Vigilance performance during acute exercise

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Abstract

Vigilance, the cognitive function that determines goal maintenance and attention deployment, is involved in many day life activities, which often implicate physical activity. We investigated vigilance performance during exercise, with a particular focus on exercise intensity. In Experiment 1, participants performed the psychomotor vigilance task (PVT) for 5' at 40%, 60%, 80% and 100% of the ventilatory anaerobic threshold (VAT), in different sessions. The results showed that PVT performance depended on exercise intensity with an “optimal” point at 80% of VAT. In Experiment 2, participants completed a 45' version of the PVT at a low-effort (control) condition and at a 75% VAT light-moderate effort condition. Reaction times were faster at the light-moderate effort than at the low-effort condition over the 45'. The present study demonstrated that the vigilance performance changes during acute exercise, an effect that is moderated by effort intensity.

Keywords: Physical activity; sustained attention; reaction time; cognition; psychomotor vigilance task.

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60 **Introduction**

61 Vigilance determines goal maintenance and the deployment of attention in order to respond
62 appropriately (quickly and accurately) to relevant stimuli (Sarter et al., 2001). Vigilance is involved
63 in numerous everyday life activities, many of them including physical activity. In effect, human
64 behaviours occur more often in movement than in the motionless, non-physically stressful
65 conditions of the majority of cognitive neuroscience laboratories (see Walsh 2014, for discussion on
66 this issue). Many investigators have taken this into consideration, resulting in a rapid growth of the
67 interest on the links between brain/cognition and sport/exercise in the last two decades. However, to
68 the best of our knowledge, there are no previous studies investigating vigilance during exercise.

69 A review of the literature reveals that performance in cognitive tasks that range from simple
70 reaction time (RT) tasks to more attention demanding (e.g., working memory) tasks is affected by
71 concurrent physical exercise (Chang, Labban, Gapin & Etnier, 2012). These effects have been
72 linked to variations in activation/arousal (e.g., Davranche & Audiffren, 2004) induced by
73 physiological changes (e.g., blood lactate, plasma catecholamines, cortical activation) at central and
74 peripheral levels (McMorris & Hale, 2015). The direction and magnitude of these physiological
75 changes depend on the intensity of the exercise, a moderating variable influencing cognitive
76 performance during acute exercise (Brisswalter, et al., 2002). Indeed, improvements in cognitive
77 performance have been most commonly associated with light-to-moderate intensity exercise, while
78 lower or higher intensities (as a function of the participant's anaerobic threshold) result in
79 performance decline or in no significant variations (with respect to the peak performance; e.g.,
80 Chmura et al., 1998). Even though there is evidence of the influence of acute exercise during
81 cognitive performance, little is known regarding the effect on vigilance as noted earlier.

82 In this first empirical study of the effects of exercise intensity on vigilance, we take an
83 exploratory approach (cf. Wagenmakers, Wetzels, Borsboom, Van der Maas, & Kievit, 2012) to the

84 study of vigilance during exercise. Participants were asked to perform a modified version of the
85 psychomotor vigilance task (PVT) while pedaling on an indoor ergometer. The emphasis on
86 vigilance in the PVT is created by the highly unpredictable target onset (see Methods for details)
87 that requires participants to maintain their attention focused on the task and to re-orient attention to
88 task goals in case of mind wandering and distraction, in order to respond as rapidly as possible to
89 the target onset. Performance in the PVT has been shown to depend on the overall attention state of
90 the participant, that can be influenced by various factors such as sleep deprivation (e.g., Basner &
91 Dinges, 2011), circadian rhythmicity (e.g., Correa, Molina, & Sanabria, 2013; Muto et al., 2016) or
92 cardiovascular fitness (e.g., Luque-Casado, Perakakis, Ciria, & Sanabria, 2016a; Luque-Casado et
93 al., 2016b). The demands of attention of the PVT are also supported by neuroimaging studies (e.g.,
94 Drummond et al. 2005) showing brain activity typically associated with the sustained attention
95 network (cf. Lawrence, Ross, Hoffmann, Garavan, & Stein, 2003) and the allocation of attentional
96 resources (cf. Culham, Cavanagh, & Kanwisher, 2001). Luque-Casado et al. (2016a, 2016b) also
97 showed the involvement of top-down attention in the PVT using event-related brain and cardiac
98 potentials. We believe, on the basis of this prior research, that the PVT is far more than a simple
99 visuo-motor reaction time (RT) task as it involves attention demands that tap the sustained attention
100 (or tonic alerting in terms of Posner's attention network systems; see Petersen & Posner, 2012, for a
101 review) brain network that has been identified in numerous neuroimaging studies (including the
102 midcingulate cortex, prefrontal cortex, ventral premotor cortex, temporoparietal junction, among
103 other areas; Rosenberg et al., 2016; see Langner & Eickhoff, 2013, for a review).

104 In sum, the current empirical study was conceived to investigate vigilance during exercise,
105 considering exercise intensity as a crucial moderator. In Experiment 1, participants performed the
106 PVT during 5' bouts of exercise at 40%, 60%, 80% and 100% of Ventilatory Anaerobic Threshold
107 (VAT) on different days. In Experiment 2, participants performed a 45' PVT during low-effort and
108 light-moderate effort corresponding to 75% of the VAT. On the basis of the previous research on
109 cognitive task performance during physical exercise, we expected that exercising at light-to-

110 moderate intensity (between 60% and 80% of VAT) would improve RT performance in the PVT
111 with respect to lower and higher intensities.

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114 **General Methods**

115 *Participants*

116 All participants were recruited via flyers and they reported normal or corrected to normal
117 vision, had no history of neurological or physical disorders, and gave informed consent prior to the
118 start of the experiment (see Table 1). They participated in the studies in exchange for \$30 or extra
119 course credits. This research was approved by the institutional review board of the University of
120 Granada.

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124 *Equipment and materials*

125 A RS800CX Polar monitor (Polar Electro, Finland) was used to monitor and record heart
126 rate (HR) during the exercise sessions. Ventilatory gas exchange was measured during a
127 submaximal incremental exercise test using a Jaeger Master Screen gas analyzer and a Viasprint
128 150 P cycle-ergometer. In addition to HR recordings, the rating of perceived exertion (RPE) scale
129 (Borg, 1998) was used to measure perceived effort immediately after the experimental sessions. The
130 RPE scale ranged from 6 (not exertion) to 20 (maximal exertion).

131 A LCD 15.6'' laptop was used to present the stimuli for the PVT. The center of the screen
132 was situated 60-80 cm from the participant's head and at eye level. The E-Prime software
133 (Psychology Software Tools, Pittsburgh, PA, USA) was used to control stimulus presentation and
134 data collection. A wireless button connected to the computer USB-2 port was used to collect
135 responses.

136 *Psychomotor vigilance task*

137 The PVT consisted of the presentation of an empty red circle in a black background at the
138 centre of the screen. After a random interval between 2000 and 10000 ms, the circle started to fill in
139 with red beginning from the vertical radius and proceeding in a clockwise direction at an angular
140 velocity of 0.094 degrees per second. Verbal and written instructions were given to the participant
141 prior to the start of the PVT in every session, stressing that they had to fixate on the centre of the
142 screen, try not to move their eyes, and respond as quickly as possible (while avoiding anticipation
143 errors) as soon as the circle started filling in. Feedback in ms was given during a 300 ms inter-trial
144 interval. Then, the next trial began.

145 *Procedure*

146 The participant visited the lab on five occasions in Experiment 1 and three in Experiment 2,
147 always at the same time of day, between 9:30 am – 5:00 pm, and separated by at least 48 hours and
148 no more than 96 hours. The Polar HR monitor was attached around the chest of the participant upon
149 arrival at the laboratory. During the first session, participants performed a sub-maximal incremental
150 fitness test on a stationary ergometer. They were equipped with a facemask connected to the
151 metabolic cart. We followed the guidelines of the American College of Sports Medicine (ACSM,
152 2010) to ensure the safety of the participants. The protocol (Astrand, 1965) consisted of a
153 submaximal incremental test with a fixed cadence of 60 revolutions per min (rpm). The warm-up
154 started at 0 W and the workload was increased by 10 W every min until min 5. The participant
155 began the exercise phase pedaling at 50 W, and the workload was increased 25 W every two min
156 for women and 50 W every two min for men. After each increase, the workload remained stable for
157 the next 2 minutes. Determination of VAT was based on the respiratory gas-exchange method
158 (RER) ($[RER] = \text{CO}_2 \text{ production} / \text{O}_2 \text{ consumption}$), which detected the VAT at the point at which
159 RER exceeds the cut-off value of 1.0 (Myers & Ashley, 1997; Yeh et al., 1995). The researcher
160 knew that the participant had reached the VAT when the RER was equal to 1.00 and did not drop
161 below that level during the 2 min constant load period or during the next load step increase in
162 wattage, never reaching the 1.1 RER. The submaximal test ended once the VAT was reached. VAT
163 was measured in $\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$, and the results of this test were used to establish the power load in

164 the subsequent experimental conditions. After completing the submaximal test and having
165 approximately 5 minutes to recover, participants completed 8-10 trials of the PVT while pedaling to
166 familiarize them with the task.

167 In Experiment 1, participants completed 4 experimental sessions on separate days and in a
168 counterbalanced order. On each session, after a 3' warm up, participants performed the PVT for 5'
169 while pedaling either at 40% of the VAT, 60% of the VAT, 80% of the VAT or 100% of the VAT.
170 The participant's HR was monitored throughout the effort sessions to ensure the maintenance of the
171 proper intensity and reduced or increased the cyclo-ergometer resistance in steps of 1 W as
172 necessary.

173 In Experiment 2, participants completed the PVT, after a 3' warm up, during a 45' bout of
174 low-effort and a 45' bout of light-moderate effort corresponding to 75% of the VAT, on separate
175 days. The order of presentation of the two effort conditions was counterbalanced.

176 *Design, data reduction, and statistical analysis*

177 Experiment 1 consisted of a one-way within-participants design with the factor of effort
178 condition (40%, 60%, 80%, 100% of the VAT). Participants completed 47.46 (± 2.55), 48.38 ($\pm$
179 2.61), 48.17 (± 2.39), 46.83 (± 2.18) trials in the 40%, 60%, 80%, 100% of the VAT effort
180 conditions, respectively.

181 Experiment 2 consisted of the within-participants factors of effort condition (light-moderate-
182 effort and low-effort) and time-on-task (9 blocks of 5' each). Note that the 45' were divided in
183 blocks of 5' to investigate the time course of RT in the PVT. Participants completed 430.94 (± 9.42)
184 and 432.94 (± 10.68) trials in the light-moderate-effort and low-effort conditions, respectively.

185 Trials with RTs below 100 ms (1.39% for Experiment 1, and 0.87%, for Experiment 2) were
186 assumed to represent anticipation errors and were discarded from the analysis (Luque-Casado et al.,
187 2016, a,b). Analyses of variance (ANOVAs) were used to analyze the RT, HR and RPE data.
188 Statistically significant effects were further analyzed by paired-sample t-tests corrected by Holm-
189 Bonferroni for multiple comparisons. Effect size is indicated with Cohen's d for t-tests and partial

190 eta squared for Fs. The Greenhouse-Geisser correction was applied when sphericity was violated
191 (Jennings and Wood, 1976). If so, corrected probability values are reported.

192 **Results**

193 *Experiment 1*

194 A repeated measures ANOVA with participants' mean RPE data (see Table 2), revealed a
195 significant main effect of effort condition, $F(3, 69)=496.48, p<.001, \eta^2_{\text{partial}}=.95$. T-tests showed
196 significant differences between all conditions, all $ps<.001$. A repeated measures ANOVA with
197 participants' mean HR data from Experiment 1 (see Table 2), revealed a significant main effect of
198 effort condition, $F(3, 69)=6852.50, p<.001, \eta^2_{\text{partial}}=.99$. Paired-sample t-tests showed significant
199 differences between all conditions, all $ps<.001$.

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201 Insert Table 2 around here
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203 A repeated measures ANOVA with participants' mean RT, revealed a significant main effect
204 of effort condition $F(1.44, 33.17)=7.87, p<.01, \eta^2_{\text{partial}}=.25$ (see Figure 1). RTs followed a quadratic
205 trend, $F(1, 23)=19.00, p<.001$, with peak performance in 80% VAT effort condition (321 ± 24.72
206 ms) and the worst performance in the 100% VAT effort condition (370 ± 74.40 ms). Pairwise
207 comparisons showed significant differences in RT between the 80% VAT effort condition and the
208 100% VAT effort condition, $t(23)=-3.61, p<.008, d=-0.89$, and between the 60% VAT effort
209 condition and the 100% VAT effort condition, $t(23)=-3.25, p<.017, d=-0.71$. The comparison
210 between 60% VAT effort condition and 80% VAT, $t(23)=2.67, p<.054, d=0.42$, and the comparison
211 between 40% VAT effort condition and 80% VAT effort condition, $t(23)=2.41, p<.072, d=0.56$,
212 failed to reach statistical significance. Comparison between the 40% VAT effort condition and the
213 60% VAT effort condition, and comparison between the 40% VAT effort condition and 100% VAT
214 effort condition were not significant, $t(23)=1.08, p<.10, d=0.25$ and $t(23)=-2.02, p<.28, d=-0.54$,
215 respectively.

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219 The peak performance in Experiment 1 was obtained in the 5' version of the PVT at the 80%
220 VAT. In Experiment 2, we decided to use a slightly lower intensity, corresponding to the 75% VAT
221 instead, to investigate the time course of the “optimal” effort condition on vigilance over a
222 substantially longer exercise duration. That way, we ensured a constant effort during the longer 45'
223 bout. In fact, the 75% VAT intensity in Experiment 2 resulted in the same RPE as the 80% VAT
224 intensity in Experiment 1. Moreover, the difference in the relative effort intensities (80% VAT and
225 75% VAT) was only 9 bpm, around 3% of HR_{max} (see Table 2).

226 *Experiment 2*

227 A t-test with the data from the RPE scale and HR showed higher values in the light-
228 moderate effort condition than in the low-effort condition, in both cases, $t(18) = 3.55$, $p < .001$,
229 $d = 1.90$, and $t(18) = 11.41$, $p < .001$, $d = 3.82$, respectively (see Table 2).

230 A repeated measures ANOVA with participants' mean RT revealed a significant main effect
231 of effort condition, $F(1, 17) = 5.42$, $p < .03$, $\eta^2_{partial} = .24$, with shorter RTs in the light-moderate-effort
232 condition than in the low-effort condition. The analysis revealed a significant main effect of time-
233 on-task, $F(3.03, 51.62) = 17.42$, $p < .001$, $\eta^2_{partial} = .50$, with RT increasing over the course of the task.
234 The interaction between effort condition and time-on-task, $F < 1$, was not significant (see Figure 2).

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238 At this point, we wondered whether the relative effect on PVT performance (with respect to
239 the low-effort condition) of the 75% VAT bout of effort in Experiment 2 was significantly different
240 from that in the 80% VAT condition in Experiment 1. If so, one would expect a statistically
241 significant interaction between experiment (1, 2) and effort condition (low-effort, light-moderate-
242 effort). We selected the data from the 40% VAT condition as the low-effort condition in
243 Experiment 1. Data from the first 5' of each effort session in Experiment 2 were entered in the
244 analysis.

245 The ANOVA revealed a significant main effect of experiment, $F(1, 40)=10,72, p<.01,$
246 $\eta^2_{\text{partial}}=.21$, with shorter RTs in Experiment 1 than in Experiment 2. The analysis also showed a
247 significant main effect of effort condition, $F(1, 40)=8,03, p<.01, \eta^2_{\text{partial}}=.16$, with shorter RTs in
248 light-moderate-effort than in the low-effort condition. Crucially, the interaction between experiment
249 and effort condition was not significant, $F<1$, i.e., the magnitude of the main effect of effort condition
250 did not significantly differ as a function of experiment.

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253 Discussion

254 The present study confirmed that the participants' state of vigilance changed during exercise
255 and that it was moderated by the intensity of the physical activity. The results in Experiment 1
256 showed a peak RT performance at 80% VAT intensity in the PVT. The results of Experiment 2
257 revealed a significant main effect of effort condition with shorter RTs in the 75% VAT light-
258 moderate intensity exercise condition than in the low-effort condition. The main effect of time-on-
259 task was also significant, with RT gradually increasing over the course of the task. The null
260 interaction in Experiment 2, together with the main effect of effort condition, suggests that,
261 although task performance suffered from a similar time-on-task decrement in both conditions,
262 exercising at light-moderate intensity resulted in a constant RT enhancement. Note that the results
263 in Experiment 2 appear to contradict previous outcomes reported when studies are summarized
264 meta-analytically suggesting that at least 20 min of exercise are needed to observe enhancement of
265 cognitive performance (Chang, Labban, Gapin & Etnier, 2012).

266 The outcome of the present study confirmed that the participants' state of vigilance changes
267 during exercise (compared to a low-effort condition) and that it is moderated by the intensity of the
268 physical activity. Crucially, exercising at light-moderate effort intensity resulted in constant
269 vigilance enhancement during a relatively long session of effort, at least for 45'. These findings
270 extend previous research on the cognition-during-exercise topic to the case of vigilance or sustained
271 attention. Importantly, all effort conditions were matched in terms of dual-task demands. Therefore,

272 any variation in vigilance performance was presumably due to the physiological changes induced
273 by the particular effort condition.

274 Exercising elicits a variety of physiological alterations (e.g., increases in core temperature,
275 cortical blood flow, heart rate, catecholamine concentration; McMorris & Hale, 2015). Many of
276 these physiological responses have been linked to enhanced activation/arousal (that relates to the
277 overall activation/excitability of cortical neurons; Langner & Eickhoff, 2013; Oken, Salinsky, &
278 Elsas, 2006) that may in turn be responsible for the observed variations in PVT performance as a
279 function of exercise intensity. Interestingly, the peak vigilance performance was found at light-
280 moderate effort intensity. On one hand, this latter result is consistent with recent accounts
281 suggesting that activation of the reticular system during moderate exercise would boost cognitive
282 performance (Dietrich & Audiffren, 2011; McMorris & Hale 2012). Indeed, there is a wealth of
283 literature supporting the notion that performance in the PVT is dependent upon the overall
284 activation state of the participant when influenced by sleep deprivation (Dorrian, Rogers, & Dinges,
285 2005) or time of day (Correa et al., 2014). On the other hand, exercising at light-moderate intensity
286 might have also enhanced attention control, as suggested by previous research (McMorris et al.,
287 2009; Pesce, Capranica, Tesitore, & Figura, 2002). Thus, given the demands of focused attention of
288 the PVT, it would also be reasonable to state that exercising at light-moderate intensity improved
289 performance by enhancing attention control.

290 While the 80% VAT bout of effort seemed to enhance PVT performance in Experiment 1,
291 the largest RTs were found in the 100% VAT exercise condition. That detrimental effect of exercise
292 on cognitive performance in the PVT was similar to that observed in previous studies that have
293 measured performance in tasks with high demands of attention during high intense exercise (see
294 Brisswalter, et al., 2002; Chang, Labban, Gapin & Etnier, 2012; Lambourne & Tomporowski, 2010,
295 for reviews). Increasing exercise intensity up to the 100% VAT might have simply resulted in
296 surpassing the “optimal” arousal level for the PVT in line with the Yerkes-Dodson law (Yerkes &
297 Dodson, 1908) which suggests that performance improves with increasing arousal up to a
298 “moderate” level and then shows detriments with additional increases in arousal. Alternatively, it

299 might have also induced a higher competition between the PVT and the cycling task (which
300 demanded participants to keep the effort intensity and the pedaling rate constant throughout the 5')
301 resulting in a detrimental effect in the PVT (see Dietrich & Audiffren, 2011; Pontifex & Hillman,
302 2007 for a related account). In any case, according to the current results, the “optimal” vigilance
303 performance during exercise is achieved at an intensity corresponding to the 75-80% of the VAT
304 and future research will be necessary to elucidate the underlying mechanisms that explain this
305 effect.

306 In sum, the present empirical study demonstrated that the vigilance state during a task with
307 high demands of vigilance attention is affected during acute exercise, an effect that is moderated by
308 effort intensity. It also contributes to the extant research on cognitive performance during exercise
309 and opens interesting avenues for future research.

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402 **Table 1.** Anthropometrical and physiological characteristics in Experiments 1 and 2 (mean $\pm$ SD).

	Experiment 1	Experiment 2
Sample Size	24	18
Gender	12 females	18 females
Age (yrs)	20.29 $\pm$ 0.95	19.94 $\pm$ 1.98
Height (cm)	170.92 $\pm$ 9.34	163.33 $\pm$ 2.85
Weight (kg)	66.70 $\pm$ 8.91	61.32 $\pm$ 6.31
Body fat (%)	22.72 $\pm$ 1.54	23.12 $\pm$ 2.61
Power max (W)	173.75 $\pm$ 40.03	96.67 $\pm$ 21.49
Relative power (W/kg)	2.64 $\pm$ 0.48	1.58 $\pm$ 0.33
VAT (ml/kg/min)	34.26 $\pm$ 6.32	23.72 $\pm$ 5.61

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404 **Table 2.** Physiological parameters in Experiments 1 and 2 (mean $\pm$ SD).

Experiment 1				
Effort condition	HR (bpm)	% of HR _{max}	% of VAT	RPE
40% of VAT				
Very light <50% of HR _{max}	79 $\pm$ 9	40.77 $\pm$ 4.51	49.53 $\pm$ 5.69	6.75 $\pm$ 0.74
60% of VAT				
Light 50- <64% of HR _{max}	97 $\pm$ 5	50.05 $\pm$ 2.76	60.45 $\pm$ 1.86	8.67 $\pm$ 1.01
80% of VAT				
Moderate 64-<77% of HR _{max}	129 $\pm$ 7	66.57 $\pm$ 3.82	80.27 $\pm$ 3.48	12.17 $\pm$ 1.09
100% of VAT				
Vigorous 85-<100% of HR _{max}	159 $\pm$ 12	82.05 $\pm$ 6.23	99.07 $\pm$ 6.64	16.92 $\pm$ 1.35
Experiment 2				
Effort condition	HR (bpm)	% of HR _{max}	% of VAT	RPE
Low-effort condition				
Low load	84 $\pm$ 7	43.97 $\pm$ 1.45	52.13 $\pm$ 4.20	8.83 $\pm$ 2.07
Light-moderate-effort condition				
75% of VAT	120 $\pm$ 11	63.04 $\pm$ 0.80	74.25 $\pm$ 6.97	12.39 $\pm$ 1.65

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406 Figure 1

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408 Figure 2.

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413 **Captions.**

414 Figure 1. Mean RT ($\pm$ SE) as a function of effort condition in Experiment 1.

415 Figure 2. Participants' mean RT as a function of effort condition and time-on-task in Experiment 2.

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