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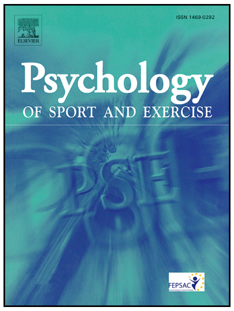

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# EEG Neurofeedback Improves Cycling Time to Exhaustion

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**Conflict of Interest**

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**Author Note**

The dataset can be made available upon reasonable request to the corresponding author.

# EEG Neurofeedback Improves Cycling Time to Exhaustion

## Abstract

**Objective:** The role of the brain in endurance performance is frequently debated; surprisingly, few investigations have attempted to improve endurance performance by directly targeting brain activity. One promising but untested approach to modifying brain activity is electroencephalogram (EEG) neurofeedback. Consequently, our experiment is the first to examine an EEG neurofeedback intervention for whole-body endurance performance. **Method:** We adopted a two-part experiment. The first consisted of a randomized parallel controlled design. Forty participants were allocated to three experimental groups; increase relative left cortical activity (NFL), increase relative right (NFR), and passive control (CON). They performed a depleting cognitive task, followed by either six 2-min blocks of EEG neurofeedback training (NFL or NFR) or time-matched videos of the neurofeedback display (CON). Next, they performed a time-to-exhaustion (TTE) test on a cycle-ergometer. We then tested participants of NFL and NFR groups in an additional experimental visit and administered the opposite neurofeedback training within a fully repeated-measures protocol. **Results:** EEG neurofeedback modified brain activity as expected. As hypothesized, the NFL group cycled for over 30% longer than the other groups in the parallel controlled design, NFL: 1382 ± 252 s, NFR: 878 ± 167, CON: 963 ± 117 s. We replicated this result in the repeated-measures design where NFL: 1167 ± 831 s performed 11% longer than NFR: 1049 ± 638 s). There were no differences in pre-exercise fatigue, vigor or self-control; area under the curve group-differences for perceived effort were interpreted within a goal persistence framework. **Conclusion:** The brief EEG neurofeedback intervention elicited greater relative left frontal cortical activity and enhanced endurance exercise performance.

***Keywords*****:** Brain stimulation, endurance performance, approach motivation, frontal alpha asymmetry.

## Introduction

The role of the brain in endurance exercise performance has been debated for a number of years. During this time, however, surprisingly few investigations have attempted to alter endurance performance by directly targeting brain activity (Angius et al., 2018). One novel approach to directly modifying brain activity is electroencephalogram (EEG) neurofeedback. Neurofeedback is a non-invasive technique based on operant conditioning whereby individuals learn to self-regulate their electrocortical activity with the aid of positive or negative reinforcement whenever electrocortical activity meets a pre-designated pattern (Enriquez-Geppert et al., 2017). Accordingly, neurofeedback provides an exciting opportunity to train individuals to produce brain activation patterns that might be conducive for endurance performance, and thereby yield a new non-invasive intervention to enhance endurance performance. This technique could also shed important new light on brain and endurance performance mechanisms. This paper reports on the first investigation of these pressing issues.

### EEG-Neurofeedback

The EEG assesses cerebral activity via electrodes attached to the scalp to record voltages emitted from the brain. This signal is dominated by oscillations that are usually decomposed into five characteristic frequencies [delta (0.5–3.5 Hz), theta (4–7 Hz), alpha (8–12 Hz), beta (13–30 Hz), and gamma (30-80 Hz)] reflecting specific brain states and cognitive functions (Knyazev, 2007). Slow frequencies within the delta-band are prevalent during deep sleep, theta-band has been associated with different cognitive functions like encoding information, alpha-band reflects suppressed brain activity and it has been associated with resting states, inhibition of cortical activity and directed attention, while faster frequencies (e.g. beta-band) are associated with alertness and attention (see Engel & Fries, 2010; Knyazev, 2007). In a typical EEG-neurofeedback session, the EEG signal is recorded from the scalp and computer software extracts the EEG feature that is the target of the neurofeedback training (e.g., spectral power in the alpha frequency band). This EEG feature is then compared to a criterion (e.g., a pre-defined target alpha power level) and displayed back via visual and/or auditory stimuli (e.g., graphs on a computer screen; an auditory tone). In this way, performers receive instantaneous, real-time feedback that indicates the current activity of the selected brainwave compared to the desired level of activation, hence they can begin to develop strategies to control their brainwaves to match the pre-defined target level (Enriquez-Geppert et al., 2017).

Research has used EEG-neurofeedback training to enhance cognitive performance (Gruzelier, 2014) and, more recently, neurofeedback has been utilized with self-paced target sports (e.g. Ring et al., 2015) as studies have reported cortical signatures that appear to characterize optimal performance during the final moments of motor preparation for such tasks (Cooke et al., 2014). However, compared to fine-motor skills (e.g., golf putting), whole-body exercise presents methodological hurdles such as muscular artefacts, electrode movement and sweat (Perrey & Beson, 2018), which make it difficult to discern brainwaves that characterize superior performance for data-driven neurofeedback interventions. To tackle this issue, we have advocated a prescription approach that allows the development of theory-driven neurofeedback protocols in the absence of prior data (Cooke et al., 2018). In the present study, we developed and tested a prescription for neurofeedback to enhance endurance performance, drawn from the approach-withdrawal model of frontal asymmetry (Davidson, 1992) alongside the psychobiological model of endurance performance (Marcora, 2008).

## The Brain and Endurance Performance

According to the psychobiological model of endurance performance, exercise capacity is a goal-directed behavior that is limited by a conscious decision to withdraw from exercise when the effort is perceived as no longer possible or justified (Marcora, 2008). During endurance events, athletes face increasingly unpleasant physical sensations, such as fatigue, pain and discomfort (McCormick et al., 2018). In this context, the motivation to continue, despite the rising urge to quit, is pivotal (Schiphof-Godart et al., 2018). The psychobiological model of endurance performance therefore predicts that any intervention that reduces the perception of effort will improve endurance performance (Blanchfield et al., 2014).

According to the approach-withdrawal model of frontal asymmetry (Davidson, 1992; Harmon-Jones & Gable, 2018), lateralization of brain activity across the prefrontal cortical hemispheres reflects opposite motivational directions that drive behaviors and emotions. Left-sided frontal activity is associated with approach-related processes whereas right-sided frontal activity is associated with avoidance-related processes (Harmon-Jones & Gable, 2018). EEG research has measured asymmetric frontal cortical activity by subtracting alpha power at the left frontal leads from alpha power at the right leads (i.e., relative frontal alpha asymmetry). Power within the alpha frequency band (8-13 Hz) is *inversely* related to cortical activity. Hence, positive values are indicative of greater left over right frontal cortical activity, while negative values indicate a greater right over left frontal cortical activity (Smith et al., 2017). Using this asymmetric index, previous studies reported that relative left frontal cortical activation is associated with positive affective responses to appetitive stimuli (Harmon-Jones & Gable, 2009) and action motivation (Berkman & Lieberman, 2010). More importantly, experimentally manipulated changes in relative left over right frontal cortical activity led to increased persistence during an unsolvable cognitive task (Shiff et al., 1998) and an action-orientated mindset (Harmon-Jones et al., 2008). These findings collectively suggest that relative left frontal cortical activity initiates motivational and cognitive processes that favor the maintenance of performance, especially when effort is at its highest.

Pertinently, Allen et al. (2001) demonstrated that EEG-neurofeedback can be used to modify relative frontal alpha asymmetry. In their study, individuals were trained to increase either relative right or relative left frontal cortical activity with five 6-minute sessions of neurofeedback performed over five consecutive days. They found that the group trained to increase relative left frontal cortical activity reported significantly more amusement, interest, and happiness in response to a film and significantly more zygomatic activity ('smile' faces) than the group trained to increase relative right frontal cortical activity. Similar effects have been reported by more recent studies (e.g., Peeters et al., 2014; Quaedflieg et al., 2016) with Peeters et al. reporting that just a single session of neurofeedback effectively modified relative frontal alpha asymmetry. However, these studies primarily focused on the effect of neurofeedback training for asymmetric frontal cortical activity on affective responses, whereas behavioral outcomes received little attention. Behavioral outcomes are central, however, in endurance events.

## Aim of the Present Experiment

The present research is the first to test the use of neurofeedback as a brain-based intervention to improve endurance exercise performance; specifically, the effect of increased relative left frontal cortical activity on whole-body endurance performance. We implemented a two-part experiment; the first involved a between-subject design, while in the second part the same group of participants was tested in a fully repeated measures design (i.e., crossover trial). Based on the aforementioned research, we reasoned that an alpha asymmetry neurofeedback protocol designed to increase relative left frontal cortical activity would enhance approach motivation and delay the urge to withdraw that is thought to terminate endurance exercise. We also anticipated that the intervention could be especially useful when participants are already in a state of cognitive depletion and fatigue prior to the start of endurance exercise. This is because a state of cognitive depletion is thought to elevate perceived effort and impair subsequent endurance exercise (e.g. Bray et al., 2008). Accordingly, we manipulated individuals' asymmetric frontal activity after they engaged in an effortful, depleting cognitive task used to exacerbate the feelings of fatigue (Inzlicht & Berkman, 2015). We then assessed the effect of our frontal asymmetry neurofeedback protocol on performance and perception of effort (i.e., RPE) during a cycling time-to-exhaustion test. On the basis of the approach-withdrawal motivational model of asymmetric frontal activity (Harmon-Jones & Gable, 2018) that we adopted to prescribe the neurofeedback interventions, we hypothesized that increased relative left frontal cortical activity would allow individuals to cycle for longer during a constant load time-to-exhaustion task compared to both the opposite neurofeedback intervention (increased relative right frontal cortical activity) and a passive control intervention. Based on the psychobiological model of endurance performance (Marcora, 2008), we further expected that neurofeedback-induced performance differences would be characterized by reduced perception of effort.

## Experiment 1A: Between-Subject Design

## Materials and Methods

### Participants

Forty volunteers (*n* = 26 males and *n* = 14 females) between 18 and 45 years old were recruited from university and local sports clubs. The sample was informed by power analysis based on previous research illustrating the effect of neurofeedback on alpha asymmetry. Research by Quaedflieg et al. (2016) and Mennella et al. (2014) reported that EEG-neurofeedback protocols such as the one used in this experiment elicited a significant and medium effect size ($\eta^2_p = 0.08$ and $\eta^2_p = 0.14$, respectively). Using the average of these effect sizes, GPower indicated that a sample of 27 participants would be sufficient to detect a comparable effect via the between-subject factorial ANOVA design that we planned to employ [($f$ = 0.33), $\alpha$ = 0.05, and $\beta$ = 0.80)]. Accordingly, by recruiting a sample of 40, we were more than sufficiently powered to detect the expected effect.

In order to participate in this research, participants had to be free from self-reported illness, injury and dyslexia, and not taking medication except the contraceptive pill. Participants were asked to sleep at least seven hours, avoid heavy exercise and alcohol during the 24 hours preceding each experimental visit, to avoid nicotine and caffeine for three hours before each experimental visit, and to consume a light meal two hours before attending each visit. Compliance with these instructions was confirmed at the start of each visit. All participants provided written informed consent and the study was approved by the Research Ethics Committee according to the Declaration of Helsinki.

## Design

We adopted a randomized between-groups design to investigate the effect of EEG-neurofeedback on exhaustive endurance exercise performance. Participants were randomly allocated to either an increase relative left frontal cortical activity neurofeedback group (NFL group), or one of two control groups: an increase relative right frontal cortical activity neurofeedback group (NFR group), or a no-neurofeedback passive control group (CON group) Randomization was performed in blocks of six and the scheme was generated by using the Web site Randomization.com. After receiving the neurofeedback intervention, or the passive control intervention, all participants completed a time-to-exhaustion exercise test on a cycle ergometer.

## Experimental Procedures

Participants made two laboratory visits, separated by a minimum of 48 hours, and a maximum of 14 days. Laboratory conditions were standardized at a temperature of 20 ± 1ºC, atmospheric pressure of 1015 ± 9 mbar, and humidity of 53 ± 7%.

**Visit 1.** The first session was identical for all three groups and involved a maximal incremental ramp test on a cycle-ergometer (Excalibur Sport, Lode, Groningen, Netherlands) to assess individuals' maximal oxygen consumption ($\dot{V}O_2max$) and peak power output (PPO). Before the test, anthropometric measurements (body mass and height) were recorded. The ramp test started with 2-min rest after which the power automatically increased from 50 W by 25 W every minute until voluntary exhaustion. Verbal encouragement was provided close to the end of the test to ensure that participants reached their maximal effort. During the maximal incremental test, oxygen consumption was measured breath by breath via a computerized metabolic gas analyzer (Metalyzer 3B, Cortex Biophysik, Leipzig, Germany) connected to a mouth mask (7600 series, Hans Rudolph, Kansas City, MO, USA). The device was calibrated before each test using a known concentration of gases and a 3L calibration syringe (Series 5530, Hans Rudolph). Maximal oxygen consumption was defined as the highest value of oxygen uptake averaged over 15 s. Heart rate (HR) was recorded continuously throughout the test with a wireless chest strap (S610, Polar Electro, Kempele, Finland) and rating of perceived effort (RPE) was measured at the end of every incremental stage using the Category Ratio scale (CR-10) developed by Borg (1998) . The standard instructions of the scale were provided to participants prior to starting the test and low and high anchor points were established using the procedures advocated by Noble and Robertson (1996). This first visit allowed participants to familiarize with the laboratory setting and testing procedures that were used for the experimental trial.

All exercise tests were performed on the same braked cycle-ergometer (Excalibur Sport, Lode, Groningen, Netherlands) set in hyperbolic mode, which allows the power to change independently of pedal frequency. For all exercise tests, exhaustion was defined as the point at which the individual voluntarily stopped the test, or the cadence had fallen below 60 revolutions per minute (rpm) for more than five consecutive seconds. During the tests, participants were asked to remain in the saddle and were allowed to freely choose their cadence so long as it remained between 60 and 100 rpm.

**Visit 2.** Upon arrival, all participants were briefed about the visit and then prepared for the EEG recording (see details below). The procedure took 20 min after which the Brunel Mood State Scale (BRUMS) and the State of Self-Control Capacity Scale (SSCCS) were administered (see section on psychological measures). All participants then completed a brief writing task designed to elicit a state of mild cognitive depletion and fatigue (see section on written task) followed by a second assessment of mood (BRUMS) and self-control (SSCCS). They then received an EEG-neurofeedback intervention (NFL or NFR) or a time-matched viewing of EEG signals without actively controlling them (CON) followed by a final assessment of self-reported mood and self-control. Next, participants moved onto the cycle-ergometer to perform a time-to-exhaustion cycling test, which required them to pedal for as long as possible at an intensity of 65% of their peak power output (see section on cycling time-to-exhaustion test, TTE).

## Manipulations and Measures

**Written Task (WT).** Before the neurofeedback/control interventions, all participants were instructed to produce a handwritten copy of a typed piece of text consisting of 336 words (one page) describing physics processes. Importantly, they were asked to omit the letters *A* and *N* from every word when producing their handwritten copy. This meant that the performer had to override their automatic writing habits so as to comply with the instructions of the written task. This task was adapted from similar versions previously used successfully to induce a state of mild cognitive depletion (Myers et al., 2018). The same text was used for all individuals and the time taken to complete the writing task was recorded. In each visit 30 min elapsed between the completion of the written task and the start of the TTE tests.

**EEG Recording.** EEG signal was recorded from F3 and F4 sites on the scalp using Ag/AgCl electrodes (Blue Sensor SP, Ambu) connected to a DC amplifier (PET-4, Brainquiry, neuroCare Group) that digitalized the signal at 1000 Hz. The active electrodes were positioned with a stretchable lycra cap in accordance with the 10-20 system (Jasper, 1958) and were referenced to linked mastoids, with a ground electrode positioned at FPz. The recording sites were abraded using a blunt needle and a conductive gel was applied, while an abrasive cream (Nuprep, Weaver and Company) and alcohol wipes were used to clean the mastoids and the forehead, before electrodes were attached. Electrode impedance at each site was kept below 10 kΩ. Before completing the written task, five 5 s baseline recordings were taken while participants sat still and maintained their gaze toward a black fixation cross printed on a white background. The power within the alpha frequency band (8-13 Hz) was averaged over the five baseline recordings and across the two sites, F3 and F4, and the value was used to individualize the thresholds for the neurofeedback interventions.

**EEG-Neurofeedback Interventions (NFL and NFR Groups).** The neurofeedback interventions consisted of six blocks of two minutes with one minute of rest in between each block. During each block, a computer running Bioexplorer software (Cyberevolution, Brainquiry, neuroCare Group) extracted the signal from each lead and simultaneously calculated the alpha frequency power using a fast Fourier transform algorithm with Hanning windowing function. The signal was 8-13 Hz band-pass filtered using the 6th order Butterworth IIR filter and averaged continuously every 5 ms. The resulting values were then displayed to participants on-screen via bar charts displaying alpha power at the F3 and F4 sites and an auditory tone that changed in pitch with changes in the ratio of F3 and F4 alpha power.

***NFL Group.*** Importantly, for members of the NFL group, the tone was set to silence and the color of the bar changed from red to blue when participants decreased their F3 alpha power by 1.5% and increased their F4 alpha power by 1.5% from their baseline level (blocks 1-3), or when they decreased F3 by 3% and increased F4 by 3% (blocks 4-6). Participants were told that decreasing the height of the F3 bar and increasing the height of the F4 bar would silence the tone and that their goal was to silence and keep it silent for as long as possible.

***NFR Group***. The procedure for the NFR group was identical except that their goal was to increase the height of the F3 bar and decrease the height of the F4 bar. The tone silenced when they increased their F3 alpha power and decreased their F4 alpha power from baseline by 1.5% (sessions 1-3) and 3% (sessions 4-6). To help ensure the signal was being regulated by cognitive processes and was not contaminated by artifacts, the tone was prevented from silencing in both the NFL and the NFR interventions during any periods where there was >10µV of 50 Hz activity in the EEG signal.

**Passive Control Group**. Participants in the passive control group underwent the same procedures as the other groups (i.e., EEG set up, baseline assessment, and written task); however, instead of receiving the neurofeedback training, they watched six 2-min video clips displaying a replay of the neurofeedback session from random participants in the experimental groups (3 from the NFL and 3 from NFR group, ordered randomly and then presented to all participants in a standardized sequence). This ensured that members of the passive control group were exposed to the same auditory and visual stimuli as members of both experimental groups. The passive control group were not given any instructions about controlling the bars on the screen, they were instead told that they were to watch a video of a neurofeedback recording while sitting still and remaining silent.

**Cycling Time-to-Exhaustion (TTE) Test.** After the neurofeedback intervention, participants performed a TTE on the cycle ergometer. The test started with a 3-min warm-up with the intensity set at 30% of individuals' PPO. After the warm-up, the intensity was increased automatically to a power output corresponding to 65% PPO and participants were instructed to cycle for as long as they could. Before starting the test, participants were reminded to cycle until exhaustion, to remain sitting in the saddle for the duration of the TTE test and to maintain the cadence between 60 and 110 rpm. No verbal encouragement, or feedback about elapsed cycling time, were provided at any point during any cycling TTE.

HR was recorded continuously throughout the TTE using the Polar HR monitor (Polar RS800CX, Polar Electro, Kempele, Finland). HR value in the final 15 s of each minute was recorded and used for analysis. RPE was evaluated using the CR-10 scale (Noble & Robertson, 1996) presented to participants at the final 15 s of every minute of the TTE test. Participants were instructed to rate how hard, heavy and strenuous the cycling TTE test felt at that moment (Marcora, 2010). Three minutes after the end of the TTE test, a 0.5 µl sample of whole fresh blood was taken from the left earlobe and blood lactate concentration was measured with a portable lactate meter (Lactate Pro 2 LT-1730, Arkray, Shiga, Japan).

**Psychological Questionnaires.** Upon their arrival (baseline), after the written task and after the interventions, participants completed the following questionnaires:

***Brunel Mood Scale (BRUMS).*** Mood state was recorded using the BRUMS (Terry et al., 2003). The scale includes 24 items divided into 6 subscales (depression, fatigue, vigor, tension, confusion, anger). Participants were instructed to indicate the extent to which they were experiencing the feeling described by the item at that moment in time (‘how do you feel right now’) using a 5-point scale (0 = *not at all* to 4 = *extremely*). A total score for each subscale was computed by summing the ratings of its respective items. For the purpose of this experiment, we were interested in ratings of fatigue and vigor, and focused our analyses on these subscales.

***State Self-Control Capacity Scale (SSCCS).*** The SSCCS developed by Ciarocco et al. (2004) was used to assess participants’ momentary state of self-control. The scale included

26 items (e.g., “I feel sharp and focused”) rated on a 7-point Likert-type scale from 1 (*not true*) to 7 (*very true*). Higher values were representative of a greater state of self-control (no depletion) while lower values indicated a greater state of depletion.

## Data Reduction

**EEG.** Matlab (R2017b) was used to extract EEG data recorded during the neurofeedback and control interventions for statistical analyses. The signal from F3 and F4 was down-sampled offline at 256 Hz, and a 1 Hz high pass filter (cut off frequency 0.8 Hz and transition bandwidth 0.4 Hz), and 30 Hz low pass filter (cut off frequency 35 Hz and transition bandwidth 10 Hz), were applied. Continuous EEG data were manually corrected for eye blinks artefacts. Each 2 min block was divided into 2 s epochs (75% overlap) and epochs containing artefacts greater than ± 75 μV were rejected. The power spectrum was derived from each retained epoch by a fast Fourier transformation using a 100% Hanning windowing function. For each NF block, power within the alpha frequency (8-13 Hz) was averaged across epochs and the resulting values used to compute the index of alpha asymmetry defined as the log-transformed alpha power at F4 minus the log-transformed alpha power at F3 (Ln [alphaF3] – Ln [alpha F4] (Smith et al., 2017).

**HR and RPE.** To give insight into the temporal changes of RPE and HR throughout the cycling TTE test, we split each participant’s TTE test into five time-points; the first time-point corresponded to the end of the first minute of the test, the last four time points corresponded to the 25%, 50%, 75% and 100% of the individual’s total cycling time. For each individual TTE test, the values of HR and RPE attained at the minutes corresponding to the 5 time-points were used for the analysis. To provide further insight into the time-responses of these two variables, we computed the area under the curve (AUC) for RPE and HR using the integrated trapezoid formula (Pruessner et al., 2003). For each individual TTE test, the trapezoid areas were calculated from the values of HR and RPE attained at the minutes corresponding to the 25%, 50%, 75%, 100% of the total time to exhaustion test and the time distance between these points,

e.g. $AUC_{RPE} = (RPE_i + RPE_{i+1}) \cdot {}^{t_i}/_{2}$ where $i$ = height at the start of the quartile, $i+1$ = height at the end of the quartile, and $t_i$ = duration (length) of the quartile (Pruessner et al., 2003).

## Statistical Analysis

**Main Analyses**. We performed a 3 (Group) × 6 (Block) mixed-model ANOVA to assess the effectiveness of the neurofeedback intervention in manipulating frontal asymmetry. We ran planned orthogonal contrasts to compare the TTE achieved by participates in the NFL group with the TTE achieved by participants in the NFR (a form of active control) and CON (passive control) groups. Finally, 3 (Group) × 5 (Time) ANOVAs were used to examine the effects of neurofeedback on HR and RPE during the cycling TTE test. Planned orthogonal contrasts were used to compare the AUCs for RPE and HR.

**Control Analyses.** We also performed a number of control analyses. First, to check that our random assignment was successful in balancing the groups at baseline, we subjected fitness levels, anthropometric characteristics, baseline alpha-asymmetry, fatigue, vigor and self-control to one-way between-group ANOVAs. Second, to ensure that our written task and our neurofeedback interventions had a similar effect on the self-control, fatigue and vigor of participants, we tested these self-report measures with 3 (Group) × 3 (Time; baseline, post-written task, post neurofeedback) ANOVAs. Finally, to check that all participants reached a similar level of exhaustion at the end of each TTE test, mean cadence, RPE at exhaustion, HR at exhaustion, and blood lactate at exhaustion were analyzed with one-way between group ANOVAs. In all cases the assumptions of homoscedasticity and sphericity were tested with Levene and Mauchly tests and results were reported with the appropriate corrections (Welch’s F and Greenhouse–Geisser correction) applied when the assumptions had not been met. The nonparametric Kruskal-Wallis test was used on data that did not meet the assumption of normality as assessed with the Shapiro-Wilk test. Significant interactions were investigated with planned contrasts. For all analyses, statistical significance was set at $p \leq 0.05$ and the effect sizes were reported as partial eta squared ($\eta_p^2$) and Hedges's $g_s$ (Lakens, 2013).

## Results

### Alpha asymmetry

The 3 (Group) × 6 (Block) ANOVA on the alpha asymmetry indices revealed a significant interaction, $F(6,116)=2.29$, $p=.038$, $\eta_p^2=.11$. Post-hoc planned contrasts revealed a significant difference in alpha asymmetry between the NFL and NFR groups in blocks 4, $t(37)=2.10$, $p=.043$, $g_s=.65$ and 5, $t(37)=2.64$, $p=.012$, $g_s=.82$. Accordingly, alpha asymmetry scores in the two active groups diverged as the intervention progressed, with the NFL group manifesting more left-sided frontal cortical activity, and the NFR group more right-sided frontal cortical activity in the last three blocks of the neurofeedback intervention. This indicates that our neurofeedback intervention was successful in establishing two distinct frontal asymmetry groups immediately prior to the TTE. This effect is illustrated in Figure 1.

** Insert Figure 1 about here **

### Cycling time to exhaustion test

Results of the TTE tests are summarized in Figure 2. We hypothesized that the NFL group would outperform the NFR and passive control groups. Orthogonal planned contrasts confirmed that the NFL group performed significantly better than the other two groups, $t(37)=2.03$, $p=.050$, $g_s=.64$, while the performance of the NFR and the passive control groups did not differ from each other, $t(37)=0.33$, $p=.744$, $g_s=.10$.

** Insert Figure 2 about here **

## RPE and HR

The 3 (Group) × 5 (Time) ANOVAs performed on the RPE and HR values revealed a main effect of time on RPE, $F(3,101)=400.25$, $p<.001$, $\eta_p^2=.91$, and HR, $F(2, 63)=270.55$, $p<.001$, $\eta_p^2=.88$. As expected, both variables increased significantly at every time point. There was also a significant effect of group for RPE, $F(2, 37)=3.54$, $p=.039$, $\eta_p^2=.16$. Post hoc tests indicated that RPE in the NFL group (6.8) did not differ significantly from that in the other groups, $p=.719$; however, RPE in the CON group (7.6) was significantly higher than RPE in the NFR group (6.4), $p=.012$. The HR data yielded no significant differences between groups ($F(2,36)=0.91$, $p=.412$, $\eta_p^2=.05$). No significant Group × Time interactions emerged. Effects are summarized in Figure 3A and 3B.

Overall, the AUC for RPE and HR were greater in the NFL compared to the other two groups, but contrast tests did not reach the statistical level for significance, RPE: $t(37)=1.84$, $p= .074$ and HR: $t(36)=1.74$, $p=.090$. This reflects the greater amount of total work performed by participants in NFL and implies a slower rate of increase in RPE and HR in the NFL group (see Figure 3C and 3D).

** Insert Figure 3 about here **

## Control Analyses

Our control analyses are reported in full in the digital supplementary material (see Experiment 1A, Results, Supplementary Material). In brief, there were no baseline differences between the groups on any measures, indicating that our randomization was effective (see Table 1). The 3 (Group) × 3 (Time) ANOVAs performed on the self-report measures of fatigue, vigor and state of self-control revealed no main effects for group and no Group × Time interactions. There were main effects for time, indicating that self-control and vigor decreased, and fatigue increased after the writing task and tended to increase again after the intervention. This confirmed that all our participants were in a similar state of fatigue and mild cognitive depletion prior to commencing the cycling TTE test. Finally, there were no group differences in the mean cadence or in any of the physiological assessments made at exhaustion, confirming that all groups reached a similar level of physiological fatigue at the end of the cycling TTE test (see Experiment 1A, Table S2, Supplementary Material).

## Conclusion and Introduction to Experiment 1B

The results from Experiment 1A showed that EEG-neurofeedback can be used to non-invasively modify frontal hemispheric asymmetry. More importantly, they suggested that greater relative left frontal cortical activity enhanced cycling-based endurance exercise performance. However, between-person variability in many psychophysiological signals can be high such that some researchers have argued that within-person designs are preferred (e.g., Jennings et al., 2007). As such, to examine the replicability and robustness of our finding, we followed up Experiment 1A with a fully repeated measures design in Experiment 1B.

## Experiment 1B: Within-Subject Design

## Materials and Methods

### Design, Participants, and Procedures

A cross-over, single-blind, counterbalanced design was used for the second experiment whereby the same individuals who had received the EEG-neurofeedback interventions in Experiment 1A (groups NFL and NFR) were tested for a third experimental session. The twenty-six NFL and NFR participants (*n* = 17 males and *n* = 9 females) from Experiment 1 performed the additional, third experimental visit. This was identical to the second experimental session described in Experiment 1A (see visit 2 above for details), except that participants received the opposite neurofeedback intervention in this additional session. Accordingly, in Experiment 1B, all 26 participants received both the NFL and NFR interventions on separate occasions, allowing for within-subject comparisons. The order of the two visits was counterbalanced across participants, who were scheduled at the same time of day to control for possible circadian rhythm effects on physical performance and alpha asymmetry. Participants were allowed a minimum of 3 days and a maximum of 3 weeks from the previous experimental session to perform the additional visit. This design is illustrated in Figure S1 alongside the Consolidated Standards of Reporting Trials (CONSORT) checklist for crossover trials (Supplementary Material). Participants were asked to keep their training routine consistent throughout their involvement in the study. All apparatus, measures and other procedures were identical to those reported in Experiment 1A.

## Data Reduction

**HR and RPE**. The HR and RPE values attained in each TTE test at the minutes corresponding to the 25%, 50%, 75% and 100% of the total endurance time were used for the within-subject comparison (‘relative iso-time’ in Nicolò et al., 2019). For the first time point, we used the values recorded at the end of the first minute of each test. In addition, AUCs were derived from RPE and HR data recorded during the TTE with the same formula described in Experiment 1A (see data reduction above).

## Statistical Analysis

**Main Analyses**. In accord with our fully within-subject design, we performed 2 (Condition) × 6 (Block) repeated measures ANOVA to assess the effectiveness of our neurofeedback intervention in manipulating frontal asymmetry. We performed a paired-samples (i.e., repeated measures) *t*-test to compare the TTE achieved by participants during the NFL and NFR conditions. Finally, we performed 2 (Condition) × 5 (Time) ANOVAs to examine the effects of neurofeedback on RPE and HR throughout each cycling TTE test and paired sample *t*-test to test the effect of neurofeedback on AUC for RPE and HR.

**Control Analyses.** Paired samples *t*-tests were used to compare baseline vigor and fatigue, self-control, and alpha-asymmetry across the two experimental visits. Paired samples *t*-tests also compared mean cadence, and HR, RPE and blood lactate level at exhaustion. We employed separate 2 (Condition) × 3 (Time; baseline, post written task, post neurofeedback) repeated measures ANOVAs to examine the effect of the writing task and the neurofeedback interventions on reported self-control, fatigue, and vigor. Finally, to examine the potential for sequence effects within the crossover design (Wellek & Blettner, 2012), we performed a 2 (Order; AB and BA) × 2 (Condition) mixed-model ANOVA on TTE where condition (NFL, NFR) was a within-subject factor and order was entered as a between-subject factor (order A = participants who completed NFL on visit 1 and NFR on visit 2; order B = participants who completed NFR on visit 1 and NFL on visit 2). This was followed by separate paired-samples *t*-tests for each order. Significant interaction effects were investigated with orthogonal contrasts. For all analyses, statistical significance was set at $p \leq 0.05$ and effect sizes were estimated with Cohen's $d_{av}$ calculated with the average standard deviation and corrected as Hedges's $g_{av}$ (see Formula 10, Lakens, 2013).

## Results

### Alpha asymmetry

A 2 (Condition) × 6 (Block) ANOVA performed on the alpha asymmetry indices revealed a significant main effect of condition, $F(1,25)=4.81$, $p=.038$, $\eta_p^2=.16$. Alpha asymmetry was significantly greater (and positive; 0.14 ± 0.28 $\mu V \cdot Hz^{-1}$) indicating dominant left-sided frontal cortical activity in the NFL condition, compared to the NFR condition (-0.02 ± 0.16 $\mu V \cdot Hz^{-1}$), where the smaller (and negative) score indicates dominant right-sided frontal activity. This finding confirms that our neurofeedback intervention was effective in establishing two distinct asymmetry conditions, and the effect emerged across all blocks (Fig. 4). There was no Block main effect or Block × Condition interaction.

** Insert Figure 4 about here **

## Time to Exhaustion

The TTE test was longer in the NFL condition (1167 ± 831 s) compared to the NFR condition (1049 ± 638 s). This difference, 118 s, 95% CI [14, 221] was significant, $t(25)=2.34$, $p=.028$, $g_{av}=.16$, supporting our finding in Experiment 1A.

## RPE and HR

The 2 (Condition) × 5 (Time) ANOVAs performed on the RPE and HR values revealed a significant main effect of time (RPE: $F(2,60)=312.26$, $p<.001$, $\eta_p^2=.93$; HR: $F(2,35)=178.21$, $p<.001$, $\eta_p^2=.89$). Both RPE and HR increased significantly at every time point ($p$-values of the repeated contrasts between time points were <.001). There were no significant effects of condition, or Condition × Time interactions for either RPE, or HR. These results are summarized in Figure 5A and 5B.

Areas under the curves were greater in the NFL condition compared to the NFR condition for both HR, $t(22)=2.51$, $p=.020$, $g_{av}=.17$, and RPE, $t(24)=2.52$, $p=.019$, $g_{av}=.12$ (Figure 5C and 5D). Given the aforementioned empirical findings (i.e., lack of quartile differences and significant TTE effect) and the visual representation in Figures 5C and 5D, it would appear that when participants were under the NFL condition, they persisted on the cycling task for longer demonstrating a suppressed rate of increase in RPE and HR.

** Insert Figure 5 about here**

## Control Analyses

Our control analyses are reported in full in the digital supplementary material (Experiment 1B, Results, Supplementary Material); they confirmed our expectations. In brief, there were no baseline differences across the conditions, indicating that participants reported to the laboratory in a similar state for both of their experimental visits. The 2 (Condition) × 3 (Time) ANOVA performed on the self-report measures of fatigue, vigor and state of self-control capacity revealed no main effects for Condition and no Condition × Time interaction. There were main effects for Time, indicating that self-control and vigor decreased, and fatigue tended to increase after the writing task and the neurofeedback intervention. This confirmed that our participants were in a similar state of mild cognitive depletion prior to the cycling TTE in both conditions. There were no differences in the mean cadence of the TTE tests or in any of the physiological assessments made at exhaustion, confirming that participants displayed a similar level of physiological fatigue in both conditions (see Experiment 1B, Table S3, Supplementary Material). Finally, the 2 (Order) × 2 (Condition) mixed-model ANOVA performed on TTE confirmed the previously reported main effect for condition, where TTE was significantly greater in NFL than in NFR. There was no effect of Order and no Order × Condition interaction. Paired samples *t*-tests confirmed that the effect of condition was similar irrespective of the order in which participants completed the neurofeedback interventions. This provides some assurance that the beneficial effects of the NFL intervention on TTE were not bias by sequence or carryover effects (Wellek & Blettner, 2012).

## General Discussion

### Main Findings

This is the first investigation to assess the effect of neurofeedback on whole-body endurance exercise performance. The results from both datasets provide consistent evidence that increasing relative left frontal cortical activity (NFL) via EEG-neurofeedback has a beneficial effect on endurance exercise performance. In Experiment 1A, participants who received this NFL intervention were able to cycle for approximately six minutes (about 30%) longer than participants who received either an increase in relative right frontal cortical activity (NFR) via neurofeedback, or the passive control group (CON) who received no neurofeedback intervention. This finding was replicated in Experiment 1B using a within-subject design when the same individuals performed the TTE test after receiving both NFL and NFR on separate occasions. In this instance, participants cycled for approximately two minutes (11%) longer in the NFL condition compared to the NFR condition.

Importantly, in Experiment 1A, TTE performance was not significantly different between the NFR and CON groups. Therefore, we can exclude the possibility that the NFL performance improved simply because individuals underwent a neurofeedback intervention per se (e.g., placebo effect), or due to mechanisms underlying the neurofeedback training (e.g., operant conditioning). Also, the physical stimuli during the interventions were the same across conditions, adding further evidence to indicate that the significant effect of NFL on performance was due to changes in frontal asymmetry (i.e., were genuine) rather than any other features associated with the experimental protocol (e.g., auditory and visual stimuli).

A more invasive brain stimulation method, transcranial direct current stimulation (tDCS) has been reported to elicit either a 23% improvement (Angius et al., 2018), or no improvement (Angius et al., 2015) of endurance performance when assessed using a within-subject design. However, ethical concerns that have been raised about tCDS may limit its mass uptake in applied settings (e.g., Davis, 2013). Our findings are the first to confirm that a non-invasive approach to modifying brain activity via EEG-neurofeedback could offer a practical and realistic performance enhancing alternative for individuals or situations where tCDS is not acceptable, or viable.

## Mechanisms

In the current study, as expected, HR and perceived effort during the TTE test increased over time and reached on average 96% and the 100% of their maximal values, respectively. Contrary to our hypothesis, NFL did not significantly reduce perception of effort during any TTE. Specifically, ANOVAs failed to reveal the expected Group x Time (Experiment 1A) or Condition x Time (Experiment 1B) interactions for RPE. While previous studies show that psychological interventions can improve endurance exercise performance by reducing perception of effort during the task (Blanchfield et al., 2014), the results of our study suggest that EEG-neurofeedback may act in a different way. Rather than reducing perception of effort, NFL may instead have supported participants to exercise for longer while experiencing a high level of effort. Hence, NFL allowed participants to perform a greater amount of physical work when fulfilling their goal to exercise for as long as possible. To provide some support for this interpretation, we found differences in AUC of RPE and HR which were marginally greater for NFL compared to NFR and CON in Experiment 1A and significantly greater after NFL compared to NFR in Experiment 1B. Since the absolute levels of RPE and HR at the end of each quartile of exercise were the same between groups and conditions (i.e., no ANOVA interactions), the greater AUC for NFL can be attributed to differences in the length (i.e., time; longer in NFL) rather than the height (i.e., RPE and HR) factors in the AUC formula. Figures 3 and 5 illustrate this effect and reveal a slower rate of increase in RPE and HR for NFL, reflecting the longer time taken to reach the same terminal levels as achieved after NFR or CON, implying greater sustained effort in NFL than in NFR or CON. Although we reported discrepant findings between our AUC and the traditional ANOVA approach to analyzing time-series data in endurance studies, these were highly informative. We encourage researchers to further explore the merits of the AUC approach in future endurance-oriented experiments.

At a cortical level, our results imply that NFL prompted a neurophysiological shift towards approach motivation and increased behavioral persistence. This perspective is supported by the fact that our NFL neurofeedback intervention led to significantly greater left-sided frontal cortical activity. Pertinently, relative left frontal cortical activity is involved in approach motivation, which is considered to represent the tendency to move toward something (Harmon-Jones & Gable, 2018). Approach-related processes engage the same neural activation underlying local attentional scope. Specifically, relative left frontal-central asymmetry induced by approach-related stimuli predicted narrowed attentional scope (Harmon-Jones & Gable, 2009) which could assist goal-directed action by narrowing the attention toward task-relevant information (Gable & Harmon-Jones, 2010) and increasing cognitive stability and persistence (Liu & Wang, 2014). For example, in the context of the current endurance exercise, left-sided frontal activity may help individuals maintain focus and engagement with their progressively more painful and fatiguing task, thereby delaying the urge to withdraw and stop. Consistent with this interpretation, Schiff et al. (1998) used a lateral muscular hand contraction to modify asymmetric frontal cortical activity and found higher persistence on an unsolvable puzzle after the right lateral muscular contractions (said to increase left cortical activity) compared to the contralateral contraction and passive control. Taken together these findings suggest that greater relative left frontal cortical activity, following NFL, facilitated cognitive control by delaying attentional disengagement. This, in turn, would allow individuals to allocate attention towards coping with the increasing time-on-task demand of exercise helping them to tolerate high effort for longer. Further support for this may be gleaned from the fact that activation of the left dorsolateral prefrontal cortex (DLPFC) has been found when individuals implemented cognitive control to form and maintain task-goal representation of the Stroop test (MacDonald et al., 2000). Similarly, Bekerman and Lieberman (2010) used fMRI while participants performed a virtual task to examine the relationship between asymmetric brain activation, stimulus valence, and motivational direction. They found that relative left frontal activation of the DLPFC was associated with action (eat), independently from the stimulus valence (pleasant food or disgusting food). Because relative left frontal activity increased in response to approach-related actions coupled with both positive stimuli and negative stimuli, the authors argued that left-sided activity in the DLPFC should be involved in self-regulatory processes relevant for successful goal pursuit.

In addition to being interpretable via models of approach and avoidance motivation, our effects are also broadly in accordance the valence model (Heller, 1993) and the capability model (Coan et al., 2006) of frontal hemispheric asymmetry. The valence model argues that increased left-sided frontal asymmetry elicits more positively valanced emotions, and previous research has demonstrated that greater positive emotions can facilitate endurance performance (e.g., Hutchinson et al., 2018). However, the valance hypothesis has been challenged by research demonstrating that while left-frontal activation is associated with some positive emotions, it is also associated with the negative emotion of anger (Harmon-Jones, 2003; Harmon-Jones & Allen, 1998; Hortensius et al., 2012). Accordingly, frontal asymmetry may not be associated with valence per se, rather it reflects the motivational system engaged by that stimulus or situation (Davidson & Irwin, 1999). This is why we preferred the approach and avoidance motivational account of frontal asymmetry to the valence model.

The capability model proposes frontal hemispheric asymmetry as a predictor of individual capability for displaying certain affective styles (Coan et al., 2006). More specifically, it predicts that individuals displaying greater left over right frontal activation will also have more positive affective responses to external situations or stimuli, whereas individuals reporting greater right over left frontal activation, within the same context, will experience more negative affective responses (see Coan et al., 2001). As positive affect can enhance endurance (Hutchinson et al., 2018), our results could be interpreted as supportive of the capability model. Future research could incorporate features to tease apart the capability model and the approach and avoidance model to shed more light on which of these explanations provides the mechanism that underlies the effects of hemispheric asymmetry neurofeedback on performance.

## Limitations and Future Directions

Despite the encouraging findings provided, some limitations should be considered when interpreting the results. Firstly, from a theoretical perspective, cortical activity was measured during the neurofeedback procedure, but not afterwards, nor during the physical task. Therefore, despite confirming the validity of a single session of EEG-neurofeedback (Peeters et al., 2014), we can only assume that the neural changes induced during the single session of neurofeedback persisted throughout the exercise. Further research is warranted to assess the longevity of neurofeedback training effects and provide additional support for the relationship between frontal asymmetric cortical activity and performance.

Secondly, our theory-driven approach was focused on perception of effort. However, it may be possible that other psychological variables mediated the effect of the frontal asymmetric cortical activity during the exhaustive cycling task. In this regard, Allen et al. (2001) demonstrated that neurofeedback to modify asymmetric frontal cortical activity altered self-reported emotional responses elicited by external stimuli. It is well-known that feelings can change throughout the exercise (Hardy & Rejeski, 1989) and influence performance (e.g. Hutchinson et al., 2018); therefore, future studies should assess affective responses during endurance exercise following this neurofeedback intervention. Similarly, additional markers of approach motivation could be assessed to further investigate the psychological mechanisms underlying the relationship between asymmetric frontal cortical activity and behavior (see Harmon-Jones & Gable, 2018).

It should be noted that due to the intended design of our experiment, our effects emerged when participants entered exercise in a state of mild cognitive depletion and fatigue, as indicated by the reduction in self-reported self-control that remained lower than baseline after the manipulation. Thus, our performance results suggest that the left-sided frontal cortical asymmetry may be particularly relevant when effort is aggravated by prior fatigue. However, it would be useful for future research to replicate our experiments without prior fatigue and/or with varying levels of prior fatigue to test the generalizability of our findings. One could argue that any benefits of neurofeedback on physical endurance could be stronger without any prior cognitive fatigue since this could help participants achieve more intense left frontal activation during the neurofeedback intervention, beyond the levels achieved here. These predictions await future testing.

The sample of the present study comprises recreational athletes, as such, it is not clear if the effect found will generalize to elite athletes. On the one hand, elite athletes are already closer to their endurance limits than recreational performers, possibly creating a ceiling with less scope for neurofeedback (or any) intervention benefits to manifest. On the other, the reduced between- and within-person variability displayed by elite compared to recreational performers may render greater scope for statistically meaningful “marginal gains” to emerge in elite performers. This can be tested by future research.

**Practical Applications**

From an applied perspective, our data support the use of EEG-neurofeedback in the context of endurance performance and indicate that the application of EEG-neurofeedback for as little as 12 minutes could offer a safe and ethically viable approach to performance enhancement for athletes who engage in endurance exercise events lasting for around 20 minutes. In addition, Ring et al. (2015) reported that athletes undergoing repeated sessions of neurofeedback training could learn to regulate their own cortical activity even when they are not receiving the physical feedback. This offers a valuable advantage in an applied setting where athletes might eventually be able to reproduce the performance-boosting brain activity without any equipment, following a short period of neurofeedback training.

## Conclusion

This is the first investigation to show that neurofeedback can be used as a form of non-invasive brain stimulation to improve endurance performance. Specifically, increasing relative left frontal cortical activity via neurofeedback was able to improve exhaustive exercise performance by 30% and 11% using between-group and within-subject designs, respectively. Despite this performance enhancement, neurofeedback did not lead to differences in perception of effort during the TTE tests. Thus, from a theoretical perspective, neurofeedback might act in a different way to other cognitive interventions (e.g., Blanchfield et al., 2014) that acutely enhance endurance capacity. Our novel application of AUC analyses generated findings indicative that neurofeedback might aid endurance performance through increased goal-directed persistence resulting from a shift towards greater approach motivation. As such, the current study and associated datasets introduce an original *and* effective brain-oriented endurance performance intervention, reveal a new potential mechanism bridging left-sided frontal cortical asymmetry and whole-body endurance exercise performance, and can be used as an exemplar by future theory-driven neurofeedback investigations interested in enhancing endurance performance.

## Appendix

### Supplementary Material

Complete results of control analyses are presented in the Supplementary Material.

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**Table 1.**

*Descriptive Statistic and One-Way ANOVA of the Demographic Characteristics and Baseline Variables.*

| Measure | NFL | NFR | CON | *p* |
|---|---|---|---|---|
| | *M* (*SD)* | *M* (*SD)* | *M* (*SD)* | |
| n | 13 | 13 | 14 | |
| Age (yr) | 27 (6) | 27 (7) | 27 (8) | .977 |
| Weight (kg) | 74.0 (11.2) | 73.9 (18.4) | 70.5 (9.4) | .741 |
| Height (m) | 1.76 (0.06) | 1.73 (0.09) | 1.75 (0.10) | .793 |
| BMI (kg·m$^{-1}$) | 24 (4) | 24 (5) | 23 (2) | .623 |
| $\dot{V}O_2$ max (ml·kg·min$^{-1}$) | 46.8 (12.4) | 43.0 (11.6) | 45.7 (9.4) | .672 |
| PPO (W) | 278 (82) | 254 (70) | 285 (76) | .556 |
| Max HR (bpm) | 176 (6) | 174 (10)[a] | 175 (10) | .674 |
| Fatigue (BRUMS) | 2.5 (2.3) | 3.3 (3.1) | 3.7 (3.2) | .528 |
| Vigor (BRUMS) | 8.7 (1.9) | 7.8 (4.1) | 8.21 (2.8) | .752 |
| SSCCS | 142 (13) | 139 (20) | 135 (21) | .620 |
| Alpha Asymmetry (a.u.) | 0.02 (0.09) | 0.00 (0.10) | - 0.01 (0.05) | .542 |

*Note*. NFL = neurofeedback to increase relative left cortical activity group; NFR = neurofeedback to increase relative right cortical activity group; CON = passive control group; BMI = Body Mass Index; $\dot{V}O_2$max = Maximal oxygen consumption; PPO = Peak Power Output; SSCCS = State of Self-Control Capacity Scale.

[a] n = 12 because of recording problems during the test.

There were not significant differences between group.

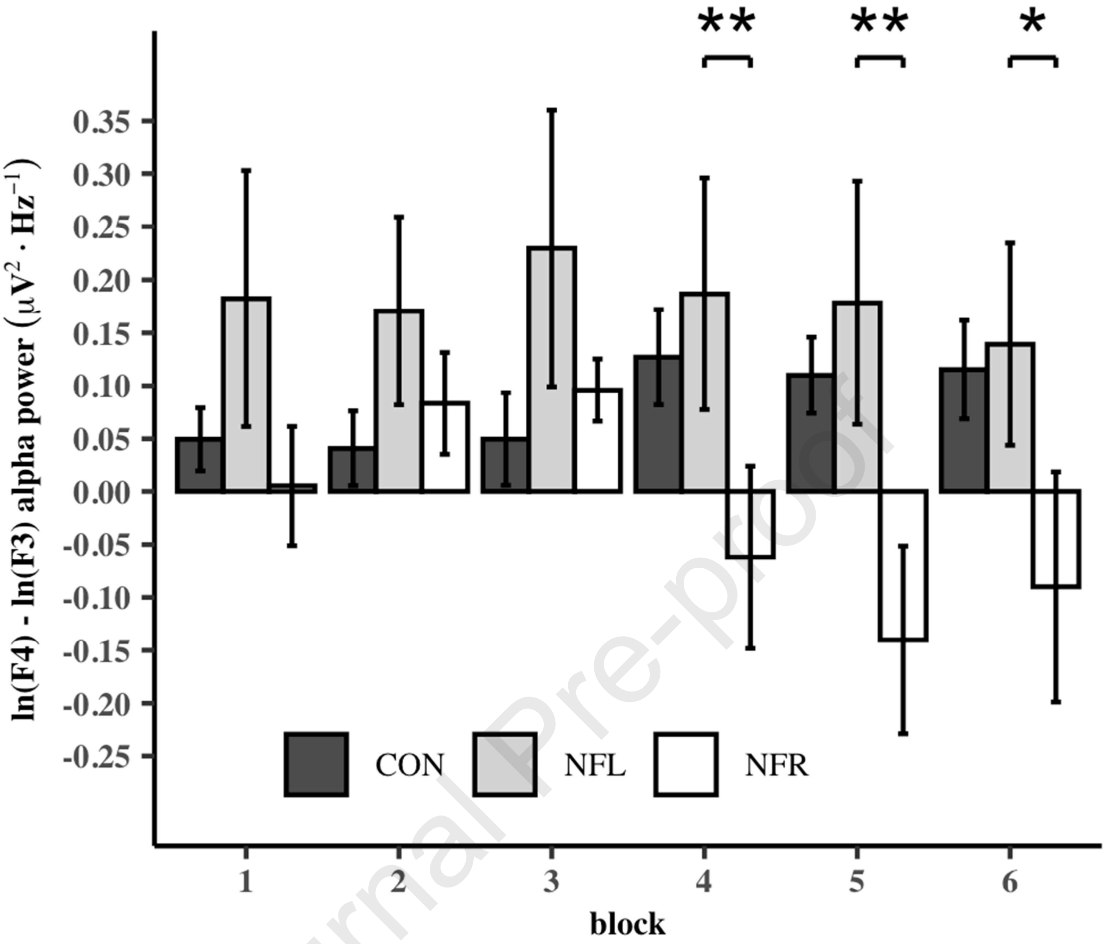


**Figure 1**

*Frontal Alpha Asymmetry, Experiment 1A.*

*Note.* Average value of 2-min six intervention blocks for each group, increase relative left, NFL, increase relative right, NFR, frontal cortical activity and passive control CON group, means and SE.

*Differences between groups NFL and NFR (**p <.05 and * p <.10).

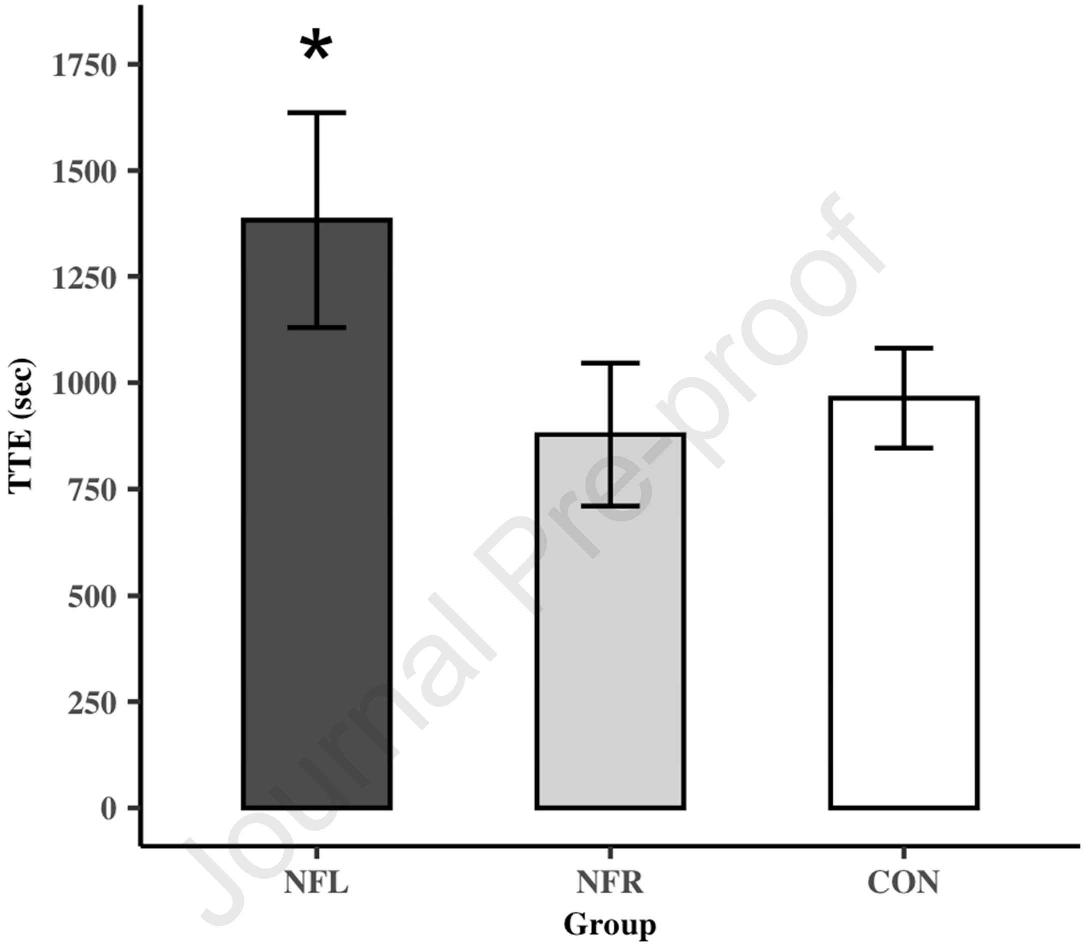


**Figure 2**

*Effect of EEG-Neurofeedback on Time-to-Exhaustion, Experiment 1A.*

*Note*. Mean ± SE for each group, increase relative left, NFL, increase relative right, NFR, frontal cortical activity and passive control CON group.

* Significant difference between NFL and controls group, NFR and CON (*p* =.05).

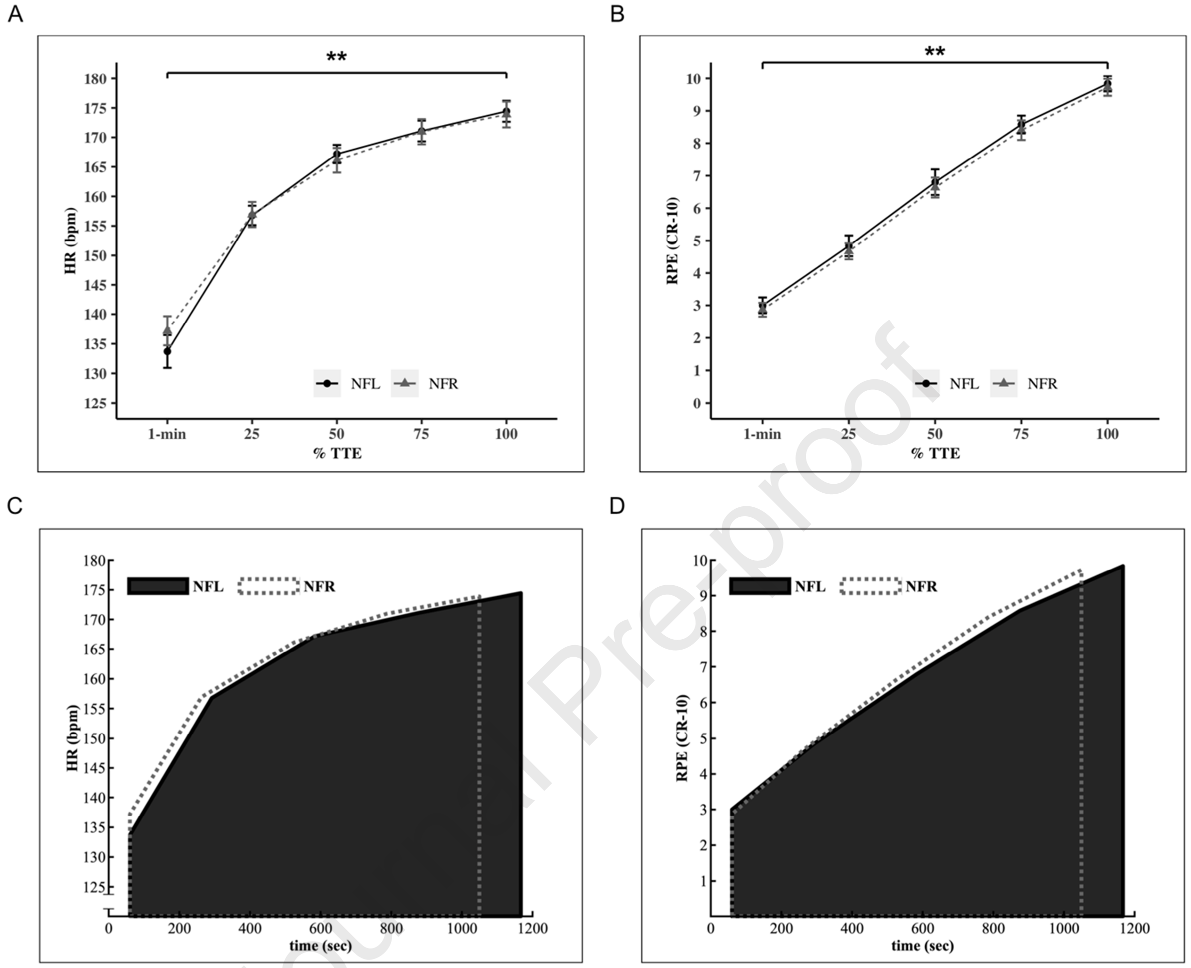


**Figure 3**

*Heart Rate (A) and Rating of Perceived Effort (B) during TTE and Area Under the Curve of HR (C) and RPE (D), Experiment 1A.*

*Note*. Means and SE, at first minute and 25%, 50%, 75% and 100% of TTE test for each group. **Significant main effect of time (*p*<.001);

$^{\#}$ Significant difference between groups NFR and CON (*p*=.012).

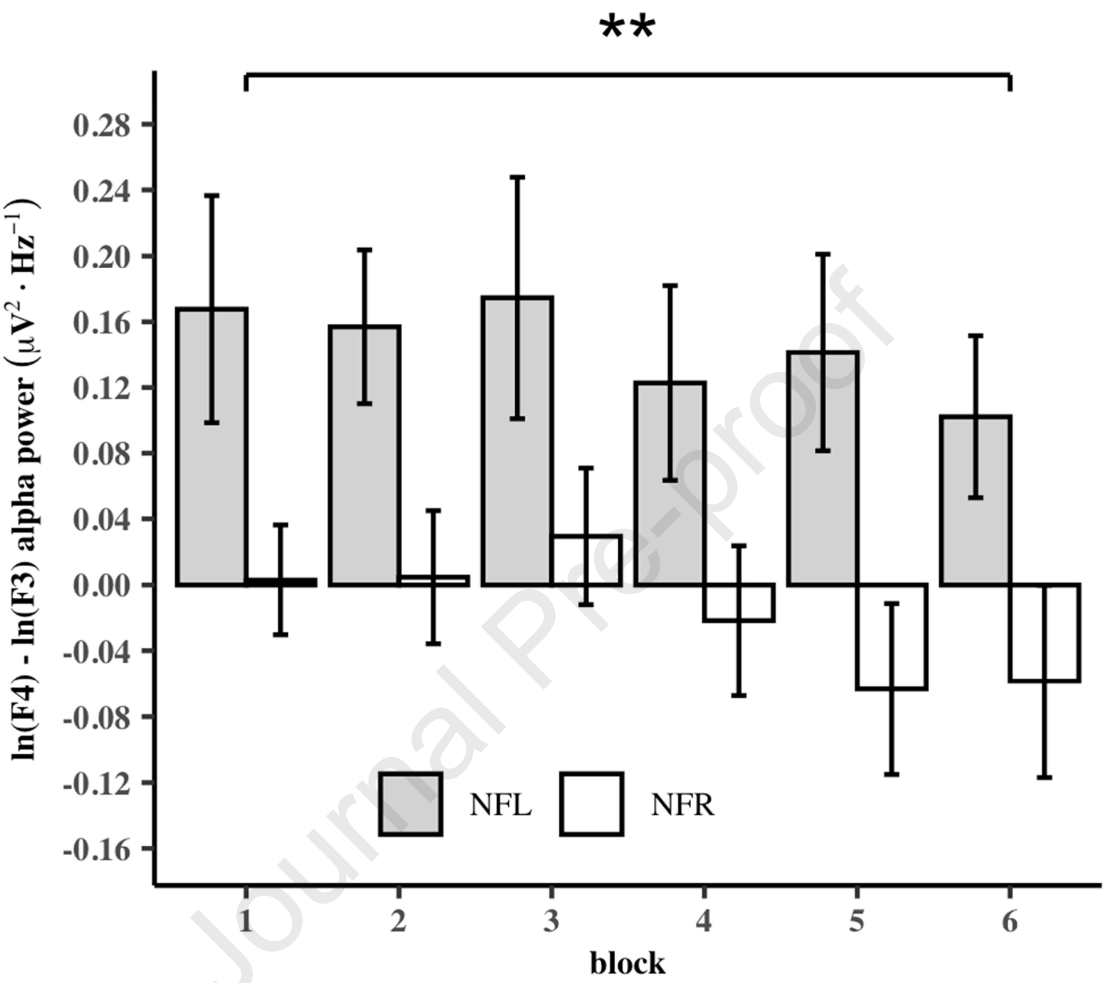


**Figure 4**

*Frontal Alpha Asymmetry, Experiment 1B.*

*Note.* Average value of 2-min six neurofeedback blocks for each condition, increase relative left, NFL, increase relative right, NFR, frontal cortical activity, means and SE.

*Significant main effect of condition (*p*=.038).

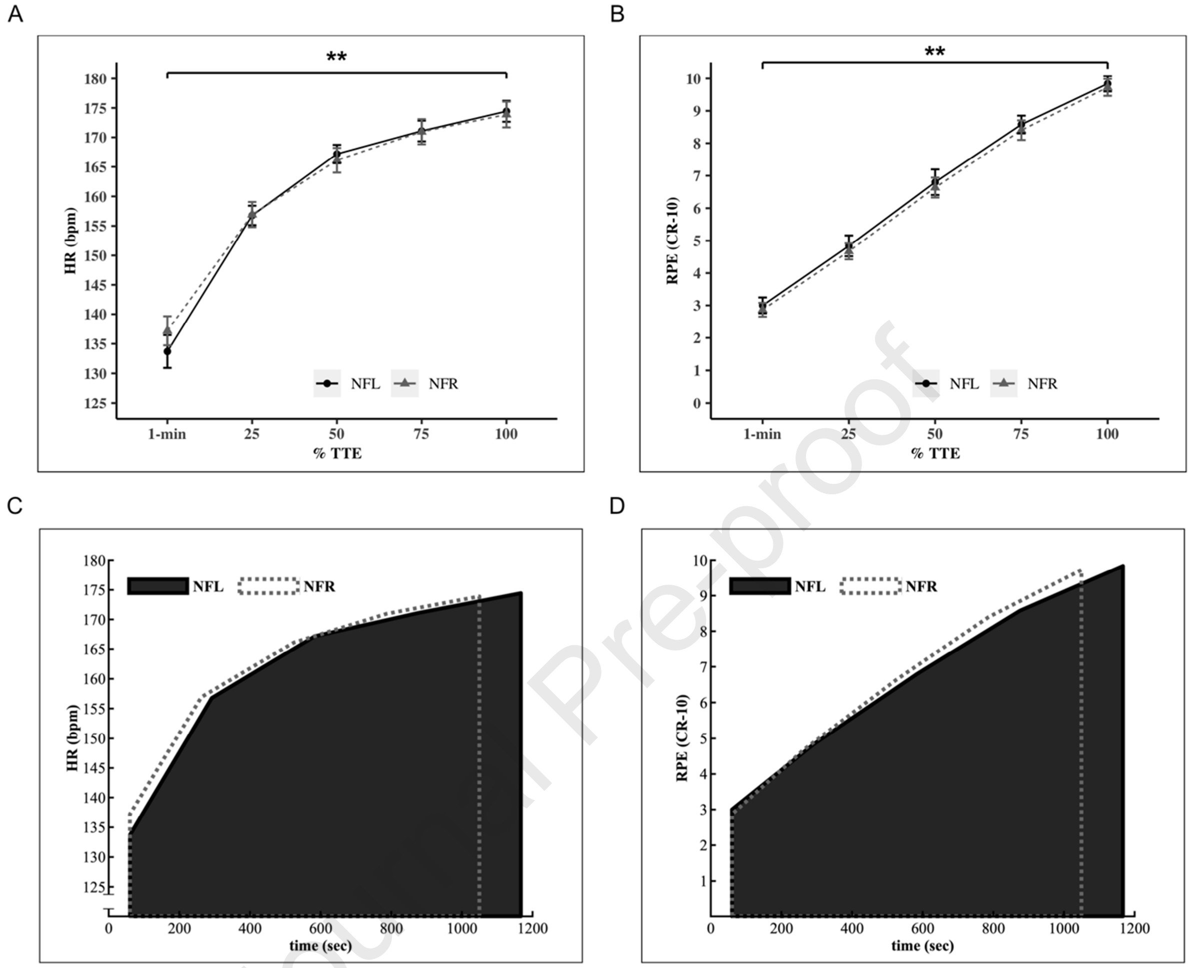
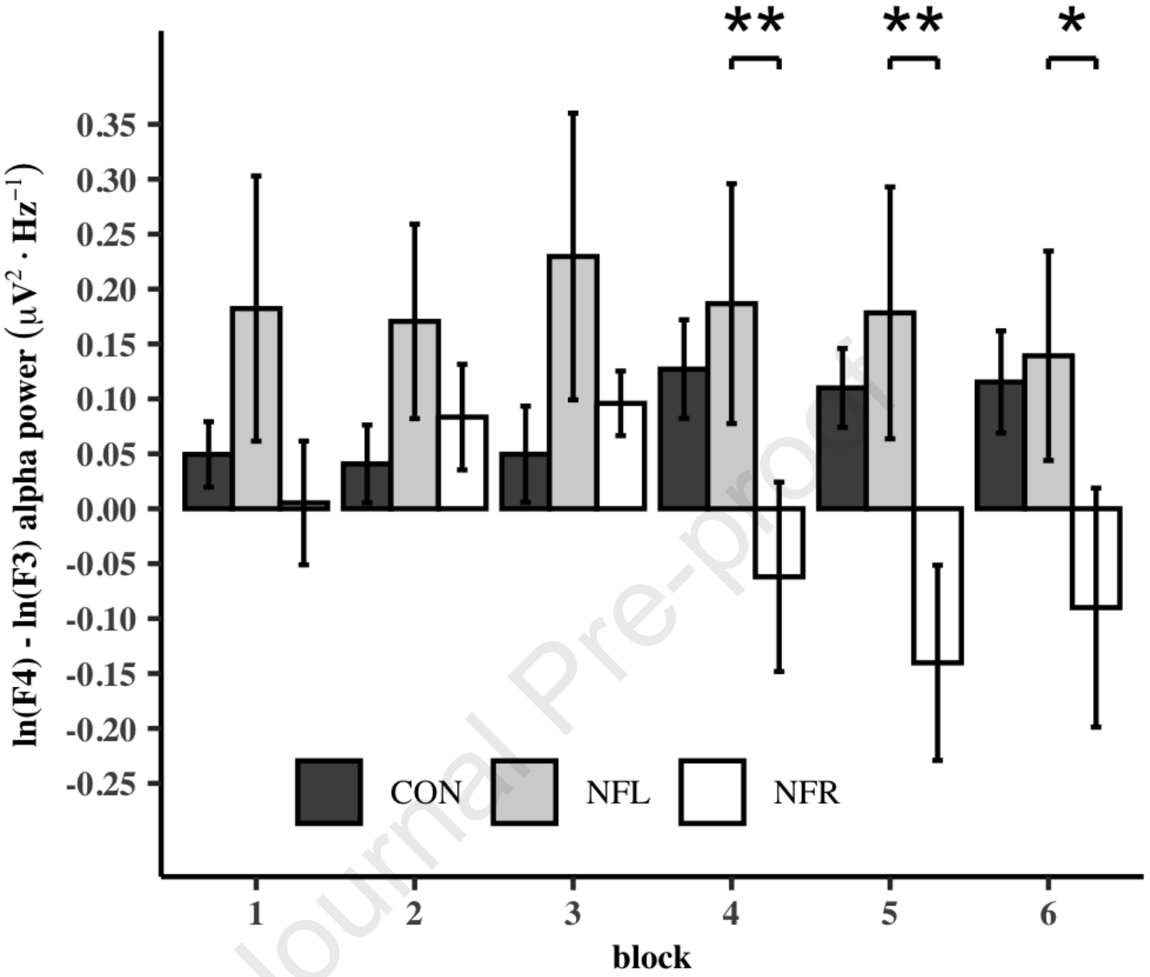


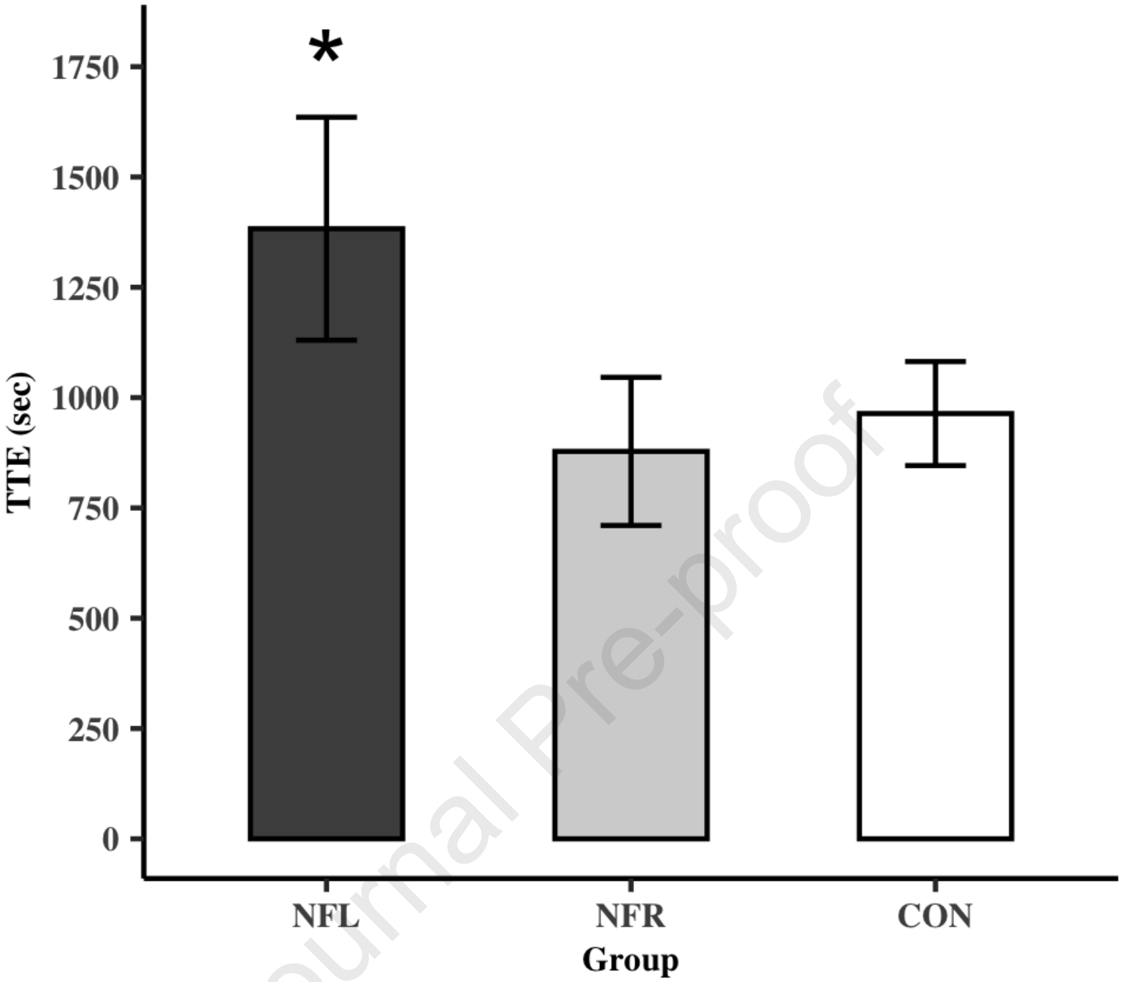
**Figure 5**

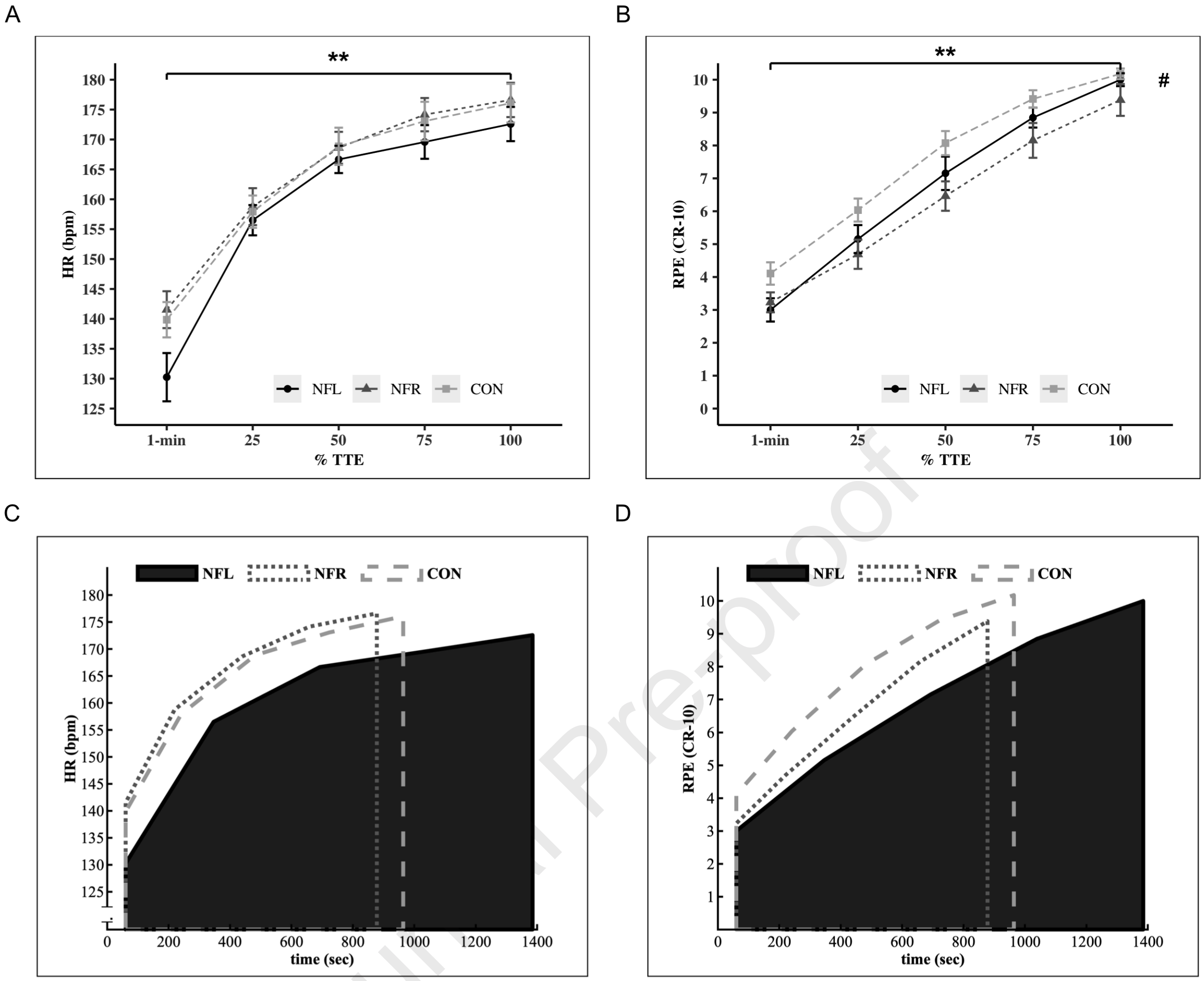
*Heart Rate (A) and Rating of Perceived Effort (B) during TTE and Area Under the Curve of HR (C) and RPE (D) during TTE, Experiment 1B.*

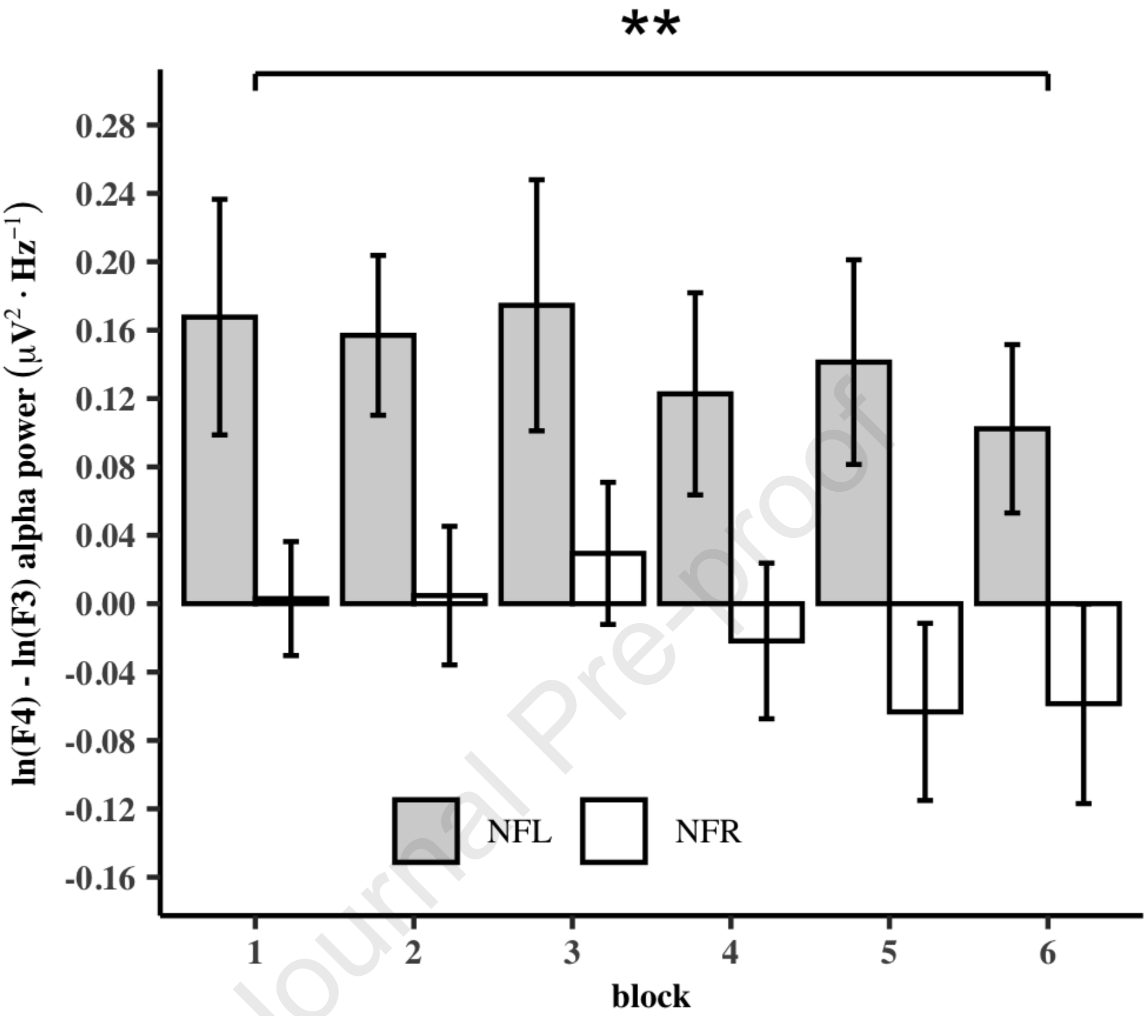
*Note*. Means and SE, at first minute and 25%, 50%, 75% and 100% of the TTE test for each condition.

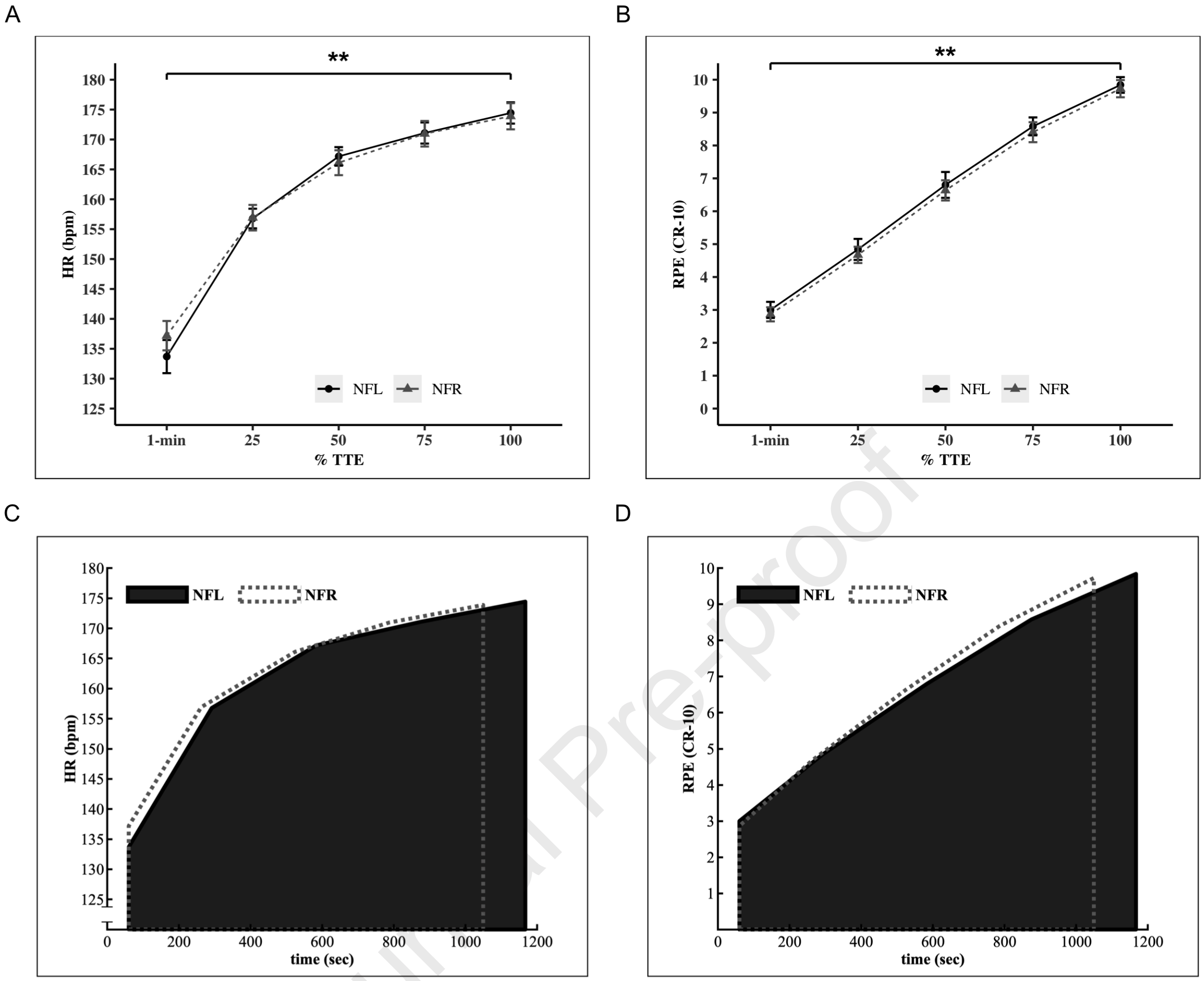
**Significant main effect of time ($p$<.001).


**
**
*
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
-0.25
ln(F4) - ln(F3) alpha power ($\mu V^2 \cdot Hz^{-1}$)
CON
NFL
NFR
1
2
3
4
5
6
block


*
1750
1500
1250
1000
750
500
250
0
TTE (sec)
NFL
NFR
CON
Group


A
**
HR (bpm)
180
175
170
165
160
155
150
145
140
135
130
125
1-min
25
50
75
100
% TTE
NFL
NFR
CON
B
**
#
RPE (CR-10)
10
9
8
7
6
5
4
3
2
1
0
1-min
25
50
75
100
% TTE
NFL
NFR
CON
C
NFL
NFR
CON
HR (bpm)
180
175
170
165
160
155
150
145
140
135
130
125
0
200
400
600
800
1000
1200
1400
time (sec)
D
NFL
NFR
CON
RPE (CR-10)
10
9
8
7
6
5
4
3
2
1
0
200
400
600
800
1000
1200
1400
time (sec)


**
ln(F4) - ln(F3) alpha power (μV² · Hz⁻¹)
0.28
0.24
0.20
0.16
0.12
0.08
0.04
0.00
-0.04
-0.08
-0.12
-0.16
NFL
NFR
1
2
3
4
5
6
block


A
**
HR (bpm)
180
175
170
165
160
155
150
145
140
135
130
125
1-min
25
50
75
100
% TTE
NFL
NFR
B
**
RPE (CR-10)
10
9
8
7
6
5
4
3
2
1
0
1-min
25
50
75
100
% TTE
NFL
NFR
C
NFL
NFR
HR (bpm)
180
175
170
165
160
155
150
145
140
135
130
125
0
200
400
600
800
1000
1200
time (sec)
D
NFL
NFR
RPE (CR-10)
10
9
8
7
6
5
4
3
2
1
0
200
400
600
800
1000
1200
time (sec)

# EEG Neurofeedback Improves Cycling Time to Exhaustion

## Highlights

- We investigated EEG neurofeedback in the context of endurance performance.
- A single session of EEG-neurofeedback modified frontal asymmetric activation.
- EEG-neurofeedback to increase left cortical activity improved cycling performance.

# EEG Neurofeedback Improves Cycling Time to Exhaustion

**Conflict of Interest**

The authors declare no conflicts of interest. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sector.

# EEG Neurofeedback Improves Cycling Time to Exhaustion

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**Author Note**

The dataset can be made available upon reasonable request to the corresponding author

**Authorship contribution**

**Francesca Mottola**: Conceptualization, Methodology, Software, Investigation, Formal Analysis, Data Curation, Writing- original draft, Writing - review and editing, Visualization. **Andrew Cooke**: Conceptualization, Methodology, Software, Writing - original draft, Writing – review and editing. **James Hardy**: Conceptualization, Methodology, Writing - review and editing. **Anthony Blanchfield**: Conceptualization, Methodology, Writing - review and editing.

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