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Article

Neural and Cardio-Respiratory Responses During Maximal Self-Paced and Controlled-Intensity Protocols at Similar Perceived Exertion Levels: A Pilot Study

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Abstract: Self-paced exercise protocols have gained attention for their potential to optimize performance and manage fatigue by allowing individuals to regulate their efforts based on perceived exertion. This pilot study aimed to investigate the neural and physiological responses during a self-paced $\dot{V}O_2\max$ (SPV) and incremental exercise tests (IET). Six trained male cyclists (mean age 39.2 ± 13.3 years; $\dot{V}O_2\max$ 54.3 ± 8.2 mL·kg⁻¹·min⁻¹) performed both tests while recording their brain activity using electroencephalography (EEG). The IET protocol involved increasing the power every 3 min relative to body weight, while the SPV allowed participants to self-regulate the intensity using ratings of perceived exertion (RPE). Gas exchange, EEG, heart rate (HR), stroke volume (SV), and power output were continuously monitored. Statistical analyses included a two-way repeated measures ANOVA and Wilcoxon signed-rank tests to assess differences in alpha and beta power spectral densities (PSDs) and the EEG/ $\dot{V}O_2$ ratio. Our results showed that during the SPV test, the beta PSD initially increased but stabilized at around 80% of the test duration, suggesting effective management of effort without further neural strain. In contrast, the IET showed a continuous increase in beta activity, indicating greater neural demand and potentially leading to an earlier onset of fatigue. Additionally, participants maintained similar cardiorespiratory parameters ($\dot{V}O_2$, HR, SV, respiratory frequency, etc.) across both protocols, reinforcing the reliability of the RPE scale in guiding exercise intensity. These findings suggest that SPV better optimizes neural efficiency and delays fatigue compared to fixed protocols and that individuals can accurately control exercise intensity based on perceived exertion. Despite the small sample size, the results provide valuable insights into the potential benefits of self-paced exercise for improving adherence to exercise programs and optimizing performance across different populations.

Keywords: brain activity; incremental exercise test; $\dot{V}O_2\max$; self-regulation in exercise; aerobic capacity; exercise physiology; cycling performance; effort perception



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1. Introduction

Self-pacing exercise allows individuals to regulate their exercise efforts according to subjective sensations and physiological states. This approach has been shown to improve adherence to exercise programs, particularly in certain populations, such as overweight and obese populations [1,2], and this trend also extends to normal-weight individuals [3,4]. The improved feelings of autonomy and enhanced positive affective responses contribute to exercise adherence. In addition, self-paced maximal exercise tests—where individuals regulate their pace during maximal exertion—have been shown to produce similar [5,6] or even higher maximal oxygen uptake ($\dot{V}O_2\max$) values compared to traditional fixed incremental exercise tests (IETs). This suggests that giving individuals control over their

spacing can optimize performance outcomes by allowing better management of effort and fatigue throughout the exercise [7–9].

However, despite these advantages, self-pacing requires careful application, particularly when working with less experienced athletes or when external feedback is limited. Ensuring that athletes maintain appropriate intensities is important to avoid potential risks of under- or overtraining [10]. With proper guidance and feedback, self-pacing can help athletes benefit from individualized intensity regulation while minimizing these risks.

The Self-Paced $\dot{V}O_2$ max (SPV) protocol employs a progressive exercise design, where intensity increases are guided by the limits of ratings of perceived exertion (RPE), allowing individuals to self-regulate their pace. The RPE, developed by Borg, is a widely used subjective measure allowing individuals to rate their exertion levels during physical activity on a scale from 6 to 20 [11]. The RPE scale correlates well with physiological markers, such as heart rate (HR) and oxygen uptake ($\dot{V}O_2$), in healthy subjects, making it a reliable tool for prescribing and regulating exercise intensity [11,12]. Recent research has further highlighted the utility of self-paced exercise, demonstrating that the RPE scale can effectively guide exercise intensity in various settings, including prolonged endurance events, like marathons [13]. This scale is an integral part of self-pacing, as it enables individuals to modulate their exercise intensity according to perceived exertion, thus aligning their physical effort with their subjective experience [14,15].

The Central Governor Model proposed by Noakes and Gibson suggests that the brain plays a crucial role in regulating exercise performance by modulating effort perception and fatigue, further underscoring the importance of subjective measures like RPE in exercise science [16–18]. This theory is supported by recent findings showing early modifications in brain activity during prolonged exercise, even when cardiorespiratory responses remain steady [13]. This highlights the brain's critical role in managing exertion and preventing overexertion during endurance events, as indicated by the electroencephalography (EEG) and $\dot{V}O_2$ relationship, where EEG changes can precede observable drops in $\dot{V}O_2$, suggesting central regulation of fatigue.

However, the literature still lacks proof of concept concerning the direct link between RPE and brain response during exhaustive exercise. Consequently, whether the brain acts as a limitation or, conversely, as a super controller for power optimization at the same RPE remains unknown.

EEG is an effective method for assessing brain activity during exercise, providing high temporal resolution and enabling real-time monitoring of neural responses. Technological advancements have facilitated the use of EEG in dynamic exercise settings, reducing movement artifacts and enabling detailed analysis of cortical activity [19–24]. EEG allows for the examination of how perceived exertion translates into measurable brain activity, linking subjective sensations with physiological responses [25,26]. Key frequency bands studied in exercise research include alpha (8–13 Hz) and beta (13–30 Hz) waves, which are associated with relaxation, cognitive processing, and motor control [25,27]. Studies indicate that both alpha and beta wave activity increase with exercise intensity, reflecting enhanced neural synchronization and motor planning [24,28]. However, conflicting evidence exists regarding the patterns of cortical activity during IET, with some studies reporting linear increases, while others observe plateaus or declines in neural activity as fatigue sets in [29,30].

To our knowledge, only one study, by Dykstra et al. (2019), has directly compared EEG responses between IET and SPV tests, using RPE as both a dependent and an independent variable [31]. Dykstra found significant differences between the two protocols, with the SPV test showing continuous increases in alpha and beta activity, while the IET exhibited a peak followed by a decline, suggesting an earlier onset of fatigue.

Maceri et al. (2019) also employed RPE as an independent variable and used EEG to assess brain activity during the SPV test [28]. Their study, which investigated EEG responses in younger and middle-aged adults, found that alpha and beta wave activity increased with exercise intensity regardless of age, highlighting the effectiveness of RPE in regulating exercise intensity. However, unlike Dykstra's study, Maceri did not compare

different exercise protocols but rather examined EEG variations within a single self-paced protocol across different age groups.

Both studies imposed RPE levels (11, 13, 15, 17, and 20 on Borg's scale) rather than basing subsequent test steps on the RPE given by subjects at the end of each step [28,31]. Imposing a standard RPE on each subject does not account for individual variations in response. For instance, at an RPE of 15, subjects may be at different percentages of their ventilatory threshold or $\dot{V}O_2\text{max}$. Our study aims to fill this gap by defining the steps of the second test based on the RPE indicated by subjects at the end of each step of the first test.

The primary objectives of this study are (1) to investigate neural responses to self-paced and externally controlled incremental exercise using EEG and (2) to assess whether individuals can effectively regulate their effort based solely on perceived exertion, as indicated by the RPE scale. We hypothesize that alpha and beta power spectral density (PSD) will increase with exercise intensity in both the IET and SPV tests, but this increase will be more pronounced in the incremental exercise test due to higher levels of perceived exertion and physiological strain. Additionally, we expect that a decline in the EEG/ $\dot{V}O_2$ ratio will be observed as exercise intensity increases, particularly in the IET, suggesting that neural activity decreases relative to physiological demand, and potentially serving as a marker of central fatigue. Furthermore, we hypothesize that subjects will demonstrate a capacity to control their exercise intensity accurately using the RPE scale, reflected by similar cardiovascular parameters ($\dot{V}O_2$, respiratory rate (Rf), HR, power output) between the IET and SPV tests.

2. Materials and Methods

2.1. Subjects

Six non-elite male cyclists with the following characteristics were recruited from local sports clubs to participate in the study: mean age \pm SD 39.2 ± 13.3 years; height 179.8 ± 9.0 cm; weight 70.8 ± 9.7 kg; and body mass index 21.9 ± 2.4 kg/m². Eligible participants met the following inclusion criteria: (1) non-smokers, (2) performed in at least 8 h of cycling training per week, and (3) no existing health issues. Although classified as "non-elite", the participants demonstrated a good level of aerobic fitness, as indicated by their $\dot{V}O_2\text{peak}$ values (mean $\dot{V}O_2\text{peak} = 54.3 \pm 8.2$ mL·kg⁻¹·min⁻¹), which are consistent with cyclists competing at a departmental or regional level.

The study was approved by the ethics committee of the University Hospital of Brugmann (Brussels, Belgium; reference: B0772022000014). All subjects provided informed consent prior to participation in the study.

2.2. Measurement Protocols

Each participant completed two separate exercise test sessions: the IET and the SPV test. The IET gradually increases intensity until exhaustion is reached, while the SPV allows participants to regulate their effort based on perceived exertion (RPE) [11]. Both tests were conducted in a laboratory setting, with two days of rest between sessions to ensure full recovery. The experimental sessions are presented in Figure 1.

2.2.1. Incremental Exercise Test

The IET was designed to assess maximal aerobic power (MAP) and $\dot{V}O_2\text{max}$ [32]. The test started at a power output of 1.5 W per kilogram of body mass (i.e., 105 W for a 70 kg participant), and the intensity increased by 0.5 W per kilogram every three minutes. Participants were instructed to maintain a cadence of at least 60 rotations per minute (rpm) until exhaustion. At random intervals within a 30 s window before the end of each step, the experimenter prompted the subject to rate their perceived exertion using the Borg 6–20 scale [11]. The test was terminated if the participant's cadence dropped below 60 rpm for five consecutive seconds.

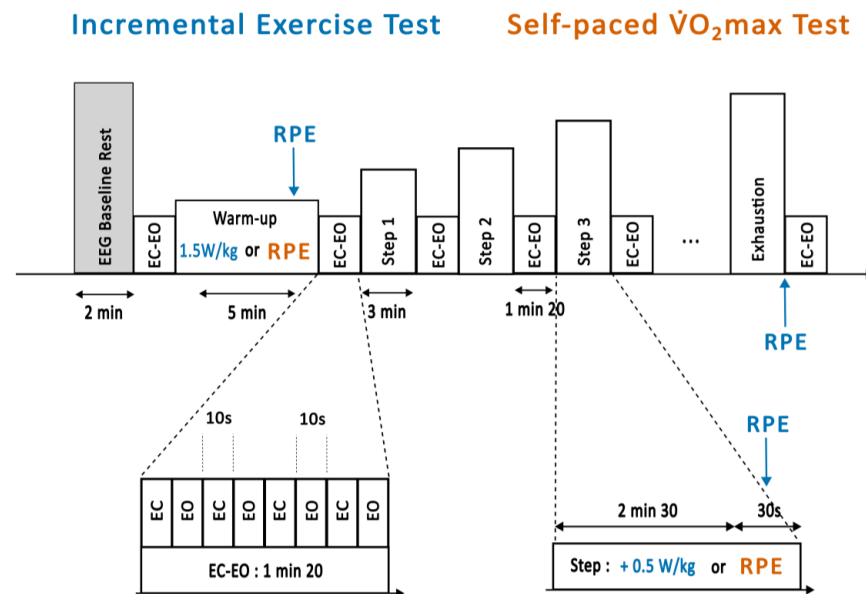


Figure 1. Schematic representation of the incremental exercise test (IET) and the self-paced $\dot{V}O_2$ max test (SPV). During the IET, intensity increases progressively by 0.5 W/kg every 3 min until exhaustion, while the SPV test allows participants to adjust their pace based on perceived exertion. Between each step, there was an alternation between eyes open (EO) and eyes closed (EC) at rest. In the figure, elements common to both tests are shown in black, IET-specific elements are shown in blue, and SPV-specific elements are shown in orange. Abbreviations: EEG = electroencephalogram; RPE = rate of perceived exertion; EC-EO = eyes closed eyes open phase.

2.2.2. Self-Paced $\dot{V}O_2$ max Test

The SPV test followed a similar structure to the IET but replaced power increments with RPE regulation. Participants self-regulated their exercise intensity based on their perceived exertion (using the RPE scale) [11], adjusting their cadence and/or resistance to maintain the target RPE for each step. The RPE values obtained during the IET were used to guide the SPV.

For both tests, participants were seated on a cycling ergometer (Cyclus2, RBM elektronik-automation GmbH, Leipzig, Germany) and underwent a two-minute baseline EEG recording while resting with their eyes open. The tests then proceeded according to the measurement protocols, with real-time data collected from all devices, including the EEG, metabolic cart, heart rate monitor, and cycling ergometer.

Participants alternated between eyes open and eyes closed phases at each exercise stage, lasting 80 s in total, to allow for more accurate EEG data collection by reducing movement artifacts. No information regarding power output, cadence, or time remaining was provided to the participants, and no verbal encouragement was given to ensure that effort regulation was based solely on perceived exertion.

2.3. Measurement Tools

To capture detailed physiological and neural data, several measurement tools were employed during both exercise tests.

2.3.1. Gas Exchange Measurements

Gas exchange was measured breath by breath using a facemask connected to a metabolic cart (Quark CPET, Cosmed, Rome, Italy) [33,34]. Flow and gas calibrations were performed approximately 10 min before each test, following the manufacturer's guidelines to ensure accuracy. The data were processed using Omnia Software (version 2.2, Cosmed, Rome, Italy), which calculated the R_f , tidal volume (V_t), ventilation rate (\dot{V}_E), $\dot{V}O_2$, and carbon dioxide output ($\dot{V}CO_2$). The software also synchronized gas exchange

data with HR measurements (HRM-Run, Garmin, KS, USA) and ergometer data, including power output and cadence.

2.3.2. Cardiac Output and Heart Rate Monitoring

HR was continuously monitored using a chest strap (HRM-Run, Garmin, KS, USA) [35]. Hemodynamic function was assessed using the Physioflow[®] PF07 Enduro (Manatec Biomedical, Poissy, France), an impedance cardiograph device that measures changes in transthoracic impedance during the cardiac cycle. This method allows for the calculation of HR and stroke volume (SV), as well as the estimation of cardiac output (CO). It has been validated in both resting and exercise conditions, including up to $\dot{V}O_2\text{max}$, and it is considered reliable for continuous hemodynamic monitoring [36,37].

2.3.3. Electroencephalography (EEG) Recording

Brain activity was recorded using a 64-channel ActiCap system (actiCHamp Plus, Brain Products, Gilching, Germany), which uses high-quality Ag/AgCl active electrodes. Conductive gel (SuperVisc, EasyCap GmbH, Wörthsee, Germany) was applied to enhance electrode–skin contact and to maintain low impedances. Active electrodes were chosen due to their reliability in capturing electro-cortical activity during intense exercise while minimizing movement artifacts [29].

Data were recorded from all 64 electrode sites, but the analysis focused on 15 sites in the extended 10–20 system: F3, F1, Fz, F2, F4, C3, C1, Cz, C2, C4, P3, P1, Pz, P2, and P4. These sites were chosen based on both the quality of the recorded signal and their relevance to the motor, sensory, and cognitive processes associated with exercise [21,38]. Some other electrode sites were excluded due to poor signal quality or noise artifacts. The ground electrode was positioned at AFz, and all electrodes were referenced to FCz. Impedances were maintained below 5 k Ω for all sensors to ensure high-quality signal acquisition [39]. Data were amplified using the BrainVision amplifier, sampled at 512 Hz, and recorded with BrainVision Recorder software (version 1.25.0204, Brain Products GmbH, Gilching, Germany).

2.4. Data Analysis

2.4.1. Data Synchronization

Markers were systematically placed at the start and end of each step, as well as during the transitions between eyes open and eyes closed conditions, to ensure the precise synchronization of data collected from the different measurement devices. This allowed for accurate alignment of the physiological and neural data streams.

2.4.2. EEG Analysis

EEG data were processed using MATLAB R2024a-based software EEGLAB (version 2023.4) [40]. After reducing the sampling rate to 256 Hz, high- and low-pass filters were applied to retain a frequency range from 0.5 to 80 Hz.

For the analysis of brain activity recorded during both tests, only the last 90 s of every 3-min step were used to minimize the possible influence of adaptation processes due to changes in load. A 50 Hz notch filter was applied, followed by an independent component analysis [41]. Recurring artefacts, such as those from eye blinks, eye movement, and muscular activity, were identified and removed. The cleaned data were then transformed into power spectra using a fast Fourier transform, and power spectral densities were calculated for two key frequency bands: alpha (α : 8–12 Hz) and beta (β : 12–30 Hz).

In addition, the power spectrum for each electrode was averaged across specific scalp zones. The frontal zone included electrodes F3, F1, Fz, F2, and F4; the central zone included C3, C1, Cz, C2, and C4; and the parietal zone included P3, P1, Pz, P2, and P4. To obtain an overall measure of brain activity, the data from all electrodes were also averaged to calculate the total brain power (total power, TP). Finally, exercise data were expressed as percentage changes from baseline PSD measures to account for day to day and between-subject variability, as reported in a previous study [25,42].

2.4.3. Statistical Analysis

All collected data were compiled and analyzed using XLSTAT 2023 (version 2.0, Paris, France). Descriptive statistics were calculated for all variables, and the results are presented as mean \pm standard deviation (SD). Given the small sample size ($n = 6$), the normality of the data was tested using the Shapiro–Wilk test. For variables where normality was confirmed ($p > 0.05$), a two-way repeated measures ANOVA was conducted to assess the main effects of the condition (IET vs. SPV), the time, and the interaction between the condition and the time on alpha and beta PSD, as well as the EEG/ $\dot{V}O_2$ ratio. In cases where the sphericity assumption was violated, the Greenhouse–Geisser correction was applied to adjust the degrees of freedom. Additionally, a post hoc Wilcoxon signed-rank test was used to compare the two conditions at each time point. For variables where normality was not confirmed ($p \leq 0.05$), a Friedman test was used to assess the main effects of the condition and the time. The Wilcoxon signed-rank test was used as a post hoc test to compare the two conditions at each time point for non-normally distributed variables. Statistical significance was set at $p < 0.05$ for all analyses.

3. Results

3.1. Physiological and Power Variables

Table 1 provides the maximal values for physiological and power variables during the IET and SPV tests. Across both protocols, most variables showed no significant differences, except for cadence, which was significantly higher in the SPV test compared to the IET test ($p = 0.031$).

Table 1. Maximal values for physiological and power variables during the incremental exercise test and the self-paced $\dot{V}O_{2\max}$ test.

Variable	IET	SPV	<i>p</i>
Rf (1/min)	61.1 \pm 5.1	61.7 \pm 8.1	0.844
Vt (L(btps))	2.9 \pm 0.6	2.8 \pm 0.5	0.131
$\dot{V}E$ (L/min)	147.8 \pm 27.4	144.7 \pm 31.4	0.844
RER	1.2 \pm 0.1	1.1 \pm 0.04	0.674
Relative $\dot{V}O_2$ (mL·kg ⁻¹ ·min ⁻¹)	54.3 \pm 8.2	53.7 \pm 7.7	0.313
Absolute $\dot{V}O_2$ (mL·min ⁻¹)	3832.0 \pm 648.3	3792.1 \pm 630.3	0.313
Relative $\dot{V}CO_2$ (mL·kg ⁻¹ ·min ⁻¹)	58.0 \pm 9.6	57.2 \pm 8.6	0.438
Absolute $\dot{V}CO_2$ (mL·min ⁻¹)	4088.3 \pm 721.9	4030.2 \pm 673.0	0.438
HR (bpm)	171.8 \pm 14.7	173.0 \pm 15.5	0.498
SV (mL)	145.1 \pm 8.4	145.8 \pm 11.8	0.813
CO (L/min)	24.4 \pm 2.2	24.4 \pm 3.7	0.813
MAP (W)	326.5 \pm 67.3	331.7 \pm 67.1	0.563
Pmax (W)	358.3 \pm 74.3	374.8 \pm 66.3	0.343
Cadence (rpm)	89.16 \pm 4.5	96.65 \pm 4.4	0.031

Note: the value in bold indicates a statistically significant difference between the two tests ($p < 0.05$). Abbreviations: IET = incremental exercise test, SPV = self-paced $\dot{V}O_{2\max}$ test, Rf = respiratory frequency, Vt = tidal volume, $\dot{V}E$ = ventilatory flow, RER = respiratory exchange ratio, $\dot{V}O_2$ = oxygen uptake, $\dot{V}CO_2$ = carbon dioxide output, HR = heart rate, SV = stroke volume, CO = cardiac output, MAP = maximal aerobic power, Pmax = maximal power output, rpm = rotations per minute.

3.2. EEG

3.2.1. Alpha PSD

There were no significant differences in the alpha frequency band between the two protocols in the central, frontal, and parietal scalp zones, nor for TP (all $p > 0.05$) (Table 2). However, a significant main effect of the time was observed in the parietal scalp zone ($F = 1.71$, $p = 0.043$), indicating a time-related increase in alpha power in this region. No significant effects were found for the condition ($F = 0.24$, $p = 0.623$) or the time \times condition interaction ($F = 0.54$, $p = 0.898$). Additionally, in the central scalp zone, there was a trend towards a time-related effect, but it did not reach significance ($F = 1.65$, $p = 0.053$).

Table 2. Comparison of EEG alpha and beta power spectral densities between the incremental exercise test and the self-paced $\dot{V}O_2$ max test.

Variable	IET	SPV	<i>p</i>
Central α	2.03 \pm 1.6	1.92 \pm 1.1	0.856
Frontal α	1.80 \pm 1.2	1.72 \pm 1.0	0.856
Parietal α	1.83 \pm 1.3	1.74 \pm 0.8	0.579
TP α	1.83 \pm 1.3	1.75 \pm 0.9	0.587
Central β	1.65 \pm 0.9	1.33 \pm 0.8	<0.001
Frontal β	1.54 \pm 0.7	1.49 \pm 0.7	0.309
Parietal β	1.63 \pm 0.8	1.57 \pm 0.8	0.274
TP β	1.58 \pm 0.8	1.46 \pm 0.7	0.027
Central α/β ratio	0.99 \pm 0.7	0.87 \pm 0.9	0.122
Frontal α/β ratio	1.16 \pm 0.6	1.12 \pm 0.6	0.422
Parietal α/β ratio	0.81 \pm 0.5	0.84 \pm 0.6	0.618
TP α/β ratio	1.01 \pm 0.6	0.96 \pm 0.5	0.310

Note: central, frontal, and parietal scalp zones are assessed for both alpha and beta bands, along with the alpha/beta (α/β) ratio and total power (TP). Values are expressed as a percentage of baseline EEG measures. The value in bold indicates a statistically significant difference between the two tests ($p < 0.05$). Abbreviations: IET = incremental exercise test, SPV = self-paced $\dot{V}O_2$ max test, α = alpha, β = beta, α/β = alpha/beta ratio, TP = total power.

3.2.2. Beta PSD

Significant differences in beta PSD were observed between the two protocols in the central scalp zone ($p < 0.001$) and TP ($p = 0.027$), but not in the frontal or parietal zones (all $p > 0.05$) (Table 2). Protocol differences occurred at 80% ($p = 0.028$) and 100% ($p = 0.044$) of the test duration (Figure 2). Within the IET protocol, beta power increased significantly from 60% to 80% ($p = 0.006$), with no significant change from 80% to 100% ($p = 0.069$). Similarly, within the SPV protocol, beta power differed from 60% to 80% ($p = 0.048$), but not from 80% to 100% ($p = 0.733$) (Figure 2).

Unlike cadence, which was consistently higher in the SPV protocol than in the IET protocol, EEG responses were greater in the IET only towards the end of the tests (after 80% of the time to exhaustion) (Figure 2). Additionally, a significant main effect was observed for the time ($F = 7.73$, $p < 0.001$) and the condition ($F = 6.32$, $p = 0.014$) in the central scalp zone, although no significant interaction between the time and the condition was found.

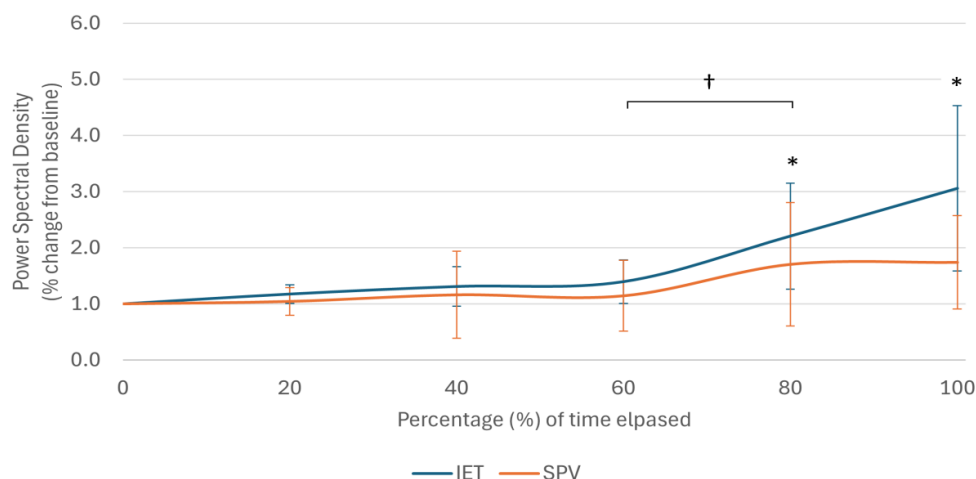


Figure 2. Comparison of changes in beta power spectral density in the central brain scalp zone during the incremental exercise test (IET) and the self-paced $\dot{V}O_2$ max (SPV) test. The IET data are represented by the blue curve, and the SPV data are shown by the orange curve. The error bars are color-coded to match the corresponding condition (blue for IET and orange for SPV) to enhance the visual distinction between the two tests. Significant differences ($p < 0.05$) between the two tests are marked with asterisks (*), and differences between previous steps within the same test are indicated by daggers (†).

3.2.3. Alpha/Beta Ratio

No significant differences were observed for the alpha/beta ratio between the two protocols in the central, frontal, or parietal scalp zones, nor for TP (all $p > 0.05$) (Table 2). Additionally, there were no significant main effects of the time, the condition, or the time x the condition in any of the scalp zones or for TP.

3.3. EEG/ $\dot{V}O_2$ Ratio

The EEG Alpha/ $\dot{V}O_2$ and Beta/ $\dot{V}O_2$ ratio graphs (Figure 3) show a sharp initial decline in both ratios at the beginning of the exercise for both the IET and SPV tests. Following this initial drop, the ratios stabilize and remain relatively flat for the majority of the test duration. When around 80% of the time has elapsed, a slight increase is observed in both the Alpha/ $\dot{V}O_2$ and Beta/ $\dot{V}O_2$ ratios, with this increase being slightly more pronounced in the IET compared to the SPV. However, it is important to note that these changes were not statistically significant (Alpha/ $\dot{V}O_2$: $p = 0.636$; Beta/ $\dot{V}O_2$: $p = 0.977$).

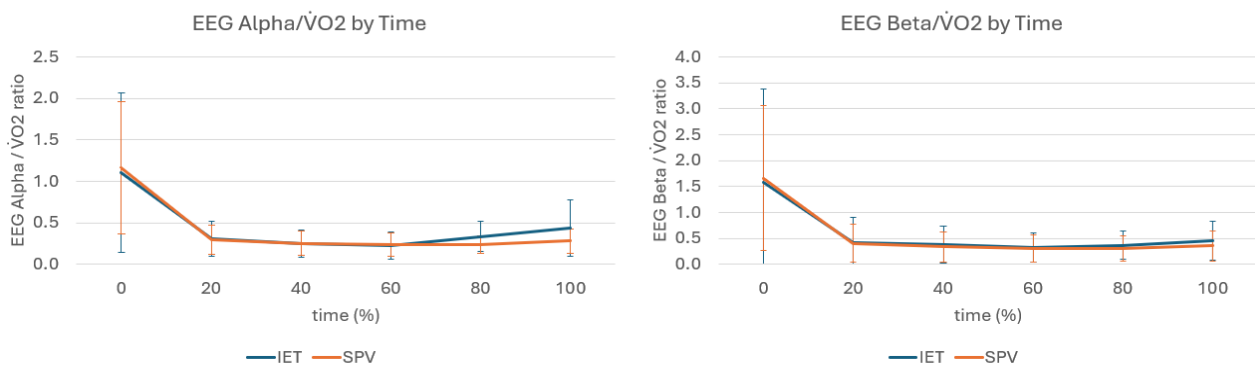


Figure 3. Comparison of EEG Alpha/ $\dot{V}O_2$ and Beta/ $\dot{V}O_2$ ratios between the incremental exercise test (IET, blue line) and the self-paced $\dot{V}O_2$ max (SPV, orange line) test. The error bars are color-coded to match the corresponding condition (blue for IET and orange for SPV) to enhance the visual distinction between the two tests.

3.3.1. EEG Alpha/ $\dot{V}O_2$ Ratio

There was a significant main effect of the time for the Alpha/ $\dot{V}O_2$ ratio in the central ($F = 6.37, p < 0.001$), frontal ($F = 19.4, p < 0.001$), and parietal ($F = 8.86, p < 0.001$) scalp zones, as well as for TP ($F = 13.49, p < 0.001$). However, no significant effects were observed for the condition or the time x condition interaction across any of the scalp zones or TP (Table 3).

Table 3. Multi-factor ANOVA outcomes for the EEG Alpha/ $\dot{V}O_2$ ratio analyzed across various brain scalp zones (central, frontal, parietal) and total power (TP) during the incremental exercise test and the self-paced $\dot{V}O_2$ max test.

	Condition			Time (%)		Condition × Time (%)			
	R ²	F	Pr > F	F	Pr > F	F	Pr > F		
Central Alpha/ $\dot{V}O_2$	0.275	3.035	0.002	0.954	0.331	6.374	<0.001	0.145	0.981
Frontal Alpha/ $\dot{V}O_2$	0.528	8.952	<0.001	0.384	0.537	19.399	<0.001	0.232	0.947
Parietal Alpha/ $\dot{V}O_2$	0.343	4.177	<0.001	0.090	0.764	8.861	<0.001	0.322	0.899
TP Alpha/ $\dot{V}O_2$	0.438	6.237	<0.001	0.185	0.668	13.486	<0.001	0.198	0.962

3.3.2. EEG Beta/ $\dot{V}O_2$ Ratio

A significant main effect of the time was observed for the Beta/ $\dot{V}O_2$ ratio in the central ($F = 13.43$, $p < 0.001$), frontal ($F = 10.87$, $p < 0.001$), and parietal ($F = 4.87$, $p = 0.001$) scalp zones, as well as for TP ($F = 8.68$, $p < 0.001$). However, there were no significant effects for the condition or the time \times condition interaction across any of the scalp zones or TP (Table 4).

Table 4. Multi-factor ANOVA outcomes for the EEG Beta/ $\dot{V}O_2$ ratio analyzed across various brain scalp zones (central, frontal, parietal) and total power (TP) during the incremental exercise test and the self-paced $\dot{V}O_{2max}$ test.

	R ²	Condition			Time (%)		Condition \times Time (%)		
		F	Pr > F	F	Pr > F	F	Pr > F	F	Pr > F
Central Beta/ $\dot{V}O_2$	0.466	6.810	<0.001	2.415	0.124	13.439	<0.001	1.250	0.293
Frontal Beta/ $\dot{V}O_2$	0.389	4.969	<0.001	0.052	0.819	10.867	<0.001	0.054	0.998
Parietal Beta/ $\dot{V}O_2$	0.225	2.270	0.017	0.475	0.493	4.868	0.001	0.041	0.999
TP Beta/ $\dot{V}O_2$	0.336	3.964	<0.001	0.030	0.863	8.682	<0.001	0.032	0.999

4. Discussion

The objective of this study was to investigate neural responses to both IET and SPV tests using EEG and to determine whether individuals can regulate their effort based solely on perceived exertion, as indicated by the RPE scale. The results yield substantial insights into the neural mechanisms governing exercise regulation and the effectiveness of the RPE scale for guiding exercise intensity.

Our results showed that during the SPV test, the beta PSD initially increased but then stabilized at around 80% of the test duration. This suggests that participants reached a point where their perceived exertion allowed them to maintain their effort without requiring further increases in neural engagement. In contrast, the IET exhibited a continuous increase in beta activity throughout the test, reflecting a gradual rise in neural demand as participants neared exhaustion.

Our findings diverge from those reported by Dykstra et al. (2019). He observed sustained elevations in both alpha and beta wave activity during the SPV test and during the IET, and beta activity peaked before declining, indicating an earlier onset of fatigue [31]. The possible explanations for these discrepancies are several. Dykstra focused on the dorsolateral prefrontal cortex, which is associated with executive function and inhibitory control [43,44], whereas our study examined the central area of the brain [45,46], particularly motor-related cortical regions. These central regions may show different activation patterns due to their direct involvement in motor control and sensory feedback integration during intense physical exertion [46–48].

Finally, another possible explanation for the divergence in results is the methodological difference between the studies. Unlike Dykstra's study, which imposed specific RPE levels, our study allowed participants to self-regulate their exertion based on subjective feedback at each step of the exercise. This individualized approach likely provides a more accurate reflection of how individuals naturally regulate exertion, leading to more sustained neural engagement. However, it is worth noting that the advantages of self-paced protocols may be less pronounced in populations that are not as aware of their physiological cues or in those with less exercise experience [10,48], which could explain variations across different studies.

The stabilization of beta activity in the SPV test in our study could be interpreted in line with the Central Governor Model, as proposed by Noakes [18]. This model suggests that the brain regulates effort to prevent overexertion and maintain homeostasis, potentially explaining why beta activity plateaus during self-paced exercise [49]. In contrast, the

continuous rise in beta activity during the IET reflects the higher neural strain imposed by the lack of self-regulation, which may have contributed to earlier fatigue onset [12,21,25].

Another notable finding in our study was the behavior of the EEG/ $\dot{V}O_2$ ratio, which remained stable throughout most of the exercise but increased slightly around 80% of the test duration in both the alpha and beta bands. This increase, which was more pronounced in the IET, indicates a tendency towards heightened neural engagement relative to physiological demand as exercise intensity peaked. This suggests that the brain was allocating more resources to manage the escalating strain. The more pronounced rise in the IET may indicate that this protocol required greater cognitive and motor effort, potentially contributing to earlier fatigue compared to the SPV test. In contrast, the stable EEG/ $\dot{V}O_2$ ratio in the SPV test suggests better exertion management, thus maintaining neural efficiency and delaying central fatigue.

This pattern of neural engagement aligns with the concept of the Estimated Time Limit (ETL), which posits that individuals subconsciously regulate their effort based on an internal estimate of how long they can sustain a given intensity before reaching exhaustion [50,51]. As exercise progresses, the brain continually reassesses this internal time limit, adjusting neural and physical effort to prevent premature fatigue. The stabilization of the EEG/ $\dot{V}O_2$ ratio around 80% of the test duration across both protocols suggests that participants may have been tapping into this internal pacing strategy as they approached their perceived time limit. This regulatory mechanism is thought to involve both physiological signals, such as cardiovascular and metabolic feedback, as well as psychological factors, including motivation and perceived exertion, as suggested by previous research [10,52]. Although we did not directly assess psychological factors in this study, the observed increase in neural engagement towards the end of the exercise could reflect the brain's efforts to marshal additional resources to extend performance as participants neared their ETL, thereby delaying the onset of central fatigue and maintaining overall effort.

These findings regarding the EEG/ $\dot{V}O_2$ ratio contrast with those of Billat et al. (2024), who observed a significant decline in the EEG/ $\dot{V}O_2$ ratio during the IET, suggesting reduced neural engagement [53]. The divergence in results could be attributed to several factors. First, while both studies employed an IET, Billat's study used 2 min stage durations, whereas our protocol used 3 min stages. Research suggests that shorter stages, like those used by Billat, may lead to quicker attainment of peak values but may not allow sufficient time for physiological stabilization, particularly for $\dot{V}O_{2max}$ and other physiological parameters. In contrast, the longer stages in our protocol likely promoted more stable physiological responses, which could explain the variation in the EEG/ $\dot{V}O_2$ ratio between the two studies [54,55]. Additionally, our IET protocol included alternating eyes open and eyes closed phases between increments, potentially introducing brief moments of neural recovery that were absent in Billat's continuous protocol. These differences in stage duration and protocol design may account for the distinct neural and physiological responses observed in our study. Furthermore, the strictly controlled incremental protocol employed by Billat might have imposed a higher cognitive load and led to more pronounced central fatigue earlier in the exercise [10].

Moreover, the populations studied could also contribute to the differences in results. Billat's study included active males who participated in a variety of sports, such as judo and water polo, and not exclusively endurance sports. The diversity in training backgrounds certainly would have influenced their physiological responses and how they engaged neural resources during exercise. In contrast, our study involved trained cyclists, which might explain the more stable neural engagement observed in our participants. Additionally, variations in fitness levels [56–58], age [59,60], and training backgrounds [61,62] between the two studies may have significantly affected both physiological responses and participants' perceived exertion, potentially explaining the discrepancies between our findings and those of Billat [53].

The second major objective of our study was to assess whether individuals could effectively regulate their effort based on perceived exertion, as indicated by the RPE scale. Our findings revealed that participants maintained similar cardiovascular parameters ($\dot{V}O_2$, Rf, HR, power output, etc.) across both the SPV and the IET tests. This reinforces the reliability of the RPE scale as a tool for guiding exercise intensity, even when the pacing strategy differs. Previous studies support these findings, showing that when using RPE to regulate exercise intensity, participants can achieve similar physiological responses compared to when power output is externally controlled [5,8,63].

It is important to consider the role of cadence in these findings. During self-paced cycling, individuals tend to favor higher cadence over applying more force, which may optimize energy efficiency and delay the onset of fatigue. Research by Marsh and Martin (1993) demonstrated that self-selected cadences are generally higher, which can reduce the overall force required per pedal stroke, allowing for sustained effort over longer periods [64]. In our study, we found that at equal power outputs and physiological parameters (e.g., $\dot{V}O_2$, HR), the cadence was higher in the SPV test compared to the IET test. This could be explained by the self-regulation aspect of the SPV, where participants may subconsciously choose a higher cadence to maintain a steady perception of effort. Higher cadence at the same power output reduces the force required per pedal stroke, potentially minimizing muscle fatigue and maintaining comfort throughout the test. Research by Takaishi et al. (1996, 1998) supports this notion, suggesting that higher cadences are preferred in self-paced settings as they help sustain effort by reducing muscular strain [65,66]. This preference for higher cadence in self-paced exercise aligns with the idea that individuals naturally regulate their effort to optimize both comfort and performance, thus contributing to the similar cardiovascular outcomes observed across different exercise protocols.

The findings of this study suggest several practical applications for exercise prescription and training. The demonstrated reliability of the RPE scale in guiding exercise intensity across both self-paced and fixed protocols highlights its utility as a versatile tool in various settings, including clinical and athletic populations. Importantly, the higher cadence observed during self-paced exercise—which likely contributes to the similar cardiovascular outcomes despite different pacing strategies—suggests that encouraging self-regulated exercise may help optimize both comfort and performance. This has significant implications for exercise adherence, as explicit recommendations for self-paced exercise have been shown to improve adherence to exercise programs, particularly among populations less accustomed to structured training [2,67,68].

Additionally, recent research by Palacin et al. (2024) underscores the importance of self-paced exercise in long-duration endurance events, such as marathons, where maintaining an appropriate pacing strategy can significantly influence performance outcomes [13]. Their study demonstrated that brain activity and RPE can be effectively monitored to optimize pacing and delay the onset of fatigue during a marathon. These findings suggest that similar principles could be applied in various exercise contexts to enhance both performance and adherence. By allowing individuals to tailor their effort based on perceived exertion, self-paced exercise can enhance feelings of autonomy and enjoyment, key factors in promoting long-term adherence to exercise programs and improving overall health outcomes. Exercise adherence plays a significant role in reducing the risk of cardiovascular disease [69,70], which remains the leading cause of death in both Europe and the United States [71].

Furthermore, the observed stability and slight increases in the EEG/ $\dot{V}O_2$ ratio suggest that monitoring neural activity relative to physiological demand could be a valuable tool in personalized training programs. This approach could be particularly beneficial in settings that require fine-tuning exercise intensity to manage cognitive and motor demands effectively, such as in rehabilitation or high-performance sports. The differences in neural engagement between self-paced and fixed protocols also highlight the importance of tailoring exercise strategies to individual needs, thus potentially reducing the risk of central fatigue and enhancing overall performance.

Despite the valuable insights provided by this pilot study, several limitations must be considered.

First, the small sample size of six trained male cyclists limits the generalizability of the results. This may reduce the external validity, and future research should consider larger, more diverse samples to ensure that findings are applicable across broader populations. Additionally, because the participants in this study were trained, it is important to investigate whether the relationships between neural effort, exercise regulation, and performance observed here remain consistent in less-trained cohorts. These individuals may not be as accustomed to the sensations of self-pacing, exhaustion, and fatigue, making it crucial for future research to examine how self-paced exercise protocols perform across a wider range of fitness levels.

Second, the lack of randomization in the order of the two exercise tests introduces the potential for a learning or familiarization effect. However, this design was necessary, as the SPV test required the RPE values from the IET to determine appropriate intensity levels. Future studies could explore alternative methods to address this limitation.

Third, the protocol requiring participants to cease pedaling and to alternate between eyes open and eyes closed phases for 80 s between each step may have influenced both physiological and neural responses. Although this design was intended for a separate research focus, it could have impacted the results. Minimizing such interruptions in future studies could provide more continuous and reliable data.

Moreover, while the study focused on EEG measures, incorporating additional neuroimaging techniques, such as fMRI or near-infrared spectroscopy, could offer a more comprehensive understanding of the neural mechanisms involved in exercise regulation. Future studies should also consider longitudinal designs to examine how neural and physiological responses evolve over time with training adaptations.

5. Conclusions

This study provides important insights into neural and physiological responses to self-paced versus externally controlled exercise protocols. We found that during the SPV test, the beta PSD initially increased but then stabilized, as participants managed their effort effectively. This aligns with the Central Governor Model, which suggests that the brain modulates effort to prevent overexertion. In contrast, the IET test showed a continuous increase in beta activity, indicating greater neural strain and a potentially earlier onset of fatigue. These findings highlight the potential benefits of incorporating self-paced exercise into training programs, especially for improving exercise adherence and optimizing performance.

Additionally, the consistent cardiovascular parameters across both protocols reinforce the reliability of the RPE scale in guiding exercise intensity. The higher cadence observed during self-paced exercise suggests that participants intuitively adopt strategies to optimize energy efficiency and delay fatigue, supporting the utility of self-paced exercise in various settings. The observed stability and slight increases in the EEG/ $\dot{V}O_2$ ratio also suggest that this metric could serve as a valuable marker for monitoring neural engagement and fatigue during exercise, potentially informing more personalized training protocols.

Future research should consider larger, more diverse samples and longitudinal designs to further explore the impact of self-paced exercise across different populations and over extended periods. Additionally, minimizing interruptions during exercise testing and integrating additional neuroimaging techniques could provide a more comprehensive understanding of the brain's role in exercise regulation.

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