The relationship between vigilance capacity and physical exercise: a mixed-effects multistudy analysis

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A substantial body of work has depicted a positive association between physical exercise and cognition, although the key factors driving that link are still a matter of scientific debate. Here, we aimed to contribute further to that topic by pooling the data from seven studies (N=361) conducted by our research group to examine whether cardiovascular fitness (VO_2), sport type participation (externally-paced [e.g., football or basketball] and self-paced [e.g., triathlon or track and field athletes] vs. sedentary), or both, are crucial factors to explain the association between the regular practice of exercise and vigilance capacity. We controlled for relevant variables such as age and the method of VO_2 estimation. The Psychomotor Vigilance Task was used to measure vigilance performance by means of reaction time (RT). The results showed that externally-paced sport practice (e.g., football) resulted in significantly shorter RT compared to self-paced sport (e.g., triathlon) and sedentary condition, depicting larger effects in children and adolescents than in adults. Further analyses revealed no significant effect of cardiovascular fitness and self-paced sport practice, in comparison to the sedentary condition, on RT. Our data point to the relevance of considering the type of sport practice over and above the level of cardiovascular fitness as crucial factor to explain the positive association between the regular practice of exercise and vigilance capacity

1   **The relationship between vigilance capacity and physical exercise: a mixed-effects**

2   **multistudy analysis**

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20 **Abstract**

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22 and cognition, although the key factors driving that link are still a matter of scientific debate.

23 Here, we aimed to contribute further to that topic by pooling the data from seven studies

24 (N=361) conducted by our research group to examine whether cardiovascular fitness (VO_2),

25 sport type participation (externally-paced [e.g., football or basketball] and self-paced [e.g.,

26 triathlon or track and field athletes] vs. sedentary), or both, are crucial factors to explain the

27 association between the regular practice of exercise and vigilance capacity. We controlled for

28 relevant variables such as age and the method of VO_2 estimation. The Psychomotor Vigilance

29 Task was used to measure vigilance performance by means of reaction time (RT). The results

30 showed that externally-paced sport practice (e.g., football) resulted in significantly shorter RT

31 compared to self-paced sport (e.g., triathlon) and sedentary condition, depicting larger effects in

32 children and adolescents than in adults. Further analyses revealed no significant effect of

33 cardiovascular fitness and self-paced sport practice, in comparison to the sedentary condition, on

34 RT. Our data point to the relevance of considering the type of sport practice over and above the

35 level of cardiovascular fitness as crucial factor to explain the positive association between the

36 regular practice of exercise and vigilance capacity.

37 **Introduction**

38   The current trend towards a sedentary lifestyle in modern societies clashes with the

39 human natural tendency to be physically active[1,2]. This pervasive lack of regular physical activity

40 has been related to numerous chronic physical and mental diseases and, relevant to this article, to

41 suboptimal cognitive functioning[3]. Indeed, there is a substantial body of work depicting a

42 positive association between regular practice of physical activity and cognition[4,5]. The key

43 factors driving that link, however, are still a matter of scientific debate[6]. The aim of this brief

44 report was to further contribute to that topic by testing the role of two critical variables,

45 cardiovascular fitness and sport type participation, on the association between the regular

46 practice of exercise and the level of vigilance (i.e., the ability to stay focused, and to detect and

47 respond efficiently to target stimuli in order to attain the goals of the task). The interest in the

48 study of vigilance (or sustained attention) was motivated by its crucial role in general cognitive

49 capacities and to achieve optimal performance in many daylife activities (e.g., driving, attending

50 to an academic lesson, etc.)[7]. To accomplish the objective of the present study, we performed a

51 mixed-effects analysis including data from seven studies conducted by our research group (total

52 N=361) that used the same reaction time (RT) measure from the Psychomotor Vigilance Task

53 (PVT)[8].

54   Exercise is typically defined as physical activity performed in a structured, planned and

55 repetitive manner[9]. Enhanced physical or cardiovascular fitness is one of the main consequences

56 of the regular practice of physical exercise that has been related to cognitive performance[4,10–12].

57 In the particular case of vigilance, our studies showed that higher-fit individuals outperformed

58 lower-fit individuals in the PVT[8,13,14]. The evidence comes from both behavioural (RT) and

59 electrophysiological measures (event related brain and cardiac potentials). The outcome of this

60   research appears to support the cardiovascular fitness hypothesis, by virtue of which,

61   physiological adaptations (e.g., increased VO_2 , increased BDNF, etc.) induced by regular

62   exercise are assumed to be responsible for observed cognitive improvements[15,16].

63   Given the variety of exercise-related contexts available, however, exercise practice is far

64   more than just a way for enhancing cardiovascular fitness[17]. In fact, given its inherent and

65   varying perceptual and cognitive demands, it is expected that cognitive enhancement would

66   follow sustained practice[18]. For instance, optimal performance in football or basketball requires,

67   together with a sufficiently good level of fitness, rapid adaptation and response to the constantly

68   varying exercise environment (i.e., they are instances of externally-paced activities). In contrast,

69   endurance cycling or long distance running involve self-regulation of the effort in a relatively

70   consistent and predictable environment (i.e., they are instances of self-paced exercise). It is

71   therefore reasonable to expect that any cognitive improvement related to the regular practice of

72   exercise would depend on the particular activity and the associated cognitive demands. Our

73   research on vigilance[19] has taken that possibility into consideration, reporting that individuals

74   (children) who practice externally-paced exercise regularly outperform those who practice self-

75   paced exercise (i.e., they show shorter RTs in absence of differences in cardiovascular fitness

76   between the two groups of athletes). These findings are consistent with the "cognitive skill"

77   hypothesis[20,21], whereby the learning of basic cognitive abilities through practice of one

78   particular activity can be transferred to other domains. This result may in turn jeopardize the

79   notion that cardiovascular fitness is critical for differences in vigilance performance to occur as a

80   function of exercise practice.

81   At this point, our research has not hitherto provided a clear answer to the issue of whether

82   cardiovascular fitness, sport type participation, or both, are among the key factors determining

83 the relationship between regular practice of exercise and vigilance performance. For this reason,

84 we have decided to perform a mixed-effects multistudy analysis on data from seven studies (6

85 published and 1 non-published) that our research group has conducted so far on this topic (Table

86 1) involving a total of 361 participants.

87   The use of the same task (the PVT) in all studies enabled us to incorporate the raw RT

88 data, which we believe represents an advantage over the use of standardized effect sizes that are

89 included in typical meta-analytical reports. To maintain homogeneity between studies, we only

90 analyse RT from the first 5 minutes of the task, that corresponds to the shortest version of the

91 PVT we have used so far. Note that the 5 minutes version of the task has been reported to be a

92 reliable tool to assess vigilance performance[22]. Importantly, apart from including cardiovascular

93 fitness and sport type participation as main variables of interest in the analysis, we controlled for

94 age, sex and the method of cardiovascular fitness estimation (that differed between studies).

95   In brief, this report aims to advance our current understanding of the research linking

96 physical exercise and cognition, with a focus on vigilance. The details of the analysis are

97 reported below and the raw data and the R scripts can be downloaded here

98 (https://osf.io/wcbev/?view_only=b308817398c3477092d2ee267fa3ed08).

99

Method

Types of studies and sample characteristics

102   The seven studies included in the present manuscript were carried out by our research

103 group and employed cross-sectional quasi-experimental designs. To the best of our knowledge,

104 there are no other studies so far comparing groups as a function of physical fitness and/or type of

105 sport practice, that used the same task (i.e., PVT) as a vigilance measure and reported VO_2 as an

106 index of cardiovascular fitness, both essential requirements to be included in the analysis. A total

107 sample of 361 participants (114 females) of an age range between 10 and 50 years old, different

108 levels of cardiovascular fitness (i.e., high-fit vs. low-fit) and sport type participation (i.e., self-

109 paced vs. externally-paced exercise) were included in the present multi-study analysis (Table 1).

110 All participants reported normal or corrected-to-normal vision, had no history of neurological

111 problems or cardiovascular diseases, and were not taking any medications that may affect

112 cognitive functions.

113

114 ***Sport type characteristics and VO₂ estimation method***

115   Participants included in the externally-paced group practiced sport modalities such as

116 football, basketball, volleyball, tennis or martial arts, while participants included in the self-

117 paced group practiced sport modalities such as track & field, running, swimming, triathlon or

118 cycling. Importantly, all participants included in sedentary groups (i.e. low-fit groups) reported

119 no historical participation in any sport and were not physically active (less than 2 hours per

120 week).

121 Across studies, VO_2 consumption ($ml \cdot kg^{-1} \cdot min^{-1}$) during exercise was employed as the main

122 index of cardiovascular fitness and was estimated and reported using three different methods: A

123 = estimation of the VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$) from the maximum power output measured in watts

124 in a maximal incremental cycle-ergometer test[25] (Studies 1 and 7; see Luque-Casado et al.[8] and

125 Ballester et al.[24] for details); B = estimation of the VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$) from the Léger Multi-

126 stage fitness test[27] (Studies 2 and 6; see Ballester et al.[19,23] for details); C = direct measure of

127 oxygen uptake ($ml \cdot kg^{-1} \cdot min^{-1}$) at the ventilatory anaerobic threshold (VAT; $VO_{2\ at\ VAT}$) in a

128 submaximal incremental cycle-ergometer test (Studies 3-5; see Ciria et al.[13] and Luque-Casado

129 et al.[14] for details).

130   In order to obtain a single measure of cardiovascular fitness across studies, we

131 standardized the VO_{2max} (or $VO_{2\ at\ VAT}$) data for each participant using the corresponding

132 sedentary group as reference (i.e., the participant's VO_2 minus the mean VO_2 of the sedentary

133 group (in the same study) divided by the unbiased -populational- VO_2 standard deviation

134 estimated from the same sedentary group). Henceforth, we will refer to this standardized

135 measure as simply VO_2, which is interpreted as a measure of individual (higher or lower)

136 cardiovascular fitness, relative to same age range and similar sociodemographic extraction peers

137 who do not exercise regularly. Extra measures to prevent different VO_2 estimation methods to

138 bias results will be described in the statistical analysis and results sections.

139

140 ***Psychomotor Vigilance Task***

141   A modified version of the PVT developed by Wilkinson & Houghton[28] was used in all

142 studies included in the multi-study analysis. This task was designed to measure sustained

143 attention by recording participants' RT to visual stimuli that occur at random inter-stimulus

144 intervals[22,29]. The PVT is a simple and reliable task to measure vigilance given the monotonous,

145 repetitive, and unpredictable nature of the target onset[30]. In the standard procedure, a black circle

146 with a red edge (6.68° × 7.82°) is displayed at the center of the screen in a black background.

147 Later, in a random time interval (from 2000 to 10000 ms), the circumference begins to be filled

148 in a red color and in a counter-clockwise direction with an angular velocity of 0.094 degrees per

149 second. The participants are instructed to respond as fast as they can to stop it. They must

150 respond with their dominant hand by pressing the space bar on the PC. Feedback of the response

151   time is displayed on the screen on each trial for 300 ms. The next trial begins after 1500 ms.

152   Response anticipations are considered as errors. Participants are allowed 3750 ms to respond. If a

153   response is not made during this time, the message "You did not answer" appears on the screen.

154   Different task durations (5, 9, 10, 12 and 60 minutes) and characteristics of the stimuli (gabor

155   patch or red circumference) were used according to the necessary adaptation to the aims of each

156   study (Table 1). In any case, the original paradigm of the PVT task was always maintained

157   making possible the comparison between studies. In extended task durations (i.e., 60 minutes),

158   we observed a differentiated pattern of RT performance between groups of participants as a

159   function of the time-on-task[14]. Therefore, in order to maintain homogeneity between studies, we

160   only analysed the RT from the first 5' of the task based on three main reasons: 1) this duration

161   corresponds to the shortest version of the PVT we have used in all studies; 2) given that the

162   Group and Time-on-task factors seem to interact in extended task durations, the selection of the

163   first 5 minutes (when the effects of greater magnitude were observed and these do not depend on

164   the time-on-task) reduces the complexity of the statistical model; 3) five minutes are sufficient

165   for a reliable measure of vigilance[22]. As a common premise for the studies included in the

166   analysis, the experimental session was administered alternatively between morning or afternoon

167   hours among participants of each group except for studies including children (i.e., study 2 and 6),

168   which were carried out during the afternoon due to hourly restrictions of the participants.

169

170   ***Design and statistical analyses***

171   RTs from the seven studies conducted in our laboratory were collapsed into a single

172   dataset to estimate the effects of sport type (i.e., self-paced, externally-paced, and sedentary

173   conditions) on them. In face of the diversity of samples' characteristics and study features, we

174   fitted RTs using multilevel linear mixed-effects modelling, as implemented in the *lme4* R

175   package[31].

176   In order to take into account the dependencies potentially generated by any procedural

177   differences between studies, we treated RTs as obeying to a multilevel data structure (Figure 1),

178   with participant (level 3), nested into study (level 2), and study nested into estimation method

179   (level 1). Thus, the random part of the model consisted of intercepts for participant (nested in),

180   study (nested in), VO_2 estimation method. This random part was common to all models. The

181   fixed part in a first, *baseline model* (H_0) consisted of VO_2, age, and trial number (to facilitate

182   model convergence, gender was not included as a fixed factor, as it is mostly controlled for by

183   participant and VO_2, and not included in any further interactions). Additionally, the effect of age

184   consisted of a linear and a quadratic component, to allow for non-linearity in the age-reaction

185   time association. This baseline model was pitched against a second, *H_1 model* with the same

186   random and fixed parts as H_0, plus sport type (self-paced, externally-paced, sedentary) as an

187   added fixed-effects factor. A third, *saturated* model further included the sport type x age, the

188   VO_2 x age, and the sport type x trial interactions (please, note that interactions involving age

189   actually refer to two different interaction effects, one involving the linear component and the

190   other involving the quadratic component of the age effect, that were always jointly

191   included/excluded for model comparisons). Interactions were later removed one-by-one

192   (*Interaction 1*, *Interaction 2*, and *Interaction 3* models; see Table 2). If any of the three

193   interactions contributed to the model fit, it was kept in the final, *best-fitting* model. This last,

194   best-fitting model thus consisted of the same random and fixed parts as the H_1 model plus the

195   interactions identified as substantially contributing to model fit. This model was used to estimate

196   effects.

197   Prior to fitting, RTs larger than 1000 ms (i.e., omission errors; 0,5% trials) were removed

198   from further analyses, and the remaining ones (16,239) were log-transformed. To enable model

199   convergence and facilitate interpretation of regression coefficients, trial number and log-

200   transformed RTs, were scaled and zero-centered. Models were compared using the Akaike

201   Information Criterion (AIC), and a Likelihood ratio test. For model comparisons performed to

202   identify the best-fitting model, a relatively lenient 0.010 p-value criterion was adopted.

203   Inferences were subsequently made based on the results of the best-fitting model.

204

205   **Results**

206   Table 2 shows the fitting indices for all the models included in the relevant comparisons

207   described above (baseline, H1, saturated, interaction 1-3, and best-fitting models). Table 3

208   (columns 1-5) displays unstardardized regression coefficients (B), their standard errors (SE) and

209   significance levels (according to t-tests), for each fixed component in the best-fitting model. The

210   best-fitting model included the effects of sport type, and the sport type x age interaction.

211   In the best-fitting model, the contrast corresponding to the comparison between

212   externally paced sports and the other two conditions (sedentary and self-paced sports, pooled

213   together) yielded a significant t-test (contrast 1); whereas self-paced sports did not differ from

214   the sedentary condition (contrast 2). Neither C1 nor C2 interacted with either the linear or the

215   quadratic effect of age.

216   The absence of a significant effect of VO_2 in the best-fitting model (p = 0.247) was also

217   confirmed by an approximated Bayes Factor[32]. In order to compute it, we built a third model

218   ($H1_b$), equivalent to the best-fitting model, but with VO_2 removed from the fixed part. The AIC

219   value for this model was 34861.02. The Bayes Factor approximation for this comparison

220   between the best-fitting model and $H1_b$ was $BF_{10} = 0.016$, which supports $H0_b$ relative to the

221   best-fitting model, and suggests the absence of any substantial influence of VO_2 on RTs if sport

222   type is controlled for.

223   The upper panel of Figure 2 displays predicted (standardized) RTs across age for the

224   three sport types. Although the age x sport type interactions were not significant, the effect of

225   sport type seems to vanish for intermediate ages. Additionally, given there were virtually no

226   practitioners of externally paced sport among 40-50 years-old participants, predictions for that

227   age group mostly resulted from fitting the effect of age on RT for younger participants. In order

228   to ensure the effect of sport type was not inflated in the previous analysis, we run the best-fitting

229   model with a dataset restricted to the studies in which there were participants in the three sport

230   types (study 6 and 7). As shown in columns 6-9 in Table 3, the effect of sport type remained

231   largely significant, but there also was an interaction between the sport type C1 contrast and the

232   linear component of age. The lower panel of Figure 2 shows the shape of this interaction.

233   Importantly, qualitative predictions for these studies were virtually identical to the ones made

234   from the full dataset for the 10-35 age range.

235   **Discussion**

236   Sedentarism has been related to numerous health issues and, according to a wealth of

237   literature, to poorer cognitive function (with respect to active individuals)[4] . The aim of this

238   paper was to contribute to that body of work by pooling the data from seven studies (N=361) to

239   examine whether VO_2 (index of cardiovascular fitness), type of sport participation (externally-

240   paced and self-paced), or both (controlling for sex, age and the method of VO_2 estimation), are

241   crucial factors to explain the association between the regular practice of exercise and vigilance

242   capacity (measured by means of the PVT).

243   The results were straightforward. Sport type was significantly related to RT, although

244   only externally-paced sport differed from the sedentary condition (and also from the self-paced

245   sport condition). Sport type and age interacted, showing that the (same) pattern of differences

246   between sport types was more evident in children and adolescents than in older participants.

247   Both the multilevel linear mixed-effects modelling and Bayesian analysis confirmed the absence

248   of effect of VO_2 and self-paced sport practice (with respect to the sedentary condition) on RT.

249   Maximum oxygen consumption (VO_{2max}) has been the primary index of cardiovascular

250   fitness to associate with cognitive and brain functioning (and anatomy) over the last years. The

251   positive findings to date establish that the greater the VO_{2max}, the higher the cardiovascular

252   fitness and the better the cognitive and brain functioning[4,10–12]. Together with the outcome of

253   randomized controlled trials (RCT; where increased VO_{2max} after exercise intervention was

254   accompanied by enhanced cognition)[35] this evidence has fueled the cardiovascular (selective)

255   hypothesis, i.e., the regular practice of cardiovascular exercise (not other forms of physical

256   activity such as stretching; cf. Kramer et al.[36]) positively affect cognition (with a selective

257   influence on executive function) by means of its physiological effects at neural level. The null

258   effect of VO_2 and the non-significant RT difference between self-paced exercise and the

259   sedentary condition (well differentiated in terms of cardiovascular fitness) in our study appear to

260   challenge that hypothesis (cf. Etnier et al.[37]).

261   A simple explanation of our null result is that VO_{2max} is a measure of cardiovascular

262   fitness that is not sensitive enough to variations in cognitive performance (RT in the PVT here),

263   even though, as we said above, it is the main index used to date. Proponents of the cardiovascular

264   selective hypothesis could also argue that our null finding was due to the low executive demands

265   of the PVT. The evidence from neuroimaging data speaks against that account. There is indeed

266 work reporting that PVT performance involves selective activation of brain areas related to

267 sustained attention and cognitive control[30,38], presumably driven by the (large) temporal

268 uncertainty of the target appearance, the repetitive and monotonous nature of the task and the

269 need of generating temporal expectations. Of course, in defense of the cardiovascular selective

270 hypothesis, it could still be claimed that the executive demands of the PVT are much lower than

271 those of the conflict or working memory tasks used in previous research on this topic. This is a

272 matter open to opinion and debate as no study to date has addressed this issue directly.

273   The fact that self-paced exercise was not related to improved RT with respect to the

274 sedentary condition is not surprising if one considers that only half of the studies in which we

275 compared a group of self-paced sport athletes with a group of sedentary individuals revealed

276 statistically significant RT differences. Assuming that the large N in the present analysis ensures

277 sufficient statistical power, one could argue that those reported significant group RT differences

278 were false positives (at least considering the first 5' of the task). However, those RT group

279 differences from the single studies might still be meaningful but explained by the influence of an

280 unknown (uncontrolled) variable. Moreover, in the studies showing positive results, group

281 differences were not only seen in terms of RT but also in accuracy performance in an oddball

282 task (with much lower RT demands than the PVT; see Ciria et al.[13]), and, more importantly, in

283 task-related cardiac and electroencephalographic measures[8,14,39]. If those group differences were

284 to be true, the result of the present analysis suggests that they were not due to mere differences in

285 cardiovascular fitness.

286   Even if it involves executive functioning, the PVT is clearly a task demanding

287 visuomotor coordination to react as rapidly as possible to the target appearance. This could

288 explain that only externally-paced sport practice associates to (enhanced) RT performance in our

289   study, supporting the cognitive skills hypothesis whereby sport practice is just another medium

290   for cognitive training[21], over and above its effect due to cardiovascular physiological adaptations.

291   Obviously, this result cannot be taken as evidence of the *effect* of externally-paced sport practice

292   on the vigilance capacity of our participants for other variables not related to the sport practice

293   itself could well account for the reported positive relationship. For instance, pre-existing

294   individual differences that biased the choice of the particular sport practice (Belsky et al.[40] for a

295   related argument) might explain the sport-type effect in our multi-study analysis, and also the

296   interaction between sport type and age. In fact, most of the younger participants in the

297   externally-paced sport type groups were football players from (two) Spanish 1st Division League

298   junior teams (with strict selection criteria and talent identification programs) while older

299   participants were amateur/recreational athletes. However, the above and any other alternative

300   explanation are speculative, for only well-designed RCTs would establish cause-effect

301   relationships between exercise practice and cognitive performance. Also, future research should

302   clarify whether indexes of response accuracy (beyond psychomotor response speed typical of the

303   PVT) from other cognitive tasks measuring sustained attention (e.g., oddball task) discriminate

304   between the type of sport practice and cardiovascular fitness in relation to the ability to maintain

305   attention over time.

306   In the absence of that RCT, one could still argue that the extant evidence on the effect of

307   chronic exercise on cognition supports the hypothesis that practicing exercise and sport regularly

308   would have a positive effect on vigilance capacity. However, that evidence is not as conclusive

309   as it may appear, with some systematic reviews and meta-analysis reporting positive results[41,42]

310   and other showing null effects[43–46].

311

312   **Conclusions**

313   The results of the multistudy analysis reported here point to the type of sport practice as a

314   major factor to explain differences in vigilance performance as a function of regular exercise

315   over and above the level of aerobic fitness, which in turn challenges the cardiovascular

316   hypothesis. In any case, this topic warrants further well-designed research (RCTs) to unveil

317   whether chronic exercise (and sport practice) has a true effect on cognition in general, and

318   vigilance in particular. Interested researchers are facing a challenging task, as they would have to

319   take into account the cognitive demands of the sport (exercise) activity as we highlighted here,

320   the many other factors related to exercising (such as the intensity and duration of each exercise

321   session or the periodization of the exercise program) and all potential mediators (BDNF, sleep,

322   motivation, etc.)[6]. Only after solid evidence is acquired, researchers would be ready to pave the

323   road for prescription of exercise as a potential tool to enhance cognition and prevent cognitive

324   decline.

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453

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Figure 1

Schematic representation of the multilevel data structure

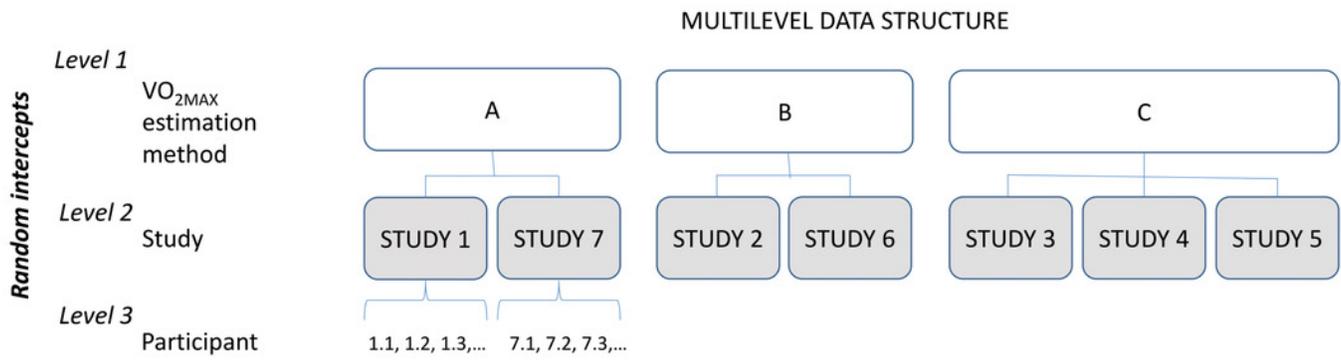
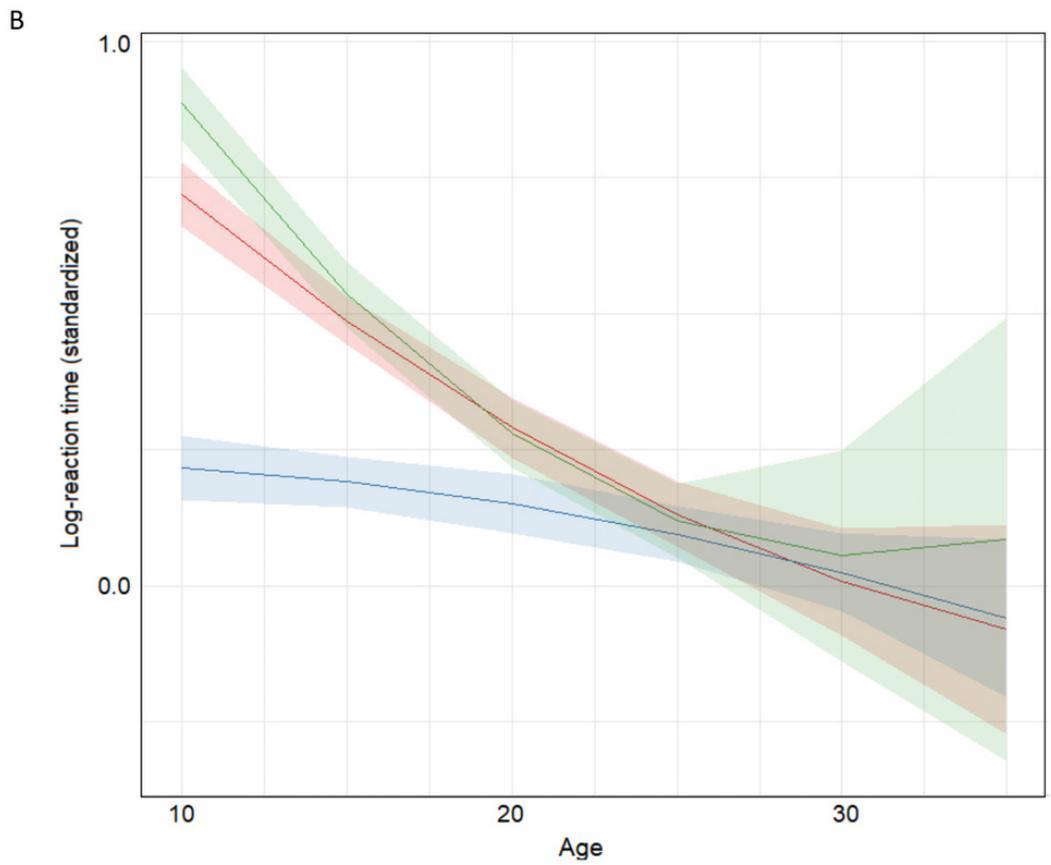
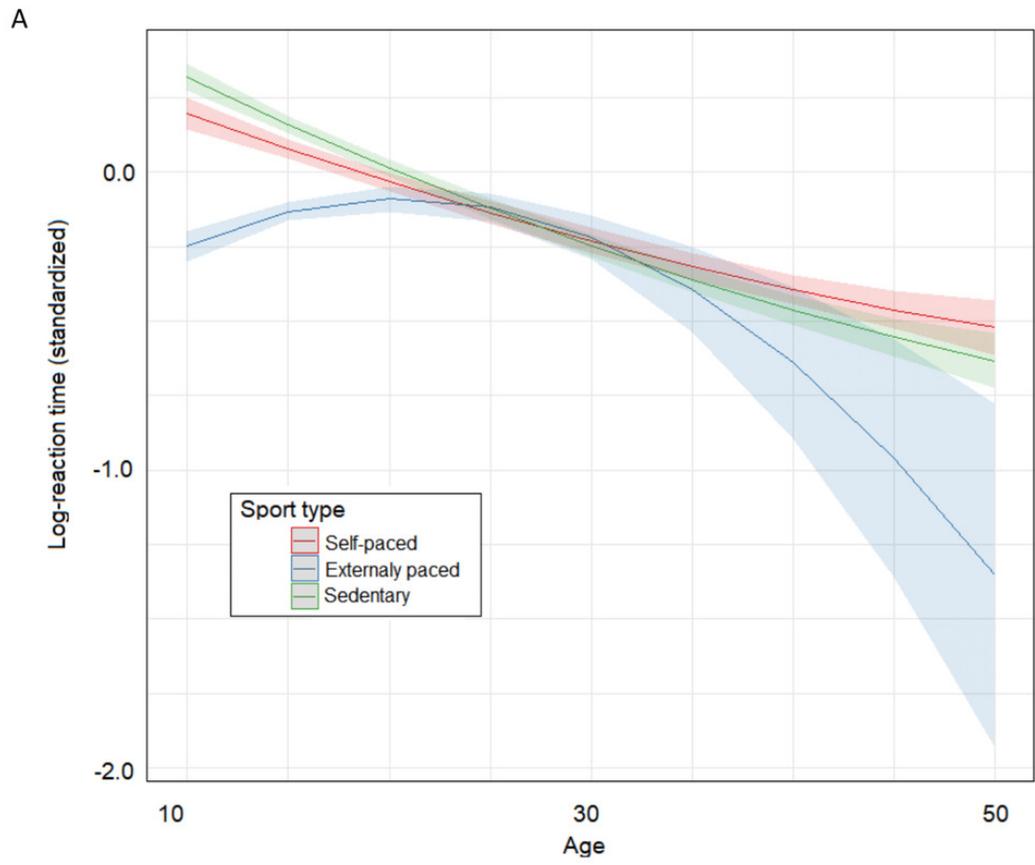



Figure 2

Predicted effect of sport type across age.

(A) predicted (standardized) reaction times (RTs) across age for the three sport types including the full dataset; (B) predicted (standardized) RTs across age for the three sport types including only dataset restricted to the studies in which there were participants in the three sport types (study 6 and 7). Figure shows that externally-paced sport practice (e.g., football) entail significantly shorter RT compared to self-paced sport (e.g., triathlon) and sedentary condition irrespective of the cardiovascular fitness level, depicting larger effects in children and adolescents.

A

B

Summary of sample and task characteristics, VO$_2$ estimation methods and results of the studies included in the analysis.

Sex: M= Male, F= Female; Sport type: SP= Self-paced, EP=Externally-paced, S= Sedentary;

Stimuli: RC = red circumference, GP = gabor patch; VO$_2$ (ml•kg^{-1}•min^{-1}) estimation methods: A = estimation of the VO$_{2max}$ from the maximum power output in a maximal incremental cycle-ergometer test, B= estimation of the VO$_{2max}$ from the Léger Multi-stage fitness test and C = direct measure of oxygen uptake at the ventilatory anaerobic threshold (VAT; VO$_{2\,at\,VAT}$) in a submaximal incremental cycle-ergometer test. (*) the shorter RT showed by SP group was limited to the first 36' of the task.

1   **Table 1.** Summary of sample and task characteristics, VO_2 estimation methods and results of the

2   studies included in the analysis.

Study	Sample size	Age range	Sex	Groups and Sport type	PVT paradigm peculiarities	VO₂ estimation methods	Results (RT)
Study 1 Luque-Casado et al.[8]	N = 26	17-29	M	SP=13 S=13	Duration: 10 min Stimuli: RC	A	SP < S
Study 2 Ballester et al.[23]	N = 75	13 - 14	M & F	EP= 39 (15 females) S = 36 (18 females)	Duration: 9 min Stimuli: GP	B	EP < S
Study 3 Luque-Casado & Sanabria (unpublished)	N = 41	40 - 50	M	SP=22 S=19	Duration: 12 min Stimuli: GP	C	SP = S
Study 4 Luque-Casado et al.[14]	N = 50	18-32	M	SP=25 S=25	Duration: 60 min Stimuli: RC	C	SP < S (*)
Study 5 Ciria et al.[13]	N = 43	18 - 23	M & F	SP = 21 (10 females) S = 22 (11 females)	Duration: 5 min Stimuli: RC	C	SP < S
Study 6 Ballester et al.[19]	N = 60	10 - 11	M & F	EP = 20 (8 females) SP = 20 (12 females) S = 20 (10 (females)	Duration: 9 min Stimuli: GP	B	EP < S EP < SP SP = S
Study 7 Ballester et al.[24]	N = 66	18 – 37	M & F	EP = 22 (10 females) SP = 22 (8 females) S = 22 (12 Females)	Duration: 9 min Stimuli: GP	A	EP < S EP = SP SP = S

3   Sex: M= Male, F= Female; Sport type: SP= Self-paced, EP=Externally-paced, S= Sedentary; Stimuli: RC

4   = red circumference, GP = gabor patch; VO_2 (ml•kg^{-1}•min^{-1}) estimation methods: A = estimation of the

5   VO_{2max} from the maximum power output in a maximal incremental cycle-ergometer test, B= estimation of

6   the VO_{2max} from the Léger Multi-stage fitness test and C = direct measure of oxygen uptake at the

7 ventilatory anaerobic threshold (VAT; $VO_{2\ at\ VAT}$) in a submaximal incremental cycle-ergometer test. (*)

8 the shorter RT showed by SP group was limited to the first 36' of the task.

Models, fitting indices, and Likelihood Ratio comparisons.

Note: All models have been adjusted with the Maximum Likelihood (ML) method. Age effects include a linear and a quadratic component, jointly included/excluded for model comparisons. The random part is common to all models (see text). ">" indicates better fit than, "<" worse fit than, and "=" not substantially worse fit than. *For factor inclusion/exclusion comparison, a relatively lenient $p<.010$ significance level has been used.

1   **Table 2.** Models, fitting indices, and Likelihood Ratio comparisons.

Model	Fixed part	df	AIC	L.ratio	p	
Baseline	Age + VO2 + trial	9	34881.04			
H_1	baseline + sport type	11	34866.47	18.569	<0.001	> baseline
Interaction 1	saturated - (sport type x age)	15	34865.81	8.089	0.088	< saturated*
Interaction 2	saturated - (VO2 x age)	17	34863.70	1.977	0.372	= saturated
Interaction 3	saturated - (sport type x trial)	17	34863.59	1.868	0.393	= saturated
Saturated	H_1 + (sport type x age) + (VO2 x age) + (sport type x trial)	19	34865.72			
Best-fitting	H_0 + sport type + (sport type x age)	15	34861.58	31.465	<0.001	> baseline

2   Note: All models have been adjusted with the Maximum Likelihood (ML) method. Age effects include a linear and a quadratic

3   component, jointly included/excluded for model comparisons. The random part is common to all models (see text). ">" indicates

4   better fit than, "<" worse fit than, and "=" not substantially worse fit than. *For factor inclusion/exclusion comparison, a relatively

5   lenient p<.010 significance level has been used.

Effect estimates (B), standard errors (SE), and significance levels for all fixed effects in the best-fitting model

Note: The best fitting model was adjusted with the REML method. The selected model was fitted and run with the full dataset, and subsequently also run with a restricted dataset including the studies in which there were participants in the three sport types. C1 represents the contrast between the externally paced and the other two sport types. C2 represents the contrast between externally paced and self-paced sport types. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.005$

1 **Table 3.** Effect estimates (B), standard errors (SE), and significance levels for all fixed effects in the best-fitting model.

	Full dataset				**Restricted dataset**			
	B	**SE**	**t**	**p**	**B**	**SE**	**t**	**p**
Intercept	-0.047	0.231	-0.202	0.840	0.356	0.544	0.654	0.513
Trial	0.044	0.006	8.001	<0.001***	0.069	0.009	8.145	<0.001***
VO2	-0.018	0.016	-1.157	0.247	-0.012	0.038	-0.316	0.752
Age (linear)	-24.731	9.549	-2.590	0.010**	-16.066	16.541	-0.971	0.332
Age (quadratic)	-5.087	8.515	-0.597	0.550	2.671	8.961	0.298	0.766
Sport type (C1)	-0.071	0.026	-2.667	0.008**	-0.097	0.029	-3.318	0.001***
Sport type (C2)	0.024	0.035	0.696	0.487	0.032	0.058	0.560	0.577
Age (linear) x sport type (C1)	1.422	7.381	0.193	0.847	5.647	2.310	2.445	0.015*
Age (quadratic) x sport type (C1)	-7.877	5.671	-1.389	0.165	-1.850	2.622	-0.706	0.481
Age (linear) x sport type (C2)	-3.673	3.037	-1.209	0.227	-2.171	4.782	-0.454	0.651
Age (quadratic) x sport type (C2)	0.413	2.972	0.139	0.890	2.038	5.765	0.354	0.724

3 Note: The best fitting model was adjusted with the REML method. The selected model was fitted and run with the full dataset, and
4 subsequently also run with a restricted dataset including the studies in which there were participants in the three sport types. C1
5 represents the contrast between the externally paced and the other two sport types. C2 represents the contrast between externally paced
6 and self-paced sport types. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.005$