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Title: Ocular accommodative response is modulated as a function of physical exercise intensity.

Running head: High-intensity exercise impairs accommodation.

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Abstract

Purpose: The present study aimed (1) to examine the impact of two high-intensity interval training (HIIT) protocols differing in exercise intensity (low-intensity and high-intensity) on the dynamic accommodative response (AR), and (2) to elucidate whether the ocular accommodation changes are associated with the function of the autonomic nervous system during stimulus processing, as measured by the heart rate variability (HRV).

Methods: Twenty physically active university students (9 women; age = 23.9 ± 3.3 years) were tested on three separate sessions. The lag of accommodation and the RMSSD (root-mean-square of successive R-R interval differences) parameter of HRV were obtained at the beginning and at the end of each testing session, while one of the following protocols was applied in a randomised order between the measurements: low-intensity HIIT (8 sprints with 60 seconds of rest), high-intensity HIIT (8 sprints with 30 seconds of rest), and Control (walking for 8 minutes).

Results: Our data demonstrated a higher lag of accommodation after the high-intensity HIIT compared to the low-intensity HIIT ($p = 0.006$, $d = 0.798$) and control ($p = 0.007$, $d = 0.741$), but no significant differences were observed between the low-intensity HIIT protocol and control condition ($p = 0.598$, $d = 0.12$). As expected, lower HRV values were observed with higher exercise intensity, but the changes of AR and HRV were not significantly correlated ($p > 0.05$ in all cases).

Conclusions: The present findings indicate that the acute effects of exercise on ocular accommodation depend on exercise intensity, showing that highly demanding physical effort induces a greater lag of accommodation, which may be of relevance when performing near activities after physical efforts.

1. Introduction

The acute effect of physical exercise on sensory and cognitive performance has been thoroughly addressed due to its relevance in laboratory and applied scenarios.[1–4] Most findings have been explained by the arousal theory, which states that an increase in arousal up to a certain point due to physical exercise could promote an enhancement in both sensory and cognitive performance, while highly demanding physical exercise promotes over-arousal and it impairs sensory and cognitive performance.[5] Nevertheless, there are numerous factors such as exercise type, exercise intensity, exercise duration, participants´ fitness level, study population, measured time points, sensory or cognitive processes being assessed that may affect the acute impact of physical effort on sensory and cognitive performance.[6] In general, the effect of physical effort on sensory and cognitive performance seems to be instantaneous and it disappears rapidly when the exercise is terminated.[2,7] However, while there is a large body of knowledge about the effect of physical effort on cognitive performance, the impact of physical effort on sensory functioning has been less studied.

The main channel to gather information in the majority of situations is the visual system, being highly necessary during sports practice.[8] Physical effort induces physiological changes, which also influence the ocular function. For example, intraocular pressure,[9] retinal activity[10] or neural conductivity in the visual pathway[11] have been shown to be sensitive to exercise. An important visual ability is the accommodative response (AR), since it allows to see clearly at different distances[12] and, thus, it is of vital importance in numerous contexts (e.g., reading). AR has been linked to the cardiovascular system, as measured by heart rate variability (HRV), suggesting that both are highly dependent on the balance between the sympathetic and parasympathetic branches of the autonomic nervous system.[13] Indeed, changes of the level of arousal as consequence of mental fatigue have been demonstrated to alter AR[14,15] and these variations have been explained by variations of the neural integrator in the accommodation control system.[16,17] In view of this, it is plausible that changes in the level of arousal induced by physical effort may impact AR, as it has been evidenced with mental effort.

Focusing on the type of physical exercise and in accordance with the arousal theory, high-intensity interval-training (HIIT) has emerged as a time-efficient strategy to improve the health status,[18] promoting similar physical and psychological benefits in comparison with continuous exercise.[19] To date, there are limited studies that have examined the effect of HIIT on brain function. For example, Hillman and Biggan[20] recently suggested that HIIT may lead to neural, cognitive and academic enhancements. Therefore, assuming that HIIT induces autonomic nervous system changes and modulates the levels of arousal, the assessment of the acute effects of different HIIT protocols on AR would expand our knowledge of the association between physical effort and sensory functioning.

The main objectives of the present study were: (1) to examine the impact of low-intensity and high-intensity HIIT protocols on the AR dynamically measured during a task that requires constant attentional demand, and (2) to elucidate whether the ocular accommodation changes are associated with the function of the autonomic nervous system during stimulus processing, as measured by HRV. We hypothesised that (1) following the arousal theory the ocular AR would be enhanced and impaired (i.e., lower and higher lags of accommodation, respectively) after the low- and high- intensity HIIT protocols, respectively,[5] and (2) the ocular accommodation would be significantly associated with the autonomic function after both HIIT protocols, as shown during mentally demanding tasks.[15]

2. Methods

2.1. Ethical approval and participants

This study followed the Code of Ethics of the World Medical Association (Declaration of Helsinki) and was approved by the Institutional Review Board. Twenty healthy and physically active university students (9 women; mean age ± SD = 23.9 ± 3.3 years) took part in this study. All participants were free of any general or ocular condition that could affect or mask the dependent variables assessed. Hence, the inclusion criteria were: 1) be free of any ocular disease, as checked by slit lamp and direct ophthalmoscopy examination, 2) not suffering any systemic disease, and not taking any medication that might cause visual alterations, 3) have no history of strabismus, refractive surgery and orthokeratology, 4) achieve a visual acuity with their best refractive correction of ≤0 logMAR (20/20 Snellen) in each eye, 5) belong to the asymptomatic group as measured with the Conlon survey (cut off value of ≤24),[21] 6) be soft contact lenses users at least for one year, since differences in ocular accommodation have been demonstrated between contact lenses and spectacles,[22] and 7) present no significant uncorrected refractive error that could affect accommodative and vergence systems (myopia < 0.50 D, astigmatism and anisometropia < 0.50 D, and/or hyperopia < 1.50 D).[14] Participants′ refractive errors without optical compensation were: mean spherical equivalent ± SD = -0.61 ± 0.86 D, ranging from -2.27 to +1.56 D. Additionally, participants were asked to avoid alcohol and caffeine-based drinks 24h and 12h before experimental sessions, respectively. Finally, they were instructed to sleep at least 7h the night before testing. The level of alertness across experimental sessions was checked by the Stanford Sleepiness Scale (SSS),[23] and a cut off-value <4 was considered as inclusion criteria.[14]

2.2. Instruments and measures

2.2.1. Subjective questionnaires

The Borg CR10 scale[24] was used to assess the perceived exertion of the three protocols through a numerical scale ranging from 0 (“nothing at all”) to 10 (“extremely strong”). The ratings of perceived exertion (RPE) were collected before the testing period, after each of the 8 sprints (or every 45 seconds for the Control condition), and after 15 min of rest. Additionally, the SSS[23] was used to check the level of sleepiness/alertness before the commencement of each experimental session. This scale ranges from 1 “Feeling active, vital, alert, or wide awake” to 7 “No longer fighting sleep, sleep onset soon, having dream-like thoughts”, and it provides a global subjective measure of the level of alertness.

2.2.2. Ocular accommodation assessment and visual task

The Grand Seiko WAM-5500 open field autorefractor (Grand Seiko Co. Ltd., Hiroshima, Japan), was used to measure dynamic AR values before and after each HIIT protocol. This instrument permits the examiner to continuously record the mean spherical equivalent refractive error and pupil size in the dynamic mode with a sensitivity of 0.01D and 0.1mm, respectively. The temporal resolution is ~5 Hz. In order to obtain a robust dynamic AR and following previous recommendations,[25] we measured static refraction at far distance before starting each experimental session, which would be used for data analysis. We considered the average value from ten static AR measurements in each eye. Participants wore their contact lenses when necessary based on exact ocular refraction and were asked to position their chin and forehead on the respective supports. After it, dynamic AR was continuously measured while participants performed a 10-minute visual task (see below) in binocular and free-viewing conditions by using a high-contrast target stimulus displayed at 50 cm from their eyes. Although the WAM-5500 permits binocular viewing, the accommodative response cannot be measured for both eyes simultaneously. In the current study, the dominant eye, which was determined by the hole-in-the card method, was chosen to record AR data.[26] For data analysis and based on previous investigations, values varying more than 3 SD from the mean were considered as blinks or recording errors and, thus, they were excluded from further analysis. Each 10-min task was divided into five temporal blocks of 2-min each in order to investigate the possible changes over time (time-on-task effects; blocks: 1, 2, 3, 4 and 5). For the calculation of the lag of accommodation, we subtracted the accommodative response to the accommodative demand (2D) of the visual task. The accommodative response was considered as the dynamic measure during the Psychomotor Vigilance Task (PVT) corrected by the baseline static refractive value at far distance to avoid the effects of residual refractive errors.[14,25,27]

$$Accomodative\ lag\ (D) = -2 - dynamic\ AR - residual\ refractive\ error\ at\ far\ distance$$

A modified version of the PVT[28] was used as a standardized procedure to control the presentation of visual stimuli in order to measure the accommodative response in the different experimental conditions. A 15.6″ LCD laptop PC and the E-Prime software (Psychology Software Tools, Pittsburgh, PA, USA) were used to control for stimulus presentation and response collection. The centre of the laptop screen was situated at 50cm from the participants' head and at their eye level. The device used to collect responses was the PC keyboard. The procedure of the PVT was originally designed to measure vigilance by recording participants' reaction time to visual stimuli that occur at random inter-stimulus intervals.[28] This procedure was used for two main reasons: first, to standardize the random presentation of visual stimuli between experimental conditions in order to obtain reliable data of accommodative response; second, we tried to match the different experimental conditions in terms of attentional demands with the aim of ensuring that participants were paying appropriate attention to the stimuli presented on the screen. It should be noted that the PVT requires to maintain the viewer´s attention, however, an accurate accommodation may not be essential for detection of the visual stimuli.

The procedure of presentation of the visual stimuli was as follows (see Figure 1 for a graphical description of the PVT procedure): each trial began with the presentation of an empty black circle in a blank background, which subtended 6.73° in the horizontal and vertical axes, for 2000ms. Later, in a random time interval (between 2000 and 10000ms), the circle was filled all at once in a black colour. Participants were instructed to respond as fast as they could once they had detected the presentation of the filled circle. The filled circle was presented for 500ms and the participants had a maximum of 1500ms to respond. They had to respond with their dominant hand by pressing the space bar on the keyboard. A reaction time visual feedback message was displayed for 300ms after response, except in case of an anticipated response (‘‘wait for the target’’) or if no response was made within 1000ms after target offset (‘‘you did not answer’’). Following the feedback message the next trial began. The task lasted 10 minutes.

2.2.3. ***Cardiovascular function assessment***

Heart rate and HRV were recorded throughout the experimental sessions using a Polar RS800 CX monitor (Polar Electro, Kempele, Finland). The heart rate monitor was placed at the beginning of each experimental session and participants rested for six minutes (the first minute was discarded from the analysis to obtain a more reliable measure) in a supine position to record the baseline HRV. Participants were encouraged to stay as relaxed as possible. Moreover, the average HR was calculated for the main part of the testing session (i.e., from the first to the last sprint) to check the cardiovascular demands of the different HIIT protocols and HRV was analysed during the stimuli presentation (see *ocular accommodation assessment and visual task* section for details). Subsequently, each R-R interval file was analysed by means of the Kubios HRV Analysis Software 2.0.[29] The recordings were preprocessed to exclude artifacts by eliminating R-R intervals which differed more than 25% from the previous and the subsequent R-R intervals. A detrending procedure based on smoothness priors approach was applied to avoid any distortion in HRV results due to its non-stationary behavior (e.g., slow linear or more complex trends in the HRV signal).[30] The root-mean-square difference of successive normal R-R intervals (RMSSD) was used to analyse the HRV within the time domain. The denotations and definitions for the HRV analysis in this paper follow the procedure used in previous studies[31] and the guidelines given in *Task Force of the European Society of Cardiology* and the *North American Society of Pacing and Electrophysiology*.[32]

2.3. Procedure

All participants attended to the laboratory on four different occasions. In the first visit, participants signed the consent form, were checked for their compliance with the inclusion criteria, and were familiarized with the visual task. The next three experimental sessions comprised the main part of the study. Upon arrival to the laboratory, participants completed the SSS and were fitted with a heart rate monitor. At this point, they rested for six minutes in supine position for baseline cardiovascular assessment. Subsequently, we assessed ocular accommodation while performing the 10-min visual task before any physical effort. Just after it, participants carried out the warm-up and performed the corresponding HIIT protocol. The general warm-up for both HIIT sessions consisted of 10 min of jogging and dynamic stretching, which was followed by 2 sets of sprints with a 180º change of direction (see details below) performed at 50% and 90% of the maximum intensity. Afterwards, participants rested for 5 min before the initiation of the HIIT protocol. Each sprint consisted of running at the maximum possible velocity for 15m, a 180º change of direction, and then running again at the maximum possible velocity until crossing the starting line (total distance: 30m). The time needed to complete each sprint was collected by means of a telemetric photocell (Microgate, Bolzano, Italy) placed on the starting line. The starting position was standardized with the lead-off foot placed 1 m behind the starting line. Participants were instructed to complete each sprint in the shortest possible time. The three exercise protocols were performed on separate occasions and in a randomized order. They were defined as follows: low-intensity HIIT (8 sprints with 60 seconds of rest between sprints), high-intensity HIIT (8 sprints with 30 seconds of rest between sprints), and Control (walking for 8 minutes).

After each of the eight sprints, or every 45 seconds for the control condition, they reported their level of perceived exertion (eight points of measure in each condition), using the RPE scale. When the HIIT protocol was completed, a 2 minutes cool-down protocol (recovery) was carried out to avoid sudden heart rate decelerations as recommended by the American Heart Association for submaximal physical effort,[33] and AR was evaluated again (see Figure 1 for a graphical description of the experimental design). In order to avoid any circadian effect on arousal levels, all experimental sessions were scheduled at the same time of the day (± 1 hour). Also, the order of the experimental sessions was counterbalanced to avoid potential practice/learning effects. All evaluations were performed under constant environment (~22ºC and ~60% humidity) and illumination (217±12 lx, as measured in the corneal plane [Illuminance meter T-10, Konica Minolta, Inc., Japan]) conditions.

2.4. Experimental design and statistical analysis

A repeated measures design was carried out to test the effects of HIIT protocols differing in the level of effort on the ocular accommodation and cardiovascular functioning.

To check whether participants attended to the laboratory under similar conditions, we conducted an one-way ANOVA with the exercise-intensity (control, low-intensity, and high-intensity) as the only within-participants factor, and considering the level of alertness (SSS) reported by participants at the beginning of each experimental session, baseline HR and HRV measures (RMMSD), as well as for the lag of accommodation measured before physical effort as the dependent variables. The success of the experimental manipulation was checked by a repeated measures ANOVA, considering the exercise-intensity (control, low-intensity, and high-intensity) and the point of measure (sprint 1 to sprint 8) as the within-participants factors, and with RPE and HR as the dependent variables.

The main set of analyses aimed to assess the effect of physical exercise intensity on the dynamic accommodative function (lag of accommodation). To do it, a two-way ANOVA with the intensity (control, low-intensity, and high-intensity) and the time-on-task (blocks: 1, 2, 3, 4 and 5) as the within-participants factors was carried out for the changes in the lag of accommodation (post-exercise minus pre-exercise) as well as for the changes in the RMSSD component of HRV (post-exercise minus pre-exercise). We also calculated the Pearson product-moment correlation coefficients (Pearson r) to explore the possible associations between the lag of accommodation and the HRV at the different points of measure. The magnitude of the differences was also assessed through the Cohen's d for pairwise comparisons and the partial eta squared (η_p^2) for multiple comparisons. All statistical analyses were performed using JASP software (version 0.8.5.1). Statistical significance was set at an alpha level of 0.05, and post hoc tests were corrected using Holm-Bonferroni procedures.

3. Results

Firstly, we checked that the level of alertness ($F_{2, 38} = 0.755$, $p = 0.477$), the baseline HRV measure ($F_{2, 38} = 0.408$, $p = 0.668$), and the measures of the main dependent variables obtained before physical effort were not different between the three experimental conditions ($F_{2, 38} = 0.067$, $p = 0.935$ for the lag of accommodation and $F_{2, 38} = 1.370$, $p = 0.266$ for the RMSSD component of HRV). A successful exercise-intensity manipulation was confirmed by the analysis of HR and RPE ($F_{2, 38} = 1596.52$, $p < 0.001$, $\eta_p^2 = 0.99$ for HR and $F_{2, 38} = 138.02$, $p < 0.001$, $\eta_p^2 = 0.88$ for RPE), showing progressively higher values of HR and RPE as the exercise intensity increased (Table I).

A two-way ANOVA for the changes in the lag of accommodation revealed significant differences for the intensity ($F_{2, 38} = 7.875$, $p = 0.001$, $\eta_p^2 = 0.293$), whereas the time on task and the interaction intensity x time on task did not reach statistical significance ($F_{4, 76} = 1.632$, $p = 0.175$; and $F_{8, 152} = 0.751$, $p = 0.646$; respectively). Post-hoc comparisons demonstrated greater lags of accommodation for the high-intensity HIIT compared to the low-intensity HIIT (corrected p-value = 0.006, d = 0.798) and control condition (corrected p-value = 0.007, d = 0.741) after physical effort. However, there was no statistical difference between the control and low-intensity conditions (corrected p-value = 0.598, d = 0.12) (Figure 2 and Table II).

The RMSSD component of HRV demonstrated a statistically significant effect for the intensity ($F_{2, 38} = 38.463$, $p < 0.001$, $\eta_p^2 = 0.669$), whereas no statistically significant differences were found for the time on task ($F_{4, 76} = 1.685$, $p = 0.162$) and the interaction intensity x time on task ($F_{8, 152} = 1.060$, $p = 0.394$). Post-hoc comparisons exhibited statistically significant differences for the high-intensity vs. control (corrected p-value < 0.001, d = 1.41) and the low-intensity vs. control (corrected p-value < 0.001, d =1.57), whereas no significant differences were found between the high-intensity and low-intensity conditions (corrected p-value = 0.443, d = 0.175) (Figure 3 and Table II).

Finally, we conducted separate Pearson correlations between the values of lag of accommodation and RMSSD measured after exercise, considering the mean value from the 10-min visual task, as well as the five 2-min blocks, however, no statistically significant correlations were found at any point of measure (all p-values > 0.05). Additionally, the same procedure was carried out, but considering the differences between the AR and HRV values obtained before and after each experimental condition. Again, the level of correlation did not reach statistical significance (all p-values > 0.05).

4. Discussion

We aimed to test the acute impact of two HIIT protocols with different physical requirements (low and high-intensity) on dynamic, binocular and free-viewing ocular accommodation (AR), as well as the possible links between ocular accommodation changes and the autonomic function measured by means of the HRV. Our results demonstrated that AR varied as a function of exercise-intensity, with higher lag of accommodation values (lower AR) after the high-intensity HIIT protocol compared to the low-intensity HIIT protocol and control condition. Complementarily, HRV was also sensitive to HIIT-intensity, showing lower HRV values with higher exercise intensity (high-intensity<low-intensity<control). However, we found that the behaviour of both indices was not significantly correlated. This set of data indicates that highly demanding physical effort impairs ocular accommodation, causing an increased lag of accommodation, which may alter performance in applied settings. These AR changes may be explained by arousal-based effects, as it has been previously evidenced by the variation of individuals' level of activation in mental and driving tasks.[14,15]

First, we checked a successful experimental manipulation by confirming that participants attended the lab under similar conditions (SSS and baseline HRV), and the pre-exercise measures (accommodative response and HRV) during the 10-min visual task were comparable across experimental sessions. These indices were far from showing any significance, and thus, it permits us to control possible confounding factors. Additionally, exercise-intensity manipulation was controlled by the analysis of heart rate during physical effort, as well as by RPE values. As expected, both variables increased with higher exercise intensity, demonstrating different physiological and subjective responses depending on exercise intensity (Table I).

Our first hypothesis was partially confirmed since ocular accommodation changes were dependent on exercise-intensity. This finding converges with the assumption that very demanding physical effort may induce poorer performance than at rest, thus revealing an inverted-J effect, whereas when the stressor is purely psychological promotes an inverted-U effect. The inverted-J and inverted-U effects reveal that performance depends on the level of activation. However, different activities require different levels of activation for optimal performance and, thus, this relationship is task-dependent (e.g., physical, mental or a combination of both).[34] In particular, the inverted-U theory postulates that certain level of arousal is beneficial for performance, while extreme levels of activation (very low or high) decrease performance. For its part, the inverted-J effect indicates that performance is reduced at very high levels of activation, which has been commonly described for physical tasks.[5] The lack of effect on AR after performing the less physically demanding protocol is somewhat surprising, since moderate physical exercise is known to increase the concentration of dopamine and norepinephrine, moderately raise physiological arousal levels, and improve motor unit coordination and contractile function,[5,7] being this last especially relevant for an accurate function of the ciliary muscle, and thus, for ocular accommodation.[35] For example, a recent study by Kujach et al., (2018)[36] demonstrated that sedentary individuals improved their executive function after performing a HIIT session at 60% of maximal aerobic power, which was linked with the activation of the left-dorsal-lateral prefrontal cortex. Nevertheless, the previous literature has been mainly focused on cognitive and executive performance,[37] and multiple circumstances such as the lack of individualized exercise intensity, the fact that the effects of HIIT exercise on sensory performance has not been investigated to date, or the non-existent evidence of the impact of physical exercise on the ocular accommodation may explain these novel outcomes. The high-intensity condition clearly showed a detrimental effect on the dynamics of ocular accommodation after physical effort, and although its clinical significance may be modest, it may be of relevance in tasks requiring a sustained accurate accommodative functioning, especially at near viewing distances (e.g., occupational settings, viewing a smartphone, etc.). This finding agrees with the related research in the area of cognition, supporting a negative effect of highly intense exercise.[5,37] The changes found for ocular accommodation are important since small increments in the accommodative lag have been linked to visual discomfort,[38] being these effects more significant at closer viewing distances.[39] Relevantly, the execution of highly demanding exercise promotes an excessive concentration of catecholamines and the dysfunction the hypothalamo–pituitary–adrenocortical axis, which are known to play a major role in the control of the ocular dynamics.[40–42] Moreover, we can state from our results that HIIT induces an inverted-J effect on AR, showing no effects of the low-intensity condition whereas the high-intensity protocol caused an acute increase on the lag of accommodation.

The effects of physical effort on the cardiovascular function are well-known, exhibiting higher values of heart rate and lower of HRV as exercise intensity increases and it was corroborated in the present investigation.[43] However, HRV was included to explore the association between the ocular accommodation and cardiovascular functioning after performing two HIIT protocols differing in the level of effort. Here, we did not find any significant correlation between them. Although these variables have been found to be significantly correlated during cognitive processing,[15] the lack of association when incorporating physical demands may be explained by the fact that physical effort disrupts the autonomic nervous system balance that is reflected in HRV.[44] Notably, ocular accommodation is directed by the ciliary muscle, which is innervated by the dual action of the sympathetic and parasympathetic branches of the autonomic nervous system and an anomalous autonomic input leads to inaccurate accommodation responses.[35] In this sense, Davies, Wolffsohn, & Gilmartin, (2009)[13] found that the alteration of the accommodative demands modifies the cardiovascular function, and also observed that ocular accommodation correlates with the parasympathetic autonomic innervation during a cognitive task.[15] A similar result was found by Vera et al., (2017)[45] when considering intraocular pressure, who reported an association between this ocular variable and the autonomic cardiovascular control during the execution of a mental workload task. Physical and mental efforts are known to induce specific physiological changes.[46] The fatigue induced by physical effort is caused by the complex interaction of multiple peripheral physiological systems and the brain. Particularly, it should be noted that the effects of HIIT on the human physiology are still not well understood.[47] The lack of association between ocular accommodation and HRV observed in the present study may be explained by the different physiological mechanisms involved in predominantly physical and mental tasks.

4.1. Limitations and future research

The validity of our findings may be limited by several factors that should be acknowledged. First, as we failed to find any association between ocular accommodation and cardiovascular functioning after HIIT, the assessment of brain areas, which play a role in controlling ocular accommodation (e.g., extrastriate cortex, parietal cortex, frontal eye fields, cerebellum or midbrain), may help to elucidate possible mechanisms underlying the influence of central nervous system alterations as consequence of physical exercise on ocular accommodation.[35] We assessed ocular accommodation in a pre/post manner, with the post-exercise measure obtained after 2 minutes of recovery. Further studies should explore the impact of physical fatigue during exercise on the ocular accommodation and cardiovascular function, as well as the possible association between them. In the present study, we assessed ocular accommodation while participants were performing a sustained attention task. In this regard it should be noted that the inclusion of tasks with different viewing demands (e.g., size, colour, contrast, attentional requirements, time of presentation, etc.) may also alter the present results. Participants´ characteristics (sex or fitness level), exercise type, variables assessed or the points of measure may also influence the results of the present study and, therefore,, our results must be cautiously interpreted in this regard. The inclusion of other ocular indices may be of interest to elucidate the influence of physical effort on the ocular physiology. For example, the assessment of choroidal thickness, which is the ocular structure with the highest blood flow, could help to clarify the ocular accommodation changes as consequence of physical efforts.[48] Lastly, previous studies have found that adults with progressing and stable myopia exhibit different accommodative responses at near,[49] and consequently, future investigations are needed with this population. We consider that the effects of physical effort on the ocular functioning may have an impact on task performance in applied contexts, especially in activities performed at near working distances (e.g., computer work, reading, etc.). It is our hope that the effects of physical effort on visual performance during real-world situations will be tested in future investigations.

5. Conclusions

In summary, ocular accommodation is sensitive to physical effort depending on exercise-intensity, obtaining a higher lag of accommodation after performing the most demanding HIIT protocol. Overall, this finding corroborates and expands the evidence about the effects of exercise on sensory functioning, and particularly on accommodative function, based on the arousal theory. HIIT induces changes on HRV, but these variations are independent of ocular accommodation. Our results incorporate novel insights into the capacity of the visual system to reflect the nervous system´s activation changes caused by physical effort, which may have important applications when performing near tasks after highly demanding physical activities.

6. References

1. Davranche K, Burle B, Audiffren M, Hasbroucq T. Information processing during physical exercise: A chronometric and electromyographic study. Exp Brain Res. 2005;165(4):532–40.

2. Lambourne K, Audiffren M, Tomporowski PD. Effects of acute exercise on sensory and executive processing tasks. Med Sci Sports Exerc. 2010;42(20):1396–402.

3. Mcmorris T, Hale BJ. Is there an acute exercise-induced physiological / biochemical threshold which triggers increased speed of cognitive functioning ? A meta-analytic investigation. J Sport Heal Sci [Internet]. 2015;4(1):4–13. Available from: http://dx.doi.org/10.1016/j.jshs.2014.08.003

4. Davranche K, Brisswalter J, Radel R. Where are the limits of the effects of exercise intensity on cognitive control? J Sport Heal Sci [Internet]. 2014;4:56–63. Available from: http://linkinghub.elsevier.com/retrieve/pii/S2095254614001215

5. McMorris T, Hale BJ, Corbett J, Robertson K, Hodgson CI. Does acute exercise affect the performance of whole-body, psychomotor skills in an inverted-U fashion? A meta-analytic investigation. Physiol Behav [Internet]. 2015;141:180–9. Available from: http://dx.doi.org/10.1016/j.physbeh.2015.01.010

6. Zimmer P, Binnebößel S, Bloch W, Hübner ST, Schenk A, Predel HG, et al. Exhaustive

exercise alters thinking times in a tower of london task in a time-dependent manner. Front Physiol. 2017;7(JAN):1–11.

7. Lambourne K, Tomporowski P. The effect of exercise-induced arousal on cognitive task performance: A meta-regression analysis. Brain Res [Internet]. 2010;1341:12–24. Available from: http://dx.doi.org/10.1016/j.brainres.2010.03.091

8. Memmert D, Simons DJ, Grimme T. The relationship between visual attention and expertise in sports. Psychol Sport Exerc. 2008;10(1):146–51.

9. Vera J, Jiménez R, Redondo B, Cárdenas D, De Moraes CG, Garcia-Ramos A. Intraocular pressure responses to maximal cycling sprints against different resistances: the influence of fitness level. J Glaucoma. 2017;26(10):881–7.

10. Zwierko T, Czepita D, Lubiński W. The effect of physical effort on retinal activity in the human eye: Rod and cone flicker electroretinogram studies. Graefe's Arch Clin Exp Ophthalmol. 2010;248(5):659–66.

11. Zwierko T, Lubiński W, Lubkowska A, Niechwiej-Szwedo E, Czepita D. The effect of progressively increased physical efforts on visual evoked potentials in volleyball players and non-athletes. J Sports Sci [Internet]. 2011;29(14):1563–72. Available from: http://www.scopus.com/inward/record.url?eid=2-s2.0-82055180623&partnerID=tZOtx3y1

12. Millodot M. Dictionary of optometry and visual science. Elsevier Health Sciences; 2014.

13. Davies LN, Wolffsohn JS, Gilmartin B. Autonomic correlates of ocular accommodation and cardiovascular function. Ophthalmic Physiol Opt. 2009;29(4):427–35.

14. Vera J, Diaz-Piedra C, Jiménez R, Morales JM, Catena A, Cardenas D, et al. Driving time modulates accommodative response and intraocular pressure. Physiol Behav [Internet]. 2016;164:47–53. Available from: http://www.sciencedirect.com/science/article/pii/S0031938416303110

15. Davies LN, Wolffsohn JS, Gilmartin B. Cognition, ocular accommodation, and cardiovascular function in emmetropes and late-onset myopes. Investig Ophthalmol Vis Sci. 2005;46(5):1791–6.

16. Schor CM, Kotulak JC, Tsuetaki T. Adaptation of tonic accommodation reduces accommodative lag and is masked in darkness. Investig Ophthalmol Vis Sci. 1986;27(5):820–7.

17. Winn B, Pugh J, Gilmartin B, Owens H. Arterial Pulse Modulates Steady-state Ocular Accommodation. Curr Eye Res. 1990;9(10):971–5.

18. Gillen JB, Gibala MJ. Is high-intensity interval training a time-efficient exercise strategy to improve health and fitness? Appl Physiol Nutr Metab = Physiol Appl Nutr métabolisme [Internet]. 2014;39(3):409–12. Available from: http://www.ncbi.nlm.nih.gov/pubmed/24552392

19. Stork MJ, Banfield LE, Gibala MJ, Ginis KAM. A scoping review of the psychological responses to interval exercise: is interval exercise a viable alternative to traditional exercise? Health Psychol Rev [Internet]. 2017;11(4):324–44. Available from: https://doi.org/10.1080/17437199.2017.1326011

20. Hillman C, Biggan J. A Review of Childhood Physical Activity, Brain, and Cognition: Perspectives on the Future. Pediatr Exerc Sci. 2017;29(2):170–6.

21. Conlon EG, Lovegrove WJ, Chekaluk E, Pattison PE. Measuring Visual Discomfort. Vis cogn [Internet]. 1999 Dec 1;6(6):637–63. Available from: http://dx.doi.org/10.1080/135062899394885

22. Jiménez R, Martínez-Almeida L, Salas C, Ortíz C. Contact lenses vs spectacles in myopes: Is there any difference in accommodative and binocular function? Graefe's Arch Clin Exp Ophthalmol. 2011;249(6):925–35.

23. Hoddes E, Zarcone V, Dement W. Development and use of Stanford Sleepiness scale

(SSS). Psychophysiology. 1972;9(1):150.

24. Borg G. Borg´s perceived exertion and pain scales. Human Kine. Champaing, Illinois; 1998. 31 p.

25. Poltavski D V., Biberdorf D, Petros T V. Accommodative response and cortical activity during sustained attention. Vision Res [Internet]. 2012;63:1–8. Available from: http://dx.doi.org/10.1016/j.visres.2012.04.017

26. Momeni-Moghaddam H, McAlinden C, Azimi A, Sobhani M, Skiadaresi E. Comparing accommodative function between the dominant and non-dominant eye. Graefe's Arch Clin Exp Ophthalmol. 2014;252(3):509–14.

27. Redondo B, Vera J, Molina R, García JA, Ouadi M, Muñoz-Hoyos A, et al. Attention-deficit/hyperactivity disorder children exhibit an impaired accommodative response. Graefe's Arch Clin Exp Ophthalmol. 2018;1–8.

28. Basner M, Dinges DF. Maximizing Sensitivity of the Psychomotor Vigilance Test (PVT) to Sleep Loss. Sleep. 2011 May;34(5):581–91.

29. Tarvainen MP, Niskanen J-P, Lipponen JA, Ranta-aho PO, Karjalainen PA. Kubios HRV — A Software for Advanced Heart Rate Variability Analysis. In: Sloten J, Verdonck P, Nyssen M, Haueisen J, Magjarevic R, editors. 4th European Conference of the International Federation for Medical and Biological Engineering. Springer Berlin Heidelberg; 2009. p. 1022–5. (IFMBE Proceedings; vol. 22).

30. Tarvainen MP, Ranta-aho PO, Karjalainen PA. An advanced detrending method with application to HRV analysis. Biomed Eng IEEE Trans. 2002 Feb;49(2):172–5.

31. Luque-Casado A, Perales JC, Cárdenas D, Sanabria D. Heart rate variability and cognitive processing: The autonomic response to task demands. Biol Psychol [Internet]. 2015;113:83–90. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0301051115300880

32. Malik M, Bigger JT, Camm AJ, Kleiger RE, Malliani A, Moss AJ, et al. Heart Rate Variability Standards of Measurement, Physiological Interpretation, and Clinical Use. Eur Heart J. 1996 Jan;17(3):354–81.

33. Fletcher GF, Ades PA, Kligfield P, Arena R, Balady GJ, Bittner VA, et al. Exercise standards for testing and training: A scientific statement from the American Heart Association. Circulation. 2013;128(8):873–934.

34. Dickman SJ. Dimensions of arousal: wakefulness and vigor. Hum Factors [Internet]. 2002;44(3):429–42. Available from: http://www.ncbi.nlm.nih.gov/pubmed/12502160

35. McDougal DH, Gamlin PD. Autonomic control of the eye. Compr Physiol. 2015;5(1):439–73.

36. Kujach S, Byun K, Hyodo K, Suwabe K, Fukuie T, Laskowski R, et al. A transferable high-intensity intermittent exercise improves executive performance in association with dorsolateral prefrontal activation in young adults. Neuroimage [Internet]. 2018;169:117–25. Available from: https://www.sciencedirect.com/science/article/pii/S1053811917310170

37. McMorris T, Hale BJ. Brain and Cognition Differential effects of differing intensities of acute exercise on speed and accuracy of cognition : A meta-analytical investigation. Brain Cogn [Internet]. 2012;80(3):338–51. Available from: http://dx.doi.org/10.1016/j.bandc.2012.09.001

38. Koulieris G-A, Bui B, Banks MS, Drettakis G. Accommodation and comfort in head-mounted displays. ACM Trans Graph [Internet]. 2017;36(4):1–11. Available from: http://dl.acm.org/citation.cfm?doid=3072959.3073622

39. Rosenfield M. Computer vision syndrome: A review of ocular causes and potential treatments. Ophthalmic Physiol Opt. 2011;31(5):502–15.

40. Arnsten AFT. Stress signalling pathways that impair prefrontal cortex structure and

function. Nat Rev Neurosci [Internet]. 2009;10(6):410–22. Available from: http://dx.doi.org/10.1038/nrn2648

41. Neuhuber W, Schrödl F. Autonomic control of the eye and the iris. Auton Neurosci [Internet]. 2011;165(1):67–79. Available from: http://dx.doi.org/10.1016/j.autneu.2010.10.004

42. Dos Santos Júnior ED, Da Silva A V., Da Silva KRT, Haemmerle CAS, Batagello DS, Da Silva JM, et al. The centrally projecting Edinger-Westphal nucleus-I: Efferents in the rat brain. J Chem Neuroanat [Internet]. 2015;68:22–38. Available from: http://dx.doi.org/10.1016/j.jchemneu.2015.07.002

43. Kaikkonen P, Nummela A, Rusko H. Heart rate variability dynamics during early recovery after different endurance exercises. Eur J Appl Physiol. 2007;102(1):79–86.

44. Hautala AJ, Kiviniemi AM, Tulppo MP. Individual responses to aerobic exercise: The role of the autonomic nervous system. Neurosci Biobehav Rev. 2009;33(2):107–15.

45. Vera J, Jiménez R, García JA, Cárdenas D. Intraocular pressure is sensitive to cumulative and instantaneous mental workload. Appl Ergon [Internet]. 2017;60:313–9. Available from: http://www.sciencedirect.com/science/article/pii/S000368701630271X

46. Marcora SM, Staiano W, Manning V. Mental fatigue impairs physical performance in humans. J Appl Physiol. 2009;106:857–64.

47. Laursen PB, Jenkins DG. The scientific basis for high-intensity interval training: optimising training programmes and maximising performance in highly trained endurance athletes. Sport Med. 2002;32(1):53–73.

48. Wylegala A. The effects of physical exercises on ocular physiology: a review. J Glaucoma. 2016;25:e843–9.

49. Schmid KL, Strang NC. Differences in the accommodation stimulus response curves of adult myopes and emmetropes: A summary and update. Ophthalmic Physiol Opt.

2015;35(6):613–21.

Figure 1. Graphical overview of the experimental design (upper panel) and timeline of the psychomotor vigilance task (lower panel).

Figure 2. Effects of physical effort on the lag of accommodation in diopters (D). Differences are calculated as post-exercise minus pre-exercise values of accommodative lag at each of the five 2-min blocks from the 10-min visual task and the average value of accommodative lag for the complete 10-min visual task. Error bars represent the standard error. All values are calculated across participants (n = 20).

Figure 3. Effects of physical effort on the root mean squared of successive differences (RMSSD) component of heart rate variability (HRV) in milliseconds (ms). Differences are calculated as post-exercise minus pre-exercise values of RMSSDD at each of the five 2-min blocks from the 10-min visual task and the average value of accommodative lag for the complete 10-min visual task. Error bars represent the standard error. All values are calculated across participants (n = 20).

Table I. Differences in subjective responses before and during physical effort across experimental sessions.

	Control	Low-intensity	High-intensity	p-value
Baseline				
Level of alertness (SSS)	2.2 ± 0.52	2.15 ± 0.67	2.00 ± 0.56	0.477
HRV (RMSSD [ms])	75.95 ± 12.8	74.90 ± 12.29	75.76 ± 12.67	0.668
During physical effort				
Heart rate (bpm)**	83.23 ± 5.17	141.17 ± 5.28	158.13 ± 4.11	< 0.001
Perceived exertion (RPE)**	0.26 ± 0.3	4.67 ± 1.53	5.34 ± 1.64	< 0.001
Reserve heart rate (%)	0.14 ± 0.04	0.58 ± 0.06	0.71 ± 0.07	< 0.001

Note: ** indicates p-values < 0.001. SSS = Stanford Sleepiness Scale; HRV = heart rate variability; rMSSD = root-mean-square of successive R-R interval differences; ms = milliseconds; bpm = beats per minute; RPE = ratings of perceived exertion.

			Block 1	Block 2	Block 3	Block 4	Block 5
Lag of accommodation (D)	*Pre-effort*	*Control*	0.66 ± 0.34	0.66 ± 0.31	0.64 ± 0.28	0.64 ± 0.26	0.65 ± 0.27
		Low-intensity	0.73 ± 0.39	0.65 ± 0.36	0.62 ± 0.42	0.65 ± 0.33	0.64 ± 0.31
		High-intensity	0.63 ± 0.29	0.65 ± 0.33	0.66 ± 0.28	0.64 ± 0.27	0.65 ± 0.29
	Post-effort	*Control*	0.71 ± 0.25	0.70 ± 0.27	0.64 ± 0.30	0.70 ± 0.27	0.73 ± 0.30
		Low-intensity	0.71 ± 0.39	0.66 ± 0.40	0.68 ± 0.38	0.68 ± 0.40	0.69 ± 0.38
		High-intensity	0.78 ± 0.36	0.80 ± 0.30	0.80 ± 0.34	0.87 ± 0.41	0.88 ± 0.37
HRV (RMSSD [ms])	*Pre-effort*	*Control*	57.24 ± 29.39	50.87 ± 31.31	54.09 ± 31.37	55.02 ± 23.96	50.93 ± 23.96
		Low-intensity	55.22 ± 29.17	54.12 ± 29.15	53.12 ± 29.97	49.34 ± 28.28	52.70 ± 29.04
		High-intensity	49.09 ± 20.29	48.49 ± 25.73	47.51 ± 24.36	45.66 ± 22.50	44.18 ± 21.53
	Post-	*Control*	61.55 ±	62.73 ±	58.95 ±	59.13 ±	57.31 ±

	effort		31.40	35.22	30.78	33.07	26.99
		Low-intensity	10.32 ± 5.46	10.55 ± 5.51	10.55 ± 5.99	9.92 ± 4.87	11.52 ± 6.91
		High-intensity	7.46 ± 3.54	7.86 ± 3.66	7.77 ± 3.93	7.12 ± 3.14	8.35 ± 5.18

Table II. Descriptive values (mean ± standard deviation) of lag of accommodation and heart rate variability during the five blocks of 2-minute measured before and after each HIIT protocol.

Note: HRV = heart rate variability; RMSSD = Root mean square of successive R-R interval differences; D = diopters, ms = milliseconds.

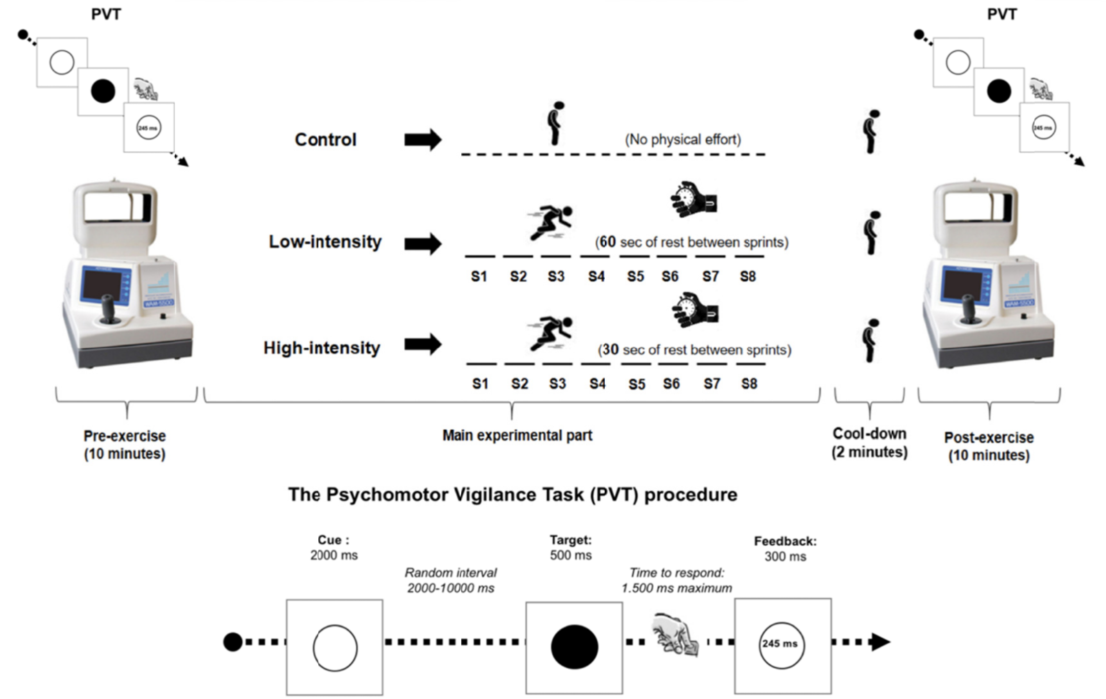

Fig 1

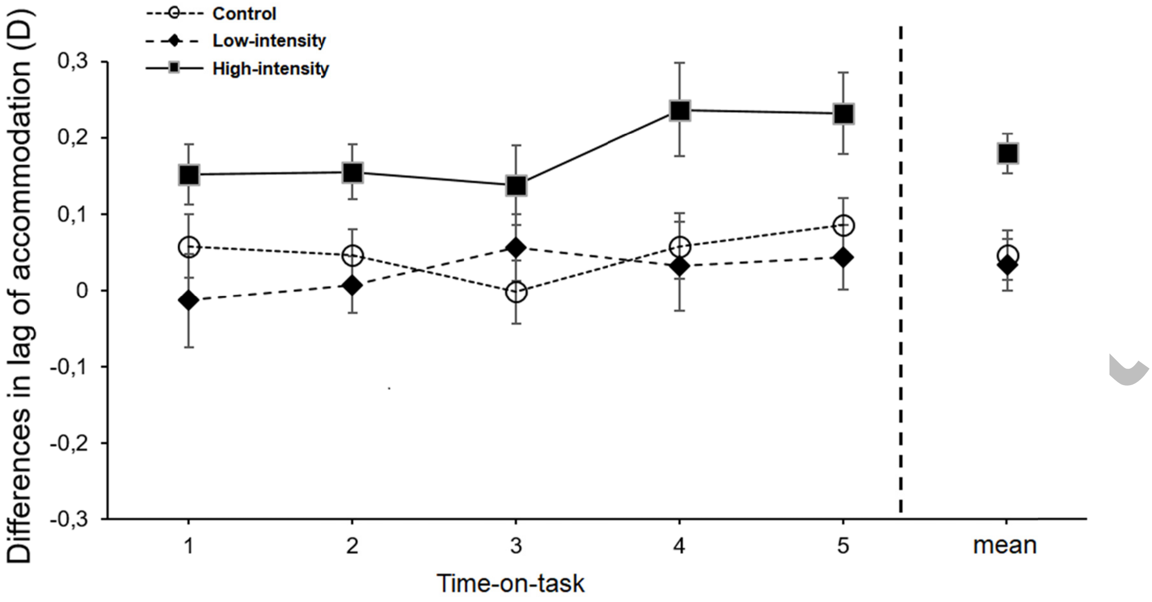
Control
Low-intensity
High-intensity
Differences in lag of accommodation (D)
0,3
0,2
0,1
0
-0,1
-0,2
-0,3
1
2
3
4
5
mean
Time-on-task

Fig 2

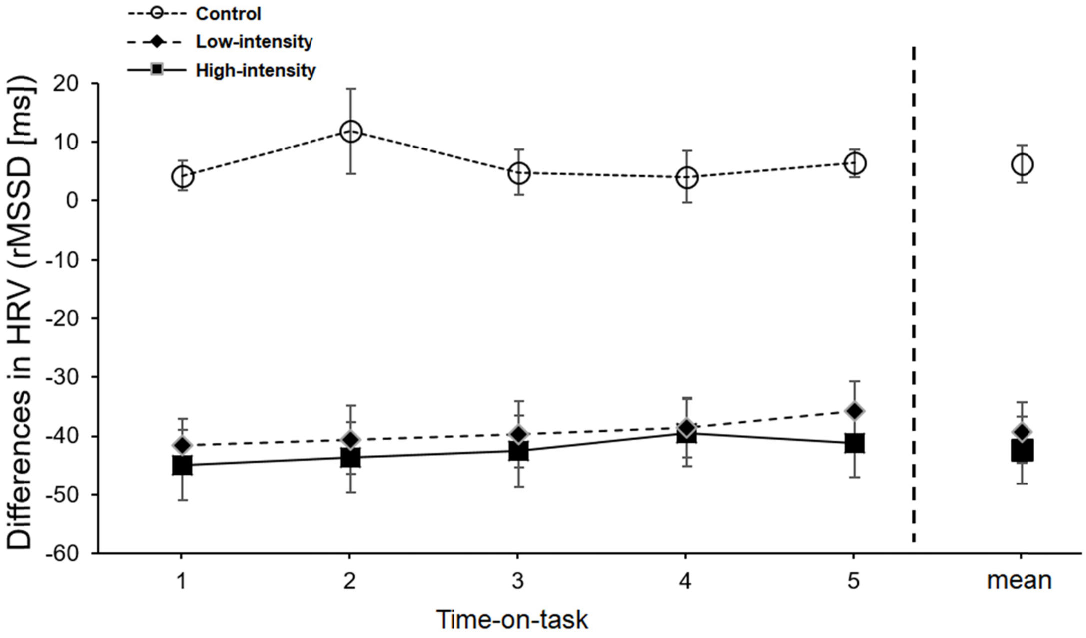
Control
Low-intensity
High-intensity
Differences in HRV (rMSSD [ms])
20
10
0
-10
-20
-30
-40
-50
-60
1
2
3
4
5
mean
Time-on-task

Fig 3