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BRAIN ENDURANCE TRAINING IMPROVES PHYSICAL, COGNITIVE AND MULTI-TASKING PERFORMANCE IN PROFESSIONAL FOOTBALL PLAYERS

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Abstract

Purpose: Brain endurance training (BET)—the combination of physical training with mentally fatiguing tasks—could help athletes adapt and increase their performance during sporting competitions. Here we tested whether BET completed after standard physical training improved physical and mental performance more than physical training alone during a preseason football training camp. ***Methods***: The study employed a pretest/training/posttest design, with 22 professional football players randomly assigned to BET or a control group. Both groups completed 40 physical training sessions over 4 weeks. At the end of a day of physical training, the BET group completed cognitive training, whereas the control group listened to neutral sounds. Players completed the 30–15 Intermittent Fitness Test, repeated sprint ability random test, soccer-specific reactive agility test, and Stroop and psychomotor vigilance tests pretraining and posttraining. Mixed analysis of variance was used to analyze the data. ***Results***: In the posttest (but not pretest) assessments, the BET group consistently outperformed the control group. Specifically, the BET group was faster (P= .02–.04) than the control group during the 30–15 Intermittent Fitness Test, the directional phase of the repeated sprint ability random test, and the soccer-specific reactive agility test. The BET group also made fewer errors (P = .02) during the soccer-specific reactive agility test than the control group. Finally, the BET group responded faster (P = .02) on the Stroop test and made fewer (P = .03) lapses on the psychomotor vigilance test than the control group. ***Conclusion***: The inclusion of BET during the preseason seems more effective than standard physical training alone in improving the physical, cognitive, and multitasking performance of professional football players.

Keywords: cognitive training, mental fatigue, elite athletes, sport performance, team sport, neuro-performance

Introduction

Mental fatigue has been defined as a psychobiological state induced by prolonged periods of demanding cognitive activity, which is characterized by feelings of tiredness and lack of energy.[1,2] Football players are required to react to various stimuli, make quick decisions, remember and switch strategies, and stay alert during the whole match. As a result, they can develop mental fatigue over time.[3] Stressors other than playing football (eg, travel and education) can also induce mental fatigue.[4] With regards to performance, this is not optimal because research studies have demonstrated that mental fatigue can impair aerobic capacity,[5] intermittent running velocity,[6] decision making,[5,6] technical skills,[5,7] and psychomotor vigilance.[8] Therefore, it is necessary to develop strategies to reduce the negative effects of mental fatigue in football players.

Given evidence that physical and mental effort involve several overlapping brain regions,[9] Marcora et al.[10] proposed an innovative training method—brain endurance training (BET)—to increase the cognitive load of physical training to make athletes more resilient to mental fatigue and improve their endurance performance. Their seminal study showed that the addition of a 60-minute cognitive task to a standard physical training program focusing on endurance (ie, a 60-min cycling task performed 3 times per week for 12 wk) led to greater improvements in endurance measured with a cycling time to exhaustion test. The improved endurance performance with BET was explained in terms of brain adaptations to the systematic cognitive overload resulting in a reduction in the perception of effort during the cycling to exhaustion test. The benefit of *concurrent* BET for endurance performance has since been replicated by another research group using a rhythmic handgrip exercise task.[11] Taken together, these studies argue for a beneficial effect of BET on endurance performance when the cognitive task is performed *during* exercise. However, adding a concurrent cognitive task may not always be practical during football training on the field. Therefore, other combinations of cognitive training and physical training should be investigated. For example, the coach could ask the players to perform a demanding cognitive task before the physical training session (*pre* BET) so that they train in a state of mental fatigue. Another possibility is to perform a demanding cognitive task during the recovery periods of a high-intensity interval training session (*intermixed* BET) so that, while the body recovers between the exercise bouts, the brain remains highly engaged. Finally, it is possible to add the demanding cognitive task immediately after the session when the players are fatigued by the physical training (*post* BET). Potentially, all of these combinations could induce positive brain adaptations and increase the overall training load imposed on the players without increasing the physical load. In injured athletes or athletes at high risk of overuse injuries, coaches could also use BET to maintain the overall training load when the physical load is reduced. Given these potential practical applications, further experimental research on the effects of BET is warranted. Such research should also include other outcomes in addition to endurance performance. Indeed, because of its multitasking nature, BET may also help to improve performance when physical and cognitive tasks have to be performed simultaneously (dual tasking) or in rapid succession (task switching), which would obviously be highly beneficial in football players and other team sports in which optimal multitasking performance is required.

The aim of the present investigation was to evaluate the effects of *post* BET during the preseason stage of professional footballers' training. To the best of our knowledge, this is the first study to investigate the effects of BET in football players. We hypothesized that *post* BET would enhance physical and cognitive performance in both single and multitasking conditions compared with standard physical training alone.

Methods

Participants

A convenience sample of 25 male professional football players from a team in the Italian third division (mean [SD], age 22.4 [4.3] y, height 175.4 [6.2] cm, weight 72.8 [6.6] kg) were recruited. They signed an informed consent form to participate in this study, which was approved by the ethics committee for the Region of Southern Denmark in accordance with the standards of the Declaration of Helsinki. Players with injuries or bespoke training plans were excluded from the study. During the study, 3 participants (one from the BET group and 2 from the control group) dropped out due to injuries; therefore, the analyses were performed on an effective sample of 22 players. All players received written instructions describing the study protocol but were naïve to its aims and hypotheses. Post hoc power calculations using G*Power indicated that, with a sample size of 22, our study was powered at 80% to detect significant ($P < .05$) between-within interaction effects ($f = 0.31$, $\eta 2p = .09$) corresponding to a small to medium effect size by analysis of variance.

Experimental Design

The study employed a stratified randomized, pretest/posttest, con- trolled design. After baseline testing (pretest), participants were stratified according to playing position (goalkeepers, defenders, midfielders, and forwards) and randomly assigned to a BET group (n = 13) or control group (n = 12). Participants were tested again after 4 weeks of training (posttest).

Testing

Players performed physical and cognitive tests over 7 testing sessions: 1 familiarization session, 3 pretest sessions, and 3 posttest sessions. All testing sessions were conducted on the same football pitch and at the same time of day during the preseason (July– August). Tests were completed in the week before and the week after the 4-week training period. Prior to each testing session, players followed a standardized routine regarding sleep, recovery, meals, hydration, supplementation, and medication. Temperature and humidity were monitored, and testing sessions rescheduled if environmental conditions were unusual. At the start of each testing session, players completed a motivation questionnaire (see "Psychological Measures" section) and a standardized physical warm- up. During group testing sessions, players verbally encouraged each other, but no verbal encouragement was provided by the experimenter in any of the testing sessions. During testing session 1, players completed the battery of physical and cognitive tests and questionnaires to familiarize them with the assessments.

During testing session 2, players performed the 30 to 15 intermittent fitness test (IFT),[12] an incremental running test de- signed to measure endurance in team sport athletes. The velocity in kilometers per hour of the final and fully completed stage was recorded as the velocity IFT. This test has been shown to have good test–retest reliability with a typical error of measurement to be of 0.3 km/h (intraclass correlation coefficient = .96). Heart rate (HR) and a capillary blood sample were obtained upon task completion. Players rested for 30 minutes before completing a 30-minute incongruent Stroop color-word test[13] on a personal computer. Reaction time (in milliseconds) and accuracy (in percentage of correct answers) were computed. Finally, players completed a NASA task load index (NASA-TLX)[14] to assess the demands of the Stroop test.

During testing session 3, players performed the soccer-specific reactive agility test (S-RAG)[15] using a Fit Light Trainer system (Fitlight Corp). This test measures ability to sprint, agility, change direction, and visuomotor response and have good test–retest reliability (intraclass correlation coefficient = .88 for reactive agility time). We adapted the original test by asking players to sprint continuously and complete the circuit without rests. Their goal was to run toward the illuminated light, touch it with their contralateral hand, and return to base. They completed 3 sets of 10 lights, with a 20-second recovery between sets. The lights were illuminated in a counterbalanced pseudorandom order. This version of the task was designed to increase mental fatigue (eg, by requiring participants to inhibit the natural isomorphic response to respond by touching the light with their closest hand). This feature also simulated a match situation where a defending player blocks an attacker with the opposite side compared with the direction. Performance was measured as time (in seconds) to complete the task and response accuracy (in percentage errors). A capillary blood sample was obtained upon task completion.

During testing session 4, players performed the repeated sprint ability random test (RSA).[16] This test measures acceleration, change of direction, visuomotor response, and decision making. Test–retest reliability for the mean time variable is high with an intraclass correlation coefficient between .88 and .90. The test comprised 12 × 20-m sprints, with each sprint followed by 20 seconds of active recovery while jogging back 20 m to the starting position. Each sprint comprised a 10-m linear sprint plus a 10-m directional sprint to 1 of 3 randomly cued locations. The location of each directional sprint was cued by the illumination of 1 of 3 colored lights after completing the previous 10-m linear sprint. Performance was measured as the average time taken to complete the 10-m linear sprint (time [in seconds]) and 10-m directional sprint (time [in seconds]). Participants also completed a 10-minutes psychomotor vigilance test[17] 30 minutes before and 30 minutes after the sprint test. Reaction time (in milliseconds), for responses between 100 and 500 milliseconds, and number of lapses, defined as responses slower than 500 milliseconds, were computed. We aimed to compare the effect of BET training on PVT player's performance in a fresh state (before the RSA) and in a fatigued state (after the RSA).

Training interventions

All players completed 40 physical training sessions over a 4-week period under the supervision of the club's physical trainer. They trained once or twice per day, 5 days per week. They were instructed to follow the prescribed physical training program without completing any extra physical training session in order to standardize the impact of physical training on posttest performance. Intensity, frequency, load, and type of training were monitored by the physical trainer and coach. Weekly training load was measured using the number of minutes training in the 5 HR zones.[18] NASA-TLX[14] was used to measure various aspects of the perceived workload of each training session and averaged over each week before analysis.

The BET group was asked to complete, 4 to 5 times a week, a cognitive task for 20 to 30 minutes immediately following the last daily physical training session, for a total of 400 minutes over the 4-week period. If there were 2 training sessions in the same day, players performed the cognitive tasks after the second session. The duration of the cognitive task used for *post* BET session was constrained by the players' high daily volume of physical training. However, Giboin and Wolff[19] demonstrated that mental fatigue and its acute detrimental effects on physical performance are dependent not only on the duration but also on the demands of the cognitive task. In other words, high demand cognitive activity for a short period or low-demand cognitive activity for a prolonged period can similarly increase mental fatigue. In the current study, players performed 1 of 3 highly demanding cognitive tasks—flanker task, go/no-go task, AX-continuous performance test using the SOMA-NPT app (Sswitch.ch) running on a tablet computer. All 3 tasks include response inhibition that induce mental fatigue.[20] Participants were instructed to choose to complete 1 of the 3 cognitive tasks on each session while ensuring balance between the 3 cognitive tasks across the 4 weeks of training. To reduce placebo effect, participants were told that these tasks were used to assess their cognitive performance throughout the preseason rather than being a new mode of training.

The control group listened to 3 emotionally neutral sounds in a random order for 20 to 30 minutes following the last daily physical training session for 4 to 5 sessions per week for a total of 400 minutes over the 4-week period. They were told the sounds were designed to induce relaxation. However, the emotional valence of these specific sounds was neutral to avoid any positive or negative psychological effect.[21] This control treatment was chosen to reduce threats to internal validity, like resentful demoralization and compensatory rivalry, in the players not randomly allocated to *post* BET.

Physiological Measures

The HR was measured using a telemetric sensor (Polar S610i, Polar Electro Oy) during each physical training session and upon completion of the 30–15 IFT. Blood lactate concentration (in millimoles per liter) was measured by taking a 5-μL sample of whole fresh capillary blood from the right middle finger and analyzed using a portable analyzer (Lactate Pro LT-1710, Arkray) upon completion of the 30–15 IFT and the reactive agility test.

Psychological Measures

Motivation was measured by asking players to rate the statement “I am motivated to perform the test” using a 5-point Likert scale, with anchors of 0 (not at all) and 4 (extremely). Perceived workload was measured using the mental demand, physical demand, and effort subscales of the NASA-TLX[14] upon completion of each training session and after the Stroop test.

Statistical analysis

All data are presented as mean (SD) unless otherwise stated. A series of mixed group (BET and control) by time (pretest and posttest) analyses of variances (ANOVAs) were performed on the variables measured during the testing sessions. A series of mixed group (BET and control) × week (1, 2, 3, and 4) ANOVAs were performed on the training variables. Significant group × time interactions were followed up with unpaired *t* tests for the simple main effects of group. Significance was set at .05 (2-tailed) for all analyses. The effect sizes for the ANOVAs were calculated as partial eta squared (η2p), with .02,.13, and .26 indicating small, medium, and large effects, respectively. Data analysis was conducted using the Statistical Package for Social Science (version 27).

Results

Training Variables

All players completed 40 physical training sessions, including occasional daily double sessions and friendly practice matches, during the 4-week training period. Group × week ANOVAs on the total number of minutes across the 5 HR zones found effects of week but no group or group × week effects (Table 1). Group × week ANOVAs on the NASA-TLX variables found an effect of group on mental demand and effects of time on all of the 3 subscales. No other group effects or group × week effects were found on the NASA-TLX variables. All players in the BET group complied with the prescribed 400 minutes of cognitive tasks spread among 18 (2) training sessions. Similarly, the control group listened to 400 minutes of neutral sounds spread among 19 (1) training sessions.

Motivation

No group ($F_{1,20} = 0.09$, $P = .77$, $\eta 2p = .01$) time ($F_{1,20} = 2.62$, $P = .13$, $\eta 2p = .14$), or group × time ($F_{1,20} = 0.22$, $P = .64$, $\eta 2p = .01$) effects were found for motivation. These data confirmed that the BET and control groups were similarly motivated throughout the pretest and posttest assessments (grand mean: 3.1 [0.9]).

Physical Performance

The ANOVA yielded a group × time interaction for velocity at the end of the 30–15 IFT ($F1,20 = 5.12$, $P = .04$, $\eta 2p = .09$; Figure 1A). Follow-up tests revealed that the BET group was faster than the control group at posttest ($P = .04$). No main effect of time was found for velocity ($F1,20 = 2.09$, $P = .14$, $\eta 2p = :05$). No group ($F1,20 = 0.85$, $P = .37$, $\eta 2p = .04$), time ($F1,20 = 1.68$, $P = .21$, $\eta 2p =.08$), or group × time ($F_{1,20} = 1.83$, $P = .19$, $\eta 2p = .08$) effects were found for blood lactate concentration (BET pre: 10.1 [1.5], BET post: 9.6 [2]; control pre: 10.5 [1.8], control post: 9.7 [1.9]). Similarly, HR at the end of the fitness test (BET pre: 194 [10], BET post 192 [8]; control pre: 196 [9], control post: 191 [11]) did not show any effects for group ($F_{1,20} = 0.30$, $P = .59$, $\eta 2p = .02$), time ($F_{1,20} = 2.90$, $P = .10$, $\eta 2p = .13$), or group × time ($F_{1,20} = 2.56$, $P = .13$, $\eta 2p = .11$).

Cognitive Performance

In the Stroop test, there was a group × time interaction for reaction time ($F_{1,20} = 6.26$, $P = .02$, $\eta 2p = .13$; Figure 2A). Reaction times decreased from pretest to posttest in both groups ($F_{1,20} = 6.38$, $P = .02$, $\eta 2p = .26$), and, importantly, the BET group was faster than control at posttest ($P < .001$). Accuracy did not vary as a function of group ($F1,20 = 0.13$, $P = .91$, $\eta 2p = .00$), time ($F1,20 = 0.31$, $P = .58$, $\eta 2p = .02$), and group × time ($F1,20 = 0.12$, $P = .73$, $\eta 2p = .01$). Accuracy was universally high (grand mean: 94% [2%] correct responses). The NASA-TLX subscales completed after the Stroop test revealed group × time interactions for mental demand ($F1,20 = 16.61$, $P < .001$, $\eta 2p = .17$) and effort ($F1,20 = 17.55$, $P < .001$, $\eta 2p = .24$). Follow-up tests revealed that at posttest, the Stroop test was less ($Ps = .02–.03$) demanding for BET (39 [6]) than control (71 [7]) and effortful for BET (48 [4]) than control (69 [5]). No main effects of time were noted for mental demand ($F1,20 = 0.40$, $P = .54$, $\eta 2p = .02$) and effort ($F1,20 = 0.01$, $P = .92$, $\eta 2p = .00$). No effects emerged for physical demand (group [$F1,20 = 0.50$, $P = 0.53$, $\eta 2pp = :03$], time [$F1,20 = 1.84$, $P = 0.21$, $\eta 2pp = :08$], and group by time [$F1,20 = 0.39$, $P = .62$, $\eta 2p = :03$], grand mean 15 [9]). No significant effects were found for lapses when players performed the PVT before the RSA (fresh state; group [$F1,20 = 0.78$, $P = .55$, $\eta 2p = .02$], test [$F1,20 = 0.99$, $P = .30$, $\eta 2p = .02$], and group × time [$F1,20 = 0.47$, $P = .46$, $\eta 2p = .01$]; grand mean 1.8 [0.3] lapses; Figure 2B). However, in the PVT performed after the RSA (fatigued state), there was a significant group × time interaction for number of lapses ($F1,20 = 5.38$, $P = .03$, $\eta 2p = .14$; Figure 2B). Follow-up tests revealed that, compared with the control group, the number of lapses in the fatigued state was significantly lower in the posttest in the BET group ($P = .01$). No main effect of time was found for lapses ($F1,20 = 1.89$, $P = .17$, $\eta 2p = :04$). No significant effects emerged for reaction time in either the fresh state (group [$F1,20= 0.49$, $P = .49$, $\eta 2p = .02$], time [$F1,20 = 1.94$, $P = .18$, $\eta 2p = .09$], and group × time [$F1,20 = 0.43$, $P = .52$, $\eta 2p = .02$]; grand mean 331 [22] ms) or in the fatigued state (group [$F1,20 = 0.78$, $P = .40$, $\eta 2p = .04$], time [$F1,20 = 1.14$, $P = .28$, $\eta 2p = .04$], and group × time [$F1,20= 0.27$, $P = .66$, $\eta 2p = .02$]; grand mean 315 [25] ms).

Multi-tasking performance

The ANOVA uncovered a group × time interaction effect for the directional sprints in the RSA ($F1,20 = 4.66$, $P = .04$, $\eta 2p = .05$; Figure 1B): Follow-up tests revealed that the BET group was faster than the control group ($P = .04$) at posttest. No main effect of time was found ($F_{1,20} = 3.09$, $P = .09$, $\eta^2_p = .08$). Analysis of the linear acceleration phase of the RSA revealed neither main effect of group ($F_{1,20} = 1.33$, $P = .26$, $\eta^2_p = .06$) nor main effect of time ($F_{1,20} = 2.10$, $P = .16$, $\eta^2_p = .06$), and no interaction ($F_{1,20} = 0.07$, $P = .80$, $\eta^2_p = .00$) (grand mean: 2.3 [0.2]). The ANOVA found a group × time interaction on time to complete the S-RAG test ($F_{1,20} = 5.41$, $P = .03$, $\eta^2_{pp} = .11$; Figure 3A), with both groups faster at posttest than pretest ($F_{1,20} = 7.70$, $P = .01$, $\eta^2_p = .10$) and the BET group faster than control at posttest ($P = .04$). A group × time interaction for hand errors ($F_{1,20} = 6.36$, $P = .02$, $\eta^2_p = .18$; Figure 3B) revealed that although both groups erred less at posttest than pretest ($F_{1,20} = 4.66$, $P = .04$, $\eta^2_p = .10$), the BET group made fewer mistakes than control at posttest ($P = .03$). Blood lactate concentration at completion of S-RAG (BET pre: 11.4 [1.8], BET post: 12.1 [2.1]; control pre: 11.9 [2.4], control post: 12.2 [2.5]) did not show any group ($F_{1,20} = 1.67$, $P = .21$, $\eta^2_p = .07$), time ($F_{1,20} = 2.60$, $P = .11$, $\eta^2_p = .08$), or group × time ($F_{1,20} = 0.85$, $P = .37$, $\eta^2_p = .04$) effects.

Discussion

The aim of the present study was to investigate the effects of a 4-week BET intervention on physical, cognitive, and multitasking performance in professional football players. Specifically, we added 20- to 30-minute demanding cognitive tasks after some of the physical training sessions (*post* BET). This experimental manipulation increased on average across the weeks by 28% the perceived mental demand of training compared with the control group that performed the same physical training program without the added cognitive tasks. This finding is in line with the results of previous studies of *concurrent* BET[10,11] and suggests that *post* BET is another effective strategy to increase the cognitive load of physical training. Importantly for the interpretation of the following results is the fact that the physical load experienced by the BET and control groups was not significantly different as indicated by both the perceived physical demand ratings and the analysis of HR during training. Therefore, any difference in the outcomes of training is most likely due to the additional cognitive load provided by *post* BET rather than differences in physical load. It is worth noting that this difference in cognitive load was achieved using relatively short (ie, 20–30 min) cognitive tasks, which were well tolerated by the players and did not affect the quantity and quality of their physical training.

BET and Physical Performance

The changes in 30–15 IFT indicated that endurance performance was maintained in the BET group, whereas there was a reduction in the control group. We had expected that the 4-week preseason physical training program would improve the endurance performance of both groups. Given that motivation did not differ significantly between pretest and posttest, we speculate that the players had not fully recovered from the intense physical training regime before completing the posttest. It is, therefore, possible that players were in a state of functional overreaching when they completed the second 30–15 IFT. Regardless, the BET group showed better intermittent running endurance than the control group. This is in line with findings of previous studies showing that participants training with concurrent BET have better endurance performance than participants performing standard physical training (control group) after 6 to 12 weeks of training.[10,11] It has been speculated that BET increases endurance performance by inducing adaptations in brain areas such as the anterior cingulate cortex, which are activated during the cognitive tasks used for BET.[2] This is relevant because the anterior cingulate cortex is involved in mental fatigue and perception of effort[2,22] which, in turn, affect endurance performance,[23] including a Yo-Yo Intermittent Recovery Test [15] and an intermittent high-intensity running test6 in soccer players and other team sport athletes. Here, we also speculate that BET may have made the players more resilient to overreaching, which has a strong psychological component.[24]

BET and Cognitive Performance

We measured the psychomotor vigilance of the players before (fresh state) and after (fatigued state) a demanding physical and cognitive task, namely, the RSA random test. As it is the case for traditional brain training programs in young healthy adults,[25] BET did not improve cognitive performance measured in optimal conditions (fresh state), However, the results of our study show that BET improves psychomotor vigilance in a fatigued state. Indeed, the BET group made 42% fewer lapses (with similar reaction times) at posttest compared pretest, while the control group did not improve over time during the PVT performed after the RSA. It is worth noting that lapses during this vigilance task are a more sensitive indicator of alertness than simple reaction time.[17] Thus, it seems that BET boosted players' ability to sustain attention when fatigued by a previous bout of repeated sprints.

An improvement in performance was also evident for the Stroop test, with the BET group responding 11% faster (with the same accuracy) from pretest to posttest compared with the control group, which improved 4% after 4 weeks of training. Notably, this relatively improved Stroop performance was obtained despite the test being perceived to be less mentally demanding and requiring less effort by players in the BET group. The Stroop test is a classic response inhibition test that has often been used to induce mental fatigue[26] and was performed after a strenuous physical task (30–15 IFT).Therefore, the improved response inhibition that characterized the BET group suggests greater resilience toward mental fatigue.[26,27] Improved inhibitory control in conditions of mental fatigue may be particularly beneficial in terms of players' behavior on the pitch because research has shown that mental fatigue reduces people's ability to control their aggressive behavior especially when provoked.[28]

BET and Multitasking Performance

In addition to using primarily physical (30–15 IFT) and primarily cognitive (PVT and Stroop) tests, we tested the effects of BET using tests that combine anaerobic metabolism and neuromuscular function with visuomotor and decision-making skills. The first of these multitasking performance tests (the RSA random test) showed that the BET group improved their performance more than the control group in the directional sprints but not in the linear sprints after 4 weeks of training. While performance in the linear acceleration phase of the RSA depends primarily on anaerobic metabolism and neuromuscular function,[29] performance in the directional sprints is also determined by the player's ability to respond quickly to a visual stimulus and decide the correct movement direction. Altogether, our findings suggest that BET improved the cognitive component of this multitasking performance test assessing physical and cognitive skills relevant to football. It is worth noting that we required players to complete twice as many sprints (12 instead of 6) as the standard RSA. Given evidence that mental fatigue is associated with poorer physical and technical performance in football[5] and decreased decision-making skill and visual search performance in basketball,[30] it is possible that the *post* BET group experienced less effort during the physical task and thereby had sufficient residual cognitive resources to focus better on the task, respond faster to visual stimuli, and decide faster how to move during the task.

The positive effect of BET on multitasking performance was confirmed by the S-RAG. In our version of the test, players continuously reacted to visual stimuli and decided which direction to run while exercising at a high intensity and experiencing increasing fatigue. From pre to posttest the BET group completed the test 8.9% faster, while the control group only 4.3% faster. Moreover, BET group completed the test with 69% less errors, whereas the control group made 21% fewer errors after 4 weeks of training. Faster reaction times and fewer hand errors in this test may translate to better performance in a sport like football in which reactive agility during intense phases of the game is thought to be an important skill. Furthermore, increased resistance to mental fatigue may generalize to superior physiological, cognitive, and technical[30] performance and thereby have fewer goals conceded during football matches.[31]

Study Limitations

The current study yielded some important new findings that can be incorporated into athletes' training schedules. However, some potential study limitations should be noted when interpreting this evidence. First, the sample size was relatively small. The number of participants recruited was limited by the size of the squad we had access to and the study inclusion/exclusion criteria, such as injuries. Future studies should collect data from a number of different clubs to increase the overall sample size and provide more robust evidence for or against the BET in professional football players. Second, we asked players in the control group to listen to emotionally neutral sounds for 20 to 30 minutes following the last daily physical training session for 4 to 5 sessions per week. This control treatment was employed to reduce threats to internal validity, like resentful demoralization and compensatory rivalry. However, despite the choice of neutral emotional valence of the sounds, the absence of a true control group with no treatment at all means that we cannot be entirely confident that the differences in cognitive load and performance outcomes measured in this study were caused by *post* BET. Although extremely unlikely, the differences observed between the 2 groups may have been caused by the control treatment. Regardless of the certainty of its cause (post-BET or the unlikely relaxing effects of the control treatment), our results suggest that higher cognitive load during 4 weeks of training is associated with better improvements in various measures of physical, cognitive, and multitasking performance. Third, players completed the Stroop test after a demanding multitasking performance test (S-RAG), which may have affected their Stroop performance. Therefore, we do not know whether the improvement in response inhibition observed in the BET group would manifest itself in the fresh condition (no previous S-RAG). Indeed, the PVT results suggest that the positive effects of BET on cognitive performance may only be evident in fatigue conditions. Finally, we monitored physical training load only using subjective ratings and HR recordings. Future investigations could supplement these measures with GPS recordings to track external load.

Practical Applications

The findings of this study provide initial support for the inclusion of BET alongside basic physical training in the overall training programming for professional football players. Specifically, BET could be used to improve players' performance by increasing the cognitive load of training without overloading the musculo-skeletal system and thereby mitigate overuse injury risk. Importantly, the *post* BET protocol used in this study was well tolerated by the players and could be adapted to the constraints of the preseason training environment.

Conclusions

The present study provides further evidence that BET improves endurance performance, extending its impact to intermittent run- ning and professional athletes. Furthermore, it provides initial evidence that BET may also improve psychomotor vigilance and inhibitory control in fatigued conditions and multitasking performance, reinforcing the important role played by the brain in sport performance.[32] Given the importance of multitasking performance and resilience to fatigue for professional athletes and other occupations like the military, further research on the effects of BET on these performance outcomes is warranted.

Disclosure Statement

No conflict of interest is reported in this research study.

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Author Contributions: Staiano and Merlini equally contributed to the manuscript.

References

1. Marcora SM, Staiano W, Manning V. Mental fatigue impairs physical performance in humans. *J Appl Physiol*. 2009;106(3):857–864. doi:10.1152/japplphysiol.91324.2008
2. 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
3. Coutts AJ. Fatigue in football: it's not a brainless task! *J Sports Sci*. 2016;34(14):1296. doi:10.1080/02640414.2016.1170475
4. Russell S, Jenkins D, Rynne S, Halson SL, Kelly V. What is mental fatigue in elite sport? Perceptions from athletes and staff. *Eur J Sport Sci*. 2019;19(10):1367–1376. doi:10.1080/17461391.2019.161839
5. Smith MR, Coutts AJ, Merlini M, Deprez D, Lenoir M, Marcora SM. Mental fatigue impairs soccer-specific physical and technical performance. *Med Sci Sports Exerc*. 2016;48(2):267–276. doi:10. 1249/MSS.0000000000000762
6. Smith MR, Marcora SM, Coutts AJ. Mental fatigue impairs intermit- tent running performance. *Med Sci Sports Exerc*. 2015;47(8):1682– 1690 doi:10.1249/MSS.0000000000000592
7. Clemente FM, Ramirez-Campillo R, Castillo D, et al. Effects of mental fatigue in total running distance and tactical behavior during small-sided games: a systematic review with a meta-analysis in youth and young adult's soccer players. *Front Psychol*. 2021;12:656445. doi:10.3389/fpsyg.2021.656445
8. Angius L, Merlini M, Hopker J, et al. Physical and mental fatigue reduce psychomotor vigilance in professional football players. *Int J Sports Physiol Perform*. 2022;17(9):1391–1398. doi:10.1123/ijspp. 2021-0387
9. Blain B, Schmit C, Aubry A, Hausswirth C, Le Meur Y, Pessiglione M. Neuro-computational impact of physical training overload on economic decision-making. *Curr Biol*. 2019;29(19):3289–3297.e4. doi:10.1016/j.cub.2019.08.054
10. Marcora SM, Staiano W, Merlini M. A randomized controlled trial of brain endurance training (BET) to reduce fatigue during endurance exercise. *Med Sci Sports Exerc*. 2015;47(suppl 5):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. Buchheit M, Al Haddad H, Millet GP, Lepretre PM, Newton M, Ahmaidi S. Cardiorespiratory and cardiac autonomic responses to 30–15 intermittent fitness test in team sport players. *J Strength Cond Res*. 2009;23(1):93–100. doi:10.1519/JSC.0b013e31818b9721
13. 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

14. 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

15. Pojskic H, Åslin E, Krolo A, et al. Importance of reactive agility and change of direction speed in differentiating performance levels in junior soccer players: reliability and validity of newly developed soccer-specific tests. *Front Physiol*. 2018;9:506. doi:10.3389/fphys. 2018.00506

16. Martin V, Sanchez-Sanchez J, Ramírez-Campillo R, Nakamura FY, Gonzalo-Skok O. Validity of the RSA-RANDOM test for young soccer players. *Int J Sports Med*. 2018;39(11):813–821. doi:10.1055/ a-0637-2094

17. Basner M, Dinges DF. Maximizing sensitivity of the Psychomotor Vigilance Test (PVT) to sleep loss. *Sleep*. 2011;34(5):581–591. doi:10.1093/sleep/34.5.581

18. Foster C, Florhaug JA, Franklin J, et al. A new approach to monitor- ing exercise training. *J Strength Cond Res*. 2001;15(1):109–115. doi:10.1519/00124278-200102000-00019

19. Giboin LS, Wolff W. The effect of ego depletion or mental fatigue on subsequent physical endurance performance: a meta-analysis. *Per- form Enhanc Health*. 2019;7(1–2):100150. doi:10.1016/j.peh.2019. 100150

20. Lorist MM, Klein M, Nieuwenhuis S, De Jong R, Mulder G, Meijman TF. Mental fatigue and task control: planning and preparation. *Psycho- physiology*. 2000;37(5):614–625. doi:10.1017/S004857720099005X

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. Williamson JW, McColl R, Mathews D, Mitchell JH, Raven PB, Morgan WP. 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

23. Van Cutsem J, Marcora S, De Pauw K, Bailey S, Meeusen R, Roelands B. 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

24. Kellmann M, Bertollo M, Bosquet L, et al. Recovery and performance in sport: consensus statement. Int J Sports Physiol Perform. 2018;13(2):240–245. doi:10.1123/ijspp.2017-0759

25. Sala G, Gobet F. Cognitive training does not enhance general cognition. Trends Cogn Sci. 2019;23(1):9–20. doi:10.1016/j.tics. 2018.10.004

26. Pageaux B, Lepers R, Dietz KC, Marcora SM. Response inhibition impairs subsequent self-paced endurance performance. Eur J Appl Physiol. 2014;114(5):1095–1105. doi:10.1007/s00421-014- 2838-5

27. Cona G, Cavazzana A, Paoli A, Marcolin G, Grainer A, Bisiacchi PS. 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

28. Barlett C, Oliphant H, Gregory W, Jones D. Ego-depletion and aggressive behavior. *Aggress Behav*. 2016;42(6):533–541. doi:10. 1002/ab.21648

29. Fortes LS, de Lima-Júnior D, Fonseca FS, Albuquerque MR, Ferreira MEC. Effect of mental fatigue on mean propulsive velocity, coun- termovement jump, and 100-m and 200-m dash performance in male college sprinters. *Appl Neuropsychol Adult*. Published online Decem- ber 28, 2021. doi:10.1080/23279095.2021.2020791

30. Fortes LS, Lima-Junior D, Barbosa BT, Faro HKC, Ferreira MEC, Almeida SS. Effect of mental fatigue on decision-making skill and visual search behaviour in basketball players: an experimental and randomised study. *Int J Sport Exerc Psychol*. Published online March 31, 2022. doi:10.1080/1612197X.2022.2058055

31. Alberti G, Iaia FM, Arcelli E, Cavaggioni L, Rampinini E. Goal scoring patterns in major European soccer leagues. *Sport Sci Health*. 2013;9:151–153. doi:10.1007/s11332-013-0154-9

32. Walsh V. Is sport the brain's biggest challenge? *Curr Biol*. 2014; 24(18):R859–R860. doi:10.1016/j.cub.2014.08.003

Figure captions

Figure 1

30–15 IFT and RSA (random test) pre and post 4 weeks of training for BET and control groups. (A) 30–15 IFT maximum performance speed at completion. (B) RSA random test average of directional sprints. Error bars are 95% CI. BET indicates brain endurance training; IFT, Intermittent Fitness Test; RSA, repeated sprint ability. §Significant group × time interaction. *Main effect of time. #Significantly different from control group.

Figure 2

Cognitive performance pre and post the intervention for the BET and control groups. (A) Stroop reaction time across groups and time. (B) PVT number of lapses across groups and time before and after the RSA random test. §Significant group × time interaction. *Main effect of time. #Significantly different from control group. Error bars are 95% CI. BET indicates brain endurance training; CI, confidence interval; PVT, psychomotor vigilance test; RSA, repeated sprint ability.

Figure 3

S-RAG pre and post the intervention for the BET and control group. (A) S-RAG time to complete the test. (B) Reactive agility test. S-RAG number of hand errors. Error bars are 95% CI. BET indicates brain endurance training; S-RAG, soccer-specific reactive agility test §Significant group × time interaction. *Main effect of time. #Significantly different from control group.

Table 1. Training variables a Function of Group and Week

	Week 1		Week 2		Week 3		Week 4		Group			Week			Group × week		
	BET	Control	BET	Control	BET	Control	BET	Control	$F_{1,20}$	*P*	η_p^2	$F_{3,60}$	*P*	η_p^2	$F_{3,60}$	*P*	η_p
Time in HR zones, min																	
Zone 1 (<60%)	186 (32)	154 (45)	234 (52)	177 (61)	60 (25)	61 (34)	80 (22)	83 (15)	1.361	.257	.08	15.01	<.001*	.31	1.781	.161	.07
Zone 2 (60%–70%)	158 (25)	162 (23)	170 (24)	164 (42)	69 (9)	61 (13)	66 (11)	84 (32)	1.546	.228	.09	14.61	<.001*	.49	0.239	.863	.01
Zone 3 (70%–80%)	128 (24)	136 (31)	130 (37)	156 (41)	86 (19)	69 (22)	78 (21)	72 (16)	0.306	.586	.07	20.33	<.001*	.41	0.594	.624	.01
Zone 4 (80%–90%)	107 (29)	138 (40)	90 (31)	107 (33)	92 (28)	84 (34)	91 (31)	92 (26)	0.721	.406	.09	4.98	.004*	.15	0.997	.407	.04
Zone 5 (90%–100%)	46 (17)	59 (14)	22 (11)	24 (8)	30 (15)	39 (17)	37 (12)	41 (20)	0.178	.678	.04	23.31	<.001*	.22	2.082	.113	.06
Total	625 (27)	649 (23)	646 (32)	628 (44)	337 (23)	314 (25)	352 (25)	372 (26)	1.358	.258	.10	22.01	<.001*	.47	0.878	.458	.10
NASA-TLX																	
Mental demand	75 (4)	55 (5)	80 (5)	63 (6)	70 (4)	55 (5)	64 (3)	52 (5)	27.33	<.001*	.15	3.301	.026*	.28	1.967	.132	.08
Physical demand	51 (3)	49 (4)	61 (4)	63 (5)	77 (5)	81 (3)	79 (6)	77 (5)	2.240	.150	.09	3.423	.023*	.34	1.733	.171	.01
Effort	71 (8)	74 (5)	91 (7)	89 (6)	80 (4)	78 (5)	75 (3)	77 (5)	2.633	.120	.09	3.831	.014*	.14	1.167	.335	.01

Abbreviations:
- BET: brain endurance training.
- HR: heart rate.
- NASA-TLX: NASA Task Load Index.

Note: BET and control values are presented as mean (SD), $*p < .05$

Figure 1

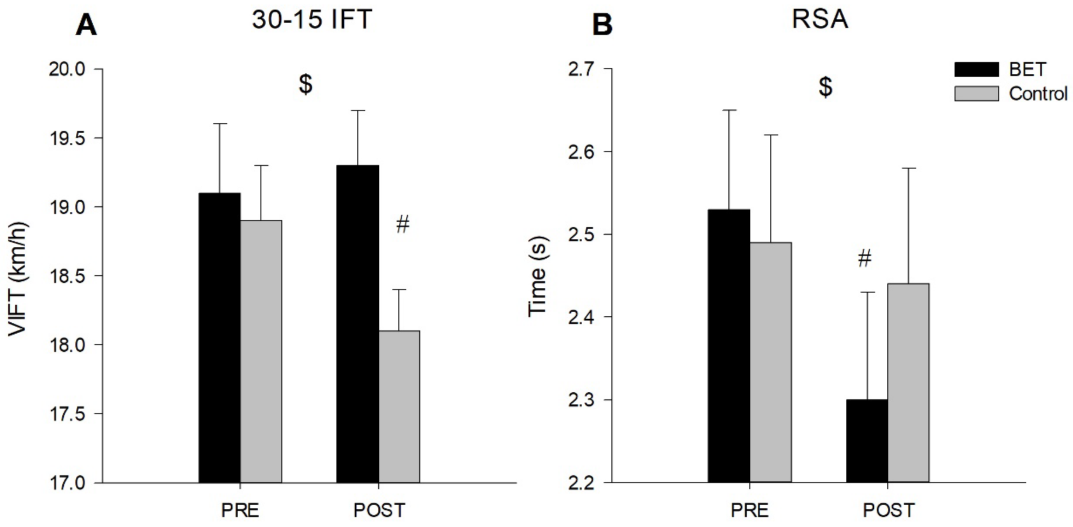


Figure 2

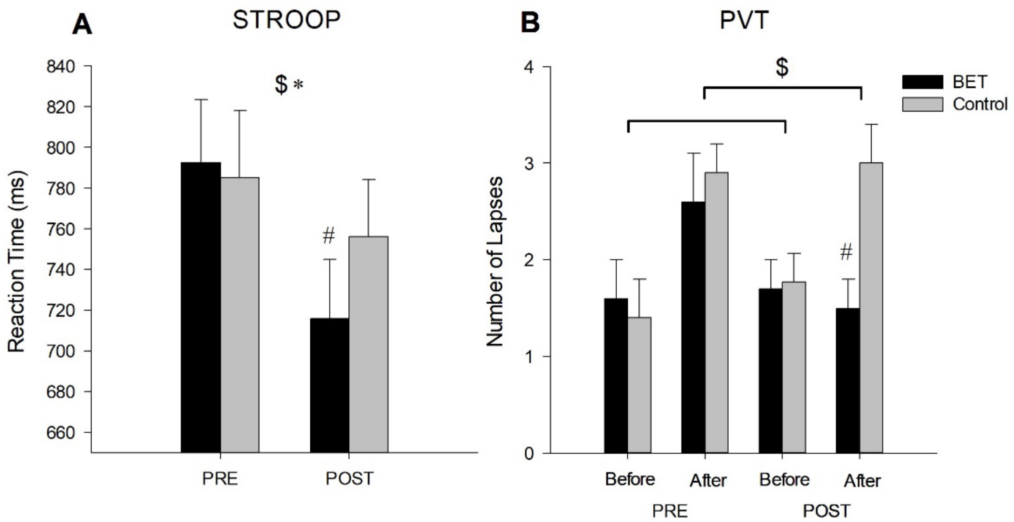
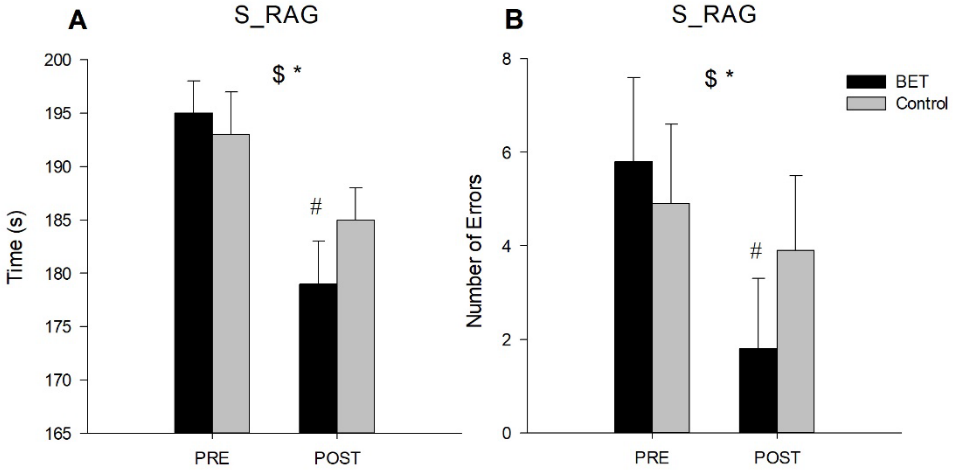


Figure 3



A
S_RAG
$ *
Time (s)
200
195
190
185
180
175
170
165
#
PRE
POST
B
S_RAG
$ *
BET
Control
Number of Errors
8
6
4
2
0
#
PRE
POST