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Original research

Brain Endurance Training improves endurance and cognitive performance in road cyclists

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A R T I C L E I N F O

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A B S T R A C T

Objectives: To evaluate the effects of brain endurance training (BET) on endurance and cognitive performance in road cyclists.
Design: Two independent randomized controlled pretest–posttest training studies.
Methods: In both studies cyclists trained five times/week for six weeks and completed either cognitive response inhibition tasks (Post-BET group) or listened to neutral sounds (control group) after each training session. In Study-1, 26 cyclists performed a time to exhaustion (TTE) test at 80 % peak power output (PPO), followed by a 30-min Stroop task, and a TTE test at 65 % PPO. In Study-2, 24 cyclists performed a 5-min time trial, followed by a 30-min Stroop task, 60-min submaximal incremental test, and a 20-min . Heart rate, lactate, rating of perceived exertion (RPE), Stroop reaction time and accuracy were also measured.
Results: During Study 1, Post-BET improved TTE at 80 % ($p = 0.032$) and 65 % PPO ($p = 0.011$) significantly more than control with lower RPE (all $p < 0.043$). In Study 2, 5-min TT performance did not differ between groups. During the 60-min submaximal incremental test, RPE was lower in the Post-BET group compared to the control group ($p = 0.034$) and 20-min TT performance improved significantly more in the Post-BET group than in the control group (all $p < 0.031$). No group differences were found in physiological measures. In both studies, Stroop reaction times improved significantly more in the Post-BET group than in the control group (all $p < 0.033$).
Conclusions: These findings suggest that Post-BET may be used to improve the performance of road cyclists.

Practical implications

- Our findings suggest that adding a cognitive task at the end of a training session (Post-BET) is feasible in road cyclists and may enhance their performance.
- Because its performance-enhancing effects are more evident in a fatigued state, Post-BET may increase the resistance to physical and mental fatigue in road cyclists.
- Post-BET increases the cognitive load of training without overloading the cardiorespiratory and musculoskeletal systems. This effect may be useful in the training of injured athletes but it should be taken into account in the assessment of the overall training load to prevent non-functional overreaching and overtraining.

1. Introduction

Traditionally training for endurance athletes, including road cyclists, has focused on improving aerobic capacity, lactate threshold, exercise economy and other biomechanical and physiological factors thought to determine endurance performance.[1] However, there is mounting experimental evidence that physiological factors, such as muscle fatigue, are not the sole limiting factors in endurance exercise,[2,3] and that perceptual, motivational and cognitive factors also play roles.[4] It has repeatedly been demonstrated that mental fatigue, defined as a psychobiological state caused by prolonged demanding cognitive activities,[5] impairs endurance exercise performance.[6,7] Studies confirming the detrimental effect of mental fatigue on endurance performance also noted its effect on increasing perceived effort.[6,8] These findings are in line with the proposal that perception of effort acts as a central mechanism limiting endurance exercise performance.[3,9]

Given this experimental evidence, the next step is to develop and evaluate specific training methods that target these perceptual, motivational and cognitive factors. Marcora and colleagues proposed a new

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training method, called brain endurance training (BET), which uses systematic repetitions of fatigue-inducing cognitive tasks alongside physical training to inoculate against mental fatigue and thereby improve endurance exercise performance.[10] A seminal study showed that the group performing a cognitive task during endurance training, namely 60-min of moderate intensity cycling exercise performed three times per week, improved endurance on a cycling time to exhaustion (TTE) test significantly more than the control group who did not perform any mentally-fatiguing task during training.[10] This BET protocol, called Concurrent-BET, incorporated progressive overloading of both physical and mental demands over the course of the 12 weeks of training. As peak oxygen uptake ($\dot{V}O_{2peak}$) improved similarly in both groups, the improved endurance performance with Concurrent-BET was explained by brain adaptations to the cognitive overload leading to reduced ratings of perceived exertion (RPE) during the TTE test. The benefit of Concurrent-BET for endurance performance has since been replicated by another research group using a rhythmic handgrip exercise task, which also noted more efficient prefrontal cortex oxygenation during exercise.[11] Collectively, these studies argue for a beneficial effect of BET on endurance performance when the mentally-fatiguing cognitive task is performed during exercise. However, adding a concurrent cognitive task may not always be practical when training outdoors. Therefore, other combinations of cognitive and physical training should be investigated. One possibility is to add the demanding cognitive task immediately after the training session when the athletes are fatigued by the physical training, which we refer to as Post-BET. A recent study[12] demonstrated that four weeks of Post-BET during pre-season training enhances the physical, cognitive and multitasking performance of professional football players. Accordingly, here we evaluated the efficacy of a Post-BET protocol that we developed to accommodate the needs of cyclists who mostly trained on the road.

The current research protocol comprised two independent studies and aimed to test the effects of Post-BET on endurance performance as well as reaction time and accuracy during a cognitive task. Given the potential of BET in reducing fatigability, we decided to test participants in a fresh and fatigued state by having them perform two maximal cycling tests in the same testing session.

The two studies assessed endurance performance in two different ways. Study 1 assessed endurance performance using a TTE test. The constant power output of a TTE test can help mitigate the potentially confounding physiological and psychological effects that may arise from changes in self-regulated power output during a TT test. This allows a more precise determination of the physiological and/or psychological mechanisms through which the intervention might affect endurance exercise performance.[13] Study 2 assessed endurance performance using TT tests. These tests simulate competitive time trialing stages and allowed us to assess the effect of Post-BET on the self-regulation of power output (pacing) by exploring differences in pacing patterns. Given evidence that competitive level moderates the effect of mental fatigue on endurance exercise performance, with less impairment among highly trained and professional athletes,[14] we explored the effect of Post-BET on road cyclists of different levels of training and competitive experience. Moreover, we evaluated two different Post-BET protocols, one in which the cognitive load was progressively increased by increasing the time spent on a cognitive task with fixed difficulty (Study 1) and one in which the cognitive load was progressively increased by increasing the difficulty of a cognitive task with fixed duration (Study 2).

For both studies, we hypothesized that Post-BET would enhance endurance performance and cognitive performance more than traditional physical training (control), especially in fatigued states. We also hypothesized that any enhancement in endurance performance induced by BET (far transfer) would be accompanied by a reduced perception of effort during exercise. Finally, we hypothesized that BET would transfer and improve cognitive performance in a response inhibition task not used during training (near transfer).

2. Study 1: Methods

A convenient sample of 28 male road cyclists [mean ± SD, age 29 ± 5 years, height 177 ± 6 cm, weight 70 ± 9 kg, peak power output (PPO) 348 ± 55 W, $\dot{V}O_{2peak}$ 64 ± 4 $ml \cdot kg^{-1} \cdot min^{-1}$, >3 training sessions/week, >250 km/week, >3 year cycling experience] was recruited. Cyclists with injuries or bespoke training plans were excluded from the study. The cyclists were classified as performance level 2/3 (trained/highly trained).[15] They belonged to two local teams and trained together. After pre-test, participants were randomly allocated with a 1:1 ratio to the BET or control group. Two participants dropped out during the training due to injuries so the statistical analysis was carried out on 26 participants (BET n = 13, control n = 13). Power calculations using G-Power indicate that with a sample size of 26, our study was powered at 80 % to detect significant ($p < 0.05$) between-within interaction effects ($f = 0.29$, $\eta p2 = 0.08$) corresponding to a small-to-medium effect size by analysis of variance. All cyclists received written instructions describing the study protocol but were naïve to its aims and hypotheses. The study was approved by the Ethics Committee for the Southern Denmark Region in accordance with the Declaration of Helsinki.

Participants completed four laboratory testing sessions (pretest: 1 = fitness, 2 = performance; posttest: 3 = fitness, 4 = performance) at similar ambient temperature, humidity, barometric pressure, and time of day (Fig. 1). The day before and during each testing session, participants adopted a standardized routine regarding sleep, recovery, meals, hydration, supplementation and medication. During the fitness testing sessions, participants completed an incremental cycling test (2-min at 50 W, 35 W increment every 2-min) until volitional exhaustion on an electromagnetically braked cycle ergometer (High Performance Ergometer, Schoberer Rad MeBtechnik, Germany) to measure $\dot{V}O_{2peak}$ and PPO. After, they rested for 30-min, participants were familiarized with the TTE tests, received instruction about the psychological measures, such as RPE scale anchoring,[16] and practiced the cognitive task.

In the performance testing sessions, participants rated motivation for the upcoming TTE tests. The first TTE test was a high-intensity constant-power test comprising a 5-min warm-up at 40 % PPO followed by a rectangular workload at 80 % PPO until volitional exhaustion, with a self-selected cadence of 60–100 revolutions/min. TTE was measured from the start of the rectangular workload until cadence was less than 60 revolutions/min for more than 5 s despite standardized verbal encouragement. Cadence was measured at end of warm-up, each minute during the TTE test, and at completion of it. Heart rate, lactate and RPE were obtained during rest, after warm-up, during test, and upon completion. After a 10-min cool-down on the ergometer, they rested for 20-min, were given standardized food and water rations, and then completed a 30-min incongruent Stroop color–word task on a desktop computer.[14] Their reaction time (ms) and accuracy (% correct responses) were computed, and they rated task workload using the NASA TLX.[17] After a 30-min rest (90-min after first TTE), they completed a second TTE test comprising a 5-min warm-up at 35 % PPO followed by a rectangular workload at 65 % PPO until volitional exhaustion. Measurements were obtained as per the previous TTE and are described in detail below.

All participants completed 5 training sessions per week (4 cycling, 1 strength and conditioning) for 6 weeks under supervision of a coach, physical trainer, and researcher. They were instructed to maintain the prescribed physical training regime without any extra session. Physical training was designed to maintain physical fitness during the off-season. Intensity, frequency, duration, and type of physical training were monitored. Weekly training load was measured by total minutes spent in five heart rate zones[18] and average NASA TLX scores.[17]

The BET group performed a demanding cognitive task after each daily physical training session. In the case of a double physical training session, the demanding cognitive task was performed only after the second session. The duration of the demanding cognitive task was

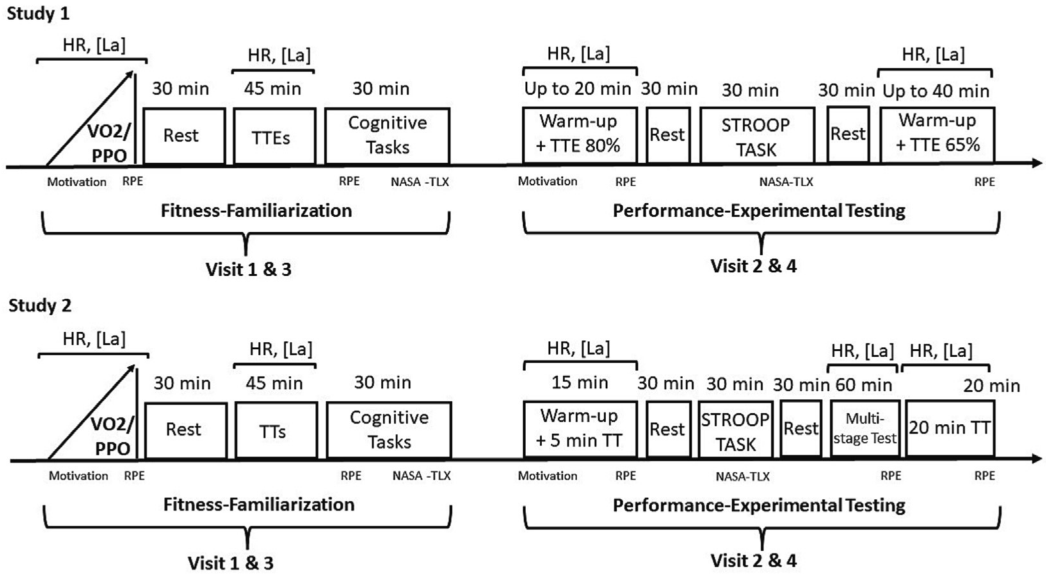

Fig. 1. Schematic of the experimental protocol.
Overall view of the experimental protocol. VO_2 indicates peak oxygen consumption, PPO indicates peak power output, TTE indicates time to exhaustion test, TT indicates time trial, HR indicates heart rate, [LA] indicates blood lactate, RPE indicates rating of perceived exertion, NASA TLX indicates National Aeronautic and Space Administration Task Load Index.

progressively increased from 30-min (weeks 1–2) to 45-min (weeks 3–4) to 60-min (weeks 5–6). This approach accounted for the possibility of neural adaptations to the cognitive training, thus ensuring that cognitive load was sustained throughout the training intervention. In each session, participants performed one of three cognitive tasks – flanker task, go/no-go task, AX-continuous performance test (CPT) – using the SOMA-NPT mobile app (SSwitch, Lucerne, Switzerland) on a tablet. These response inhibition tasks were chosen to elicit mental fatigue[9,19,20] (described in detail in the Supplementary materials) and were previously used in a similar training study using BET.[12] Participants were instructed to counterbalance cognitive tasks across the training sessions.

After each daily physical training session, the control group listened to neutral sounds for 30-min, 45-min, and 60-min per session during weeks 1–2, 3–4, and 5–6, respectively. They were told the specific sounds induced relaxation. However, the emotional valence of these sounds was neutral to avoid any positive or negative psychological effect.[21] This alternative placebo treatment was chosen as a control to reduce threats to internal validity, like resentful demoralization and compensatory rivalry, in the participants not allocated to Post-BET. It has been proven to be effective in previous BET training research.[12]

Motivation was measured by rating the statement “I am motivated to perform the test” on a 5-point scale, with anchors of 0 (not at all) and 4 (extremely). Subjective workload was measured using the mental demand, physical demand, frustration, and effort subscales of the NASA TLX[17] after each training session and Stroop test. Perceived effort was measured using the 15-point RPE scale[22] at the end of warm-up, each test minute, and exhaustion. Blood lactate concentration (mmol/l) was determined (Lactate Pro LT-1710, Arkray-Shiga, Japan) from a 5-μl sample of finger fresh blood at rest, after warm-up, and exhaustion. Cycling cadence and heart rate (H10, Polar Electro Oy, Finland) were measured at rest, end of warm-up, each test minute, and exhaustion.

Data are presented as mean ± one standard deviation (*SD*) unless otherwise stated. Assumptions of statistical tests for normal distribution and sphericity of data were checked. A series of mixed analyses of variance (ANOVAs) were performed, with group (BET, control) as the between-participant factor and test (pretest, posttest) as a within-participant factor. In some analyses, an additional within-participant factor was included, specifically group iso-time in seconds (0, 150, 300, 450, 600 for the TTE 80 %, and 0, 400, 800, 1200, 1600 for the TTE 65 %; where 0 is the final full minute completed of warm-up and 600 and 1600 respectively are the minutes of the shortest TTE test completed[23]) or training week (1, 2, 3, 4, 5, 6). Analyses on $\dot{V}O_{2peak}$ and PPO during the incremental cycling test, and motivation, heart rate, blood lactate and cadence during the TTE tests are reported in the Supplementary materials. Significant triple interactions were followed-up by Group by Test ANOVAs at each time point, and Group by Test interactions were followed-up with relevant pairwise comparisons for simple main effects within each group. If no interactions were detected, main effects were reported. Significance was set at 0.05 (2-tailed) for all analyses. The effect sizes for the ANOVAs were calculated as partial eta squared (η^2p), with 0.02, 0.13, and 0.26 indicating small, medium, and large effects, respectively. Data analysis was conducted using the Statistical Package for Social Science (SPSS, version 27).

3. Study 1: Results

Group by Week ANOVAs on time spent at different heart rate zones and total distance covered demonstrate that the Post-BET and control groups experienced similar physical training volumes and intensities. The BET group completed 22.5 h of cognitive tasks and reported higher mental demand compared to the control group that listened to neutral sounds after the physical training sessions (Table 1).

Group by Test ANOVAs showed no significant effects of Post-BET on $\dot{V}O_{2peak}$, PPO and motivation related to the performance tests (see Supplementary materials).

Group by Test ANOVAs yielded interaction effects for TTE at 80 % PPO ($F_{(1, 24)} = 5.32$, $p = 0.032$, $\eta^2p = 0.30$) and 65 % PPO ($F_{(1, 24)} = 7.91$, $p = 0.011$, $\eta^2p = 0.48$). As depicted in Fig. 2A and 2B, follow-up tests revealed that TTE in the BET group increased from pre-test to post-test at 80 % PPO ($p = 0.023$) and 65 % PPO ($p = 0.011$) while the control group's TTEs did not change at either 80 % PPO ($p = 0.191$) or 65 % PPO ($p = 0.142$). Cadence during the TTE tests was not affected by BET (see Supplementary materials).

No significant Group by Test by iso-time interactions were found for RPE at 80 % PPO ($F_{(4, 88)} = 1.46$, $p = 0.224$, $\eta^2p = 0.10$) and 65 % PPO ($F_{(4, 88)} = 1.73$, $p = 0.156$, $\eta^2p = 0.14$). However, Group by Test interactions on RPE (Fig. 3A and 3B) were found while cycling at 80 % PPO ($F_{(1, 24)} = 4.71$, $p = 0.043$, $\eta^2p = 0.33$), and 65 % PPO ($F_{(1, 24)} = 6.35$, $p = 0.023$, $\eta^2p = 0.30$) as well as main effects of iso-time (i.e., RPE increased with iso-time) at 80 % PPO ($F_{(1, 24)} = 7.00$, $p = 0.022$, $\eta^2p = 0.25$) and 65 % PPO ($F_{(1, 24)} = 5.20$, $p = 0.032$, $\eta^2p =$

Table 1
Training workload as a function of Group and Week in Study 1.

	Week 1		Week 2		Week 3		Week 4		Week 5		Week 6		Group			Week			Group x Week		
	BET	Control	BET	Control	BET	Control	BET	Control	BET	Control	BET	Control	$F_{(1, 24)}$	p	η^2p	$F_{(5, 120)}$	P	η^2p	$F_{(5, 120)}$	p	η^2p
Time (min) in HR zones																					
Zone 1 (<68 %)	102 ± 21	105 ± 15	110 ± 22	114 ± 22	111 ± 23	113 ± 34	109 ± 19	105 ± 17	107 ± 17	105 ± 19	111 ± 21	114 ± 19	1.251	0.271	0.07	1.21	0.303	0.01	1.781	0.122	0.11
Zone 2 (69–83 %)	336 ± 25	338 ± 15	362 ± 24	367 ± 32	400 ± 26	390 ± 23	387 ± 21	386 ± 19	411 ± 31	422 ± 29	414 ± 28	408 ± 29	1.646	0.212	0.13	17.6	<0.001*	0.22	0.239	0.941	0.09
Zone 3 (84–94 %)	30 ± 16	31 ± 11	35 ± 11	37 ± 9	38 ± 9	36 ± 6	40 ± 3	41 ± 4	39 ± 6	40 ± 5	45 ± 5	44 ± 3	0.306	0.585	0.13	10.3	<0.001*	0.41	0.594	705	0.13
Zone 4 (85–105 %)	5 ± 2	6 ± 3	6 ± 4	5 ± 2	10 ± 3	11 ± 2	9 ± 3	11 ± 4	13 ± 3	12 ± 4	15 ± 2	14 ± 4	0.821	0.373	0.27	3.22	0.009*	0.19	0.971	0.438	0.12
Zone 5 (>106 %)	0	0	0	0	0	0	0	0	0	0	0	0									
Zone 6 (anaerobic)	2 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1	1 ± 1	1.132	0.292	0.17	1.22	0.304	0.07	0.533	0.751	0.14
Total (min)	475 ± 27	482 ± 23	515 ± 28	525 ± 31	561 ± 13	552 ± 22	551 ± 16	545 ± 22	572 ± 23	581 ± 33	587 ± 27	582 ± 24	1.378	0.258	0.14	12.2	<0.001*	0.27	0.819	0.538	0.26
Total distance (km)	213 ± 21	220 ± 16	231 ± 22	234 ± 28	261 ± 31	255 ± 34	273 ± 28	264 ± 31	279 ± 29	281 ± 32	290 ± 37	285 ± 32	1.491	0.237	0.15	15.7	<0.001*	0.25	1.041	0.397	0.06
NASA TLX																					
Mental demand	74 ± 4	49 ± 5	70 ± 5	55 ± 2	80 ± 4	51 ± 5	76 ± 3	55 ± 4	92 ± 4	57 ± 5	89 ± 3	60 ± 5	25.15	<0.001*	0.16	2.71	0.024*	0.22	1.767	0.125	0.09
Physical demand	51 ± 3	53 ± 4	55 ± 4	56 ± 5	56 ± 4	55 ± 4	58 ± 7	60 ± 3	65 ± 6	64 ± 4	67 ± 5	68 ± 4	2.180	0.151	0.13	2.423	0.039	0.18	1.263	0.284	0.10
Frustration	41 ± 6	42 ± 11	46 ± 9	44 ± 3	47 ± 8	44 ± 7	50 ± 6	46 ± 8	52 ± 8	45 ± 9	53 ± 7	46 ± 9	1.932	0.172	0.08	1.020	0.401	0.07	1.533	0.185	0.03
Effort	72 ± 6	68 ± 4	65 ± 7	67 ± 7	72 ± 3	71 ± 5	64 ± 6	66 ± 6	75 ± 5	74 ± 5	72 ± 6	75 ± 5	2.633	0.118	0.09	2.811	0.021*	0.14	1.999	0.084	0.05

Note: Values are *M* ± *SD*.
* $p < 0.05$.

0.16). Follow-up tests revealed that RPE fell from pre-test to post-test in the BET group while cycling at 80 % PPO ($p = 0.041$) and 65 % PPO ($p = 0.022$), whereas RPE did not change in the control group at either 80 % PPO ($p = 0.211$) or 65 % PPO ($p = 0.137$). Group by Test ANOVAs yielded no significant effects on RPE at exhaustion at 80 % and 65 % PPO (see Supplementary materials).

Group by Test ANOVAs on performance during the Stroop task (Fig. 4A) yielded a significant interaction effect ($F_{(1, 24)} = 8.47$, $p = 0.011$, $\eta^2p = 0.21$) for reaction time. Follow-up tests revealed that reaction times were faster at post-test than pre-test in BET ($p < 0.001$) and control ($p = 0.035$) groups, with BET improving significantly more than control. Performance accuracy, which was universally high (grand mean: 95 ± 2 % correct responses) did not vary by group ($F_{(1, 24)} = 0.77$, $p = 0.391$, $\eta^2p = 0.07$), test ($F_{(1, 24)} = 1.11$, $p = 0.282$, $\eta^2p = 0.09$), and group by test ($F_{(1, 24)} = 0.25$, $p = 0.623$, $\eta^2p = 0.02$).

ANOVAs on the NASA TLX subscales revealed group by test interactions for mental demand ($F_{(1, 24)} = 12.68$, $p < 0.001$, $\eta^2p = 0.01$), effort ($F_{(1, 24)} = 5.41$, $p = 0.033$, $\eta^2p = 0.13$), and frustration ($F_{(1, 24)} = 5.00$, $p = 0.041$, $\eta^2p = 0.19$). Follow-up tests confirmed that compared to pretest, the BET group found the Stroop task at post-test to be less mentally demanding ($p = 0.022$; Pre: 46 ± 5 < Post: 69 ± 6), less effortful ($p = 0.034$; Pre: 49 ± 5 < Post: 72 ± 4), and less frustrating ($p = 0.013$; Pre 35 ± 7 < Post 60 ± 4). However, no pretest versus posttest significant differences were found for the control group in mental demand ($p = 0.313$; Pre 71 ± 6 = Post 67 ± 5), effort ($p = 0.294$; Pre 68 ± 6 = Post 71 ± 5), and frustration ($p = 0.227$; Pre 59 ± 5 = Post 62 ± 5).

Group by Test ANOVAs found no significant effect for HR and blood lactate in both TTE tests (see Supplementary materials).

4. Study 1: Discussion

We investigated the effects of a 6-week BET protocol on endurance performance and cognitive performance in trained/highly trained road cyclists. Specifically, we added 30–60 min of demanding cognitive tasks after the physical training sessions (Post-BET). Results confirmed our hypotheses and demonstrated that Post-BET improved performance compared to control by prolonging endurance during the TTE tests at 80 % and 65 % and decreasing reaction time during the Stroop task. Moreover, these superior performance improvements in the Post-BET group were associated with reduced perceived mental demand during the Stroop task and reduced perceived effort during the TTE tests. Because Post-BET did not affect $\dot{V}O_{2peak}$ and the physiological responses to the TTE tests, our findings provide further evidence that BET-related enhancements in endurance performance are more likely mediated by psychological rather than cardiovascular and metabolic mechanisms.[10–12]

5. Study 2: Methods

A convenient sample of 25 male road cyclists [mean ± SD, age 25 ± 4 years, height 179 ± 5 cm, weight 69 ± 7 kg, PPO 401 ± 44 W, $\dot{V}O_{2peak}$ 70 ± 5 $ml \cdot kg^{-1} \cdot min^{-1}$, >4 training sessions/week, >400 km/week, >5 year cycling experience] was recruited. The cyclists were classified as performance level 3/4 (highly trained/elite).[15] They belonged to two teams that trained together. After pretest, thirteen participants were randomly allocated to the BET group and twelve to the control group. One participant in the control group dropped out because of injuries and, therefore, statistical analysis was carried out on 24 participants (BET n = 13, control n = 11). Power calculations using G-Power indicated that with a sample size of 24, our study was powered at 80 % to detect significant ($p < 0.05$) between-within interaction effects ($f = 0.30$, $\eta p2 = 0.08$) corresponding to a small-to-medium effect size by analysis of variance. All cyclists received written instructions describing the study protocol but were naïve to its aims and hypotheses.

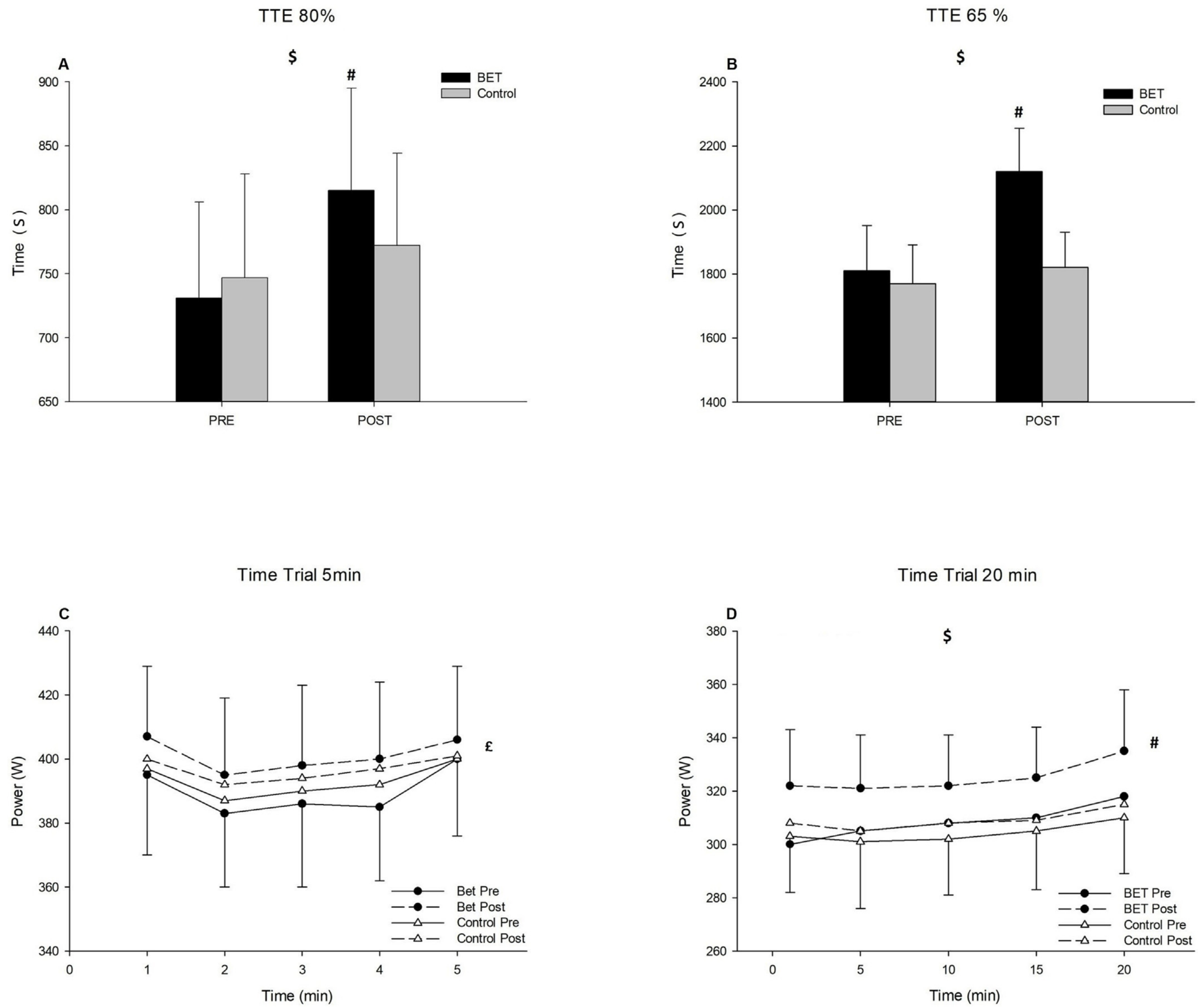

Fig. 2. Endurance performance.
Mean (SD) endurance performance at pre-test and post-test for BET and control groups for (A) TTE at 80 % PPO where 0 represents the end of the warm-up, (B) TTE at 65 % PPO where 0 represents the end of the warm-up, (C) power profile during 5-min TT, and (D) power profile during 20-min TT. $ = significant group difference. £ = Main effect of test. # = Simple main effect.

The study was approved by the Ethics Committee for the Southern Denmark Region in accordance with the Declaration of Helsinki.

The protocol of Study 2 was the same as Study 1, with the exception of the performance testing sessions and the demanding cognitive task progression within the BET group (Fig. 1). Each performance testing session consisted of a 10-min standardized warm-up followed by a 5-min cycling TT. A timer was placed in front of the ergometer and remained visible throughout. Participants began in a standard gear but were free to change gear. They were instructed to produce as much power as possible, although they were blind to power or speed data during the TT. This was followed by a 10-min cycling cool-down, 20-min rest, 30-min Stroop task on a desktop computer, and 30-min rest. Afterwards, participants completed a 60-min incremental multistage test that was structured in stages with fixed power output to simulate a competitive cycling race: 20-min at 40 % PPO, 15-min at 50 % PPO, 15-min at 60 % PPO, and 10-min at 70 % PPO.[24] At completion of the 60-min incremental multistage test, they performed a second, 20-min cycling TT. Power, distance, cadence, motivation, heart rate, blood lactate and RPE were measured during the tests using the ergometer and measurements already described for Study 1.

With regard to training, physical training prescription and monitoring were the same as in Study 1. As in Study 1, the BET group performed a demanding cognitive task after each daily physical training session using the SOMA-NPT mobile app (SSwitch, Lucerne, Switzerland) on a tablet. However, the duration of the demanding cognitive task was fixed at 30-min throughout training. A sustained cognitive load was ensured by progressively increasing task difficulty every two weeks by adding distracting cues,[10] shortening inter-stimulus intervals,[10] and/or introducing additional demands, such as stop-and-go.[25] This protocol was previously used in a similar training study using BET.[12] Participants performed one of three cognitive tasks per session as per Study 1. Cognitive tasks were the same as per Study 1. The control group listened to the same neutral sounds used in Study 1 for 30-min after each physical training session.

Data are presented as mean ± one *SD* unless otherwise stated. Assumptions of statistical tests for normal distribution and sphericity of data were checked. A series of mixed analyses of variance (ANOVAs) were performed, with group (BET, control) as the between-participant factor and test (pretest, posttest) as a within-participant factor. In some analyses, an additional within-participant factor was included,

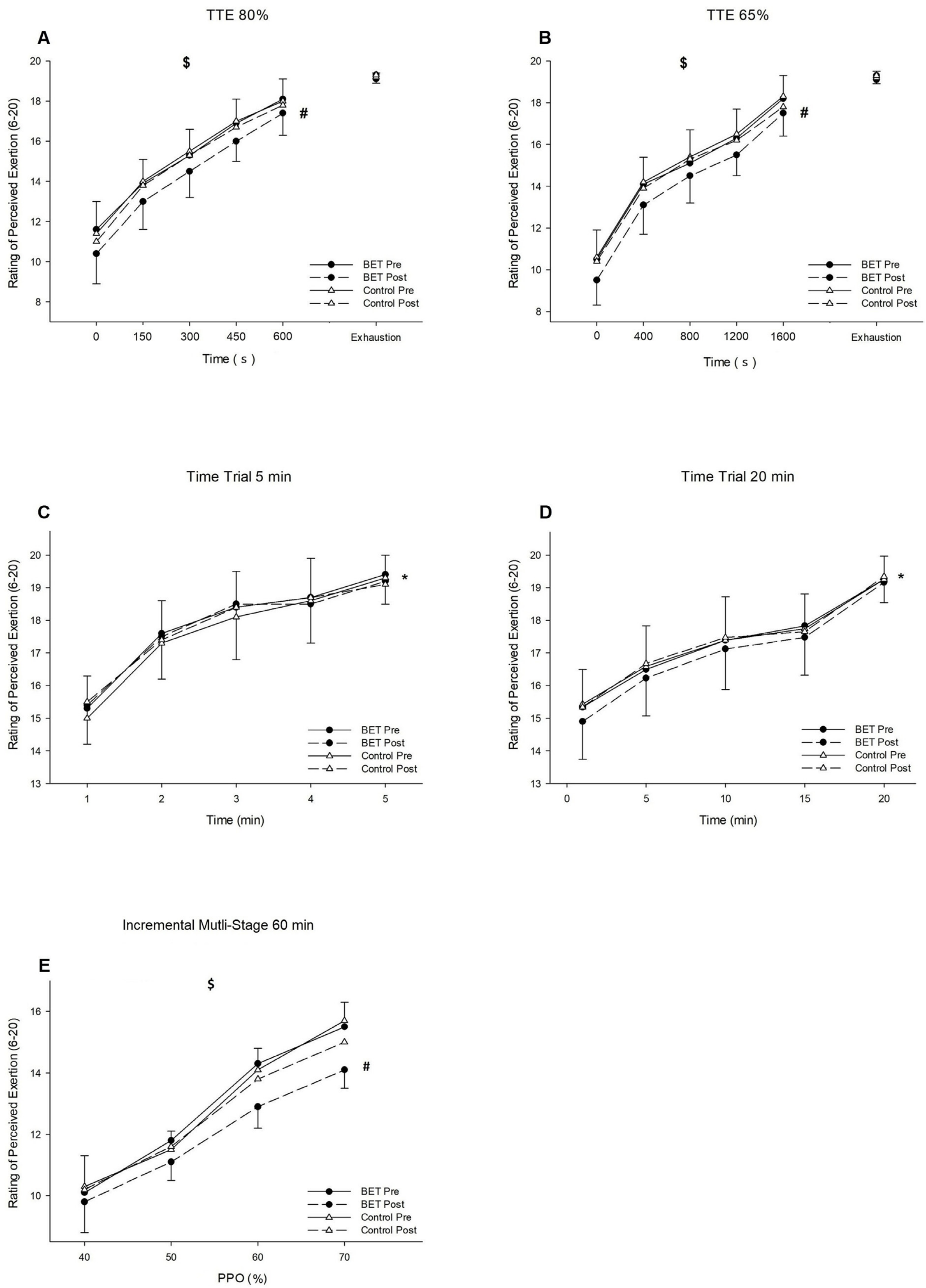

Fig. 3. Perceptual measures.
Mean (SD) ratings of perceived exertion during exercise at pre-test and post-test for BET and control groups during (A) TTE at 80 % PPO where 0 represents the end of the warm-up, (B) TTE at 65 % PPO, where 0 represents the end of the warm-up, (C) 5-min TT, (D) 20-min TT, and (E) incremental multistage 60 min. $ = Significant group difference. * = Main effect of time. # = Simple main effect.

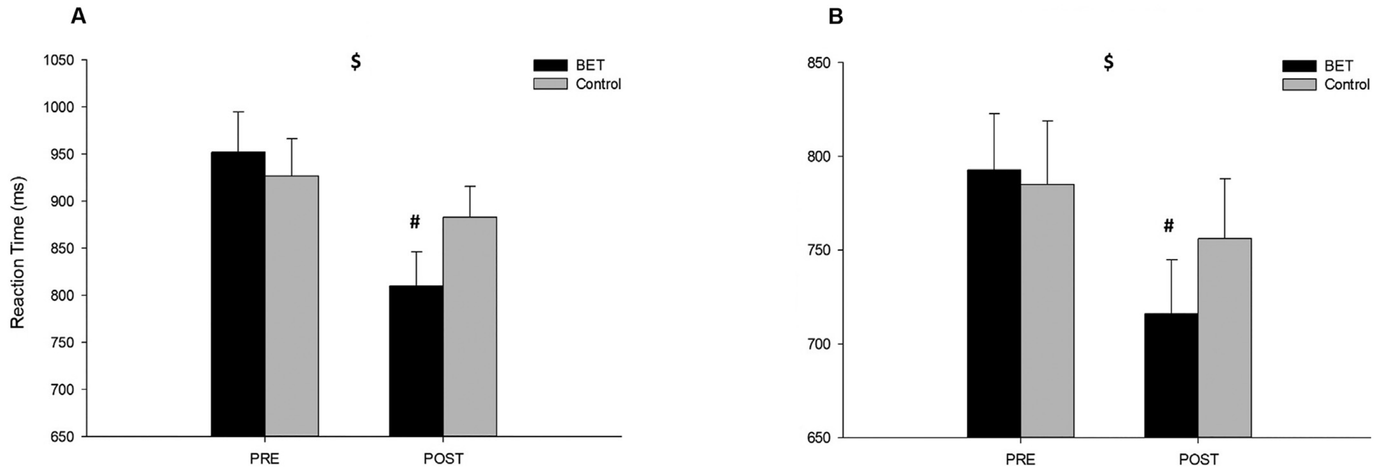

Fig. 4. Cognitive performance.
Mean (SD) reaction times at pre-test and post-test for BET and control groups for Stroop test between (A) TTE tests, and (B) TT tests. $ = Significant group difference. # = Simple main effect.

specifically time (min 1, 2, 3, 4, 5 of the 5-min TT; min 1, 5, 10, 15, 20 of the 20-min TT; 40 %, 50 %, 60 %, 70 % of PPO in the incremental multistage test) or training week (1, 2, 3 ,4, 5, 6). Analyses on $\dot{V}O_{2peak}$ and PPO during the incremental cycling test, and motivation, heart rate, blood lactate and cadence during the performance tests are reported in the Supplementary materials. Significance, effect sizes, planned comparisons, statistical plan and software were identical to Study 1.

6. Study 2: Results

Group by Week ANOVAs on time spent in the different heart rate zones and total distance covered demonstrate that the Post-BET and control groups experienced similar physical training volumes and intensities. The BET group completed 15 h of cognitive tasks and reported higher mental demand compared to the control group that listened to neutral sounds after the physical training sessions (Table 2).

ANOVAs confirmed no significant differences between groups and tests for level of fitness and motivation prior to testing sessions (see Supplementary materials).

The Group by Test ANOVA on overall average power during the 5-min TT yielded an interaction effect characterized by a small-to-medium effect size and a trend toward statistical significance ($F_{(1, 22)} = 4.00$, $p = 0.056$, $\eta^2p = 0.07$). A main effect of test ($F_{(1, 22)} = 4.81$, $p = 0.04$, $\eta^2p = 0.11$) showed PPO increased from pre to post in both the BET group (Pre: 391 ± 19 < Post: 401 ± 21) and control group (Pre: 389 ± 22 < Post: 396 ± 23). No main effect of group was detected ($F_{(1, 22)} = 3.34$, $p = 0.083$, $\eta^2p = 0.06$). Importantly, the Group by Test ANOVA on power during the 20-min TT yielded an interaction effect with a large effect size ($F_{(1, 22)} = 7.51$, $p = 0.021$, $\eta^2p = 0.29$). Follow-up tests revealed that the BET group increased power ($p = 0.041$) from pretest (308 ± 21) to posttest (325 ± 18), whereas no difference ($p = 0.124$) was noted for the control group from pre-test (304 ± 17) to post-test (309 ± 16).

No Group by Test by Time three-way interaction was detected for power profiling during the 5-min TT ($F_{(4, 88)} = 1.21$, $p = 0.311$, $\eta^2p = 0.13$). There was a group by test trend toward interaction with a small-to-medium effect size ($F_{(1, 22)} = 3.89$, $p = 0.059$, $\eta^2p = 0.07$). No main effect of group was reported ($F_{(1, 22)} = 3.22$, $p = 0.085$, $\eta^2p = 0.05$). Finally, the main effect of test ($F_{(1, 22)} = 5.43$, $p = 0.035$, $\eta^2p = 0.15$) showed that PPO increased in both groups from pre to post (Fig. 2C). No Group by Test by Time three-way interaction was detected for power profiling during the 20-min TT ($F_{(4, 88)} = 1.88$, $p = 0.12$, $\eta^2p = 0.09$). However, there was a group by test interaction for power profiling ($F_{(1, 22)} = 5.29$, $p = 0.031$, $\eta^2p = 0.29$) (Fig. 2D). Follow-up tests revealed that there was no significant pre to posttest ($p = 0.341$) difference in the control group. However, in the BET group, power was higher ($p = 0.021$) at posttest compared to pretest.

Similarly, the analyses revealed a group by test trend toward interaction for distance (m) covered during the 5-min TT ($F_{(1, 22)} = 4.31$, $p = 0.051$, $\eta^2p = 0.08$). No main effect of group was detected ($F_{(1, 22)} = 2.81$, $p = 0.101$, $\eta^2p = 0.05$), although a main effect of test ($F_{(1, 22)} = 4.51$, $p = 0.044$, $\eta^2p = 0.10$) showed distance covered increased in both groups from pre to post. The BET group increased from pre (3710 ± 41) to post (3770 ± 35) test, while the control group increased from pre (3725 ± 29) to post (3749 ± 33) test. There was an interaction, instead, for distance covered during the 20-min TT ($F_{(1, 22)} = 6.11$, $p = 0.021$, $\eta^2p = 0.19$). Follow-up tests revealed that the BET group increased ($p = 0.032$) from pre-test to post-test (13,810 ± 91 < 14,360 ± 79), while no significant difference ($p = 0.191$) was reported for the control group from pre-test to post-test (13,725 ± 79–13,860 ± 83). No significant differences in the groups and tests were reported for cadence in both TTs (see Supplementary materials).

Group by Test by Time ANOVAs were performed on RPE during the TTs. Main effects of time were found for the 5-min TT ($F_{(1, 22)} = 15.79$, $p < 0.001$, $\eta^2p = 0.65$) and 20-min TT ($F_{(1, 22)} = 14.12$, $p < 0.001$, $\eta^2p = 0.72$); perceived effort increased during the tests. For the 5-min TT, no group ($F_{(1, 22)} = 0.21$, $p = 0.451$, $\eta^2p = 0.12$), test ($F_{(1, 22)} = 1.77$, $p = 0.193$, $\eta^2p = 0.10$), and interaction ($F_{(4, 88)} = 1.78$, $p = 0.284$, $\eta^2p = 0.06$) effects were detected (Fig. 3C). Similarly, for the 20-min TT, no group ($F_{(1, 22)} = 0.21$, $p = 0.653$, $\eta^2p = 0.15$), test ($F_{(1, 22)} = 1.66$, $p = 0.214$, $\eta^2p = 0.12$), and interaction ($F_{(4, 88)} = 1.08$, $p = 0.372$, $\eta^2p = 0.05$), effects were detected (Fig. 3D). No three-way interaction was found for RPE during the 60-min incremental multistage test ($F_{(3, 66)} = 1.73$, $p = 0.15$, $\eta^2p = 0.10$). However, there was a group by test interaction ($F_{(1, 22)} = 5.62$, $p = 0.034$, $\eta^2p = 0.33$). Follow-up tests revealed that effort at post-test compared to pre-test was lower ($p = 0.032$) in the BET group but unchanged ($p = 0.672$) in the control group (Fig. 3E). A main effect of time ($F_{(1, 22)} = 17.79$, $p < 0.001$, $\eta^2p = 0.45$) showed that effort rose with increasing workload.

Group by Test ANOVAs on performance during the Stroop task yielded a group by test effect for reaction time ($F_{(1, 22)} = 5.55$, $p = 0.033$, $\eta^2p = 0.20$, Fig. 4B). Follow-up comparisons revealed that reaction times were faster at posttest than pre-test in BET ($p < 0.001$) and control ($p = 0.025$) groups, with BET faster than control. Performance accuracy, which was consistently high (grand mean 97 ± 2 % correct responses) did not vary by group ($F_{(1, 22)} = 1.17$, $p = 0.294$, $\eta^2p = 0.10$), test ($F_{(1, 22)} = 0.841$, $p = 0.37$, $\eta^2p = 0.08$), and group by test ($F_{(1, 22)} = 0.545$, $p = 0.74$, $\eta^2p = 0.01$). ANOVAs on the NASA TLX subscales

Table 2
Training workload as a function of Group and Week in Study 2.

	Week 1		Week 2		Week 3		Week 4		Week 5		Week 6		Group			Week			Group × Week		
	BET	Control	BET	Control	BET	Control	BET	Control	BET	Control	BET	Control	$F_{(1, 22)}$	p	η^2p	$F_{(5, 110)}$	p	η^2p	$F_{(5, 110)}$	p	η^2p
Time (min) in HR zones																					
Zone 1 (<68 %)	131 ± 26	142 ± 25	140 ± 24	145 ± 22	145 ± 23	151 ± 34	155 ± 29	158 ± 27	165 ± 27	161 ± 24	166 ± 31	168 ± 29	1.374	0.254	0.06	4.23	0.010*	0.18	1.321	0.265	16
Zone 2 (69–83 %)	508 ± 29	474 ± 36	553 ± 34	534 ± 32	577 ± 36	586 ± 53	638 ± 41	610 ± 37	679 ± 38	657 ± 49	725 ± 46	724 ± 53	1.592	0.220	0.15	11.61	<0.001*	0.20	0.139	0.983	0.08
Zone 3 (84–94 %)	45 ± 15	43 ± 18	47 ± 15	49 ± 9	52 ± 13	55 ± 11	57 ± 13	56 ± 15	58 ± 16	59 ± 15	61 ± 5	63 ± 19	0.706	0.410	0.14	11.33	<0.001*	0.38	0.712	0.616	0.17
Zone 4 (85–105 %)	9 ± 3	11 ± 4	13 ± 3	15 ± 5	17 ± 4	16 ± 3	18 ± 4	19 ± 4	21 ± 4	22 ± 4	23 ± 4	25 ± 6	0.777	0.388	0.25	3.99	0.002*	0.17	0.871	0.503	0.11
Zone 5 (>106 %)	0	0	0	0	0	0	0	0	0	0	0	0									
Zone 6 (anaerobic)	2 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1	1.137	0.298	0.19	1.081	0.375	0.06	0.713	0.615	0.07
Total (min)	695 ± 57	672 ± 43	755 ± 48	745 ± 41	793 ± 43	810 ± 52	871 ± 59	845 ± 45	925 ± 47	901 ± 53	977 ± 57	982 ± 64	1.232	0.279	0.12	13.77	<0.001*	0.25	0.915	0.474	0.07
Total distance (km)	329 ± 31	318 ± 27	347 ± 33	335 ± 39	390 ± 41	401 ± 38	428 ± 37	415 ± 35	455 ± 43	447 ± 46	479 ± 47	485 ± 42	1.431	0.244	0.22	19.77	<0.001*	0.31	1.101	0.364	0.15
NASA TLX																					
Mental demand	71 ± 3	45 ± 5	65 ± 5	51 ± 3	74 ± 5	51 ± 4	68 ± 3	49 ± 4	79 ± 3	53 ± 4	71 ± 4	55 ± 4	23.22	<0.001*	0.24	2.811	0.020*	0.19	1.567	0.175	0.10
Physical demand	45 ± 2	47 ± 4	47 ± 3	46 ± 6	51 ± 3	53 ± 2	56 ± 4	57 ± 4	61 ± 4	62 ± 3	62 ± 4	61 ± 4	1.980	0.173	0.11	3.171	0.012*	0.21	1.391	0.233	0.13
Frustration	54 ± 8	46 ± 11	53 ± 9	49 ± 3	50 ± 7	47 ± 7	51 ± 6	50 ± 6	47 ± 8	44 ± 7	49 ± 9	48 ± 5	1.738	0.201	0.17	1.170	0.329	0.01	1.133	0.347	0.07
Effort	55 ± 6	52 ± 4	59 ± 4	57 ± 7	63 ± 6	59 ± 5	65 ± 6	61 ± 5	68 ± 5	64 ± 5	67 ± 3	65 ± 5	2.567	0.123	0.18	2.811	0.022*	0.32	1.213	0.352	0.10

Note: Values are *M* ± *SD*.
* $p < 0.05$.

revealed group by time interactions for mental demand ($F_{(1, 22)} = 11.13$, $p < 0.001$, $\eta^2p = 0.37$), effort ($F_{(1, 22)} = 4.93$, $p = 0.041$, $\eta^2p = 0.31$), and frustration ($F_{(1, 22)} = 4.79$, $p = 0.043$, $\eta^2p = 0.29$). Follow-up comparisons revealed that relative to pretest, BET found the Stroop task at posttest to be less mentally demanding (p = 0.031; Pre: 58 ± 6 > Post: 35 ± 5), less effortful (p = 0.026; Pre: 57 ± 6 > Post: 38 ± 6), and less frustrating (p = 0.038; Pre 51 ± 6 > Post 25 ± 5). However, no test differences were found for the control group in mental demand (p = 0.183; Pre 58 ± 6–Post 55 ± 4), effort (p = 0.274; Pre 62 ± 6–Post 59 ± 6) and frustration (p = 0.323; Pre 52 ± 5–Post 49 ± 6).

No significant differences in the groups and tests were found for HR and blood lactate in both TTE tests (see Supplementary materials).

7. Study 2: Discussion

In Study 2, we tested the effects of a 6-week BET protocol on endurance performance and cognitive performance in highly trained/elite road cyclists. In contrast to Study 1, we fixed the duration (30 min) of the cognitive task performed after the physical training sessions (Post-BET) and progressively increased its difficulty. We demonstrated that Post-BET improved performance compared to control by enhancing 20-min TT tests and reaction time during the Stroop task. With a trend toward significance, BET marginally changed the 5-min TT performance in the expected direction. Similar to Study 1, the performance improvements induced by Post-BET were associated with reduced mental demand during the Stroop task and reduced RPE during the 60-min incremental multistage cycling test. Because Post-BET did not affect $\dot{V}O_{2peak}$ and the physiological responses to the 60-min incremental multistage cycling test, these findings suggest that the significant improvement in endurance performance in response to BET was mediated by psychological rather than cardiovascular and metabolic mechanisms.[10–12]

8. General discussion

The present investigation assessed the effects of two 6-week Post-BET protocols on endurance performance and cognitive performance in road cyclists. One of the main aims of BET is to increase the mental load of physical training in order to induce brain adaptations that improve physical performance, especially in conditions of mental fatigue and/or multitasking.[11,12] We found that the present Post-BET interventions increased the perceived mental demand of training by 45 % (Study 1) and 49 % (Study 2) compared to control. These findings are broadly in line with previous Concurrent-BET[10,11] and Post-BET[12] studies, and confirm that BET is an effective strategy to increase the overall training load while maintaining the same physical load as confirmed by the measures of perceived physical demand, HR, and distance covered that we collected during training.

Although the minimum Post-BET dose awaits confirmation, we show here that 30-min of Post-BET five times per week for six weeks is sufficient to improve endurance performance of highly trained and elite road cyclists. In a previous Post-BET study in professional football players, 20-min of Post-BET five times a week for 4 weeks was associated with improvements in physical, cognitive and multitasking performance.[12] Therefore, it seems that a total of about 2 h of Post-BET per week are sufficient to improve the performance of highly trained athletes. These findings suggest that Post-BET may be a practical alternative to Concurrent-BET and Intermixed-BET when these more time-efficient types of BET are not feasible for safety reasons or training logistics. Taken together, the present studies show that shorter harder cognitive tasks (when task difficulty was manipulated) can produce similar training effects as longer easier tasks (when task duration was manipulated). Accordingly, the dose of cognitive load achieved via the manipulation of task difficulty can produce sufficient mental demand and fatigue to impact performance in a more time-efficient manner.[26]

Study 1 showed that Post-BET enabled cyclists to exercise longer until voluntary exhaustion compared to the control group. Specifically, TTE increased by 11.4 % for Post-BET and 3.4 % for control when cycling at 80 % PPO, and increased by 17.1 % for Post-BET and 2.8 % for control when cycling at 65 % PPO. These changes are in the same direction but smaller than a previous BET study reporting that cycling TTE improved by 120 % with Concurrent-BET compared to 42 % in controls.[10] Methodological discrepancies could help explain differences in the size of the improvements between studies. First, sample composition. Our participants were trained/highly trained road cyclists ($\dot{V}O_{2peak}$: 64 ± 4 at baseline) whereas the participants in Marcora et al.[10] were moderately fit individuals ($\dot{V}O_{2peak}$: 40 ± 5 at baseline). Second, TTE test characteristics. In Study 1, participants performed the first TTE test at 80 % PPO when fresh, and the second TTE test at 65 % PPO when tired. The previous study assessed TTE at 75 % VO_{2max} when fresh. Third, BET type and programming. We examined the effects of 30 Post-BET sessions over 6 weeks whereas the previous study examined the effects of 36 Concurrent-BET sessions over 12 weeks. Although the differences in training and testing characteristics may have contributed to the differences in TTE improvements, the most likely explanation is the use of more experienced[15] cyclists in the current study as it is widely recognized that performance improvements in response to training stimuli are smaller in highly-trained individuals.

Study 2 showed that Post-BET improved the TT performance of elite road cyclists compared to the control group; with clear benefits during the 20-min TT only. In the 5-min TT, power increased by 2.5 % for Post-BET and 1.8 % for control, and, in the 20-min TT, power increased by 5.5 % for Post-BET and 1.6 % for control. Similarly, in the 5-min TT, distance covered increased by 1.6 % for Post-BET and 0.6 % for control, and, in the 20-min TT, distance increased by 4.0 % for Post-BET and 1.0 % for control. A number of reasons may help explain why the performance-enhancing effect of Post-BET was greater in the 20-min TT compared to the 5-min TT. First, test duration/intensity. BET may induce larger performance improvements during maximal effort cycling endurance tasks lasting longer than 5 min, as previously shown in Study 1 and Marcora et al.[10] Second, fatigue. The 5-min TT was completed when fresh whereas the 20-min TT was completed in a fatigued state after completing the 5-min TT, a 30-min cognitive task and a 60-min submaximal cycling task. The importance of test duration/intensity and fatigue state must await programmatic explorations. However, we speculate that BET may boost the resilience of athletes to perform endurance task lasting more than 5 min in a mentally and physically fatigued state. It is worth noting that the percent improvements in endurance performance in Study 2 should not be directly compared with percent improvements in endurance performance in Study 1. Indeed, it has been well established that, for the same change in endurance performance, % change in TTs is much smaller than % change in TTE.[13] When more appropriately comparing effect sizes, here expressed as partial eta squared, the effects of Post-BET on endurance performance observed in Study 1 ($\eta^2p = 0.30$–0.48) are not greatly different from the one observed for the 20-min TT in Study 2 ($\eta^2p = 0.29$). The slightly smaller effect observed in Study 2 may be explained by the elite level of the road cyclists that participated in the study. Indeed, Martin and colleagues[14] argued that elite cyclists are more resilient to mental fatigue and, therefore, the room for improvement with BET may have been smaller in such group compared to cyclists of lower performance level that participated in Study 1.

In both Studies 1 and 2, physical fitness indicators (i.e. $\dot{V}O_{2peak}$ and PPO) and the physiological responses to endurance exercise did not change in either the Post-BET groups or the control groups. The most likely explanation is the moderate volume/intensity of physical training performed by our participants in the short period during which we performed the studies. Therefore, it appears that changes in musculo-energetic and cardiorespiratory factors do not mediate the benefits of Post-BET on endurance exercise performance. However, both studies garnered evidence that endurance exercise felt easier following Post-BET. Study 1 found that RPE during the TTE test decreased at posttest in the Post-BET group but not in the control group. A similar effect of Post-BET on RPE was found during the incremental multistage test in Study 2. The rationale behind BET is grounded on evidence that mental fatigue impairs exercise performance and augments perceived effort,[6] coupled with the assumption made by the psychobiological model of endurance performance that perception of effort interacts with potential motivation to determine for how long a given speed/power will be sustained.[3] Therefore, we argue that the far transfer of BET on endurance performance is mediated by its beneficial effect on perception of effort. In line with this mechanistic account, our highly motivated BET participants in Study 1 will have taken longer to reach the point at which they stopped exercise because effort was perceived as maximal, whereas BET participants in Study 2 were able to produce more power for similar RPE values during the 20-min TT.

It is worth remembering that the current tasks that we selected for Post-BET training, which were the flanker, go/no-go, and AX-CPT tasks, have a strong response inhibition component. They have been associated with activation of the anterior cingulate cortex, which has been linked to perception of effort.[5,27] Although we did not measure brain activity, we speculate that 22.5 h (Study 1) and 15 h (Study 2) of response inhibition training would have been associated with long-term changes in anterior cingulate cortex activation and perceived effort. In partial support to this hypothesis, a study by Dallaway et al.[11] revealed changes in cortical processing efficiency in the frontal brain regions following BET with response inhibition and memory updating cognitive tasks. Furthermore, the BET-related decrease in perception of effort when cycling was accompanied by reduced mental demand, effort and frustration scores during the cognitive task. Overall, BET seems to make subsequent cognitive and physical tasks feel easier. It is therefore likely that BET altered the brain processes underlying the perception of effort during both cognitive and physical tasks.

Importantly, both studies suggest that Post-BET improves cognitive performance, measured by reaction time during the Stroop test, a classic response inhibition cognitive task which was different from the response inhibition tasks used for training. This finding reflects near transfer of the cognitive effects of Post-BET to a novel response inhibition task different from those used during training. The Post-BET group responded faster than the control group in Study 1 (19 % vs 6 %) and Study 2 (9 % vs 3 %) without losing accuracy. It is possible that the improvements in response inhibition that characterized the Post-BET groups may help explain their higher performance during the endurance tasks (TTE and TT tests) in which the capacity to inhibit the unpleasant feelings of pain and fatigue is important in order to sustain exercise and complete the goal of the task.[14,28] Notably, the improved Stroop performance was obtained with the test being perceived to be less mentally demanding and requiring less effort by the cyclists in the Post-BET groups. This finding suggests that Post-BET may have also helped develop greater resilience toward mental fatigue.[14,28] The BET-induced improvements in cognitive performance observed in the present studies with road cyclists are in line with a previous training study which used Post-BET in professional football players.[12] However, there is a consensus that, when performed in isolation, brain training does not significantly improve cognitive performance of healthy young adults outside of the very same cognitive tasks used for brain training.[29] The discrepancy between the positive effects of BET and the lack of efficacy of standard brain training suggests that a combination of cognitive tasks and exercise tasks in the same training session may be required to achieve improvements in cognitive performance. This facilitatory effect of exercise may be due, at least in part, to its positive effects on neuroplasticity.[30] Such a hypothesis requires further investigation because it may have applications beyond improving athletic performance, e.g. reducing the cognitive decline associated with aging.

Potential study limitations should be considered when evaluating our findings. First, the sample size was relatively modest. The number of participants recruited was limited by the size of the cycling squads we had access to and the study inclusion/exclusion criteria, such as injuries. Future studies should increase the overall sample size and provide more evidence for or against the efficacy of BET to improve cycling performance. It is worth noting that the samples were of comparable size to previous BET studies that found performance improvements.[11,12] Another limitation is that we assessed the effects of BET and listening to neutral sounds using the NASA-TLX scales. However, this measure referred to the overall training session involving both physical and cognitive demands. We therefore lack a measure of mental effort/demand referring only to the non-physical training (i.e., BET or sounds), that would allow us to assess the isolated effect of either treatment on the cyclists.

Future directions could aim to conduct larger efficacy studies and mechanistic studies with direct measures of brain adaptations to BET. To address this oversight, brain imaging could be used to identify and localize the brain regions/networks that may be altered by BET. Moreover, the use of a cognitive intervention aimed at increasing the overall training load of an athlete during training should be carefully considered for its potential negative impact on non-functional overreaching and overtraining syndrome.

9. Conclusion

Both studies provide further evidence in favor of adding BET as a supplement to basic physical training to improve endurance exercise performance. This performance-enhancing effect was manifested in a fatigued state during the TTE and TT tests, and in a fresh state during the TTE test. Importantly, Post-BET reduced RPE during endurance exercise, suggesting that Post-BET improves endurance performance by making exercise feel easier. Our studies confirm and extend the extant literature showing that BET also improves cognitive function, with evidence of near transfer to a novel response inhibition test that was not explicitly used during training. Taken together, our findings prove the efficacy and feasibility of BET in endurance athletes, such as trained/highly trained/elite road cyclists. Finally, both studies illustrate how BET can be customized to fit the training needs of athletes who face time constraints that might otherwise prevent them adding BET to their busy schedules.

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Confirmation of ethical compliance

The study was approved by the Ethics Committee for the Southern Denmark Region in accordance with the Declaration of Helsinki.

CRediT authorship contribution statement

Walter Staiano: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Samuele Marcora:** Conceptualization, Software, Validation, Writing – review & editing, Visualization, Supervision. **Marco Romagnoli:** Methodology, Resources, Writing – review & editing, Project administration, Funding acquisition. **Ulrich Kirk:** Software, Funding acquisition, Project administration, Writing – review & editing, Investigation. **Christopher Ring:** Conceptualization, Formal analysis, Resources, Writing – original draft, Writing – review & editing, Supervision.

Declaration of interest statement

We declare that any author of the present study does not have any conflict or personal interest related to the data collected.

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Appendix A. Supplementary data

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References

1. Joyner MJ, Coyle EF. Endurance exercise performance: the physiology of champions. *J Physiol* 2008;586(Pt 1):35-44. doi:10.1113/jphysiol.2007.1438341.
2. Morales-Alamo D, Losa-Reyna J, Torres-Peralta R et al. What limits performance during whole-body incremental exercise to exhaustion in humans? *J Physiol* 2015;593 (20):4631-4648. doi:10.1113/JP270487.
3. Staiano W, Bosio A, de Morre HM et al. Chapter 11 - the cardinal exercise stopper: Muscle fatigue, muscle pain or perception of effort?, In: Marcora S, Sarkar M, eds. *Progress in Brain Research*, *Sport and the Brain: The Science of Preparing, Enduring and Winning, Part C*Elsevier, 2018. p. 175-200. doi:10.1016/bs.pbr.2018.09.012.
4. McCormick A, Meijen C, Marcora S. Psychological determinants of whole-body endurance performance. *Sports Med* 2015;45(7):997-1015. doi:10.1007/s40279-015-0319-6.
5. Boksem MAS, Tops M. Mental fatigue: costs and benefits. *Brain Res Rev* 2008;59(1): 125-139. doi:10.1016/j.brainresrev.2008.07.001.
6. Van Cutsem J, Marcora S, De Pauw K et al. The effects of mental fatigue on physical performance: a systematic review. *Sports Med* 2017;47(8):1569-1588. doi:10.1007/s40279-016-0672-0.
7. Staiano W, Bosio A, Piazza G et al. Kayaking performance is altered in mentally fatigued young elite athletes. *J Sports Med Phys Fitness* 2019;59(7):1253-1262. doi:10.23736/S0022-4707.18.09051-5.
8. Pageaux B, Lepers R. Fatigue induced by physical and mental exertion increases perception of effort and impairs subsequent endurance performance. *Front Physiol* 2016;7:587. doi:10.3389/fphys.2016.00587.
9. Marcora SM, Staiano W, Manning V. Mental fatigue impairs physical performance in humans. *J Appl Physiol (1985)* 2009;106(3):857-864. doi:10.1152/japplphysiol.91324.2008.
10. Marcora SM, Staiano W, Merlini M. A randomized controlled trial of Brain Endurance Training (BET) to reduce fatigue during endurance exercise: 754 Board #150 May 27, 3. *Med Sci Sports Exerc* 2015;47(5S):198. doi:10.1249/01.mss.0000476967.03579.44.
11. Dallaway N, Lucas SJE, Ring C. Concurrent brain endurance training improves endurance exercise performance. *J Sci Med Sport* 2021;24(4):405-411. doi:10.1016/j.jsams.2020.10.008.
12. Staiano W, Merlini M, Romagnoli M et al. Brain endurance training improves physical, cognitive, and multitasking performance in professional football players. *Int J Sports Physiol Perform* 2022. doi:10.1123/ijspp.2022-0144. ahead of print.
13. Amann M, Hopkins WG, Marcora SM. Similar sensitivity of time to exhaustion and time-trial time to changes in endurance. *Med Sci Sports Exerc* 2008;40(3):574-578. doi:10.1249/MSS.0b013e31815e728f.
14. Martin K, Staiano W, Menaspà P et al. Superior inhibitory control and resistance to mental fatigue in professional road cyclists. *PloS One* 2016;11(7):e0159907. doi:10.1371/journal.pone.0159907.
15. McKay AKA, Stellingwerff T, Smith ES et al. Defining training and performance caliber: a participant classification framework. *Int J Sports Physiol Perform* 2022;17(2): 317-331. doi:10.1123/ijspp.2021-0451.
16. Robertson RJ, Noble BJ. Perception of physical exertion: methods, mediators, and applications. *Exerc Sport Sci Rev* 1997;25:407-452.
17. Hoonakker P, Carayon P, Gurses A et al. Measuring workload of ICU nurses with a questionnaire survey: the NASA Task Load Index (TLX). *IIE Trans Healthc Syst Eng* 2011;1(2):131-143. doi:10.1080/19488300.2011.609524.
18. Allen A, Coggan A, McGregor S. Power based training: where to begin, chapter 3, *Training and Racing With a Power Meter*, 2nd ed., Velopress, 2019.
19. Lorist MM, Klein M, Nieuwenhuis S et al. Mental fatigue and task control: planning and preparation. *Psychophysiology* 2000;37(5):614-625.
20. Kato Y, Endo H, Kizuka T. Mental fatigue and impaired response processes: event-related brain potentials in a Go/NoGo task. *Int J Psychophysiol* 2009;72(2):204-211. doi:10.1016/j.ijpsycho.2008.12.00810.
21. Yang W, Makita K, Nakao T et al. Affective auditory stimulus database: an expanded version of the International Affective Digitized Sounds (IADS-E). *Behav Res Methods* 2018;50(4):1415-1429. doi:10.3758/s13428-018-1027-6.
22. Borg G. Perceived exertion as an indicator of somatic stress. *Scand J Rehabil Med* 1970;2:92-98. pmid:5523831.
23. Nicolò A, Sacchetti M, Girardi M et al. A comparison of different methods to analyse data collected during time-to-exhaustion tests. *Sport Sci Health* 2019;15(3):667-679. doi:10.1007/s11332-019-00585-7.
24. Menaspà P, Quod M, Martin DT et al. Physical demands of sprinting in professional road cycling. *Int J Sports Med* 2015;36(13):1058-1062. doi:10.1055/s-0035-1554697.

25. Ma N, Yu AJ. Inseparability of go and stop in inhibitory control: go stimulus discriminability affects stopping behavior. *Front Neurosci* 2016;10:54. doi:10.3389/fnins.2016.00054.
26. O'Keeffe K, Hodder S, Lloyd A. A comparison of methods used for inducing mental fatigue in performance research: individualised, dual-task and short duration cognitive tests are most effective. *Ergonomics* 2020;63(1):1-12. doi:10.1080/00140139.2019.1687940.
27. Williamson JW, McColl R, Mathews D et al. Brain activation by central command during actual and imagined handgrip under hypnosis. *J Appl Physiol* 2002;92(3):1317-1324. doi:10.1152/japplphysiol.00939.2001.
28. Cona G, Cavazzana A, Paoli A et al. It's a matter of mind! Cognitive functioning predicts the athletic performance in ultra-marathon runners. *PloS One* 2015;10(7):e0132943. doi:10.1371/journal.pone.0132943.
29. Simons DJ, Boot WR, Charness N et al. Do "brain-training" programs work? *Psychol Sci Public Interest* 2016;17(3):103-186. doi:10.1177/1529100616661983.
30. Hötting K, Röder B. Beneficial effects of physical exercise on neuroplasticity and cognition. *Neurosci Biobehav Rev* 2013;37(9 Pt B):2243-2257. doi:10.1016/j.neubiorev.2013.04.005. PMID: 23623982.