in EEG bandwidths (i.e., alpha, beta, theta) have been shown to relate to certain cognitive states. Cognitive fatigue and task disengagement are typically accompanied by increases in posterior brain region alpha bandwidth activity (Barwick et al., 2012; Borghini et al., 2014; Lal and Craig, 2001; Zhao et al., 2012). Baldwin et al. (2011) reported that increases in posterior pre-stimulus higher frequency alpha power spectral density (PSD; 10–13 Hz) coincided with errors committed on a visual search task and reduced feelings of alertness. Fairclough and Venables (2006) found that alpha PSD was negatively related to ratings of task engagement during the latter half of a flight simulation task. Moreover, increased alpha power in the visual cortex is thought to reflect reduced cortical excitability (Lange et al., 2013; Romei et al., 2008) and reduced visual processing efficiency (Ergenoglu et al., 2004; Hanslmayr et al., 2005; van Dijk et al., 2008). Thus, more engagement, less fatigue, and better visual processing appear to be accompanied by attenuated alpha power in posterior brain regions.

1.4. Current study

While there is an extensive body of literature regarding cognitive states and automation, substantially less is known about the effects of oculomotor deficits on operator cognitive states in operational environments (e.g., driving, flying an aircraft). Given the relationships between AI/CI and sustained attention, the purpose of this study was to determine the extent to which oculomotor symptoms characteristic of accommodative-vergence deficits, as measured by the Convergence Insufficiency Symptom Survey (CISS), could predict participant cognitive states during the performance of a 62 min flight simulation task with or without automation. To assess the cognitive states of participants during task performance, we used self-report measures and electroencephalography (EEG). Specifically, we sought to determine how much variability in task engagement and cognitive fatigue could be accounted for by accommodative-vergence deficit symptoms above and beyond task characteristics and how the presence or absence of automation interacts with oculomotor symptoms to influence cognitive states.

With the above reviewed literature, we made five predictions. Individuals scoring higher on the CISS would: (1) report being less engaged in the task, (2) report feeling more fatigued, (3) exhibit increased posterior EEG alpha power likely in the higher alpha frequency, (4) perform worse when required to respond to high effort events, and (5) experience reduced engagement, increased fatigue, and increased posterior fast alpha power more so under conditions when automation is used.

2. Method

2.1. Participants

Ninety-five undergraduate students were recruited to participate in this study. Six participants did not complete the study and were excluded from further analysis. Five participants were excluded for not possessing 20/20 or corrected to 20/20 vision (evaluated via self-report visual acuity), resulting in a final usable sample size of 84 (25 men and 59 women) ages 18–30 years old ($M = 19.13$, $SD = 1.92$). No participants reported any form of traumatic brain injury within the past year, visual pathology, a current diagnosis of ADHD, or use of psychiatric medication. Approximately half of the participants ($n = 44$) completed the study during the morning (08:00–12:00) and the remaining participants ($n = 40$) completed the study during the afternoon (12:00–17:00). This study was approved by the University of North Dakota institutional review board. Each participant provided written consent before participating. Since ecological validity of the present investigation was not the primary purpose of the study, the researchers did not attempt to match the age and gender composition of the sample to a particular operator population.

2.2. Materials

2.2.1. Convergence Insufficiency Symptom Survey

Participants were evaluated for oculomotor symptoms characteristic of CI and AI using the Convergence Insufficiency Symptom Survey (CISS; Borsting et al., 1999). The CISS is a 15-item questionnaire that asks participants to rate the frequency to which they experience symptoms of CI (e.g., double vision, sore eyes) when reading or doing close work on a scale of 0 (*never*) to 4 (*always*). To score the CISS, items are summed to form a total score ranging from 0 to 60. Higher total scores indicate greater symptom endorsement. The CISS was chosen because previous research has indicated that it is a valid and reliable tool for identifying CI symptom severity (Borsting et al., 2003; Rouse et al., 2004). Specifically, total scores greater than or equal to 21 have been shown to identify adults with CI (sensitivity = 97.8%, specificity = 87%; Rouse et al., 2004).

2.2.2. Short Stress State Questionnaire

The task engagement scale of the Short Stress State Questionnaire (SSSQ; Helton, 2004; Helton and Näswall, 2015) was used to assess subjective task engagement. The SSSQ is a shorted version of the Dundee Stress State Questionnaire (DSSQ; Matthews et al., 2002) and consists of 24-items that load on the three higher order factors of *task engagement*, *worry*, and *distress*. Eight items load onto the task engagement scale. Participants rated from 1 (*not at all*) to 5 (*extremely*) how well either words or statements described themselves (e.g., active; I wanted to succeed on the task). SSSQ task engagement scores were computed by averaging the eight task engagement items. Higher scores indicate higher task engagement. The scale was administered pre and post task. We selected the SSSQ because it is a shortened version of the Dundee Stress State Questionnaire, which is a widely used scale that measures task engagement (Matthews et al., 2002). The task engagement scale of the full DSSQ has been shown to negatively relate to EEG alpha power (Fairclough and Venables, 2006).

2.2.3. Samn-Perelli Fatigue Scale

The Samn-Perelli Fatigue Scale (Samn and Perelli, 1982) was administered pre and post task to evaluate subjective fatigue. This single item scale has participants rate their current level of fatigue, with higher scores indicating more fatigue, on a scale consisting of the following divisions: 1 (*fully alert, wide awake*), 2 (*very lively, responsive, but not at peak*), 3 (*okay, somewhat fresh*), 4 (*a little tired, less than fresh*), 5 (*moderately tired, let down*), 6 (*extremely tired, very difficult to concentrate*), 7 (*completely exhausted, unable to function effectively*). This scale was selected because it was initially developed to assess military aircrew fatigue and correlates well with extended flight hours ($r = .52$; Samn and Perelli, 1982) and corresponds with psychomotor vigilance performance (Petrilli et al., 2006).

2.3. Simulation

The Multi-Attribute Task Battery-II (MATB; Santiago-Espada et al., 2011) was used as the experimental task. The MATB is a computerized multitasking-workload simulator that mimics the cognitive tasks pilots frequently encounter during flight; however, the MATB was designed to be used by participants with and without aviation experience (Santiago-Espada et al., 2011). Many human factors studies have used the MATB with non-aviator participants (Fairclough and Venables, 2006; Fairclough et al., 2005; Fournier et al., 1999; Hsu et al., 2015; Morgan et al., 2013; Smith et al., 2001). A screenshot of the MATB interface is displayed in Fig. 1. There are four subtasks included within the MATB: system monitoring, tracking, communications, and resource management. For this study, the resource management task was not used because it cannot be automated. That is, the tanks continually empty and would have zero quantity by the end of the simulation if participants were directed not to respond, as would be the case if the task was automated.

The system monitoring task (see Fig. 2) required participants to monitor two lights and four moving scales for changes from a normal system state. A normal system state consisted of a green left light, a colorless right light, and all four scales with the vertical shaded regions oscillating about the center of the scales. If the left light turned from green to colorless, participants had to press the F5 key on the keyboard as quickly as possible. If the right light turned from colorless to red, participants had to press the F6 key as quickly as possible. Finally, if the shaded region of the vertical scales reached either of the extremes (high or low) on the scale, participants had to press the corresponding spatially mapped F key (F1, F2, F3, or F4) on the keyboard to bring the scales back to a normal state. If the system was in a normal state, no responses from the participants were needed.

The tracking task (see Fig. 3) is a manual compensatory tracking task, which required participants to maintain a 1 cm circular reticle within a box (~2 x 2 cm) centered between two crosshairs with the use

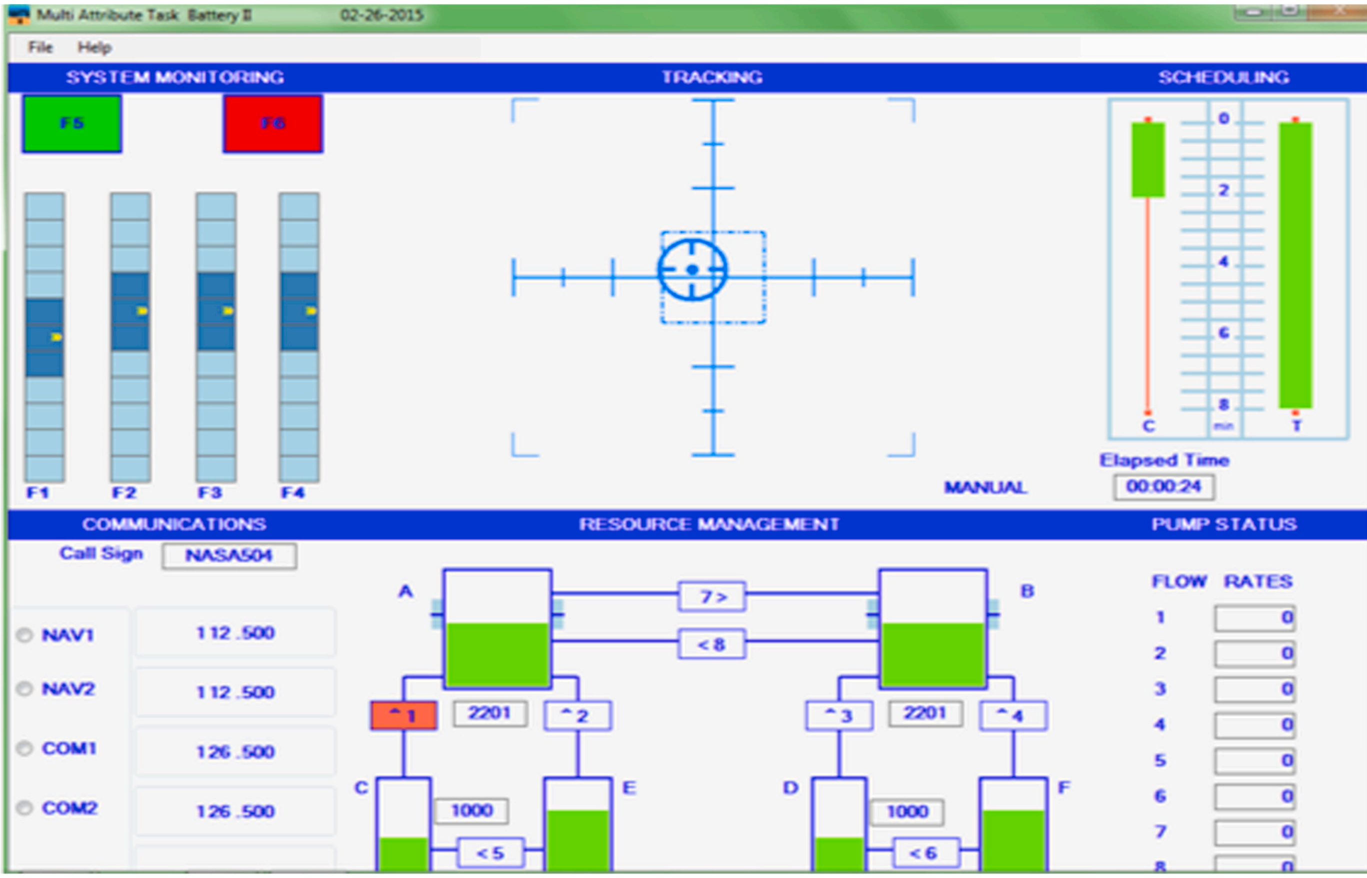

Fig. 1. A screenshot of the Multi-Attribute Task Battery-II display (Santiago-Espada et al., 2011): system monitoring (upper left), tracking (upper center), communications (lower left), and resource management (lower center) subtasks.

of a joystick (positioned in the dominant hand). The MATB program introduced random movements of the circular reticle based on pre-set low, medium, and high rates via a 4:3 horizontal-to-vertical sine wave function. The tracking task can be programmed to be in automatic mode (analogous to automatic pilot) or manual mode anytime during the simulation.

The communications task (see Fig. 4) simulates the communication between a pilot and air traffic control. Auditorily presented simulated air traffic control radio calls instruct participants to tune one of four radios to a specified frequency. Participants only responded when their call-sign, NASA 504, was indicated by the radio call. For example, a radio call might state, “NASA five zero four, NASA five zero four, tune your COMM one radio to frequency one three four point five zero zero.” The participant would then use the mouse, select the COMM one radio, and dial in the appropriate frequency using arrows located on the frequency display.

2.3.1. Conditions and testing session sequence

Three MATB conditions, each 50 min in duration, were created during a small pilot study ($N = 35$). Participants were randomly assigned to perform one of the three simulations. These conditions were labeled ***manual*, *automated*, *and psychomotor vigilance task (PVT)*.**

The manual condition required participants to manually perform both the tracking task (high reticle movement) and system monitoring task (8–10 events per min) simultaneously to simulate a manual control environment.

The automated condition simulated a highly automated environment. The tracking task was set to automatic mode and participants only monitored the system monitoring task for infrequent red light critical signals, which occurred approximately once every 4–6 min. Requiring a few number of responses was used to keep participants somewhat engaged in the task (Saxby et al., 2013).

The PVT condition was included to elucidate the effects of critical signal frequency and to mimic a standard vigilance task paradigm. In the PVT condition, the tracking task was automated and participants responded to a system monitoring red light every 10 s. This is in contrast to the automated condition in which critical signals occurred very infrequently. Moreover, in the manual condition, all possible system monitoring task events occurred, whereas in the automated and PVT conditions, only the red light occurred. In both the PVT and automated conditions, the reliability of the automation was 100%. At no point did the automation unexpectedly fail and require participants to regain manual control of the tracking task.

To measure performance consistently across the different simulations, participants also performed a 6 min performance evaluation consisting of the tracking and communications task performed together before and after their respective simulation conditions. These performance evaluations were chosen to simulate high effort situations in which a pilot must manually control an aircraft and respond to radio calls. A similar strategy has been used in previous research examining the effects of automation on performance (e.g., Saxby et al., 2013). In the current study, participants responded to 22 randomized air traffic control radio calls, half of which corresponded to the participant’s call sign (NASA 504) and required a participant response. These radio calls occurred in 5 s intervals. Separating the two performance evaluations was the participant’s randomly assigned condition. Auditory cues directed participants when to perform the subtasks corresponding to either the performance evaluation or their assigned condition. Outcomes measures included tracking task root-mean-square deviation from the center point in pixels and communications task number of correct

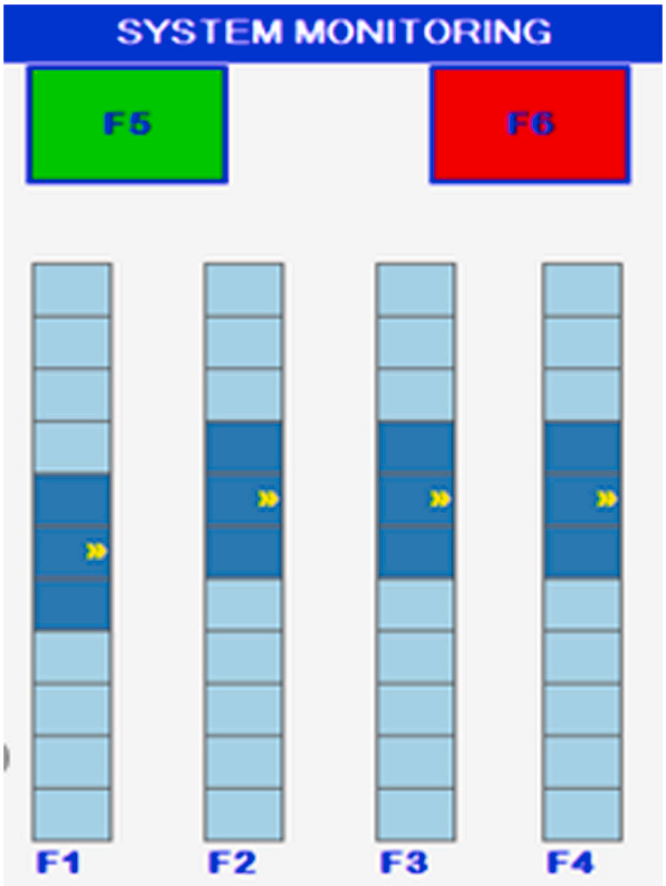

Fig. 2. The system monitoring task.

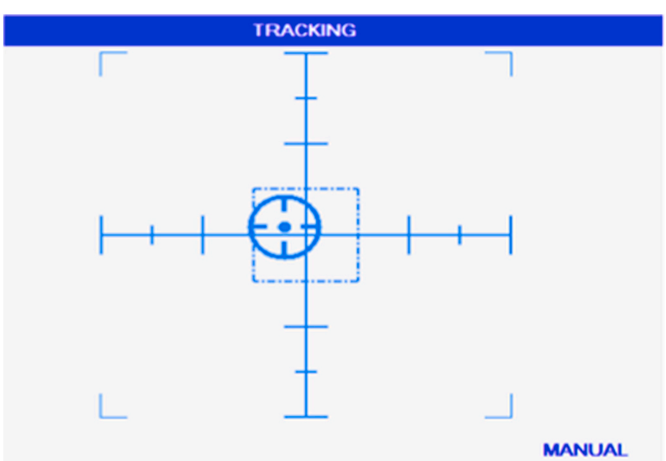

Fig. 3. The tracking task.

responses, mean response time, and d-prime. The *dprime()* function from the *psycho* package (Makowski, 2018) in R was used to compute d-prime.

2.4. Electroencephalography (EEG) recording

EEG was recorded using the Advanced Brain Monitoring (Carlsbad, California) X-10 and X-24 wireless Bluetooth systems. Approximately half of the participants ($n = 46$) were tested with the X-10 because the X-24 hardware malfunctioned and required repairs. The X-10 and X-24 incorporate 9-channel and 20-channel electrode strips, respectively,

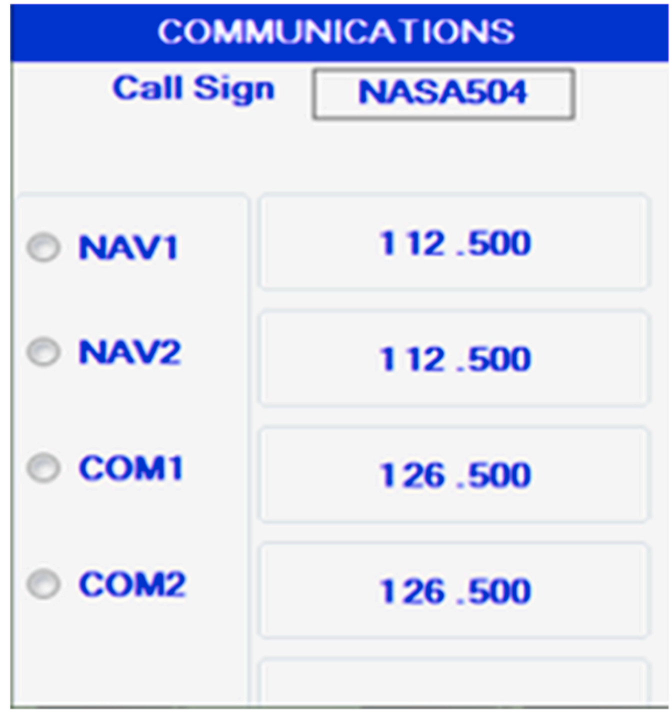

Fig. 4. The communications task.

with electrode locations placed according to the international 10/20 system. Reference electrodes for both systems were placed at the mastoids. Both systems output the same variables and use the same artifact decontamination procedure.

EEG data were sampled at 256 Hz and filtered with 50, 60, 100, and 120 Hz notch filters with a Low Pass FIR filter online during the data collection process. Power spectral density (PSD) was then calculated on a second-by-second epoch frequency by applying a 50% overlapping Kaiser window for data smoothing to three data point windows consisting of 256 decontaminated data points each. These data were then subjected to Fast Fourier Transformation and $\log_{10}$ transformed to yield final PSD values for 1 Hz bins ranging from 1 to 40 Hz. For analyses, we used relative PSD values, which were computed automatically by the data acquisition software (Advanced Brain Monitoring, 2009). The reviewed literature suggests that increases in alpha power in the parietal-occipital area can indicate reductions in task engagement (Fairclough and Venables, 2006) and visual processing efficiency (Ergenoglu et al., 2004). Moreover, Baldwin et al. (2011) reported that greater fast alpha power in the occipital region generally precedes errors during vigilance. Therefore, our analyses focused on the POz site (the most posterior midline site shared by the X-10 and X-24 EEG systems) and we split relative alpha power into slow and fast frequency ranges. Per the EEG manufacturer, slow and fast alpha were defined as 8–10 Hz and 10–13 Hz, respectively (Advanced Brain Monitoring, 2009).

2.5. Procedure

Participants first provided written consent after arriving at the laboratory. Next, participants completed a brief demographics questionnaire and the CISS. Participants then completed pre-task versions of the SSSQ and Samn-Perelli Fatigue Scale.

A trained research technician then applied the EEG system to the participant's head and tested electrode impedances. Any electrodes exceeding the manufacturer's recommended impedance threshold of 80 kΩ (Advanced Brain Monitoring, 2009) were adjusted. Participants then watched an instructional video describing how to complete the MATB. After this video, participants completed a 12 min, technician facilitated

MATB practice session. During the practice session, participants performed each MATB subtask individually for 3 min each. Then, participants practiced a performance evaluation for 3 min. Once the practice session was complete, participants were randomly assigned to either the automated (n = 31), manual (n = 26), or PVT (n = 27) simulation conditions and given an appropriate briefing. Then, the MATB simulation commenced following a pre-performance evaluation (6 min), assigned simulation condition (50 min), post-performance evaluation (6 min) sequence. During the MATB, participants sat at a normal working distance from the screen (~30–50 cm) under regular ambient indoor lighting (~500 lumen/meter^2). After the MATB, participants completed post versions of the SSSQ and Samn-Perelli Fatigue Scale. Fig. 5 displays the experimental setup.

Fig. 5. A photo of the experimental setup.

2.6. Data processing and analytics

Descriptive statistics were computed for each self-report measure. 3 (Condition) x 2 (time of day) ANOVAs were used to determine if Condition or time of day affected the CISS or any of the outcome measures.

EEG data during the MATB performance evaluations and simulation conditions were sectioned off using timed markers. The 50 min simulation conditions were separated into five, 10 min intervals and 5% trimmed means were computed for fast and slow alpha PSD. The first and last 10 min of each simulation condition (excluding performance evaluations) were analyzed. Post-task Samn-Perelli Fatigue Scale and SSSQ task engagement scores were also used as dependent variables. These analyses focused only on post MATB questionnaire scores because our research question was not concerned with changes in cognitive states from pre to post but rather an overall state during the MATB. Furthermore, initial analyses showed that pre task scales significantly correlated with both the post task measures and the CISS. Therefore, pre task measures accounted for shared variance in post task measures. It should be noted that these correlations were stronger for SSSQ task engagement scores.

Outcome measures (SSSQ task engagement scores, Samn-Perelli Fatigue Scale scores, POz alpha power, and MATB performance) were analyzed using hierarchical multiple regression. Models were specified in three steps. Step 1 included simulation condition as a predictor, with the manual condition as the reference category. The manual condition was chosen as the reference because we were interested in the effects of automation on outcome measures. Step 2 added the CISS as a predictor, which was mean centered (Cohen et al., 2003). Finally, Step 3 added the interaction between the CISS and simulation condition to uncover potential differences in slopes between the simulation conditions with the CISS as a continuous predictor (i.e., potential steeper slopes for those using automation). Change in R^2 (ΔR^2) with corresponding F-tests were used to determine if the addition of predictors in each step significantly increased variance explained. Analyses were conducted using R (R Core Team, 2017).

Outliers and influential observations were identified using studentized residuals and Cook's distances. Specifically, observations with a studentized residual more extreme than ± 2.5 and a Cook's distance greater than $4/n - k - 1$, where n is the number of participants and k is the number of predictors (Hair et al., 1998), were deemed outliers with significant influence. For the analysis of SSSQ engagement scores, one participant was removed due to a significant influence on all three models. It should be noted that the removal of this participant did not influence null hypothesis decisions. Missing data were excluded on a dependent variable basis (i.e., pairwise by analysis). Four participants failed to complete the SSSQ questionnaire, resulting in a sample size of $N = 79$ for SSSQ engagement scores. One participant failed to complete the Samn-Perelli Fatigue Scale and was excluded, resulting in a sample size of $N = 83$ for this scale. For EEG alpha power, seven participants were excluded for either technical malfunctions ($n = 6$) or extremely poor data quality ($n = 1$), resulting in a sample size of $N = 77$ for EEG data.

3. Results

3.1. Initial data analysis

Descriptive statistics for self-report measures are displayed in Table 2. Importantly, a 3 (Condition) x 2 (time of day) ANOVA on total CISS scores revealed no significant differences between the three simulation conditions [$F(2, 74) = 0.08$, $p = .920$], time of day [$F(1, 74) = 0.44$, $p = .509$], or an interaction between condition and time of day, $F(2, 74) = 2.19$, $p = .119$. Moreover, 3 × 2 ANOVAs did not reveal any significant main effects for time of day or the interaction between Condition and time of day for all outcome measures (all p-values > .05). These ANOVAs also did not reveal significant differences between the conditions on pre-task measures (all p-values > .05).

3.2. Subjective engagement – SSSQ

Hierarchical regression model parameters predicting SSSQ engagement scores are displayed in Table 3. The first model with Condition predicting subjective task engagement scores was not significant. However, the second model with the addition of CISS scores as a predictor resulted in a significant regression model and a significant increase in R^2 ($\Delta R^2 = 0.09$, $p = .006$). The negative regression coefficient for CISS scores indicates that the more CI symptoms participants reported, the less engaged participants felt during the task. Finally, the inclusion of the CISS x Condition interaction did not significantly increase model fit, indicating that a similar negative slope was evident across the MATB conditions.

3.3. Subjective fatigue – Samn-Perelli Fatigue Scale

Samn-Perelli Fatigue Scale scores were analyzed in the same fashion as task engagement. The Step 1 model accounted for a significant amount of variance (see Table 4). Specifically, compared to the manual control condition, the automated and PVT conditions resulted in higher ratings of fatigue. The addition of the CISS in Step 2 resulted in a significant overall model and a significant increase in R^2 ($\Delta R^2 = 0.12$, $p = .002$). CISS scores significantly predicted subjective fatigue, with higher CISS scores being associated with higher Samn-Perelli scores. In other words, the more CI symptoms participants endorsed, the more fatigued they generally felt after performing the MATB. Finally, Step 3 resulted in a significant overall model, but a non-significant increase in R^2. None of the interaction terms approached significance and were thus not explored further.

Table 2
Descriptive statistics for self-report measures by simulation condition.

Variable	Manual			Automated			PVT		
	n	*M*	*SD*	*n*	*M*	*SD*	*n*	*M*	*SD*
CISS	26	14.50	7.50	31	16.06	8.03	27	15.78	6.19
Pre SSSQ Engagement	25	3.61	0.52	29	3.75	0.78	25	3.54	0.39
Post SSSQ Engagement	25	3.38	0.52	29	3.35	0.72	25	3.04	0.79
Pre Samn-Perelli	26	2.77	0.86	31	2.71	0.94	26	3.00	0.80
Post Samn-Perelli	26	3.58	1.24	31	4.19	1.67	26	4.53	1.03

Table 3
Hierarchical regression predicting SSSQ task engagement scores from simulation condition and CISS scores.

Step and Predictors	F_{model}	*b*	*SEb*	*β*	R^2	ΔR^2
Step 1	1.18				.03	
Condition						
PVT		−0.27	0.19	−0.18		
Automated		−0.03	0.18	−0.02		
Step 2	3.54*				.12	.09**
Condition						
PVT		−0.21	0.18	−0.15		
Automated		0.01	0.18	0.01		
CISS		−0.03	0.10	−0.31**		
Step 3	2.10				.13	.00
Condition						
PVT		−0.22	0.19	−0.15		
Automated		0.00	0.18	0.00		
CISS		−0.02	0.02	−0.26		
PVT x CISS		−0.00	0.03	−0.02		
Automated x CISS		−0.01	0.02	−0.06		

*$p < .05$, **$p < .01$.

Table 4
Hierarchical regression predicting Samn-Perelli Fatigue Scale ratings from simulation condition and CISS scores.

Step and Predictors	F_{model}	*B*	*SEb*	*β*	R^2	ΔR^2
Step 1	4.10*				.10	
Condition						
PVT		0.91	0.34	0.35**		
Automated		0.69	0.32	0.28*		
Step 2	6.52***				.21	.12**
Condition						
PVT		0.80	0.32	0.30*		
Automated		0.61	0.30	0.25*		
CISS		0.06	0.02	0.34**		
Step 3	4.14**				.22	.01
Condition						
PVT		0.79	0.22	0.30*		
Automated		0.60	0.30	0.24+		
CISS		0.07	0.03	0.44*		
PVT x CISS		−0.03	0.05	−0.07		
Automated x CISS		−0.02	0.04	−0.10		

+$p < .10$, *$p < .05$, **$p < .01$, ***$p < .001$.

3.4. EEG alpha power

EEG slow and fast alpha power at POz were analyzed for the first and last 10 min of the simulation condition period. For slow alpha, no significant regression models were found for either time period (all *p*-values > .05). Likewise, no significant models were found for the first 10 min of the task for fast alpha power. However, during the final 10 min of the task, a pattern similar to subjective engagement was found for fast alpha power – the first step with just Condition as a predictor was not significant (see Table 5), but the inclusion of CISS scores in Step 2 resulted in a significant overall model as well as a significant increase in R^2 ($\Delta R^2 = 0.09$, $p = .027$). The more symptoms participants reported, the more fast alpha power was generally exhibited during the final 10 min of the task. The inclusion of the CISS by Condition interaction did not result in a significant increase in R^2; however, the overall model accounted for a significant amount of variance, $F(5, 71) = 3.16$, $p = .013$, $R^2 = 0.18$. An examination of the model parameter estimates for the interaction terms revealed a marginally significant slope for CISS scores predicting POz alpha power in the PVT condition relative to the manual condition. In light of this, we examined the simple slopes for CISS scores predicting POz fast alpha power at each level of Condition during the last 10 min of the MATB. Significant, positive slopes were found for the PVT ($b = 0.01$, $SE = 0.01$, $p = .013$) and automated ($b = 0.01$, $SE = 0.002$, $p = .046$) conditions but not for the manual condition ($b = 0.001$, $SE = 0.003$, $p = .693$). This indicates that the relationship between POz fast alpha power and CI symptoms marginally changed depending on the qualitative structure of the MATB. Fig. 6 displays these slopes.

3.5. MATB performance

Models were also constructed predicting MATB performance from CISS scores during the performance evaluations, which required participants to employ more effort than their assigned conditions. No significant models were found (all *p*-values > .05).

4. Discussion

The results of this study indicate that self-report symptoms of accommodative-vergence deficits measured via the CISS account for a statistically significant amount of variance in participant task engagement and cognitive fatigue during the performance of a 62 min flight simulation task. Participants with higher CISS scores generally reported

Table 5
Hierarchical regression predicting final 10 min POz fast alpha power from simulation condition and CISS scores.

Step and Predictors	F_{model}	*b*	*SEb*	*β*	R^2	ΔR^2
Step 1	2.25				.06	
Condition						
PVT		−0.03	0.04	−0.09		
Automated		0.05	0.04	0.18		
Step 2	4.15**				.16	.09*
Condition						
PVT		−0.03	0.04	−0.10		
Automated		0.04	0.04	0.15		
CISS		0.01	0.00	0.30**		
Step 3	3.16*				.18	.03
Condition						
PVT		−0.03	0.04	−0.09		
Automated		0.05	0.04	0.16		
CISS		0.00	0.00	0.07		
PVT x CISS		0.01	0.01	0.25+		
Automated x CISS		0.00	0.00	0.16		

+$p < .10$, *$p < .05$, **$p < .01$.

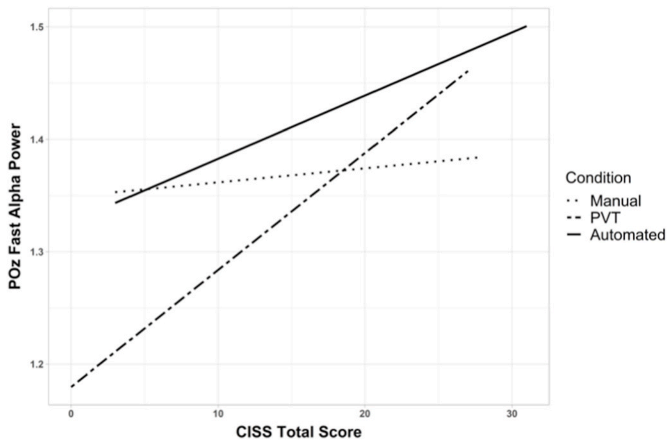

Fig. 6. Regression lines for CISS scores predicting POz fast alpha power during the final 10 min of the simulation by simulation condition.

being less engaged and more fatigued after performing the MATB. Furthermore, the CISS was positively related to fast alpha power in the parietal-occipital region during the final 10 min of the MATB. Importantly, these findings remained after the variance due to simulation condition was accounted for. That is, the CISS accounted for variance in cognitive states beyond the task itself. To our knowledge, this is the first study relating accommodative-vergence deficit symptoms to measures of task engagement and cognitive fatigue during a task that mimics a dynamic work environment. Despite the relationships found between CISS scores and cognitive states, we did not find any evidence of CISS scores relating to task performance.

4.1. CISS, task engagement, and fatigue

These results suggest that those with symptoms characteristic of accommodative-vergence deficits are more at risk for task disengagement and increased cognitive fatigue during extended working conditions requiring continuous visual monitoring. When attempting to compensate for poor accommodation and/or vergence, additional cognitive resources may be required for optimal visual processing (Poltavski et al., 2012). Over time, this additional resource demand may increase fatigue and reduce an operator's propensity for efficient cognitive processing (i.e., task engagement). Our EEG results provide some support for this claim. Increased alpha power in the occipital lobe is thought to represent reduced cortical excitability (Lange et al., 2013). Additionally, researchers have shown that increased posterior fast alpha power is predictive of missed targets during a visual search vigilance task (Baldwin et al., 2011) and that increased alpha power in posterior brain regions is indicative of cognitive fatigue (Borghini et al., 2014). Our EEG results indicated that CISS scores positively predicted fast alpha power but only after participants performed the MATB for at least 40 min. Because the relationship between CISS scores and POz alpha power appeared after 40 min of time on task, this supports our initial hypothesis that accommodative-vergence stress relates to cognitive fatigue-like constructs. Over time, accommodative-vergence stress accumulates from prolonged close work, which diverts attentional resources away from the task to resolve image blur and disparity cues. Therefore, we expected CISS scores would relate to EEG alpha power during the last 10 min of the task as opposed to the first 10 min. If CI symptoms were related to alpha power and cognitive fatigue-like constructs, this relationship would only manifest after participants experience accommodative-vergence stress from prolonged close work and attentional resources are diverted from the task. The results of this study supported this assertion.

The positive relationship between CISS scores and reports of fatigue supports prior research showing a reduced accommodative response and increased ratings of fatigue over the course of a 2 h driving simulation (Vera et al., 2016). These authors screened out individuals with potential accommodative deficits, so it is unclear if those with an exisitng deficit would have shown a sharper decrease in the accommodative response and greater cognitive fatigue. Moreover, no results relating accommodation to driving performance were reported. Vera and colleagues concluded that the accommodative response could be an objective measure of driver fatigue. Our results support this assertion in that those with more oculomotor symptoms of accommodative-vergence deficits generally report increased feelings of fatigue and less task engagement.

Futhermore, our results support Matthews and colleagues' (2017) findings that operator stressors likely reduce the availability of cognitive resources available for task performance. Matthews and colleagues examined the common cold as a stressor, while the current study examined oculomotor stress quantified with the CISS. Despite not finding a relationship between CISS scores and MATB performance, the relationships between CISS scores and the underlying constructs of task engagement and fatigue necessary for efficient task performance lends credence to the fitness of the oculomotor system as a potential variable that modulates cognitive states.

4.2. AI/CI symptomology and automation

Generally, we did not find strong evidence supporting our hypothesis that automation exacerbates the negative effects of increased AI/CI symptomology. The relationship between the CISS and subjective measures (SSSQ task engagement and Samn-Perelli Fatigue Scale) did not change as a functioin of simulation condition. However, simulation condition did marginally interact with CISS scores for POz fast alpha power, indicating that automation may change cortical activation differently for those with higher symptoms of accommodation/vergence deficits. Specifically, CISS scores significantly predicted POz fast alpha power during the final 10 min of the task for those assigned to the automated and PVT conditions but not the manual condition. Automated systems tend to result in less task engagement over extended use (Saxby et al., 2013). Therefore, we predicted that those with higher CISS scores would exhibit less engagement under automation than manual control. However, we did not find this same interactive effect with SSSQ engagement scores as we did with POz fast alpha power. Self-report measures require operators to make retrospective judgements of questions relating to task engagement (e.g., I was committed to attaining my performance goals). Thus, participants in the manual control condition may have had similar retrospective accounts of the task over the course of the simulation to those in the automated and PVT conditions after extended time-on-task. Likely, automation and CI/AI symptoms interact to change the efficiency to which information is processed (Hockey, 1997).

4.3. CI/AI symptomology and MATB performance

Although CISS scores did not predict task performance, the results regarding task engagement and cognitive fatigue are in line with previous studies that did find performance decrements with those experiencing accommodative-vergence stress. For instance, Poltavski et al. (2012) induced accommodative-vergence stress with −2.0 diopter lenses in healthy individuals and observed increased reaction times, more response variability, and less signal detection on a sustained visual attention task. These performance decrements are similar to those experienced when individuals become disengaged from a task (Berka et al., 2007; Matthews et al., 2002). One reason why CISS scores likely did not predict performance in this study is because those with higher scores on the CISS may not have had a sufficient accommodative-vergence deficit. Without a formal oculomotor examination, there was no way of knowing if scores on the CISS truly reflected if participants had severe enough accommodative-vergence deficits to affect performance. Relatedly, objectively measuring the oculomotor responses and using these measures as predictors may have accounted for more variance in all outcome measures. Another explanation is that participants may have used compensatory effort to overcome oculomotor stress to adequately perform the MATB (Hockey, 1997).

4.4. Practical implications

The main application of the current research is the enhancement of operator cognitive states. While researchers continue to explore avenues for enhancing cognitive performance, the current results suggest that operator cognitive states may be enhanced through augmentation of the oculomotor system. Indeed, previous research has shown that stressing the oculomotor system can produce inattentive behavioral responses (e.g., Daniel and Kapoula, 2019; Poltavski et al., 2012). Therefore, one "bottom-up" approach for operator cognitive state enhancement may be to first train the oculomotor system with vision-based training programs to support task engagement and sustained attention. The value of office-based vision therapy for CI and AI has been well established in clinical samples. For example, according to the results of a longitudinal study conducted by the Convergence Insufficiency Treatment Trial Study Group (2009), administration of a standard 12-week office-based vergence/accommodative therapy in children between 9 and 17 years of age diagnosed with convergence insufficiency produced an 84.4% remission rate one year following treatment completion. Clinical outcome measures included both clinical markers of convergence insufficiency and CISS scores. The latter scores significantly decreased following 12 weeks of treatment from a mean of 25.6 (SD = 8.1) to 8.6 (SD = 4.8) and remained unchanged one year later.

In non-clinical samples, oculomotor training regimens could also be investigated. For example, computer-based platforms like HTS iNet (Serna et al., 2011) combined with transcranial direct current stimulation (tDCS) applied to the visual cortex, may increase visual system robustness and buffer against resource depletions due to oculomotor stress over time. Indeed, Wendel et al. (2017) showed that tDCS applied to the visual system can improve the accommodative response to stimuli at standard working distances. Since the accommodative and vergence responses are largely involuntary, individuals working in extended vigilance environments (i.e., baggage screeners) may still benefit from reductions in CI/AI symptomology.

Another practical implication for these results is operator selection and screening. While several occupations like aircraft pilots require the assessment of accommodative and vergence responses, other occupations, like airport security personnel, do not (Czarnecki, 2018). Individuals with accommodative and/or vergence deficits operating in conditions requiring sustained vigilance may be at higher risk for missing critical signals and becoming disengaged from their task. Perhaps screening for or identifying these individuals and improving their oculomotor responses could enhance their workplace performance and comfort. The CISS could be used as a cost-effective rapid screening tool for initially identifying individuals with accommodative and/or vergence problems that may compromise sustained attention. These individuals could then be referred for a more in-depth optometric exam and potential treatment.

4.5. Limitations and future research

The main limitation of this study was that we only collected self-report symptoms of CI/AI and did not collect objective measures of vergence and/or accommodation during the simulation. These measures would further support the relationship between the oculomotor system and cognitive states. Another limitation is that the simulation duration used in this study was much shorter than what would be experienced in true working conditions. Many unmanned aerial vehicle missions can last more than 6 h, and truck drivers continuously drive for several hours. It should also be noted that ΔR^2 values found for the inclusion of CISS scores were fairly small (ΔR^2 = 0.09 - 0.12). Although a small amount of variance was accounted for by CISS scores, the findings should not be dismissed. Prentice and Miller (2016) provided a series of rationales for when small effects could be considered "impressive." One of Prentice and Miller's rationales is that minimal manipulation of the independent variable resulting in a small effect is still meaningful. Although we did not experimentally manipulate convergence or accommodative deficits, we collected a minimal measure of existing symptoms using the self-report CISS. Moreover, the short task duration also contributes to a minimal manipulation. Therefore, the minimal measurement of the oculomotor system and short task duration support the importance of these findings and hopefully sparks more research in this area.

Given these limitations, the results of this study should be considered preliminary. While we have provided evidence for accommodative-vergence responses relating to operator cognitive states, further research is required to clearly elucidate the effects accommodative-vergence stress has on operator cognitive states. Future research may recruit individuals with diagnosed accommodative-vergence deficits and incorporate objective measures of oculomotor functioning during task performance. Future studies may also manipulate oculomotor stress in a similar manner as Poltavski et al. (2012). Moreover, the use of brain stimulation techniques applied to the visual cortex may offer a route to further explore the functional relationship between the oculomotor system and cognitive states (Wendel et al., 2017). Finally, using eye-tracking technology could also provide more information about visual behaviors for individuals experiencing oculomotor stress.

5. Conclusion

Taken as a whole, the results of this study indicate that symptoms of oculomotor deficits could hamper optimal operator cognitive states in working conditions. We showed that self-report symptoms of accommodative-vergence deficits can account for variability in operator task engagement and cognitive fatigue during the performance of a multifaceted task that mimics the cognitive tasks experienced by several work conditions (e.g., airline pilots, military drone pilots, truck drivers). Future studies should experimentally examine the relationship between accommodative-vergence responses and the cognitive states of operators in complex, operational environments.

Data statement

Currently, our data are not available for posting in the public domain because we are in the process of using the data for developing classification algorithms for different operational conditions in which workers encounter automation. However, individuals interested in these data can contact Kyle Bernhardt at kyle.bernhardt@und.edu for permissioned access.

Declaration of competing interest

None.

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