



## Associations between accommodative dynamics, heart rate variability and behavioural performance during sustained attention: A test-retest study



Beatriz Redondo<sup>a</sup>, Jesús Vera<sup>a,\*</sup>, Antonio Luque-Casado<sup>b,c</sup>, Amador García-Ramos<sup>d,e</sup>, Raimundo Jiménez<sup>a</sup>

<sup>a</sup> Department of Optics, Faculty of Sciences, University of Granada, Granada, Spain

<sup>b</sup> Center for Sport Studies, King Juan Carlos University, Madrid, Spain

<sup>c</sup> Mind, Brain and Behaviour Research Center (CIMCYC), University of Granada, Granada, Spain

<sup>d</sup> Department of Physical Education and Sport, Faculty of Sport Sciences, University of Granada, Granada, Spain

<sup>e</sup> Department of Sports Sciences and Physical Conditioning, Faculty of Education, CIEDE, Catholic University of Most Holy Concepción, Concepción, Chile

### ARTICLE INFO

#### Keywords:

Accommodative response  
Microfluctuations of accommodation  
Reaction time  
Psychomotor vigilance task  
Multiple regression analysis  
Heart rate variability

### ABSTRACT

This study evaluated the time-on-task effect of a sustained attention task on the accommodative response, explored the link between ocular accommodation, cardiac autonomic regulation and behavioral performance, and tested the inter-session repeatability of these results by performing the same experimental procedure on different days. The accommodative response was measured in 25 university students using a WAM-5500 autorefractor, while participants performed a 10-minute psychomotor vigilance task at 50 cm. There were no time-on-task effects for the lag of accommodation, whereas the microfluctuations of accommodation and reaction time were modulated as a function of time-on-task, observing a progressive increment of both variables over time. Multiple regression analysis revealed that the microfluctuations of accommodation were a reasonably good predictor of behavioral performance. Analysis of inter-session repeatability showed that ocular accommodation, heart rate variability and reaction time had a low to moderate level of repeatability between two measurements. The microfluctuations of accommodation were sensitive to time-on-task effects during sustained attention, with a lower stability of accommodation being linked to reduced behavioral performance. The predictive capacity of the variability of accommodation for behavioral performance might be explained by the brain mechanisms shared by the ocular dynamics and attentional state; however, future studies would be required to elucidate this association. The low to moderate inter-session repeatability indicated that results in two measurement periods cannot be considered interchangeable, and therefore, the results of this study should be interpreted cautiously in this regard.

### 1. Introduction

It is well known that cognitive demand alters the activity of the autonomic nervous system, with these alterations being manifested in different physiological parameters such as skin conductance, respiration rate, blood pressure and heart rate variability (HRV) (Haapalainen, Kim, Forlizzi, & Dey, 2010). HRV is a particularly sensitive index of interaction between the autonomic nervous system and the cardiovascular system, which provides indirect information about the sympathovagal balance by measuring the temporal oscillations between successive R-R interval variations of sinus origin (Malik et al., 1996; Pumplrla, Howorka, Groves, Chester, & Nolan, 2002). In addition to physiological variables, a number of ocular parameters, including

oculomotor movements (Di Stasi et al., 2017; Grier et al., 2003), pupil size (Macatee, Albanese, Schmidt, & Cogle, 2017), blink rate (McIntire, McKinley, Goodyear, & McIntire, 2014), ocular aberrations (Jiménez, Cárdenas, Anera, & Jiménez, 2017), visual perception (Park, Van Bavel, Vasey, Egan, & Thayer, 2012), and intraocular pressure (Vera, Jiménez, García, & Cárdenas, 2017) have also been demonstrated to be sensitive to autonomic balance, exhibiting different behaviors depending on the level of arousal. Similarly, the accommodative response (AR), which reflects the precision of the accommodative system in providing a clear image of a target of interest on the fovea (Cogan, 1937; Millodot, 2014), has been shown to be impaired with cognitively demanding tasks, which is predominantly attributable to attenuated involvement in the parasympathetic

\* Corresponding author at: Department of Optics, University of Granada, Campus de la Fuentenueva 2, 18001 Granada, Spain.  
E-mail address: [veraj@ugr.es](mailto:veraj@ugr.es) (J. Vera).

<https://doi.org/10.1016/j.visres.2019.07.001>

Received 20 February 2019; Received in revised form 3 July 2019; Accepted 8 July 2019

Available online 28 August 2019

0042-6989/ © 2019 Elsevier Ltd. All rights reserved.

innervation (Bullimore & Gilmartin, 1988; Davies, Wolffsohn, & Gilmartin, 2005; Davies, Wolffsohn, & Gilmartin, 2009; Gilmartin, 1986). Also, ocular accommodation has been demonstrated to be sensitive to circadian variations, suggesting that the time of measurement (morning vs. night) might lead to different results (McDougal & Gamlin, 2015). Based on this, autonomic nervous system alterations seem to be partially captured by cardiovascular and ocular accommodation activity. As such, objective assessment of these physiological parameters might be used as an indicator of the state of the autonomic nervous system.

Another important parameter related to the accommodative function, which may be affected by cardiopulmonary signals or other rhythmical physiological systems, is microfluctuations of accommodation (Charman & Heron, 1988; Collins, Davis, & Wood, 1995; Jeng et al., 2014; Winn, Pugh, Gilmartin, & Owens, 1990). This index is based on AR not remaining constant throughout time when a subject is focusing on a stationary target, but instead, exhibiting small temporal variations of approximately 0.5 diopters (D), providing a mechanism to sustain AR and to acquire directional cues for the dynamic AR (Metlapally, Tong, Tahir, & Schor, 2016). The microfluctuations of accommodation are a result of central neurological control (Charman & Heron, 1988; Cogan, 1937; Gilmartin, 1986; Winn & Gilmartin, 1992), and it can be used as an indicator of the negative feedback of AR (Gray, Gilmartin, & Winn, 2000). Some studies have demonstrated that an increase in cognitive engagement might improve the accuracy of AR and reduce the microfluctuations of accommodation (Hynes, Cufflin, Hampson, & Mallen, 2018; Malmstrom, Angeles, Randle, Bendix, & Weber, 1980; Roberts, Manny, Benoit, & Anderson, 2018; Rosenfield, Jahan, Nunez, & Chan, 2015).

The ability to maintain optimal cognitive engagement in humans is not constant over time, and an extended period of attentional demands on a single task leads to fluctuations and reduction in performance, i.e., a time-on-task effect or vigilance decrements (Grier et al., 2003; Lim et al., 2010). In this regard, functional magnetic resonance imaging studies of sustained attention have shown that the execution of a psychomotor vigilance task (PVT) modulates brain areas and networks associated with attentional processes (Asplund & Chee, 2013; Lim et al., 2010). Importantly, numerous everyday activities require to preserve the cognitive capabilities for a long period of time and, therefore, are conditioned by the time-on-task effect (e.g., driving, Larue, Rakotonirainy, & Pettitt, 2011), performing surgery (Gawande, Zinner, Studdert, & Brennan, 2003), attending academic lessons (Steinmayr, Ziegler, & Träuble, 2010) and handling air-traffic control (Loft, Sanderson, Neal, & Mooij, 2007). Therefore, investigation into underlying physiological factors linked to performance fluctuations in attention over time is highly relevant. Due to a reduced vigilance state and the mitigated predominance of parasympathetic activity linked to prolonged attentional tasks (Davies et al., 2009), it is plausible to expect that ocular accommodation might be modulated by function of time-on-task, and these effects on AR could be associated with variations in autonomic vagal control. However, to the best of our knowledge, there are no studies analysing the effect of time-on-task during sustained attention on AR and their relationship with HRV since previous studies just considered short periods of cognitive demand (Davies et al., 2009; Davies et al., 2005). The previously mentioned neuropsychological signals (e.g., accommodation dynamics and HRV) have demonstrated the capacity to estimate the state of the autonomic nervous system, which is linked to task performance in multiple activities such as driving (Borghini, Astolfi, Vecchiato, Mattia, & Babiloni, 2012) or controlling air traffic (Brookings, Wilson, & Swain, 1996). Notably, the consideration of different physiological variables that may be sensitive to autonomic nervous system changes would allow to enhance the ability of predicting the state of the autonomic nervous system by objective and continuous indices.

To address the caveats found in the scientific literature, the main aims of this investigation were: (1) to assess the effect of time-on-task

during a PVT on the lag and microfluctuations of accommodation in young adults; (2) to establish the association of behavioral performance (reaction time during the PVT) with accommodative function and vagal control, as measured by HRV; and (3) to evaluate the inter-session repeatability of these effects, since it was well known that ocular accommodation and HRV measures showed large day-to-day variations (McDougal & Gamlin, 2015) and inclusion of two identical experimental sessions on two different days in the same participants could help to reduce random sources of variability (Streiner, Norman, & Cairney, 2015). We hypothesized that increments of the time-on-task would be associated with a gradual decrement in HRV and behavioral performance, along with greater values of lag and microfluctuations of accommodation (Davies et al., 2005; Jeng et al., 2014; Luque-Casado, Perales, Cárdenas, & Sanabria, 2015), with these changes being similar in two sessions performed under the same experimental conditions. In addition, these physiological indices might have an association with cognitive performance, although the lack of previous evidence did not permit us to elaborate a clear hypothesis in this regard.

## 2. Methods

### 2.1. Participants and ethics

Twenty-five undergraduate students (13 women and 12 men) participated in the study, ranging in age from 18 to 33 years (mean age  $\pm$  standard deviation,  $SD = 22.4 \pm 4.5$  years). All participants had normal or corrected-to-normal vision (visual acuity of  $\leq 0$  logMAR in each eye). They were compensated with soft contact lenses when necessary, with all contact lens users having at least one year of experience. Refractive errors were limited to myopia  $< 0.50$  D, hyperopia  $< 1.00$  D, and astigmatism or anisometropia  $< 1.00$  D. All participants included had low visual discomfort (cut off value  $< 24$ ), as measured by the Conlon visual discomfort survey (Conlon, Lovegrove, Chekaluk, & Pattison, 1999). They were also free of any systemic disease, were not under pharmacological treatment and were non-smokers. Before each experimental session, they were asked to abstain from alcohol and from caffeine drinks for 24 and 12 h, respectively, and to sleep for at least 7 h on the previous night. Both experimental sessions were carried out at the same time of the day ( $\pm 1$  h) in order to control for possible circadian variations. When participants arrived at the laboratory, the level of alertness/sleepiness was assessed using the Stanford Sleepiness Scale (Hoddes, Zarcone, & Dement, 1973), in order to check that participants performed both sessions under similar levels of activation. The present study was conducted according to the tenets of the Declaration of Helsinki, and under the guidelines of the University Institutional Review Board (IRB approval: 546/CEIH/2018).

### 2.2. Instruments and measures

#### 2.2.1. Psychomotor vigilance task

The visual stimulus used during the measurement of accommodation consisted of a modified version of the psychomotor vigilance task (PVT) used in previous research (Luque-Casado et al., 2015; Vera et al., 2019). For stimulus presentation and response collection, a 15.6" LCD laptop personal computer (PC) and E-Prime software (Psychology Software Tools, Pittsburgh, PA, USA) were used. The PC keyboard was used for response collection. This task (PVT) allows to measure attention or vigilance, and is based on a simple visual reaction time-task in which a target stimulus is presented at random inter-stimulus intervals for a standard administration length of 10 min (Basner & Dinges, 2011). This duration of the PVT at 10 min had been recommended in studies for which time constraints were not of concern, although shorter versions of 5 min have also been proposed as viable alternatives. Nevertheless, the 10-minute PVT was chosen as it was the most commonly used version, and had been demonstrated to be more sensitive to different performance metrics than shorter versions (Loh, Lamond,

Dorrian, Roach, & Dawson, 2004). The PVT had been extensively used in related investigations, and had been demonstrated to alter the brain areas linked to sustained attention (Asplund & Chee, 2013; Lim et al., 2010). Therefore, it allowed us to provide the proper stimuli for assessing accommodation, as well as determining whether participants were attending to the stimuli displayed on the screen. The simultaneous assessment of accommodative function and behavioral performance allowed us to establish associations.

The PVT commenced with the presentation of an empty high-contrast black circle, which subtended a viewing angle of  $6.73^\circ$  in the horizontal and vertical axes, at the centre of the screen against a white background. After it, the circle was filled all at once in black, and in a random time interval between 2000 and 10000 ms. Participants were asked to press as fast as possible the space bar on the keyboard, using their dominant hand, when the circle was filled. The filled circle was displayed for 500 ms and they had a maximum of 1500 ms to press the space bar. Reaction time was defined as the length of time (in milliseconds) between the stimulus presentation and the response of the participant by pressing the space bar. A visual feedback message of the reaction time was displayed for 300 ms after each response, except in the case of an anticipated response or if no response was made within 1000 ms after target offset, when messages “wait for the target” and “you did not answer” were displayed, respectively. Following the feedback message, the next trial began (see Fig. 1 for a schematic illustration of the PVT procedure). The procedure lasted 10 min, and participants were instructed to maintain the accommodative stimuli as clear as possible during the entire task.

### 2.2.2. Accommodative response

AR values were dynamically measured with a WAM-5500 binocular open-field autorefractor (Grand Seiko Co. Ltd., Hiroshima, Japan) in high-speed mode (continuous recording). This apparatus had been clinically validated and was shown to acquire reliable and accurate data of accommodation at a temporal resolution of  $\sim 5$  Hz (Sheppard & Davies, 2010). First, to determine the baseline refractive value, we obtained the monocular static refractive measure for both corrected eyes, while participants looked at a 5 m stationary target. Then, we performed a dynamic accommodative test, recording the magnitude and microfluctuations of accommodation for 10 min, while the high-contrast visual stimulus from the PVT appeared on a 15.6" LCD screen 50 cm from the observer. Participants looked at the target in binocular conditions, and AR was recorded in the dominant eye (Momeni-Moghaddam, McAlinden, Azimi, Sobhani, & Skiadaresi, 2014). They were asked to rest their forehead and chin in the corresponding supports while looking at the visual stimulus at the centre of the screen (see the *Psychomotor vigilance task* subsection above for details). The illumination in the laboratory was kept constant during the experiment ( $217 \pm 8$  lx as measured in the corneal plane). Following previous recommendations

for AR data processing, we discarded data points of  $\pm 3$  SD from the average spherical refraction value, which may be caused by blinking or measurement errors (Tosha, Borsting, Ridder, & Chase, 2009; Vera et al., 2016). Accommodative lag was calculated by subtracting from the target distance (2D), the mean point of focus during dynamic testing and the baseline static spherical equivalent refraction value (Poltavski, Biberdorf, & Petros, 2012). The microfluctuations of accommodation referred to the standard deviation (SD) of the dynamic AR recording (Redondo et al., 2018).

### 2.2.3. Heart rate variability (HRV)

We used a Polar RS800 CX monitor (Polar Electro, Kempele, Finland) to monitor the cardiovascular activity in both experimental sessions. The time series of HRV data were obtained by identifying the occurrence of each R wave (belonging to the QRS complex of the cardiac cycle) and calculating the elapsed time between two consecutive R waves (R-R interval). Thus, HRV analysis consisted of a series of measurements of successive R-R intervals and determining their variation, which provided indirect information about autonomic tone (Malik et al., 1996; Pumprla et al., 2002). Cardiovascular data were collected at a temporal resolution for 1 ms (1000 Hz). A heart rate monitor was placed on the participant before each experimental session, and then they rested for five minutes in a quiet room in a supine position so as to record the baseline HRV. Cardiovascular activity was also recorded during the 10 min of the PVT. For data analysis, we transferred all recordings to the Polar electro interface all, and then, the RR files were analyzed using the Kubios HRV analysis software 2.0 (Tarvainen, Niskanen, Lipponen, Ranta-aho, & Karjalainen, 2009). Following the recommendations of Malik, Cripps, Farrell, and Camm (1989), the recordings were preprocessed to exclude artifacts by eliminating R-R intervals which differed more than 25% from either the previous or the subsequent values. Bioelectric signal recordings could often be contaminated by low-frequency interference that would cause baseline trending of the recorded signals. In cardiac recordings, the signals might also be contaminated by various low frequency noises such as breathing, sweating, electrode motion and even the slow activities of the muscles. These low-frequency interferences or trends could often have a significant impact on signal interpretation. Thus, we applied a method based on the smoothness prior approach to detrend HRV data (Tarvainen, Ranta-aho, & Karjalainen, 2002; Zhang, Chen, Zhang, Zhang, & Li, 2014). This approach could be automatically implemented from the Kubios HRV analysis software (Tarvainen et al., 2009). In order to analyse HRV within the time domain, the root-mean-square difference of successive normal R-R intervals (rMSSD) was used as the index of vagal control. The guidelines for HRV data collection and analysis in this paper follow those established by the Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology (Malik et al., 1996).

## The Psychomotor Vigilance Task (PVT) procedure

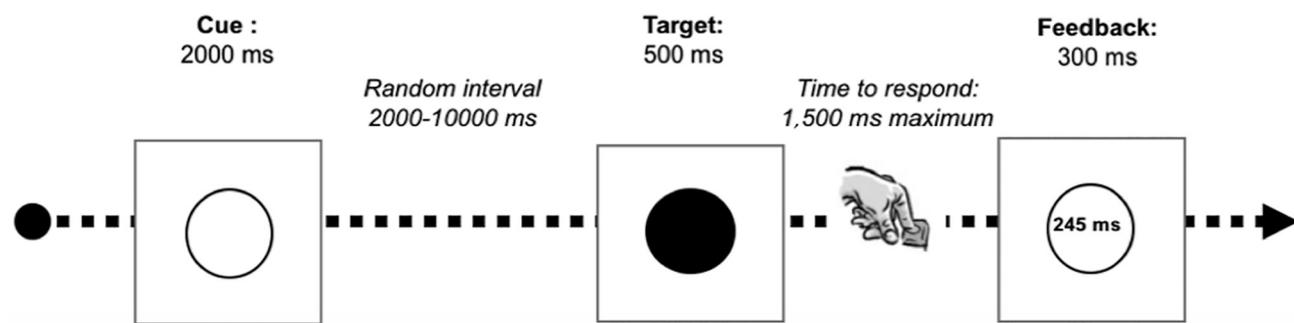
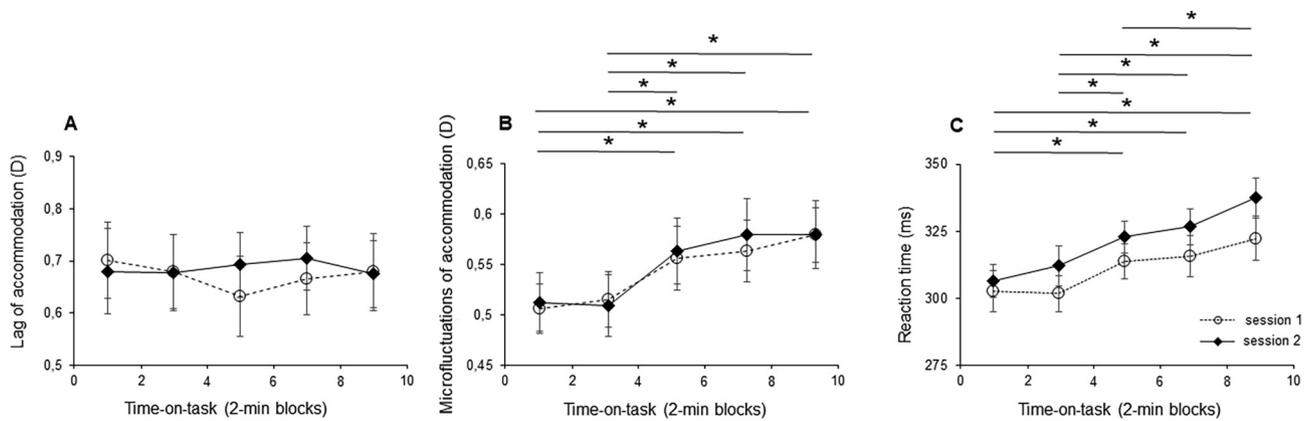


Fig. 1. Timeline of the Psychomotor Vigilance Task (PVT).



**Fig. 2.** Effects of time-on-task in both experimental sessions on lag of accommodation (Panel A), microfluctuations of accommodation (Panel B), and reaction time (Panel C). \*denotes statistically significant differences between the different time blocks (corrected p-value < 0.05). Error bars represent the standard error (SE). All values are calculated across participants (n = 25).

### 2.3. Procedure

Participants attended the laboratory on three different days. In the first session, participants were screened for the established inclusion criteria, and the experimental protocol was also explained to them. The remaining two sessions, the main experimental sessions, were identical, and were used to assess inter-session repeatability. All sessions were performed at the same time of the day ( $\pm 1$  h) and under similar environmental conditions ( $\sim 22^\circ\text{C}$  and  $\sim 60\%$  humidity). First, participants signed the consent form and filled in documentation for the Stanford Sleepiness Scale. A baseline HRV was then obtained during a six minute rest period in a supine position. No measurements were used during the first minute of this period, with the last 5 min being considered for the resting HR assessment (Vera, Jiménez, García, Perales, & Cárdenas, 2018). The participants were then sat in front of the computer in a dimly illuminated room and isolated from external noise. Prior to testing, they received instructions and practiced for one minute with the PVT. At this point, the 10-minute PVT was started, and the accommodative function and HRV were monitored during the entire period. In order to assess the time-on-task effects, the PVT, ocular accommodation and cardiovascular related variables were divided into five time blocks of two minutes each.

### 2.4. Experimental design and statistical analysis

In this study, we used a repeated measures design to assess the time-on-task effect of sustained attention during two separate experimental sessions on ocular accommodation, vagal autonomic control and behavioral performance.

Four separate two-way analysis of variance (ANOVAs) were performed to determine the effect of time-on-task on the dynamics of the accommodative response (lag and microfluctuations) during the PVT, as well as its influence on the rMSSD index of HRV and reaction for the PVT (objective 1). These statistical tests were conducted separately for each of the four dependent variables (lag of accommodation, microfluctuations of accommodation, rMSSD and reaction time), considering the time-on-task (block 1, block 2, block 3, block 4, and block 5) and the session (session 1 and session 2) as within-participants factors. The magnitude of the differences was analyzed by partial eta squared ( $\eta_p^2$ ) for multiple comparisons. Significant main effects and interactions were further explored by using pairwise comparisons with paired Student's t-tests, which were also interpreted based on the magnitude of the difference using Cohen's d. Multiple comparisons were corrected with the Holm-Bonferroni method. We also performed linear regression analysis to explore the behavior of the dependent variables over time.

In order to assess objective 2, multiple regression analysis was used

to predict behavioral performance (reaction time during the PVT) from the lag of accommodation, microfluctuations of accommodation, and HRV (rMSSD). In order to find the model that permits to explain the greatest amount of variance with the minimum number of predictors, we used the backward elimination procedure. For all dependent variables, the average value from both sessions was considered for this analysis.

In addition, inter-session repeatability (objective 3) of the different dependent variables (lag of accommodation, microfluctuations of accommodation, rMSSD, and reaction time) was examined by the analysis of the standard error of measurements in relative terms. For this, pairwise t-tests were conducted with the session (session 1 and session 2) as the only within-participants factor, and the differences were interpreted by the standardized mean differences (Cohen's d), following the recommendations of Hopkins, Marshall, Batterham, and Hanin (2009). Subsequently, we calculated the within-participants coefficient of variation (CV), intra-class correlation coefficients (ICC), and their corresponding 95% confidence intervals (95% CI) to determine inter-session repeatability. In addition, the level of agreement between both sessions was explored by the method of Bland and Altman (1986).

The level of statistical significance was set at 0.05. The JASP statistics package (version 0.9.0.1) was used for ANOVA and regression analysis. Repeatability analyses were performed with a custom spreadsheet developed by Hopkins (2000).

## 3. Results

### 3.1. Baseline differences between experimental sessions

First, the participants attending the laboratory were assessed for their baseline cardiovascular activity and perceived level of sleepiness/alertness. Similarity in the participants for these values was confirmed by analysis of baseline HRV ( $t_{24} = 0.610$ , p-value = 0.550 for the rMSSD) and from subjective levels of alertness reported by participants ( $t_{24} = 0.296$ , p = 0.770 for the Stanford Sleepiness Scale) at the beginning of each experimental session.

### 3.2. Influence of time-on-task on AR

The analysis of the lag of accommodation did not reveal any effect for either session, time-on-task or interaction (all Fs < 1 (Fig. 2A).

The microfluctuations of accommodation exhibited a statistically significant effect for time-on-task ( $F_{4, 96} = 10.060$ , p < 0.001, and  $\eta_p^2 = 0.295$ ). The main factor of session and the interaction *time-on-task*  $\times$  *session* were far from showing any significance ( $F < 1$  in both cases). Post-hoc comparisons are depicted in Fig. 2B, and they showed

statistically significant differences for block 1 when compared to block 3 (corrected p-value = 0.009, d = 0.659), block 4 (corrected p-value = 0.005, d = 0.707), and block 5 (corrected p-value = 0.002, d = 0.789; (Fig. 2B). There was a positive and linear relationship between the microfluctuations of accommodation and time (Pearson’s r = 0.97 and 0.91 for sessions 1 and 2, respectively).

3.3. Influence of time-on-task on behavioral performance

Behavioral performance, as measured by reaction time, revealed a statistically significant effect on time-on-task ( $F_{4, 96} = 15.853$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.398$ ). The main effect of session ( $F_{1, 24} = 2.913$ ,  $p = 0.101$ ) and the interaction *time-on-task* × *session* ( $F_{4, 96} < 1$ ) did not show statistical significance. Post-hoc comparisons revealed that the reaction time was significantly lower in block 1 compared to block 3 (corrected p-value = 0.004, d = 0.799), block 4 (corrected p-value < 0.001, d = 1.025) and block 5 (corrected p-value < 0.001, d = 1.172; (Fig. 2C). There was a positive and linear relationship between reaction time and time-on-task (Pearson’s r = 0.95 and 0.99 for sessions 1 and 2, respectively).

3.4. Influence of time-on-task on HRV

The rMSSD component of HRV did not reach statistical significance for either of the factors, time-on-task ( $F_{4, 96} = 1.202$ ,  $p = 0.315$ ), session ( $F_{1, 24} = 2.455$ ,  $p = 0.130$ ), or the interaction *time-on-task* × *session* ( $F_{4, 96} < 1$ ).

3.5. Prediction of behavioral performance from ocular accommodation and HRV

The results of the multiple regression model are displayed in Table 1, and they revealed that microfluctuations of accommodation were positively associated with reaction time ( $p < 0.001$ ; Fig. 3). No significant association was observed for lag of accommodation and HRV with behavioral performance (both p-values > 0.05).

3.6. Inter-session repeatability

Table 2 displays the descriptive and inter-session repeatability values (CV and ICC) of the dependent variables for the five 2-min blocks, as well as the average values from the 10 min PVT task. All dependent variables demonstrated a low to moderate inter-session repeatability, when measured on two different days under similar experimental conditions, with CV and ICC ranges: 26.79–39.46% and 0.51–0.74 for lag of accommodation; 19.08–24.90% and 0.20–0.44 for microfluctuations of accommodation; 6.05–8.27% and 0.41–0.71 for reaction time; and 24.25–31.42% and 0.65–0.78 for HRV, respectively. Bland-Altman plots revealed limits of agreement from -0.67D to 0.64D, -0.32D to 0.31D, and -66.56 ms to 46.81 ms for lag of accommodation, microfluctuations of accommodation, and reaction time, respectively (Fig. 4).

Table 1

Multiple regression coefficients ( $\beta$ ), and coefficients of determination ( $R^2$ ) examining the association of ocular accommodation (lag and variability of accommodation) and heart rate variability (RMSSD) with behavioral performance (reaction time).

Dependent Variable	Predictors	t	p	$\beta$	$R^2$
Reaction time	rMSSD	-1.077	0.294	-0.164	0.065
	Lag of accommodation	-0.330	0.745	-0.051	0.033
	Variability of Accommodation	4.332	< 0.001	0.671	0.493

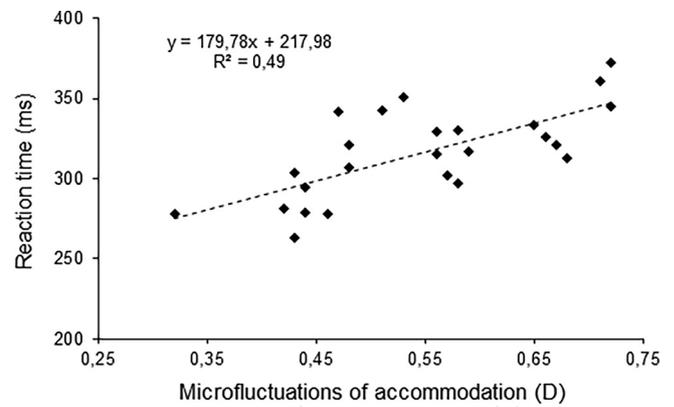


Fig. 3. Relationship between the reaction time and microfluctuations of accommodation. The linear equation is displayed with the corresponding coefficient of determination ( $R^2$ ). Values are calculated across the total sample size ( $n = 25$ ). Both indices demonstrated a considerable level of correlation ( $p < 0.001$ ,  $r = 0.70$ ).

4. Discussion

The present study was designed to explore whether the influence of time-on-task during a vigilance task modulated the accommodative response (lag and microfluctuations), as well as exploring the capacity of ocular accommodation and HRV to predict behavioral performance, as measured by reaction time. We also tested the inter-session repeatability of time-on-task effects on ocular accommodation, HRV and reaction time. Our data demonstrated that the microfluctuations of accommodation were sensitive to time-on-task during sustained attention, showing greater fluctuations over time. However, the execution of a 10 min vigilance task did not induce any change in the lag of accommodation. The microfluctuations of accommodation predicted a significant amount of variance in reaction time during the vigilance task, whereas the rest of indices were not associated with reaction time. Accommodative response indices (lag and microfluctuations), reaction time, and HRV revealed a poor level of inter-session repeatability. Taken together, these results indicated that microfluctuations of accommodation were modulated as a function of time-on-task and were associated with behavioral performance during sustained attention.

Our data revealed that the magnitude of the accommodative response did not change during the execution of the vigilance task (Fig. 2A); however, previous studies have found a bidirectional relationship between attention and ocular accommodation functioning. For example, Poltavski et al. (2012) found that alteration of the accommodative-vergence system during a sustained attention task (Conner’s continuous performance test) impaired cognitive performance, as measured by a slower reaction time, whereas Redondo et al. (2018) demonstrated that children with attentional deficits had an altered accommodative response (higher lags of accommodation) in comparison to healthy controls. Based on the findings of Rosenfield and Ciuffreda (1990), ocular accommodation seems to be a reliable objective index of brain activity during cognitively demanding tasks, with the dynamics of ocular accommodation being sensitive to the effects caused by mental effort on the sympathetic nervous system (Davies et al., 2005; Bullimore & Gilmartin, 1988). As previously stated, we found no effects of time-on-task during the PVT for lag of accommodation, in contrast to the study of Davies et al. (2005), who found a reduction of the accommodative response with increasing cognitive demand. Nevertheless, these differences might be explained by cognitive demands in the present study and those in Davies et al. (2005), not being comparable. Two different tasks were employed, PVT in the current study and a numerical forced-choice paradigm task in Davies et al. (2005), and recent investigations have showed that physiological responses to mental effort, such as intraocular pressure and HRV, are

**Table 2**

Inter-session repeatability of the values of accommodative lag, variability of accommodation, behavioral performance, and heart rate variability at each of the five 2-min block, as well as the average result from the 10-min psychomotor vigilance task.

		Session 1	Session 2	ES	CV (95% CI)	ICC (95% CI)
Lag of accommodation (D)	<i>Block 1</i>	0.70 ± 0.36	0.68 ± 0.41	0.05	39.46 (30.19 to 56.98)	0.52 (0.11 to 0.76)
	<i>Block 2</i>	0.68 ± 0.35	0.68 ± 0.37	0.00	33.22 (25.50 to 48.13)	0.62 (0.26 to 0.81)
	<i>Block 3</i>	0.63 ± 0.39	0.69 ± 0.31	0.17	37.86 (28.97 to 54.67)	0.51 (0.09 to 0.75)
	<i>Block 4</i>	0.67 ± 0.35	0.71 ± 0.31	0.12	33.65 (25.74 to 48.59)	0.52 (0.10 to 0.76)
	<i>Block 5</i>	0.68 ± 0.37	0.67 ± 0.32	0.01	26.79 (20.50 to 38.69)	0.74 (0.46 to 0.88)
	<i>Mean</i>	0.67 ± 0.35	0.69 ± 0.32	0.04	30.61 (23.42 to 44.20)	0.64 (0.29 to 0.82)
Variability of accommodation (D)	<i>Block 1</i>	0.51 ± 0.12	0.51 ± 0.14	0.05	23.75 (18.17 to 34.30)	0.20 (−0.30 to 0.56)
	<i>Block 2</i>	0.52 ± 0.14	0.51 ± 0.15	0.04	21.54 (16.48 to 31.11)	0.44 (−0.01 to 0.71)
	<i>Block 3</i>	0.56 ± 0.16	0.56 ± 0.16	0.05	23.98 (18.35 to 34.63)	0.31 (−0.17 to 0.63)
	<i>Block 4</i>	0.56 ± 0.15	0.58 ± 0.18	0.10	24.90 (19.05 to 35.96)	0.27 (−0.22 to 0.61)
	<i>Block 5</i>	0.58 ± 0.13	0.58 ± 0.17	0.00	19.94 (15.26 to 28.80)	0.43 (−0.01 to 0.71)
	<i>Mean</i>	0.54 ± 0.13	0.55 ± 0.14	0.04	19.08 (14.59 to 27.55)	0.43 (−0.02 to 0.71)
Reaction time (ms)	<i>Block 1</i>	302.69 ± 37.91	306.57 ± 30.31	0.11	8.06 (6.16 to 11.64)	0.50 (0.08 to 0.75)
	<i>Block 2</i>	301.70 ± 33.22	312.07 ± 37.13	0.29	8.27 (6.33 to 11.95)	0.50 (0.07 to 0.74)
	<i>Block 3</i>	313.84 ± 32.68	322.82 ± 30.58	0.28	7.75 (5.93 to 11.19)	0.41 (−0.05 to 0.69)
	<i>Block 4</i>	318.73 ± 38.90	326.76 ± 33.75	0.30	7.85 (6.01 to 11.34)	0.53 (0.13 to 0.77)
	<i>Block 5</i>	322.47 ± 40.72	337.51 ± 37.65	0.38	6.55 (5.01 to 9.46)	0.71 (0.41 to 0.86)
	<i>Mean</i>	311.27 ± 33.19	321.15 ± 30.07	0.31	6.05 (4.63 to 8.74)	0.65 (0.31 to 0.83)
rMSSD (ms)	<i>Block 1</i>	52.23 ± 23.00	50.39 ± 26.63	−0.07	24.25 (18.55 to 35.02)	0.76 (0.50 to 0.89)
	<i>Block 2</i>	50.70 ± 24.80	48.00 ± 30.21	−0.10	29.58 (22.63 to 42.71)	0.73 (0.45 to 0.87)
	<i>Block 3</i>	51.72 ± 25.60	48.88 ± 28.40	−0.10	32.51 (24.88 to 46.95)	0.65 (0.31 to 0.83)
	<i>Block 4</i>	49.31 ± 24.80	45.92 ± 27.31	−0.13	26.64 (20.38 to 38.47)	0.78 (0.53 to 0.89)
	<i>Block 5</i>	49.40 ± 22.50	47.24 ± 28.54	−0.08	31.42 (24.04 to 45.38)	0.67 (0.33 to 0.84)
	<i>Mean</i>	50.67 ± 23.30	48.09 ± 27.69	−0.10	27.43 (20.98 to 39.60)	0.73 (0.45 to 0.87)

Abbreviations: ES = effect size; CV = coefficient of variation; ICC = intraclass correlation coefficient.

highly dependent on task complexity (Luque-Casado et al., 2015; Vera et al., 2017).

In regard to the stability of ocular accommodation, greater microfluctuations of accommodation were found in the second half of the task, in comparison to the first 2-minute block (Fig. 2B), suggesting that more than five minutes of sustained attention were needed to observe significant changes in the dynamics of ocular accommodation. Notably, higher microfluctuations of accommodation have proven to be an accurate and sensitive indicator of visual fatigue and stress (Jeng et al., 2014; Kajita, Ono, Suzuki, & Kato, 2001), whereas other visual indices such as accommodation magnitude, pupil diameter, visual acuity, eye movement velocity and critical function frequency have been less valid in this regard (Chi & Lin, 1998). A recent study has demonstrated that young adults have a more stable accommodative response (lower variability) when viewing highly engaging tasks (Roberts et al., 2018). The increased microfluctuations of accommodation over time observed in the present study could be caused by cognitive fatigue, leading to reduced attention capabilities (Grier et al., 2003). In view of the current results, microfluctuations of accommodation could be considered as an objective indicator of performance impairment associated with mental workload, fatigue or drowsiness in real-world contexts, such as driving, piloting, and air traffic management. Clearly, this is an area for future studies.

Consistent with the microfluctuations of accommodation and previous reports (Luque-Casado, Perakakis, Ciria, & Sanabria, 2016), we found that sustained attention induced a decrement in behavioral performance over time, as measured by slower reaction times. This change was particularly pronounced in the second half of the 10-minute PVT, when compared with values obtained in the initial stages of the task (Fig. 2C). This set of results was consistent with many studies that have reported a time-on-task effect during the execution of the PVT, with reaction time increasing continuously due to the depletion of cognitive resources (Basner & Dinges, 2011; Lim et al., 2010).

Maintaining high levels of attention or cognitive engagement is paramount for professional duties, such as piloting an aircraft, performing a surgical task, driving and managing air traffic; therefore, monitoring the attentional state of individuals in these situations

constitutes a key element in terms of safety. Self-reported measures have been commonly used to assess cognitive states, including levels of attention. However, these measures present several limitations due to their dependence on personal and motivational factors (Podsakoff, MacKenzie, Lee, & Podsakoff, 2003). To overcome these constraints, numerous physiological indices, such as electroencephalographic or cardiovascular activity, ocular dynamics and intraocular pressure have attracted research interest as potential markers of levels of attention (Borghini et al., 2012; Di Stasi, Catena, Cañas, Macknik, & Martínez-Conde, 2013; Vera, Diaz-Piedra, Jiménez, Sanchez-Carrion, & Di Stasi, 2018). In regard to ocular accommodative mechanisms, there is controversy regarding the changes that occur during mental effort and attention tasks. These variations depend on the methodology, nature of the processing task and the fixation distance (Davies et al., 2005; Gray et al., 2000; Winn & Gilmartin, 1992). Overall, it has been suggested that mental processing tasks induce greater variations on the accommodative response in open-loop stimulus dependent conditions (Edgar, 2007). The present study incorporated preliminary results on the utility of microfluctuations of accommodation as a reasonably good predictor of behavioral performance for a sustained attention task, as measured by reaction time, in closed-loop conditions.

We hypothesized a gradual decrease in the vagal component of HRV (i.e., rMSSD) as a function of the time-on-task, which could presumably be associated with both the dynamics of ocular parameters and the task performance (Davies et al., 2005; Jeng et al., 2014; Luque-Casado et al., 2015). Although vagal tone has previously been linked to PVT performance and dynamics over time (Luque-Casado et al., 2016; Luque-Casado et al., 2015), our results were not consistent with these reports. However, the time-related dynamics of vagal tone have only been observed in the male population (Luque-Casado et al., 2015), and more importantly, it seems to depend on the level of physical fitness of the participants (Luque-Casado, Zabala, Morales, Mateo-March, & Sanabria, 2013). Therefore, given that the current experiment included men and women with different levels of physical fitness, it cannot be ruled out that the study sample did not influenced the null result reported for this parameter. Future studies should consider gender and fitness level as potential contributory factors. In addition, the current

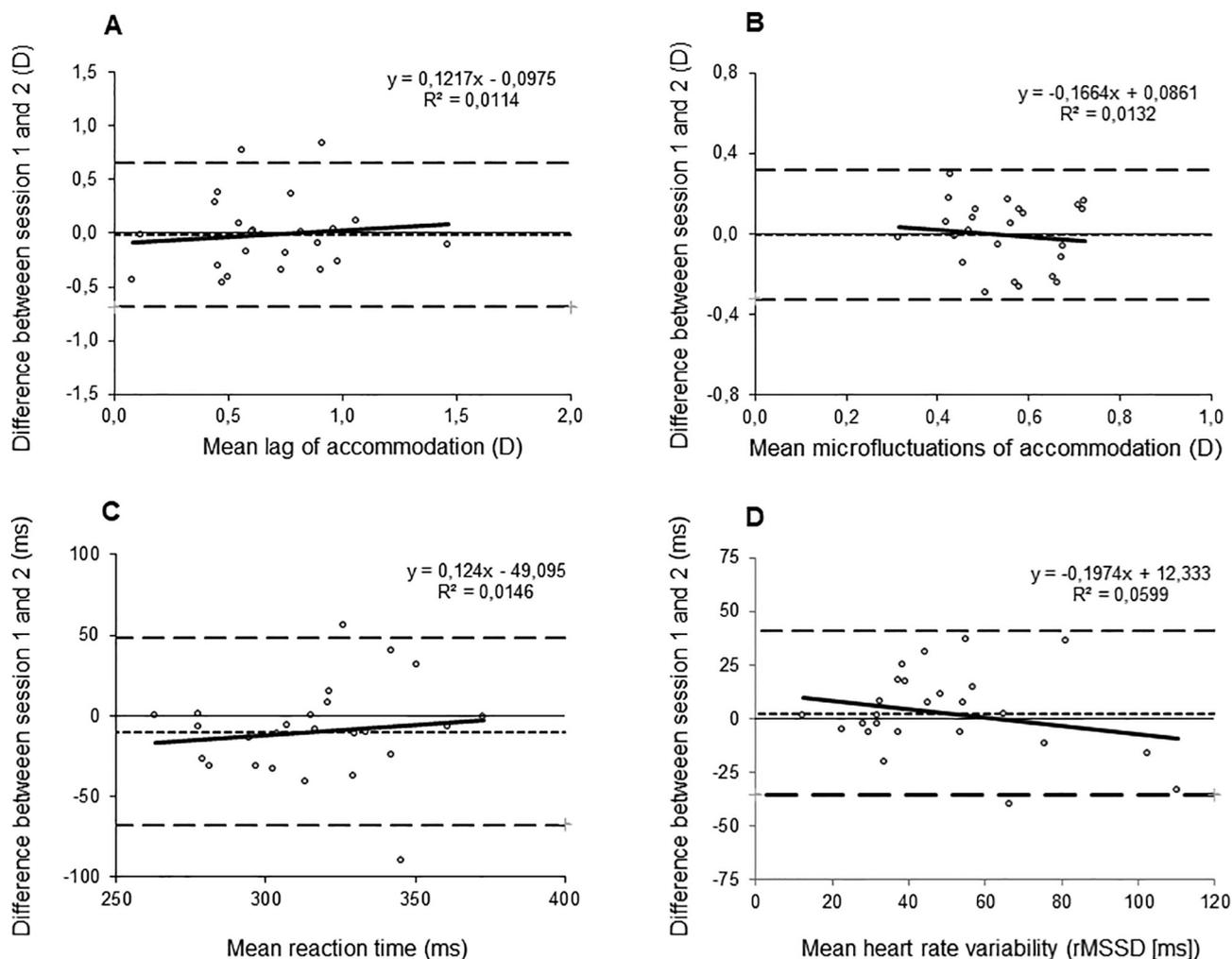


Fig. 4. Bland and Altman plots illustrating the inter-session repeatability of lag of accommodation (panel A), microfluctuations of accommodation (panel B), reaction time (panel C), and heart rate variability (panel D). The x-axis shows the mean value from session 1 and 2. The dotted line represents the mean bias and the dashed lines show the 95% limits of agreement. The regression line is represented by a solid black line, and the grey lines indicate the value zero.

study did not find a significant association between the cardiovascular and ocular accommodation functioning. In this regard, some authors have reported a relationship between the dynamics of ocular accommodation and cardiovascular activity (Davies et al., 2005; Bullimore & Gilmartin, 1988); however, the association of the frequency components of HRV with ocular accommodation seems to be fairly weak (Hampson, Dainty, Munro, & Paterson, 2005).

Repeatability concerns the precision of repeated measurements by an observer when all external factors are kept constant (McAlinden, Khadka, & Pesudovs, 2011). For the current study, repeating the protocol under the same experimental conditions generally revealed a low repeatability for ocular accommodation, behavioral performance and HRV (Table 2). This result suggested that variables measured at different times should be interpreted with caution in both a clinical and research setting. In previous studies, cardiac autonomic regulation, as measured by HRV (Cipryan & Litschmannova, 2013), as well as reaction time (Lemay, Bédard, Rouleau, & Tremblay, 2004) have demonstrated a considerable random inter-day variability, and our results for ocular accommodation seem to be consistent with these findings. There have been no previous studies examining inter-day repeatability of ocular accommodation. We found a comparable repeatability for accommodative response with respect to that observed for cardiovascular activity and behavioral performance. Nevertheless, the results of ocular accommodation for the entire group remain fairly stable, when measured on two different days under identical experimental conditions, as

shown by the negligible effect sizes between sessions. In summary, while group behavior was reasonably robust, inter-subject variation was quite substantial for accommodative responses. These findings should be taken into account when assessing ocular accommodation, both in clinical practice and the laboratory.

The functioning of ocular accommodation and attentional state are predominately mediated by the same brain structures, such as the reticular formation and cerebellum (McDougal & Gamlin, 2015); therefore, a bidirectional relationship might be expected between ocular accommodation and behavioral performance. In this regard, a recent study concluded that the superior colliculus, which is located at reticular formation, may be altered in a rodent model of attention-deficit/hyperactivity disorder (Brace et al., 2015), suggesting an association between attention capabilities and the structures involved in the control of accommodation. In the present study, we found a significant association for microfluctuations of accommodation with sustained attentional performance, whereas lag of accommodation or cardiovascular activity failed to predict behavioral performance. Future studies should explore the brain mechanisms that might explain the relationship between the stability of ocular accommodation and reaction time during a vigilance task, as well as the lack of association between the magnitude of ocular accommodation and sustained attentional performance.

#### 4.1. Study limitations and future research

This study was not exempt from limitations. Our data revealed a positive linear association between behavioral performance (reaction time) and microfluctuations of accommodation. Nevertheless, we are aware that correlation does not imply causation, and thus, our results need to be interpreted accordingly. This study was conducted in a group of university students, and the external validity of these results to the general public where there would be greater variation in age and cognitive skills was unknown. Lastly, several factors, such as circadian variations, gender, caffeine intake, fitness level and sleep deprivation (Ballard, 1996; Luque-Casado et al., 2015, 2013), may alter the physiological response during prolonged attention; therefore, these factors should be tested in future investigations, particularly due to their potential relevance in applied settings. Currently, researchers are attempting to find standardized systems to measure physiological parameters related to task overload or fatigue, especially in real-world scenarios where the aim is to enhance safety (Di Stasi et al., 2013).

#### 5. Conclusions

This study demonstrated that performing a sustained attention (vigilance) task induced greater levels of microfluctuations of accommodation over time, whereas lag of accommodation remained unchanged during the 10-minute attention task. There was a positive association between reaction time and microfluctuations of accommodation, suggesting that the dynamics of ocular accommodation might be considered as a potential predictor of behavioral performance. However, these results might be limited by the low levels of inter-session reliability of ocular accommodation and behavioral performance. The present findings might be of special relevance due to their possible implications in the design of assistance systems in real world situations, such as driving, piloting and other occupational settings where public safety is paramount.

#### Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

#### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### References

Asplund, C. L., & Chee, M. W. L. (2013). Time-on-task and sleep deprivation effects are evidenced in overlapping brain areas. *NeuroImage*, 82, 326–335. <https://doi.org/10.1016/j.neuroimage.2013.05.119>.

Ballard, J. C. (1996). Computerized assessment of sustained attention: A review of factors affecting vigilance performance. *Journal of Clinical and Experimental Neuropsychology*, 18(6), 843–863. <https://doi.org/10.1080/01688639608408307>.

Basner, M., & Dinges, D. F. (2011). Maximizing sensitivity of the psychomotor vigilance test (PVT) to sleep loss. *Sleep*, 34(5), 581–591.

Bland, J. M., & Altman, D. (1996). Statistical methods for assessing agreement between two methods of clinical measurement. *The Lancet*, 327(8476), 307–310 doi: 10.1016/S0140-6736(86)90837-8.

Borghini, G., Astolfi, L., Vecchiato, G., Mattia, D., & Babiloni, F. (2012). Measuring neurophysiological signals in aircraft pilots and car drivers for the assessment of mental workload, fatigue and drowsiness. *Neuroscience and Biobehavioral Reviews*, 44, 58–75. <https://doi.org/10.1016/j.neubiorev.2012.10.003>.

Brace, L. R., Kraev, I., Rostron, C. L., Stewart, M. G., Overton, P. G., & Dommett, E. J. (2015). Altered visual processing in a rodent model of Attention-Deficit Hyperactivity Disorder. *Neuroscience*, 303, 364–377. <https://doi.org/10.1016/j.neuroscience.2015.07.003>.

Brookings, J. B., Wilson, G. F., & Swain, C. R. (1996). Psychophysiological responses to changes in workload during simulated air traffic control. *Biological Psychology*, 42(3), 361–377 doi: 10.1016/0301-0511(95)05167-8.

Bullimore, M., & Gilmartin, B. (1988). The accommodative response, refractive error and

mental effort: 1. The sympathetic nervous system. *Documenta Ophthalmologica*, 69, 385–397.

Charman, W. N., & Heron, G. (1988). Fluctuations in accommodation: a review. *Ophthalmic and Physiological Optics*, 8(2), 153–164. <https://doi.org/10.1111/j.1475-1313.1988.tb01031.x>.

Chi, C., & Lin, F. (1998). A comparison of seven visual fatigue assessment techniques in three data-acquisition VDT tasks. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 40(4), 577–590.

Cipryan, L., & Litschmannova, M. (2013). Intra-day and inter-day reliability of heart rate variability measurement. *Journal of Sports Sciences*, 31(2), 150–158. <https://doi.org/10.1080/02640414.2012.721931>.

Cogan, D. G. (1937). Accommodation and the autonomic nervous system. *Archives of Ophthalmology*, 18(5), 739–766.

Collins, M., Davis, B., & Wood, J. (1995). Microfluctuations of steady-state accommodation and the cardiopulmonary system. *Vision Research*, 35(17), 2491–2502 doi: 10.1016/0042-6989(95)00024-0.

Conlon, E. G., Lovegrove, W. J., Chekaluk, E., & Pattison, P. E. (1999). Measuring visual discomfort. *Visual Cognition*, 6(6), 637–663. <https://doi.org/10.1080/135062899394885>.

Davies, L., Wolffsohn, J., & Gilmartin, B. (2005). Cognition, ocular accommodation, and cardiovascular function in emmetropes and late-onset myopes. *Investigative Ophthalmology and Visual Science*, 46(5), 1791–1796. <https://doi.org/10.1167/iovs.04-0986>.

Davies, L. N., Wolffsohn, J. S., & Gilmartin, B. (2009). Autonomic correlates of ocular accommodation and cardiovascular function. *Ophthalmic and Physiological Optics*, 29(4), 427–435. <https://doi.org/10.1111/j.1475-1313.2009.00635.x>.

Di Stasi, L. L., Catena, A., Cañas, J. J., Macknik, S. L., & Martinez-Conde, S. (2013). Saccadic velocity as an arousal index in naturalistic tasks. *Neuroscience and Biobehavioral Reviews*, 37(5), 968–975. <https://doi.org/10.1016/j.neubiorev.2013.03.011>.

Di Stasi, L. L., Díaz-Piedra, C., Ruiz-Rabelo, J. F., Rieiro, H., Sanchez Carrion, J. M., & Catena, A. (2017). Quantifying the cognitive cost of laparo-endoscopic single-site surgeries: Gaze-based indices. *Applied Ergonomics*, 65, 168–174. <https://doi.org/10.1016/j.apergo.2017.06.008>.

Edgar, G. K. (2007). Accommodation, cognition, and virtual image displays: A review of the literature. *Displays*, 28, 45–59. <https://doi.org/10.1016/j.displa.2007.04.009>.

Gawande, A. A., Zinner, M. J., Studdert, D. M., & Brennan, T. A. (2003). Analysis of errors by surgeons at three teaching hospitals. *Surgery*, 133(6), 614–621. <https://doi.org/10.1067/msy.2003.169>.

Gilmartin, B. (1986). A review of the role of the sympathetic innervation of the ciliary muscle in ocular accommodation. *Ophthalmic and Physiological Optics*, 6(1), 23–37. <https://doi.org/10.1111/j.1475-1313.1986.tb00697.x>.

Gray, L. S., Gilmartin, B., & Winn, B. (2000). Accommodation microfluctuations and pupil size during sustained viewing of visual display terminals. *Ophthalmic and Physiological Optics*, 20(1), 5–10 doi: 10.1016/S0275-5408(99)00030-7.

Grier, R. A., Warm, J. S., Dember, W. N., Matthews, G., Galinsky, T. L., Szalma, J. L., & Parasuraman, R. (2003). The vigilance decrement reflects limitations in effortful attention, not mindlessness. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 45(3), 349–359. <https://doi.org/10.1518/hfes.45.3.349.27253>.

Haapalainen, E., Kim, S., Forlizzi, J. F., & Dey, A. K. (2010). Psycho-physiological measures for assessing cognitive load. Proceedings of the 12th ACM International Conference on Ubiquitous Computing, 301–310. <https://doi.org/10.1145/1864349.1864395>.

Hampson, K. M., Dainty, C., Munro, I., & Paterson, C. (2005). Weak correlation between the aberration dynamics of the human eye and the cardiopulmonary system. *Journal of the Optical Society of America A*, 22(7), 1241. <https://doi.org/10.1364/josaa.22.001241>.

Hoddes, E., Zarcone, V., & Dement, W. (1973). Quantification of sleepiness: A new approach. *Psychophysiology*, 10(4), 431–436.

Hopkins, W., Marshall, S., Batterham, A., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, 41(1), 3–12 doi: 10.1249/MSS.0b013e31818cb278.

Hopkins, W. (2000). Calculations for reliability (Excel spreadsheet). A new view of statistics, 383.

Hynes, N., Cufflin, M., Hampson, K., & Mallen, E. (2018). Cognitive demand and accommodative microfluctuations. *Vision*, 2(3), 36. <https://doi.org/10.3390/vision2030036>.

Jeng, W. D., Ouyang, Y., Huang, T.-W., Duann, J.-R., Chiou, J.-C., Tang, Y.-S., & Ou-Yang, M. (2014). Research of accommodative microfluctuations caused by visual fatigue based on liquid crystal and laser displays. *Applied Optics*, 53(29), H76. <https://doi.org/10.1364/AO.53.000H76>.

Jiménez, R., Cárdenas, D., Anera, R. G., & Jiménez, J. R. (2017). Measuring mental workload: Ocular astigmatism aberration as a novel objective index. *Ergonomics*, 0139(October), <https://doi.org/10.1080/00140139.2017.1395913>.

Kajita, M., Ono, M., Suzuki, S., & Kato, K. (2001). Accommodative microfluctuation in asthenopia caused by accommodative spasm. *Fukushima Journal of Medical Science*, 47(1), 13–20.

Larue, G. S., Rakotonirainy, A., & Pettitt, A. N. (2011). Driving performance impairments due to hypovigilance on monotonous roads. *Accident Analysis and Prevention*, 43(6), 2037–2046. <https://doi.org/10.1016/j.aap.2011.05.023>.

Lemay, S., Bédard, M. A., Rouleau, I., & Tremblay, P. L. G. (2004). Practice effect and test-retest reliability of attentional and executive tests in middle-aged to elderly subjects. *Clinical Neuropsychologist*, 18(2), 284–302. <https://doi.org/10.1080/13854040490501718>.

Lim, J., Wu, W. C., Wang, J., Detre, J. A., Dinges, D. F., & Rao, H. (2010). Imaging brain fatigue from sustained mental workload: An ASL perfusion study of the time-on-task

- effect. *NeuroImage*, 49(4), 3426–3435. <https://doi.org/10.1016/j.neuroimage.2009.11.020>.
- Loft, S., Sanderson, P., Neal, A., & Mooij, M. (2007). Modeling and predicting mental workload in en route air traffic control: Critical review and broader implications. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 49(3), 376–399. <https://doi.org/10.1518/001872007X197017>.
- Loh, S., Lamond, N., Dorrian, J., Roach, G., & Dawson, D. (2004). The validity of psychomotor vigilance tasks of less than 10-minute duration. *Behavior Research Methods, Instruments, and Computers*, 36(2), 339–346.
- Luque-Casado, A., Perakakis, P., Ciriá, L. F., & Sanabria, D. (2016). Transient autonomic responses during sustained attention in high and low fit young adults. *Scientific Reports*, 6, 27556. <https://doi.org/10.1038/srep27556>.
- Luque-Casado, A., Perales, J. C., Cárdenas, D., & Sanabria, D. (2015). Heart rate variability and cognitive processing: The autonomic response to task demands. *Biological Psychology*, 113, 83–90. <https://doi.org/10.1016/j.biopsycho.2015.11.013>.
- Luque-Casado, A., Zabala, M., Morales, E., Mateo-March, M., & Sanabria, D. (2013). Cognitive performance and heart rate variability: The influence of fitness level. *PLoS One*, 8(2), e56935. <https://doi.org/10.1371/journal.pone.0056935>.
- Macatee, R. J., Albanese, B. J., Schmidt, N. B., & Cogle, J. R. (2017). The moderating influence of heart rate variability on stressor-elicited change in pupillary and attentional indices of emotional processing: An eye-tracking study. *Biological Psychology*, 123, 83–93. <https://doi.org/10.1016/j.biopsycho.2016.11.013>.
- Malik, Marek, Bigger, J. T., Camm, A. J., Kleiger, R. E., Malliani, A., Moss, A. J., & Schwartz, P. J. (1996). Heart rate variability standards of measurement, physiological interpretation, and clinical use. *European Heart Journal*, 17(3), 354–381.
- Malik, M., Cripps, T., Farrell, T., & Camm, A. J. (1989). Prognostic value of heart rate variability after myocardial infarction. A comparison of different data-processing methods. *Medical and Biological Engineering and Computing*, 27(6), 603–611. <https://doi.org/10.1007/BF02441642>.
- Malmstrom, F. V., Angeles, L., Randle, R. J., Bendix, J. S., & Weber, R. J. (1980). The visual accommodation response during concurrent mental activity, 28(5), 440–448.
- McAlinden, C., Khadka, J., & Pesudovs, K. (2011). Statistical methods for conducting agreement (comparison of clinical tests) and precision (repeatability or reproducibility) studies in optometry and ophthalmology. *Ophthalmic and Physiological Optics*, 31(4), 330–338. <https://doi.org/10.1111/j.1475-1313.2011.00851.x>.
- McDougal, D. H., & Gamlin, P. D. (2015). Autonomic control of the eye. *Comprehensive Physiology*, 5(1), 439–473. <https://doi.org/10.1002/cphy.c140014>.
- McIntire, L. K., McKinley, R. A., Goodyear, C., & McIntire, J. P. (2014). Detection of vigilance performance using eye blinks. *Applied Ergonomics*, 45(2), 354–362.
- Metlapally, S., Tong, J. L., Tahir, H. J., & Schor, C. M. (2016). Potential role for microfluctuations as a temporal directional cue to accommodation. *Journal of Vision*, 16(6), 19. <https://doi.org/10.1167/16.6.19>.
- Millodot, M. (2014). *Dictionary of optometry and visual science* (seventh ed.). Elsevier Health Sciences.
- Momeni-Moghaddam, H., McAlinden, C., Azimi, A., Sobhani, M., & Skiadaresi, E. (2014). Comparing accommodative function between the dominant and non-dominant eye. *Graefes's Archive for Clinical and Experimental Ophthalmology*, 252(3), 509–514. <https://doi.org/10.1007/s00417-013-2480-7>.
- Park, G., Van Bavel, J. J., Vasey, M. W., Egan, E. J. L., & Thayer, J. F. (2012). From the heart to the mind's eye: Cardiac vagal tone is related to visual perception of fearful faces at high spatial frequency. *Biological Psychology*, 90(2), 171–178. <https://doi.org/10.1016/j.biopsycho.2012.02.012>.
- Podsakoff, P. M., MacKenzie, S. B., Lee, J. Y., & Podsakoff, N. P. (2003). Common Method Biases in Behavioural Research: A critical Review of the Literature and Recommended Remedies. *Journal of Applied Psychology*, 88(5), 879–903.
- Poltavski, D. V., Biberdorf, D., & Petros, T. V. (2012). Accommodative response and cortical activity during sustained attention. *Vision Research*, 63, 1–8. <https://doi.org/10.1016/j.visres.2012.04.017>.
- Pumprla, J., Howorka, K., Groves, D., Chester, M., & Nolan, J. (2002). Functional assessment of heart rate variability: Physiological basis and practical applications. *International Journal of Cardiology*, 84(1), 1–14. doi: 10.1016/S0167-5273(02)00057-8.
- Redondo, B., Vera, J., Molina, R., García, J. A., Ouadi, M., Muñoz-Hoyos, A., & Jiménez, R. (2018). Attention-deficit/hyperactivity disorder children exhibit an impaired accommodative response. *Graefes's Archive for Clinical and Experimental Ophthalmology*, 1–8.
- Roberts, T. L., Manny, R. E., Benoit, J. S., & Anderson, H. A. (2018). Impact of cognitive demand during sustained near tasks in children and adults. *Optometry and Vision Science*, 95(3), 223–233. <https://doi.org/10.1097/OPX.0000000000001186>.
- Rosenfield, M., & Ciuffreda, K. J. (1990). Proximal and cognitively-induced accommodation. *Ophthalmic and Physiological Optics*, 10(3), 252–256. <https://doi.org/10.1111/j.1475-1313.1990.tb00860.x>.
- Rosenfield, M., Jahan, S., Nunez, K., & Chan, K. (2015). Cognitive demand, digital screens and blink rate. *Computers in Human Behavior*, 51(PA), 403–406. <https://doi.org/10.1016/j.chb.2015.04.073>.
- Sheppard, A. L., & Davies, L. N. (2010). Clinical evaluation of the Grand Seiko Auto Ref/Keratometer WAM-5500. *Ophthalmic and Physiological Optics*, 30(2), 143–151. <https://doi.org/10.1111/j.1475-1313.2009.00701.x>.
- Steinmayr, R., Ziegler, M., & Träuble, B. (2010). Do intelligence and sustained attention interact in predicting academic achievement? *Learning and Individual Differences*, 20(1), 14–18. <https://doi.org/10.1016/j.lindif.2009.10.009>.
- Streiner, D. L., Norman, G. R., & Cairney, J. (2015). *Health measurement scales: A practical guide to their development and use*. USA: Oxford University Press.
- Tarvainen, M. P., Niskanen, J.-P., Lipponen, J. A., Ranta-aho, P. O., & Karjalainen, P. A. (2009). *Kubios HRV — A software for advanced heart rate variability analysis*. 4th European Conference of the International Federation for Medical and Biological Engineering/Springer Berlin Heidelberg 1022–1025.
- Tarvainen, M. P., Ranta-aho, P. O., & Karjalainen, P. A. (2002). An advanced detrending method with application to HRV analysis. *Biomedical Engineering, IEEE Transactions On*, 49(2), 172–175. <https://doi.org/10.1109/10.979357>.
- Tosha, C., Borsting, E., Ridder, W. H., & Chase, C. (2009). Accommodation response and visual discomfort. *Ophthalmic and Physiological Optics*, 29(6), 625–633. <https://doi.org/10.1111/j.1475-1313.2009.00687.x>.
- Vera, J., Diaz-Piedra, C., Jiménez, R., Morales, J. M., Catena, A., Cardenas, D., & Di Stasi, L. L. (2016). Driving time modulates accommodative response and intraocular pressure. *Physiology and Behavior*, 164, 47–53. <https://doi.org/10.1016/j.physbeh.2016.05.043>.
- Vera, J., Diaz-Piedra, C., Jiménez, R., Sanchez-Carrion, J. M., & Di Stasi, L. L. (2018). Intraocular pressure increases after complex simulated surgical procedures in residents: An experimental study. *Surgical Endoscopy and Other Interventional Techniques*, 1–9. <https://doi.org/10.1007/s00464-018-6297-7>.
- Vera, J., Jiménez, R., García, J. A., & Cárdenas, D. (2017). Intraocular pressure is sensitive to cumulative and instantaneous mental workload. *Applied Ergonomics*, 60, 313–319. <https://doi.org/10.1016/j.apergo.2016.12.011>.
- Vera, J., Jiménez, R., García, J. A., Perales, J. C., & Cárdenas, D. (2018). Baseline intraocular pressure is associated with subjective sensitivity to physical exertion in young males. *Research Quarterly for Exercise and Sport*, 89(1), 25–37. <https://doi.org/10.1080/02701367.2017.1407491>.
- Vera, J., Luque-Casado, A., Redondo, B., Cárdenas, D., Jiménez, R., & García-Ramos, A. (2019). Ocular accommodative response is modulated as a function of physical exercise intensity. *Current Eye Research*, 44(4), 442–450.
- Winn, B., & Gilmartin, B. (1992). Current perspective on microfluctuations of accommodation. *Ophthalmic and Physiological Optics*, 12, 252–257.
- Winn, B., Pugh, J., Gilmartin, B., & Owens, H. (1990). Arterial pulse modulates steady-state ocular accommodation. *Current Eye Research*, 9(10), 971–975.
- Zhang, F., Chen, S., Zhang, H., Zhang, X., & Li, G. (2014). Bioelectric signal detrending using smoothness prior approach. *Medical Engineering and Physics*, 36(8), 1007–1013. <https://doi.org/10.1016/j.medengphy.2014.05.009>.