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Neural efficiency and ability to produce accurate efforts in different perceived intensity zones

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Abstract:

This study aimed to investigate the relationship between neural efficiency and the ability of an athlete to produce accurate efforts in different perceived intensity zones during a racing scenario. The α/β ratio was used to quantify the neural efficiency during cycling, as it traduced the degree of participants information processing activity with lower cortical activity possible. Twelve trained competitive male cyclists delimited their perceived intensity zones 2 to 6 on a scale to assess the rating of exercise intensity. Then, they performed a 30 min racing scenario during which they had to produce different perceived intensities. The ability of athletes to produce perceived effort with accuracy and their neural efficiency was quantified during the racing scenario. The increase in the neural efficiency with the increase in the effort intensity could partly explain the improvement in athletes' ability to produce accurately perceived efforts from intensity zones 3 to 6. Moreover, the neural efficiency during the racing scenario was significantly correlated to the ability to produce perceived effort with accuracy at submaximal intensities.

Keywords: Electroencephalography (EEG), cycling, α/β ratio, pacing, effort

Declarations:

Funding: The authors didn't receive any funding for this work.

Conflict of interests: Authors declare that they have no conflict of interests.

Availability of data and material: All data and material are available.

Ethics approval: Each participant wrote informed consent, and the study was conducted following the ethical principles of the Declaration of Helsinki (1983) and approved by the regional ethics committee

Table 1: List of abbreviations

PO	Power output
IZ	Intensity zones
MC	Motor cortex
PFC	Prefrontal cortex
PC	Parietal cortex
RCP	Respiratory compensation point
RPE	Rate of perceived exertion
RSEI	Rate of subjective exercise intensity
HR	Heart rate
ES	Effect size
MAP	Maximal aerobic power
CAD	Cadence
$PO^{IZ_{low}}$	mean relative PO at the lower limit of IZ (2 to 6)
$PO^{IZ_{middle}}$	mean relative PO at the middle limit of IZ (2 to 6)
$PO^{IZ_{high}}$	mean relative PO at the higher limit of IZ (2 to 6)
PO_{mean}	mean PO during a racing scenario block
PO%	difference between and PO_{mean} and $PO^{IZ_{middle}}$ for each IZ
FFT	Fast Fourier transformed
PSD	Power spectral density
TTE	Time trial to exhaustion

Introduction:

Performance in cycling has often been related to biomechanical and metabolic factors, such as the muscle fiber type, pedalling efficiency, aerobic and anaerobic capacity, or oxygen uptake. However, a growing body of research reported positive effects of cognitive strategies, such as attentional focus or motivational state (Barwood, Corbett, Wagstaff, McVeigh, & Thelwell, 2015; Barwood, Weston, Thelwell, & Page, 2009), on the performance.

All these cognitive strategies impact the cortical activities (Comani et al., 2014; di Fronso et al., 2018) and influence the pacing strategies of athletes (Ouvrard, Gros Lambert, & Grappe, 2019), which is an important factor of performance in an endurance sport such as cycling (Baron, Grappe, & Gros Lambert, 2018; Gros Lambert et al., 2020). Pacing results from continuous adjustments of the power output (PO), using feedforward and feedback mechanisms from the external and internal afferent signals (St Clair Gibson et al., 2006) that impact the perceived effort. Indeed, the perception of effort, defined as ‘the sensation of how hard, heavy and strenuous a physical task is’ (Borg, 1998), could impact performance during an incremental cycling exercise to exhaustion. Therefore, exercise was terminated when the perception of maximal effort was reached (Fontes et al., 2015). This termination of effort is induced by a decrease in the cortical functions that allow for the preservation of the integrity of the body (Fontes et al., 2020; Robertson & Marino, 2015). Therefore, this suggests that some cortical areas in the brain are involved in the perception of effort that would probably affect the ability of the athlete to produce effort in different perceived intensity zones (IZ).

However, studies employing EEG techniques during a cycling exercise reported no consensus concerning motor cortex (MC), prefrontal cortex (PFC), and parietal cortex (PC) activity during high-intensity exercise. These areas of the brain are involved in motor, cognitive, and sensorimotor activities, respectively (Cheron et al., 2016). During incremental exercise performed by trained cyclists, there is an increase in the PFC α , and β activity from 50% of the $\dot{V}O_2$ peak to the respiratory compensation point (RCP) and a decrease in the PFC activity until the end, after the RCP, while MC activity is maintained (Robertson & Marino, 2015). RCP describes the onset of hyperventilation, above which arterial P_{CO_2} starts to decline due to lactic acidosis. The same activation of the PC and MC were observed during an intermittent incremental cycling exercise performed by recreational cyclists and sportsmen at high intensity, at a rate of perceived exertion (RPE) from 13 to 17 on the 6–20 Borg scale (Fontes et al., 2020). However, during a time trial cycling exercise, where trained cyclists performed at 85% of maximal aerobic power until exhaustion, there was a constant increase in the MC, PFC, and PC activity (Enders et al., 2016).

Athletes' physiological levels would be one factor influencing the variability of brain cortical efficiency during exercise. It has been well established that experts used their brains more efficiently during cognitively demanding tasks, (Neubauer & Fink, 2009). Such phenomenon referred to the neural efficiency (Haier et al., 1988). A broad range of neurophysiological markers has been used during the different cognitive tasks demands to quantify the neural efficiency. Often, a good neural efficiency resulted in a more focused cortical activation on relevant cortical areas, and a decrease in total cortical activation when performing a task (Ludyga, Gronwald, & Hottenrott, 2016; Neubauer & Fink, 2009). Cycling is a cognitively demanding task that required dealing with many external (environmental conditions, other competitors) and internal (bodies state) signals (Gutmann et al., 2015), which can be very aversive especially during high-intensity exercise, leading to a hard perception of the effort. Because α is dominant during mental inactivity and β rhythm is a good marker of information processing and cognitive activity, it is suggested using the α/β ratio to quantify the neural efficiency during cycling (Cheron et al., 2016). A high α/β ratio while cycling will be the indicator of a good neural efficiency, meaning that the participants processed the sensory information's with the lower cortical activity possible.

Such phenomenon was already measured during cycling in athletes with higher $\dot{V}O_2$ max (55.6 ± 2.8 ml.min⁻¹.kg⁻¹) who had a greater neural efficiency during incremental exercise to exhaustion compared to athletes with lower $\dot{V}O_2$ max (46.4 ± 4.1 ml.min⁻¹.kg⁻¹) (Ludyga, Gronwald, & Hottenrott, 2016). Indeed, (Ludyga et al., 2016) used the α/β ratio to quantify the neural efficiency during cycling. The authors suggested that these differences were due to the ability of the participants to inhibit all task-irrelevant cognitive processes. We suggest that dealing with such aversive signals would be irrelevant during cycling. To manage aversive situations induced by cycling, strategies as the inhibition of brain cognitive areas such as the PFC were reported by Radel, Brisswalter, & Perrey, 2017. Such abilities were also reported for highly trained military personnel that allowed to reduce insula activity during aversive breathing stimuli compared to less trained participants (Haase, Stewart, et al., 2016; Haase, Thom, et al., 2016; Simmons et al., 2012). It should be relevant to explore whether the α/β ratio could be associated with the capacities of cyclists to deal efficiently with the external and internal afferent signals during cycling, which would affect their pacing strategies.

Therefore, this study aims to investigate the relationship between the neural efficiency quantified with the α/β ratio, and the ability of an athlete to accurately produce efforts in different perceived intensity zones during a racing scenario. The scale for the rating of subjective exercise intensity (RSEI) (Grappe, 2005, 2018) was used to determine six different IZs with the perception of the effort, that is without any external guidance such as PO or heart rate (HR).

Methods:

Participants

To determine the sample size, we performed a sample size calculation with the G*Power software (Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany) that adjusted for the ANOVA within factor test. Significance level (α) was fixed at 0.05, power (β) was fixed at 0.95 and the effect size (ES) was fixed at 0.5. With this parameter, power analysis indicated that at least 9 participants were needed for this study. Therefore, twelve trained competitive male cyclists (age: 25.5 ± 9.1 years, height: 175.3 ± 6.2 cm; body mass: 69.3 ± 8.8 kg, body mass index: 22.5 ± 2.2 , maximal aerobic power (MAP) = 360 ± 48.4 , hours/week: 11.1 ± 5.4 H) volunteered to participate in this study. Only males were selected to avoid gender impact on cortical activity (Ludyga, Gronwald, & Hottenrott, 2015). All participants practiced road cycling, from amateur to professional level. Prior to participating in the experiment, each participant provided written informed consent, and the study was conducted in accordance with the ethical principles of the Declaration of Helsinki (1983) and approved by the regional ethics committee.

Procedure

Each competitive participant visited the laboratory on three days, separated by at least one day (Kunzler & Carpes, 2020). The three visits consisted of three different cycling exercises on the participant's bicycle mounted on a home-trainer (Elite Drivo, Elite, Fontaniva, Italy). During the first visit, participants performed an incremental test to determine MAP. During the second visit, they performed a 30 min pedalling exercise aimed at establishing the boundaries of the participant's IZ 2 to 6 on the RSEI scale (Grappe, 2005, 2018). This scale is graduated from 1 to 7 (1 – light intensity and 7 – maximal intensity) and allows the quantifying of exercise intensity, using the subjective perception of effort to classify exercise intensity in different intensity zones according to different physiological perceived items (Supplementary Material 1).

XXXXSupplementary Material 1XXXX

Supplementary Material 1: The Scale of Rating of Subjective Exercise Intensity (RSEI) presented to the subjects during the second visit

This method has been validated by the French cycling federation and has been used by them and a large number of professional cyclists for 15 years. For each IZ, the scale associates acute physiological cues that can be perceived by the athlete in full effort, allowing him to identify the intensity zone of his effort. The third visit was a road race scenario, in which the participant had to follow a race profile projected on a TV screen and pedal in

different IZs of the RSEI scale. This session was aimed at studying the abilities of participants to regulate their effort at different intensities, according to the RSEI scale, while following the race scenario. Therefore, the cyclist's perceptual finesse is engaged in each IZ (Grappe, 2012).

1. First Day Laboratory Visit: MAP Test

During the first visit, a MAP incremental test was performed. The initial workload consisted of pedalling for 6 min at 100 W, and this was incrementally increased by 30 W every 2 min. Cadence (CAD, rpm) was freely selected by participants during the test. The test was performed until exhaustion, with both the RPE, determined by Borg's category-ratio scale (CR-10), being between 9 and 10, and a significant decrease in CAD. The MAP was calculated by considering the mean PO of the lower and the final level (Bouillod & Grappe, 2018):

$$MAP = PO_{lower\ level} + (PO_{final\ level} - PO_{lower\ level}) \times \left(\frac{Time_{final\ level}}{120}\right)$$

With $PO_{lower\ level}$ being the value of the last complete workload (W), $PO_{final\ level}$ the value of the last incomplete workload (W), and $Time_{final\ level}$ the time of the last incomplete workload (sec).

2. Second Day Laboratory Visit: IZ discrimination Test

During the second visit, a 30 min pedalling exercise was performed in the different IZs of the RSEI scale. All the participants were familiar with this scale but were reminded of the proper use of the scale before the experiment. For each IZ, a description of the perception of the effort expected, the maximal range of time that can be maintained, and a characteristic picture showing the type of effort expected (for example, a rider on a TT bike to depict an effort in the IZ4 close to the anaerobic threshold) were presented to the participants. The 30 min exercise was composed of different blocks of exercises, characterized by their duration and intensity on the RSEI scale (from IZ1 to IZ6), and the level of effort in the IZ (middle, upper, or lower boundary). The exercise plan was presented to the participants before the experiment (Figure 1). Moreover, they were verbally and visually informed during the session regarding the time and intensity of each block by the instructor. Slides also showed the IZ to be discriminate and the level of intensity inside the IZ (lower, middle or upper boundary) with pictures illustrating the corresponding effort and the time remaining in each IZ. They were not informed about the PO or HR.

XXXXFigure1XXXX

Figure 1 : Intensity zones (IZ) discrimination test. The 30 min session consisted of establishing individual IZs of the RSEI scale (IZ2, IZ3, IZ4, IZ5, and IZ6). For each IZ (except IZ6), participants had to pedal 45 sec in the middle of the IZ, 45 sec at the upper boundary of the IZ, and 45 sec at the lower boundary of the IZ, twice (from 3 to 23 min). Two min of exercise in the middle of the IZ2 were performed between IZ4 and IZ5 boundaries delimitation. For IZ6, the participant pedal in the middle, at the upper, and the lower boundary of the IZ during the 20 sec after pedalling 1min 45s in the middle of IZ2 (from 23 to 30min).

PO and CAD were continuously sampled during the 30 min pedalling session. After 3 min of pedalling in the middle of IZ1, participants had to pedal 45 sec in the middle, the upper, and the lower boundary of IZ2, twice. For each intensity change, except IZ1, the participants were asked to slowly increase or decrease their pedalling cadence until they felt that they had reached the superior or inferior limit of IZ2. Indeed, in an IZ, the PO was essentially adjusted with the change in CAD. Changes in gear ratio were only allowed when the IZ changed. The same IZ delimitation was performed twice for IZ3, IZ4, and IZ5. Between IZ4 and IZ5, 2 min of pedalling in the center of IZ2, a fundamental endurance intensity that solicited mainly the aerobic glycolysis and lipolysis (see Supplementary Materials) was inserted to allow participants to recover. Because IZ6 corresponds to a submaximal intensity which corresponds to a lactic tolerance exercise with an accumulation of H⁺ ions in the muscles, that can be maintained between 7 and 30s, participants only produced a 20-sec effort at the middle, upper, and lower boundaries to delimit this IZ, separated by 1 min 30 sec of relaxing pedalling in the center of IZ1 to allow recovery. For PO and CAD analyses, the first 15 sec after each intensity change were not considered. Instead, this time was used to allow participants to adjust the intensity to the required IZ. The upper and lower boundaries of the IZ1 were not investigated because this intensity corresponds to a decontraction effort (recreational) that did not induce enough physical strain to be discriminated against. The mean relative PO (%_{MAB}) between both efforts performed at the lower (PO^{IZlow}), middle (PO^{IZmiddle}), and upper (PO^{IZhigh}) limits of IZ2, IZ3, IZ4, and IZ5 was measured. Due to the severe difficulty of effort required for IZ6, only the 20-sec blocks performed at each limit were considered to quantify PO^{IZlow}, PO^{IZmiddle}, and PO^{IZhigh}.

3. Third-day laboratory visit: Racing scenario

XXXXFigure2XXXX

Figure 2 : Race profile describing IZ blocks and slope gradient presented to the participants before the experiment. Unexpected scenarios underlined in grey were added. These consisted of suddenly modifying the IZ to IZ4, IZ5, or IZ6 to simulate race pace elevation, attacks, and final sprint, respectively. Participants had to perform the effort in the middle of the IZ.

During the third visit, participants performed a 30 min exercise session, during which the intensity of effort was adjusted in the middle of different IZs, mimicking a race profile. This race profile was composed of different blocks, defined by their duration and intensity, based on the RSEI scale (from 1 to 6, all blocks performed in the middle of the IZ). The race profile was presented to the participants before the experiment (Figure 2). The percentages (%) of the climbs were simulated by the Elite Direto Trainer, which automatically adjusts according to the race profile scheduled on My-Elite software (My-Elite, Elite, Fontaniva, Italy). Cyclists were kept informed visually of their progress throughout the protocol. They were also informed of the time and intensities they had to produce through slides displayed on a TV screen placed in front of them. Slides also showed characteristic pictures of the corresponding IZ. To reproduce real racing conditions, sudden modifications of the intensity of effort were added to blocks IZ4, IZ5, or IZ6 to simulate the pace elevation, attacks, and final sprint, respectively. Participants were not informed about these unexpected scenarios prior to the experiment. Instead, they were only informed 10 sec before the unexpected scenario occurred. Oral guidelines, pictures representing pace elevation, attack in a climb, or final sprint, and the intensity to produce were used to inform participants about unexpected and expected changes in block intensity. The words 'PACE ELEVATION', 'ATTACK' and 'FINAL SPRINT' in large police size in orange and surrounded by a flash draw were displayed to inform the participants 10 sec before a shift in IZ4, IZ5, and IZ6, respectively. They were not informed about the duration for which they had to maintain the unexpected efforts. The race scenario guidelines that participants followed with the oral interventions are presented in the appendix. In total, participants performed 8 min in the middle of IZ1, 6 min in the middle of IZ2, 5 min in the middle of IZ3, 5 min in the middle of IZ4, 5.5 min in the middle of IZ5, and only 30 sec in the middle of IZ6 to avoid participants failure during this heavy intensity effort (Ekkekakis, Parfitt, & Petruzzello, 2011).

The mean PO (PO_{mean}) produced in each one of the 11 blocks (between IZ2 and IZ6) of the racing scenario was measured. IZ1 was not considered in the PO to analyze because it corresponds to a relaxation effort that was used as a warming-up or recovery during the racing scenario. To measure the ability of the cyclist to produce accurate efforts in the different perceived IZ, the difference (PO%) between the PO_{mean} and the PO of the middle zone of the discrimination test was calculated.

Participants had to rate their RPE every 5 min on Borg's CR10 rating scale (Borg, 1998). To investigate participants' brain responses during the expected or unexpected racing scenario, electroencephalography (EEG) measurements were done for 30 sec at the end of each intensity block. Therefore, for IZ6, records were

performed during the entire duration of the block. The methodology of EEG acquisition and analyse is described in the following section.

Electroencephalography (EEG):

The third-day laboratory test started with the participants being seated and an EMOTIV EPOX Flex (EMOTIV EPOC Flex, EMOTIV, San Francisco, California, USA) BioSemi system headset placed on their heads. Thirty-four electrodes were used in our configuration (FCz, Fz, FP1, FP2, AF3, AF4, F3, F4, F7, F8, FC3, FC4, FC7, FC8, C3, C4, T7, T8, CP3, CP4, TP7, TP8, P3, P4, P7, P8, P9, P10, Pz, POz, O1, O2, O9, and O10), according to the international 10%-system (Sharbrough, G.E. Chatrian, & R.Lesser, 1991). The EEG was recorded with the EMOTIV App Pro at 128 Hz. A saline solution (BioTrue, Bausch Health Companies Inc., Laval, Quebec, CANADA) was used to wet the electrodes to attain a minimum of 98% contact quality, according to the guidelines of the EMOTIV App Pro. The montage was a common electrical reference that used an average of AFz and FCz values as reference. In this BioSemi system, CMS and DRL electrodes situated on AFz and FCz respectively replaced the ground electrodes. Indeed, according to the BioSemi guidelines is recommended to set the CMS electrodes in the middle of the measuring electrodes and the DRL away from the measuring electrodes. Before each EEG acquisition, the participants were asked to avoid head and upper-body movements while cycling. The raw EEG data were exported as an EDF file from the EMOTIV PRO App to be processed and analysed with EEGLAB, an open-source MATLAB toolbox for the analysis of electrophysiological data (EEGLAB, Swartz Centre for Computational Neuroscience, University of California, California, USA). Records performed during each IZ block (except IZ1) were first filtered with a 1–40 Hz bandpass filter and decomposed in segments of 30 s length. Data were then inspected and cleaned for eyeblink and muscular artifacts, using an automated ICA algorithm proposed by the SASICA toolbox (Chaumon, Bishop, & Busch, 2015). Decontaminated data were then Fast Fourier Transformed (FFT) into power spectra on the whole 30s of each file recorded at a sampling rate per channel of 128Hz. Each FFT window lasted 1-s and contained 128 data points. No tapering, zero-padding neither overlapping was applied on these windows. Such FFT parameters generated a frequency precision of 1Hz and temporal precision of 7.8ms. Power spectral densities (PSD) were calculated for the α (8–13 Hz) and β (13–30 Hz) frequency bands. Prior to analysis, the EEG data were divided into three specific regions: the MC (C3, C4, and Cz), the PFC cortex (F3, F4, and Fz), and the PC (P3 and P4). To quantify the neural efficiency, the α/β ratio (Ludyga et al., 2016) for each record of each intensity block was calculated by dividing the PSD of the α bandwidth by the PSD of the β bandwidth for the MC, PFC, and the PC. The α/β ratio

was then calculated for each of the regions and averaged for the same IZ blocks (except IZ6) to obtain the mean α/β ratio for each IZ. Topographical maps on the α PSD, β PSD, and α/β ratio for IZ2 to IZ6 were provided in supplementary material 2.

XXXXSupplementary Material 2XXXX

Supplementary Material 2: Topographical maps of the mean α and β PSD, and the mean α/β ratio for each intensity zones (IZ)

Statistical Analyses:

Statistical analyses were performed with JASP (JASP, Amsterdam, Netherlands). The Shapiro-Wilk statistical test revealed that all the data were normally distributed. A sphericity test was also performed with Mauchly's tests, and a Greenhouse-Geisser correction was applied if the sphericity was violated. To compare PO% at each IZ, a one-way repeated measure ANOVA (IZ) was performed. Moreover, to investigate differences in the α/β ratio between intensities at each brain region, a two-way repeated measure ANOVA (IZ \times region) was performed. If significant interactions were found *posthoc* Conover's post-hoc tests were applied to examine significant differences between pairs of means. Conover's post-hoc test was performed when the sphericity was violated. Linear regression was performed between the mean α/β ratio of the diffuse cortical activity and the PO% for each of the IZs (2 to 6). The level of significance was set at $p < 0.05$.

ES were calculated for each set of data (Cohen, 1988). Cohen's d classification of effect size magnitude was used, whereby $d < 0.2$ = negligible effect; $d = 0.2-0.49$ = small effect; $d = 0.50-0.8$ = moderate effect and $d > 0.8$ = large effect. Statistical analyses were performed with JASP (JASP, Amsterdam, Netherlands).

Results:

The participants performed the racing scenario at a mean RPE of 3.9 ± 0.7 U.A. and a mean PO of 220 ± 28 W. The mean PO% was 10.7 ± 9.9 %. The mean relative PO during the IZ discrimination test for the low, middle, and high boundaries are presented in Table 2.

Table 2: mean \pm SD of the mean PO (in % MAP) during the IZ discrimination test for the low, middle, and high boundaries of IZ2 to IZ6

IZ/ SD PO (%MAP)	Mean \pm	low	middle	high
	IZ2	34.5 ± 9.5	38.8 ± 8.6	40 ± 9.4
IZ3	46.5 ± 12.2	49.7 ± 12.5	53.3 ± 13.3	

IZ4	59.9 ± 11.4	63.4 ± 11.9	67.7 ± 12.1
IZ5	74.9 ± 6.8	81.1 ± 7.0	86.8 ± 5.9
IZ6	121.3 ± 21.3	144.4 ± 34.0	170.2 ± 47.2

The repeated measures ANOVA revealed a significant effect of intensity on PO% ($p = 8.7 \times 10^{-14}$; $F(1.7, 18.9) = 11.3$; $\eta^2 = 0.4$). Moreover, the two-way repeated measure ANOVA reported a significant effect of IZ on the mean α/β ratio ($p = 0.01$; $F(1.5, 16.7) = 6.1$; $\eta^2 = 0.27$), but no effect of the region ($p = 0.057$; $F(1.5, 16.7) = 3.2$; $\eta^2 = 0.3$), neither the region*IZ interaction ($p = 0.3$; $F(2.2, 23.9) = 1.1$; $\eta^2 = 0.01$) on the mean α/β ratio was reported. Conover's *post-hoc* test revealed that PO% is significantly smaller for IZ6 compared to IZ3 ($-69.8 \pm 60.6\%$, $p < 0.001$, $d = 1.1$), IZ4 ($-50.7 \pm 38.9\%$, $p < 0.001$, $d = 1.3$) and IZ5 ($-14.6 \pm 22.8\%$, $p < 0.01$, $d = 1.6$) (Figure 3). Moreover, the Conover *post-hoc* test revealed that the mean α/β ratio increased significantly between IZ3 and IZ5 ($+43.4 \pm 36.2\%$; $p = 0.045$; $d = 1.1$), and between IZ3 and IZ6 ($+64.2 \pm 60.5\%$; $p = 0.028$; $d = 0.8$) for all brain regions (Figure 4). Moderate size effects were also reported between IZ2 and IZ4 ($+11.7 \pm 13.1\%$; $d = 0.56$). Finally, large size effect was reported for the mean α/β ratio between the MC and the PFC ($+168.5 \pm 91\%$; $d=0.85$), and moderate effect was reported between the MC and the PC ($+162.1 \pm 101.8\%$; $d=0.6$).

Moreover, significant regression was found between the mean α/β ratio in the MC and the power output variation (PO%) at IZ4 ($p < 0.05$, $r = 0.65$, $R^2 = 0.42$, $d=1.1$, $\beta = -0.651$) and in the PFC ($p < 0.05$, $r = 0.65$, $R^2 = 0.42$, $d=1.1$, $\beta = -0.648$), and large size effect were found between the mean α/β in the PC and the PO% at IZ4 ($r = 0.54$, $R^2 = 0.28$, $d=1$, $\beta = -0.527$) (Figure 5). Finally, significant regression was found between the mean α/β ratio in the PC and the PO% at IZ5 ($p < 0.05$, $r = 0.65$, $R^2 = 0.42$, $d=0.9$, $\beta = -0.514$), and large size effect were found between the mean α/β and PO% at IZ5 in the MC ($r = 0.51$, $R^2 = 0.26$, $d=0.8$, $\beta = -0.557$) and the PFC ($r = 0.31$, $R^2 = 0.57$, $d=0.9$, $\beta = -0.648$) (Figure 6).

XXXXFigure3XXXX

Figure 3 Difference between the PO_{mean} during the racing scenario and the PO of the middle zone of the discrimination test (PO%) for each intensity zones (IZ). * defined $p < 0.05$

XXXXFigure4XXXX

Figure 4 : Mean α/β in the diffuse cortex for each intensity zone (IZ) performed during the racing scenario. * defined $p < 0.05$

XXXXFigure5XXXX

Figure 5 : Linear regression between the mean α/β ratio in the MC, PFC, and PC and the power output variation (%PO) at intensity zone 4 (IZ4).

XXXXFigure6XXXX

Figure 6: Linear regression between the mean α/β ratio in the MC, PFC, and PC and the power output variation (%PO) at intensity zone 5 (IZ5).

Discussion:

This study aimed to investigate the link between the ability of a cyclist to produce accurate efforts in different perceived intensity zones during a racing scenario and his neural efficiency. The more important finding of this study is that the increase in the α/β ratio together with effort intensity could partly explain the decrease in PO% from IZ3 to IZ6. The low PO% at IZ2 and IZ6 were also reported by Arnold et al., 2018 and could be due to the polarized training methods practiced by most of the participants. Moreover, the mean α/β activity in the PFC and MC while pedalling in IZ4, and the mean α/β activity in the PC during IZ5 efforts would partly explain the participant's abilities to produce accurately perceived in these IZ during the racing scenario.

The significant increase of the α/β ratio with IZ (Figure 4) could be due to the growing demand for sensorimotor, cognitive, and motor activity in the cycling task (Maceri, Cherup, & Hanson, 2019). Indeed, the β and the α cortical activities are both associated with psychological activities during aerobic exercise (Cheron et al., 2016; di Fronso et al., 2018; Enders et al., 2016; Ludyga et al., 2016; Zainuddin, Omar, Zulkapri, Jamaludin, & Miswan, 2017). Our results are in line with Enders et al., 2016, who reported an increase in both α and β bandwidth during a time trial to exhaustion (TTE) at 85%_{MAP}. The same increase of α and β bandwidth activities was reported during a time-to- exhaustion incremental cycling exercise (Robertson & Marino, 2015). Authors associated these changes with greater motor planning activity associated with the increased sensory input toward the end of the exercises. Moreover, the increase in the α/β ratio has also been associated with an increase in arousal as the intensity of exercise increased (Ludyga et al., 2016; Maceri et al., 2019). Therefore, the significant reduction in PO% at IZ6 compared to IZ3, IZ4, and IZ5 would be due to a more important allocation of cognitive resources to deal with exercise-related cues, leading to more efficient processing of sensory signals (Ludyga, Hottenrott, & Gronwald, 2017).

The lack of significance between regions for the α/β ratio suggests similar variations of the α and β activities in brain regions. This result is consistent with the fact that the MC, PFC, and PC are all similarly involved in the sensorimotor pathways during aerobic effort. Indeed, it has been reported that the PFC cortex is involved in the sensory treatment during a cycling exercise composed of six blocks of two minutes at 1.25 W/kg (Fontes et al., 2015). This allows for an estimation of the sensory feedback that is associated with the sensory signals to generate an awareness state (Fontes et al., 2015). This estimation by the PFC allows the regulating of MC activity through the different afferent feedback (Craig, 2003). The PC has to synchronize with the premotor cortex to integrate the sensory information and execute motor responses during a cycling exercise at 60% $\dot{V}O_{2\text{ peak}}$ until exhaustion (Hilty, 2013) occurred between both MC and PFC. The growing solicitation of the cortex with

the increase in IZ causes a growing solicitation of the efferent pathways. These results agree with those of Marcora, 2009 who reported that the relationship between the perception of effort and the efferent pathways are driven by sensory processing. These relationships between MC, PFC, and PC during aerobic exercise agree with the similar variations of the α/β ratio with the intensities between these brain regions.

However, the ability of some cyclists to produce accurate effort according to the IZ performed seemed to be due to different mechanisms set by the brain. Indeed, for IZ4, significant negative linear relationships were found between the mean α/β ratio and the PO% in the MC and the PFC. These results seemed to support a more efficient motor execution and sensory activity in the MC and PFC respectively. Same differences in the α/β ratio were also reported by Ludyga et al., 2016 between athletes with higher $\dot{V}O_2$ max (55.6 ± 2.8 ml/min/kg) and low $\dot{V}O_2$ max (46.4 ± 4.1 ml/min/kg) during an incremental cycling exercise until exhaustion. They explained that cycling becomes automatic for highly trained athletes, leading to a decrease in the degree of arousal by inhibiting cognitive activity that is not involved with the cycling task (Hüttermann & Memmert, 2014), and therefore optimizing the motor execution (Callan & Naito, 2014). Moreover, (Callan & Naito, 2014) explained that the neural efficiency could be also due to a reduction in the sensory and motor cortex activity. Such inter-participant variability in these cognitive abilities could be due to an improvement in cognitive abilities, such as memory, learning, attention, or processing information (Comani et al., 2014; Gros Lambert et al., 2020; Wagner et al., 2017; Won et al., 2019) with moderate and high-intensity cycling exercises.

However, in IZ5, significant negative linear relationships were found between the mean α/β ratio and the PO% only in the PC. This result would highlight sensorimotor mechanisms set by some participants to improve efficiency. This hypothesis was supported by the reduction in insula's reactivity to an aversive breathing stimulus for navy SEALs or trained adventurers compared to normal participants (Haase, Stewart, et al., 2016; Simmons et al., 2012). Indeed, as the PC, insular is mainly involved in sensorimotor activities (Haase, Thom, et al., 2016). Such abilities can be improved by mindfulness-based training (Haase, Thom, et al., 2016). Therefore, such control of the PC during IZ5, which can be considered as an aversive situation due to the high intensity of exercise, would improve the ability to accurately produce effort in this IZ.

Further research is needed to investigate the effect of cognitive training on sensorimotor and cognitive activity, neural efficiency, and performance determinants, such as the ability to produce perceived effort with accuracy.

Conclusion:

The results of this study suggest that an increase in the neural efficiency with the increase of IZ appeared to positively impact the ability of a cyclist to produce efforts in different perceived intensity zones. Moreover, the degree of neural efficiency of an athlete during IZ4 and IZ5 seemed to impact his ability to accurately produce effort at different perceived intensity zones.

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