Brain Endurance Training Improves Dynamic Calisthenic Exercise and Benefits Novel Exercise and Cognitive Performance: Evidence of Performance Enhancement and Near Transfer of Training

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Abstract

Dallaway, N, Mortimer, H, Gore, A, and Ring, C. Brain endurance training improves dynamic calisthenic exercise and benefits novel exercise and cognitive performance: Evidence of performance enhancement and near transfer of training. *J Strength Cond Res* XX(X): 000–000, 2024—The purpose of this dual study was to evaluate whether brain endurance training (BET)—a mental fatigue countermeasure involving physical and cognitive training—enhanced exercise compared with physical training alone. Two studies ($N = 29$) used a pretest/training/posttest design, with participants randomized to BET or control groups. During testing, participants performed calisthenic exercises (study 1: press-ups, wall sit, and plank; study 2: burpees, jump squats, leg raises, press-ups, and plank) to failure before and after completing 20-minute cognitive tasks (study 1: memory updating; study 2: memory updating, response inhibition, and nonexecutive functions). Training comprised 3 sessions per week for 4 weeks. In study 1 training sessions, participants completed 2 submaximal exercise sets; each exercise was followed by a 3-minute cognitive task with high (BET) or low (control) cognitive loads. In study 2 training sessions, participants completed 1 submaximal exercise set; after 12-minute cognitive tasks (BET) or rest (control), each exercise was preceded by a 3-minute cognitive task (BET) or rest (control). These cognitive tasks involved response inhibition and memory updating. Performance (exercise repetitions/duration), perceived exertion, and mental fatigue were assessed. In pretesting, exercise performance was matched between groups. In posttesting, BET groups performed more dynamic exercises than control groups but the same number of static exercises. Cognitive task performance was either greater for BET or not different between groups. Neither perceived exertion nor mental fatigue differed between groups and tests. Brain endurance training enhanced dynamic but not static calisthenic exercise performance compared with physical training alongside near transfer of training benefits for novel physical and cognitive task performance.

Key Words: cognition, combined training, exercise performance, mental fatigue

Introduction

Research studies have repeatedly demonstrated that mentally fatiguing cognitive tasks can produce suboptimal physical performance (for reviews see (1,7,14,15)). Accordingly, athletes require effective long-term psychological interventions to deal with the negative impact on performance of mental fatigue, a transient state of tiredness and diminished functioning arising from exertion (20). The psychobiological training system developed by Marcora et al. (18)—brain endurance training (BET)—seeks to mitigate the deleterious effect of mental fatigue on physical performance.

They reason that athletes who repeatedly train while mentally fatigued would subsequently outperform athletes who adopt standard practices and train while not explicitly mentally fatigued. In BET protocols, cognitive tasks, including those requiring higher-order executive functions, such as response inhibition and memory updating, are used to produce a state of heightened mental fatigue during training. It is assumed that the mental workload imposed by the cognitive tasks is sufficient to produce a state of mental fatigue that impairs a physical task by increasing perceived exertion. In other words, perceived exertion is expected to be higher during mental plus physical training compared with physical training alone. Based on the assumption that perceived exertion is a limiting factor in endurance exercise (13,24), BET should adapt athletes to exercise at a level of perceived exertion that is higher than normal, and, therefore, exercise performance should be improved when the cognitive task is no longer present, namely, after completing training. In sum, BET represents a training-based countermeasure to increase mental fatigue resistance during exercise. Training studies have confirmed that performing classic cognitive tasks before (*prior* BET), during (*concurrent* BET), and after (*post* BET) physical training can improve subsequent exercise performance compared with physical training alone. Specifically, BET improved cycling (3,18,25), running (26), and muscular endurance (9,10) performance. Its applicability to other forms of exercise has yet to be established.

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Gym-based calisthenic (bodyweight) exercises are a standard feature of many athletes' strength and conditioning programs. Although it remains to be seen whether BET improves performance of this type of exercise, recent reviews have confirmed that cognitive tasks can impair performance of subsequent weight and strength exercise tasks (1,7). This evidence satisfies a necessary condition for BET to be effective, namely, that the exercise is vulnerable to a state of mental fatigue. For instance, compared with control (i.e., no or low mental workload), high mental workload cognitive tasks impaired performance to failure of calisthenic exercise tasks, including fewer press-ups (11), fewer sit ups (11), shorter wall sits (5), and shorter plank (27). It is worth noting that null findings of small studies are a feature of this literature. Nonetheless, the meta-analyses of studies that examined the effects of mental fatigue on upper- and lower-body strength endurance exercise (1) provide sufficient evidence for us to expect that BET might improve performance of calisthenic exercises.

Most athletes follow a year-long schedule or macrocycle, with their training dependent on the phase of the season. It is possible that different BET options are more suitable to specific phases or mesocycles. For instance, long duration cognitive tasks before (*prior* BET) or after (*post* BET) long duration physical sessions may be more suitable for off-season and preseason training. Some gym-based training sessions that comprise short-duration high-intensity strength and conditioning exercise sets separated by short duration rests may require a bespoke form of BET. Multiple scheduling options are possible for these sorts of physical workouts. For instance, athletes could perform cognitive tasks in the rest periods before, during, and after completing exercises (i.e., a hybrid *prior/post* or *intermixed* BET). The effectiveness of this scheduling option has yet to be examined.

The current research program examined the effects of *intermixed* BET—comprising a series of brief cognitive tasks performed instead of rests before or after brief bouts of calisthenic exercises—on subsequent exercise endurance performed to failure. To this end, we conducted 2 training studies and assessed performance of dynamic (press-ups, burpees, jump squats, and leg raises) and static (plank and wall sit) calisthenic exercises before and after 4 weeks of training.

Study 1

Our study purposes were threefold. First, we investigated whether BET improves exercise performance compared with control (standard physical training). We hypothesized that BET, with memory updating and response inhibition cognitive tasks intermixed between calisthenic exercises, would improve exercise performance compared with control. Second, we explored changes in perception of the physical tasks as a function of training. We hypothesized that BET would reduce perceived exertion associated with performance of calisthenic exercises compared with control. Third, we explored changes in performance of cognitive tasks as a function of training. We hypothesized that BET would improve cognitive performance compared with control. We evaluated performance of 2 cognitive tasks. A memory updating task, which was tested pretraining and posttraining and used during training, was used to assess learning and retention with BET. A novel response inhibition task, which was only tested posttraining, was used to assess near transfer with BET. In this context, transfer refers to performance benefits for a novel untrained task that was not included in the training program. Near and far transfer refer to performance benefits on tasks that are relatively similar and different to the tasks that were trained.

Methods

Experimental Approach to the Problem

The study used a pretest/training/posttest design, with 1 between-participant factor (group: *iBET*, control) and 2 within-subject factors (test: pretest, posttest; set: before cognitive task, after cognitive task). Subjects completed 14 sessions over 6 weeks, comprising a pretest (week 1), 12 training sessions (weeks 2–5), and a posttest (week 6). The study protocol is depicted in the Supplemental Digital Content 1 (see Materials, http://links.lww.com/JSCR/A509).

Subjects

Subjects were 29 (12 female and 17 male) fit and healthy undergraduate students aged 23 ($SD = 5$) years who received a £20 voucher upon completion of the protocol to enhance retention. They were randomly assigned, by chance, to one of 2 groups: iBET ($n = 14$) or control ($n = 15$). Subjects were asked to have a regular night's sleep (>7 hours) and abstain from exercise and alcohol consumption (24 hours), caffeine (3 hours), and food (1 hour) before each session. Exclusion criteria included current illness or injury, upper-body strength training, and changes in habitual exercise during the study. Power calculations using GPower (12) indicated that with a sample size of 29, our study was powered at 80% to detect significant ($p < 0.05$) between-within interaction effects ($f = 0.27$, $\eta_p^2 = 0.07$) corresponding to a small-to-medium effect size by analysis of variance (8). Previous studies have found exercise performance benefits of BET compared with standard training with sample sizes of 20 (3), 22 (26), 24 (9)24–26 (25), 28 (18), and 36 (10) subjects. Accordingly, the current sample size of 29 exceeds most previous BET studies. The protocol was approved by University of Birmingham Ethics Committee. Subjects gave written informed consent.

Physical Tasks

Subjects performed press-ups, wall sit, and plank to failure during testing (16). Failure was defined as the point when the exercise could no longer be performed with the correct form as determined by an observer. They performed a progressively increasing number of press-ups and squats and a set duration of wall-sit and plank during training. They watched instructional videos and read written instructions about each exercise. Performance was measured by the number (n) of repetitions of press-ups and the duration (s) of maintaining a plank and wall sit. The physical tasks are described in detail in the Supplemental Digital Content (see Materials, http://links.lww.com/JSCR/A510).

Cognitive Tasks

In pretesting and posttesting, participants performed a 20-minute 2-back task. In training, they performed a series of 3-minute cognitive tasks: the iBET group completed 2-back task (memory updating) and incongruent Stroop (response inhibition) task, whereas the control group completed 0-back task (no memory updating) and congruent Stroop tasks (no response inhibition). In posttesting, they also completed a 10-minute AX-continuous performance task (AX-CPT), a response inhibition task. For each task, they watched instructional videos, read written instructions, and practiced for 1 minute. The cognitive tasks were implemented using the SOMA-NPT app (Soma Technologies, Switzerland). Performance was measured by speed (responses/s), accuracy (% correct), and coefficient of variation (%). The cognitive tasks are described in detail in the Supplemental Digital Content (see Materials, http://links.lww.com/JSCR/A511).

Training

Both groups completed 12 training sessions: 3 sessions per week for 4 weeks. In each 30-minutes session, they performed a sequence of 8 physical tasks (c. 3-minutes) in a fixed order: plank, squats, press-ups, wall sit, plank, squats, press-ups, and wall sit. A periodized physical training schedule was used so that exercise intensity increased each week: 70, 75, 80, and 85% of pretest performance for plank, press-ups, and wall sit in weeks 1, 2, 3, and 4, respectively. Similarly, the number of squats was set at 1 squat per 4.5 seconds of wall sit time to exhaustion (e.g., 20 squats for 90 seconds wall sit time) in week 1 that was progressively increased by 20% each week thereafter (e.g., 24, 29, and 35 squats for weeks 2, 3, and 4, respectively). Each 3-minute physical task was followed by a 3-minute cognitive task. The rationale for periodized training was based on the training principle of progressive overload and pilot testing (e.g., Refs. 9,10). When setting the initial intensity, a balance was made between what the participants could complete, bearing in mind that they had the additional cognitive load. This then allowed for increases each week.

The iBET group performed the incongruent Stroop task (training weeks 1, 3, and 4) and 2-back task (training weeks 2, 3, and 4): these 2 high cognitive workload tasks require response inhibition and memory updating executive functions, respectively. The control group performed the congruent Stroop task (training weeks 1, 3, 4) and 0-back task (training weeks 2, 3, and 4): these 2 low cognitive workload tasks do not require any executive functions. A periodized mental training schedule was used so that cognitive workload was increased progressively across the weeks of the intervention. The Soma app allows task difficulty (stimulus presentation rate) to be increased from relatively slow to fast. Accordingly, the stimulus presentation rate was increased every week across training. Subjects alternated between Stroop and n-back tasks in training weeks 3 and 4 (i.e., training sessions 7–12).

Measures

Ratings of perceived exertion were obtained using a CR-10 scale (6), anchored by "0 = nothing at all" and "10 = maximal". Mental fatigue was rated on a CR-10 scale, anchored by "0 = nothing at all" and "10 = totally exhausted". Mental exertion was rated on a CR-10 scale, anchored by "0 = nothing at all" and "10 = maximal mental exertion."

Procedure

To familiarize subjects with the exercises, they watched instructional videos, read written instructions, and were given tips about technique for each exercise. They practice the exercises and were instructed to keep the same form throughout the study. In the pretest and posttest sessions, subjects completed 1 set of calisthenic exercises before and after completing a 20-minute 2-back task. Each exercise was followed by a brief 1-minute rest. Subjects provided a rating of perceived exertion after completing each set of exercises. They also provided a mental fatigue rating at baseline, after the first set of exercises, after the 2-back task, and after the second set of exercises. In the posttest session, they also completed a 10-minute AX-CPT after the second set of exercises.

Statistical Analyses

A series of mixed (i.e., both between-participant and within-participant factors) factorial ANOVAs were performed on the measures associated with the cognitive and physical tasks. Partial eta-squared (η_p^2) was reported as a measure of effect size, with values of 0.02, 0.13, and 0.26 indicating small, medium, and large effect sizes, respectively (8). Significance was set at $p < 0.05$. Analyses were conducted using the Statistical Package for the Social Sciences (SPSS) software (IBM).

Results

Physical Tasks

Figure 1 summarizes the performance of the physical tasks and overall rating of perceived exertion of the iBET and control groups. Performance was examined using 2 group (iBET, control) by 2 test (pretest and posttest) × 2 set (before cognitive task, after cognitive task) ANOVAs. Main effects for test confirmed that endurance increased from pretest to posttest in both iBET and control groups for all exercises: press-ups, $F(1,27) = 45.08$, $p < 0.001$, $\eta_p^2 = 0.625$, wall sit, $F(1,27) = 16.99$, $p < 0.001$, $\eta_p^2 = 0.386$, and plank, $F(1,27) = 23.01$, $p < 0.001$, $\eta_p^2 = 0.460$. Importantly, a group-by-test interaction effect confirmed that the iBET group improved press-ups more than the control group, $F(1,27) = 5.37$, $p < 0.03$, $\eta_p^2 = 0.166$. Main effects for set confirmed that exercise endurance decreased from the set of exercises completed before the 2-back cognitive task to those completed after the 2-back cognitive task in both iBET and control groups for press-up, $F(1,27) = 26.45$, $p < 0.001$, $\eta_p^2 = 0.495$ ($M_{\text{before}} = 35.87 > M_{\text{after}} = 32.55$), and plank, $F(1,27) = 20.67$, $p < 0.001$, $\eta_p^2 = 0.434$, ($M_{\text{before}} = 130.62$ seconds $> M_{\text{after}} = 106.46$ seconds). A marginal effect of set was found for wall sit, $F(1,27) = 3.62$, $p < 0.07$, $\eta_p^2 = 0.118$ ($M_{\text{before}} = 161.71 > M_{\text{after}} = 141.66$). No effects of group, test, or set were noted for perceived exertion.

Cognitive Tasks

Table 1 summarizes the cognitive task performance of the iBET and control groups. Performance on the 2-back memory updating task was examined using a series of 2 group (iBET and control) by 2 test (pretest and posttest) ANOVAs. Test main effects revealed that response speed and variation improved from pretest to posttest in both iBET and control groups. Importantly, group-by-test interaction effects confirmed that these improvements were greater for iBET than control. Furthermore, performance on the novel AX-CPT task was examined using 2-group (iBET and control) ANOVAs. A group main effect showed that the iBET group responded faster than the control group on this vigilance task.

Ratings of mental fatigue and exertion completed after the 2-back cognitive task were examined using 2 group (iBET, control)-by-2 test (pretest and posttest) ANOVAs. These analyses yielded a test main effect, $F(1,27) = 5.13$, $p < 0.03$, $\eta_p^2 = 0.160$, ($M_{\text{pretest}} = 5.79 > M_{\text{posttest}} = 5.19$), and group-by-test interaction

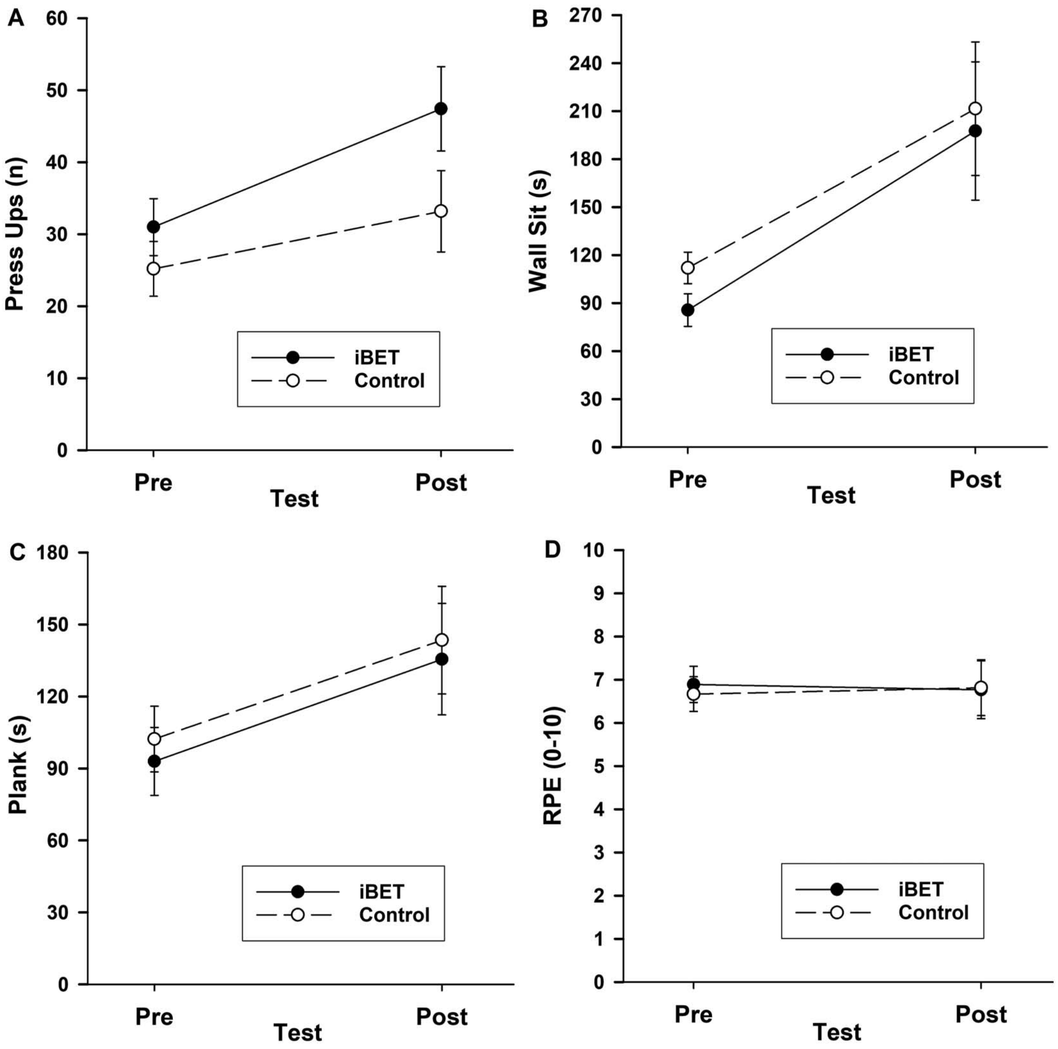

Figure 1. Mean (*SE*) maximal exercise performance to exhaustion and overall rating of perceived exertion as a function of group (iBET and control) and test session (pre and post) in study 1.

effect, $F(1,27) = 26.45$, $p < 0.001$, $\eta_p^2 = 0.495$, for mental fatigue. The mental fatigue was unchanged in the iBET group ($M_{pre\text{-}post} = -0.12$), whereas mental fatigue decreased in the control group ($M_{pre\text{-}post} = 1.28$). No effects on mental exertion were noted.

Training

The perceived impact of training was assessed using a series of 2-group (iBET and control) ANOVAs on the average ratings of perceived physical exertion, mental exertion, and mental fatigue.

Table 1

Mean (*SD*) cognitive task performance as a function of group (iBET and control) and test session (pretest and posttest) in study 1.*

	Test session				ANOVA					
	Pretest		Posttest		Group		Test		Group × test	
Task/measures	IBET	Control	iBET	Control	$F(1, 27)$	η_p^2	$F(1, 27)$	η_p^2	$F(1, 27)$	η_p^2
2-Back										
Speed (responses/s)	1.60 ± 0.40	1.52 ± 0.35	2.53 ± 0.50	2.12 ± 0.26	4.28†	0.137	97.36‡	0.783	4.92§	0.154
Accuracy (% correct)	84.79 ± 22.97	90.13 ± 6.61	91.29 ± 7.89	86.07 ± 19.21	0.00	0.000	0.11	0.004	2.06	0.071
Variation (%)	35.50 ± 8.82	31.33 ± 7.84	23.14 ± 6.15	28.93 ± 7.50	0.11	0.004	27.71‡	0.506	12.61‡	0.318
AX-CPT										
Speed (responses/s)			2.65 ± 0.62	2.13 ± 0.35	7.99§	0.228				
Accuracy (% correct)			69.64 ± 24.53	74.27 ± 25.02	0.25	0.009				
Variation (%)			41.86 ± 36.94	73.07 ± 50.19	3.59	0.117				

*CPT = continuous performance task.
†$p < 0.05$.
‡$p < 0.001$.
§$p < 0.01$.

Ratings of perceived exertion during training were similar for the iBET ($M = 4.64, SD = 1.84$) and control ($M = 4.84, SD = 1.84$) groups, $F(1,27) = 0.08, p = 0.77, \eta_p^2 = 0.003$. However, ratings of mental exertion during training were higher for the iBET group ($M = 4.51, SD = 1.85$) than the control group ($M = 2.59, SD = 1.85$), $F(1,27) = 7.82, p < 0.009, \eta_p^2 = 0.225$. Similarly, ratings of mental fatigue during training were higher in the iBET group ($M = 4.62, SD = 1.90$) compared with the control group ($M = 3.26, SD = 1.91$), $F(1,27) = 3.71, p < 0.06, \eta_p^2 = 0.121$.

Discussion

In support of our hypotheses, the study findings indicated that BET increased the number of repetitions of the press-up exercise task and increased the response speed and variation of the cognitive tasks. Contrary to our hypotheses, the current findings indicated that BET did not improve the duration of the plank and wall sit exercise tasks and did not improve the response accuracy of the cognitive tasks. These findings suggest that BET improved dynamic exercise but not static exercise performance compared with standard physical training. They also suggest that BET improved the learning and transfer of cognitive task speed and consistency but not accuracy.

Study 2

Our study purposes were fourfold. Our first and second study purposes were as per study 1. Our third study purpose, again as per study 1, explored performance of cognitive tasks as a function of training. Subjects performed response inhibition and memory updating cognitive tasks during the pretest (and BET) and novel nonexecutive function cognitive tasks during the posttest. The novel cognitive tasks, whose processing demands included attention, decision making, and vigilance, were used to assess *far transfer* of cognitive training with BET. We hypothesized that BET would aid novel cognitive performance compared with control. Our fourth study purpose investigated whether BET improved performance of a novel exercise task compared with control. We hypothesized that intermixed BET would improve performance of an untrained whole-body calisthenic exercise task compared with control. Because the novel exercise (mountain climbers) involved muscles that were trained by the other exercises (e.g., core—plank, triceps—push-ups), performance on this exercise task was used to assess *near transfer* of physical training with BET.

Methods

Experimental Approach to the Problem

As per study 1. The study protocol is depicted in the Supplemental Digital Content (see Materials, http://links.lww.com/JSCR/A509).

Subjects

Subjects were 29 (18 female and 11 male) fit and healthy undergraduate student athletes aged 21 ($SD = 2$) years. They were randomly assigned to iBET ($n = 15$) or control ($n = 14$) groups. Inclusion and exclusion criteria were as per study 1. Power was as per study 1.

Physical Tasks

Subjects performed 2 sets of burpees, jump squats, leg raises, press-ups, and plank to failure during pretesting and posttesting. They also performed mountain climbers, a whole-body exercise, to failure at the end of the posttest session. They performed a progressively increasing number of burpees, jump squats, leg raises, and press-ups and a set duration of plank during training. To familiarize participants with the exercises, they watched instructional videos, read written instructions, and were given tips about technique for each exercise. They practiced the exercises and were instructed to keep the same form throughout the study. Performance was measured by the number (n) of repetitions of burpees, jump squats, leg raises, press-ups, press-ups and mountain climbers, and the duration (s) of maintaining a plank. The physical tasks are described in detail in the Supplemental Digital Content (see Materials, http://links.lww.com/JSCR/A512).

Cognitive Tasks

During pretesting, participants performed a set of four 5-minute cognitive tasks, in fixed order: Switched Stop Visual, 2-Back, Multi-Source Interference Task, and Time-Load Dual-Back. This pretest set comprised 2 response inhibition tasks (Switched Stop Visual and Multi-Source Interference Task) and 2 memory updating tasks (2-Back and Time-Load Dual-Back). During training, the iBET group performed an initial set of four 3-minute cognitive tasks followed by a series of 3-minute cognitive tasks before each exercise task, whereas the control group rested for 12 minutes at the start and rested for 3 minutes before each exercise task. The 4 cognitive tasks were the same as those performed during pretesting. During posttesting, participants performed a novel set of four 5-minute cognitive tasks, in fixed order: switched attention task, 4-choice reaction time, Mackworth clock, and rapid visual information processing. None of these novel tasks demanded response inhibition or memory updating executive functions. For each task, they watched instructional videos, read written instructions, and practiced for 1 minute. The cognitive tasks were implemented using the SOMA-NPT app (Soma Technologies, Switzerland). Performance was measured by speed (responses/s), accuracy (% correct), coefficient of variation (%), and response correct score (responses/s). The cognitive tasks are described in detail in the Supplemental Digital Content (see Materials, http://links.lww.com/JSCR/A513).

Training

Both groups completed 12 training sessions: 3 sessions per week for 4 weeks. In each 30-minute session, they performed a sequence of 5 physical tasks (c. 3 minutes) in a fixed order: burpees, plank, jump squats, leg lifts, and press-ups. A periodized physical training schedule was used so that exercise intensity increased each week: 80, 85, 90, and 95% of pretest performance in weeks 1, 2, 3, and 4, respectively. Each physical task was followed by a 3-minute cognitive task (iBET) or rest (control).

The iBET group performed the Switched Stop Visual, Multi-Source Interference Task, 2-Back, and Time-Load Dual-Back every training session. The order of the tasks was reversed each week to counterbalance the design. All tasks imposed high cognitive workloads and required executive functions. The former 2 tasks required response inhibition, whereas the latter 2 required memory updating. The tasks were programmed to run in adaptive mode; every 10 trials, task difficulty increased or decreased (mean interstimulus interval shortened or lengthened) if the percentage of correct responses was equal or greater or less than 80%. The starting intensity (interstimulus interval) increased progressively during training. The control group simply rested.

Measures

Mental fatigue was rated on a CR-10 scale (see study 1). A sessional rating of perceived exertion was obtained using a 6–20 scale (6), anchored by "6 = very, very light" and "20 = very, very hard."

Procedure

In the pretest and posttest sessions, subjects completed one set of (the same) calisthenic exercises before and after completing 20-minute (4 × 5-minute) cognitive tasks. Subjects provided a mental fatigue rating after the cognitive tasks and a sessional rating of perceived exertion after completing the second set of exercises. In the posttest session, they also completed mountain climbers to failure (for details see Materials, Supplemental Digital Content, http://links.lww.com/JSCR/A509), a novel whole-body dynamic exercise task, after the second set of exercises.

Statistical Analysis

As per study 1.

Results

Physical Tasks

Figure 2 summarizes the performance of the physical tasks and sessional rating of perceived exertion of the iBET and control groups. Performance was examined using 2 group (iBET and control)-by-2 test (pretest and posttest) × 2 set (before cognitive task, after cognitive task) ANOVAs. Main Test main effects confirmed that performance improved from pretest to posttest for all exercises: burpees: $F(1,27) = 23.47, p < 0.001, \eta_p^2 = 0.465$; jump squats: $F(1,27) = 19.26, p < 0.001, \eta_p^2 = 0.418$; leg raises: $F(1,27) = 12.24, p = 0.002, \eta_p^2 = 0.312$; press-ups: $F(1,27) = 33.83, p < 0.001, \eta_p^2 = 0.556$; and plank: $F\ (1,27) = 5.96, p = 0.02, \eta_p^2 = 0.181$. Group-by-test interaction effects were found for burpees, $F(1,27) = 10.86, p = 0.03, \eta_p^2 = 0.287$; squat jumps, $F(1,27) = 9.32, p = 0.005, \eta_p^2 = 0.257$; and leg raises, $F(1,27) = 5.16, p = 0.03, \eta_p^2 = 0.160$. This interaction was small-to-medium size for press-ups, $F(1,27) = 2.20, p = 0.15, \eta_p^2 = 0.075$, and was null for plank, $F(1,27) = 0.086, p = 0.78, \eta_p^2 = 0.003$. Simple contrasts confirmed that the groups were the same at pretest for all exercises and that the iBET group outperformed the control group at posttest for burpees, jump squats, and leg raises. Moreover, performance improved from pretesting to posttesting for the iBET group for burpees, jump squats, leg raises, and press-ups, whereas performance improved for the control group for press-ups only. Main effects for set confirmed that exercise performance decreased from the set of exercises completed before the cognitive tasks to those completed after the cognitive tasks in both iBET and control groups for burpees, $F(1,27) = 23.62, p < 0.001, \eta_p^2 = 0.467$ ($M_{\text{before}} = 25.06 > M_{after} = 21.88$), and plank, $F(1,27) = 50.27, p < 0.001, \eta_p^2 = 0.651$ ($M_{\text{before}} = 116.35 > M_{after} = 89.50$). Marginal effects of set were found for jump squats, $F(1,27) = 3.33, p = 0.08, \eta_p^2 = 0.110$ ($M_{\text{before}} = 42.76 > M_{after} = 41.03$); leg raises, $F(1,27) = 3.56, p = 0.07, \eta_p^2 = 0.116$ ($M_{\text{before}} = 42.77 > M_{after} = 40.02$); and press-ups, $F(1,27) = 2.99, p = 0.09, \eta_p^2 = 0.100$ ($M_{\text{before}} = 22.74 > M_{after} = 21.35$). Finally, a 2 group (iBET, control)-by-2 test (pretest and posttest) ANOVA on sessional RPE yielded a main effect for test, $F(1,27) = 6.09, p = 0.02, \eta_p^2 = 0.184$ ($M_{\text{pre}} = 14.99 < M_{post} = 15.71$), but no group effects.

To explore any near transfer associated with training, a 2-group (iBET, control) ANOVA was performed on the number of repetitions to failure of the mountain climber exercises at the end of posttesting. A main effect for group, $F(1,27) = 5.23, p = 0.03, \eta_p^2 = 0.162$, indicated that the iBET group ($M = 96.47, SD = 32.59$) performed more repetitions than the control group ($M = 72.14, SD = 23.62$). This provided evidence for near transfer of training for iBET.

Cognitive Tasks

Table 2 summarizes the posttest novel cognitive task performance of the iBET and control groups. Performance on the switched attention, choice reaction time, Mackworth clock, and rapid visual information processing tasks was examined using a series of 2-group (iBET and control) ANOVAs. With the exception of response speed for the switched attention task (iBET responded faster than control), there were no other group differences. Performance on the pretest cognitive tasks is summarized in Supplemental Digital Content (see Table S1, http://links.lww.com/JSCR/A510). A 2 group (iBET and control)-by-2 test (pretest and posttest) ANOVA on mental fatigue ratings completed after the cognitive tasks analyses yielded a group-by-test interaction effect, $F(1,27) = 19.51, p = 0.02, \eta_p^2 = 0.200$. Simple contrasts indicated that the iBET ($M = 5.30, SD = 0.55$) and control ($M = 5.04, SD = 0.50$) groups were similarly fatigued at pretest ($p = 0.74$), whereas the iBET group ($M = 4.30, SD = 0.57$) were less fatigued than the control group ($M = 6.36, SD = 0.51$) at posttest ($p = 0.008$).

Discussion

In support of our hypotheses, the study findings indicated that BET increased the number of repetitions of the burpees, jump squat, and leg raise exercise tasks and, moreover, was enabled a greater number of repetitions of the novel mountain climber exercise task. Contrary to our hypotheses, the findings indicated that BET did not improve performance of press-up and plank exercise tasks and did not affect response speed, accuracy, and consistency when performing the novel cognitive tasks. These findings suggest that BET improved dynamic exercise but not static exercise performance compared with standard physical training. They also suggest that BET was associated with near transfer of learning to a novel dynamic exercise task. As participants only performed up to 95% of pretest repetitions, the findings suggest that BET may be effective as a tool to facilitate progressive overload.

General Discussion

We explored the effects of intermixed BET—comprising brief memory updating and response inhibition cognitive tasks performed between brief submaximal calisthenic exercises—on subsequent maximal endurance exercise performed to failure. We found that BET improved dynamic but not static exercise

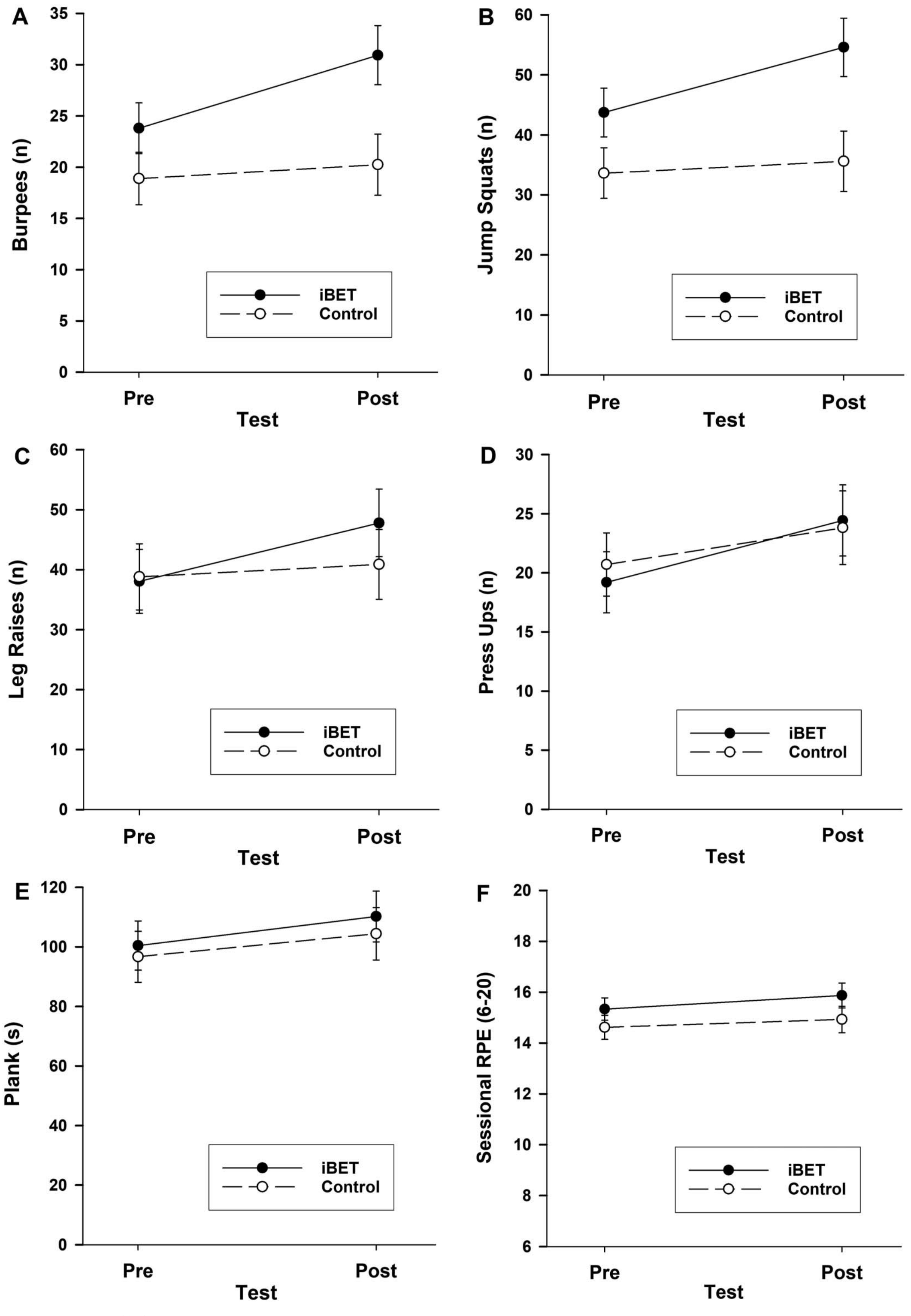

Figure 2. Mean (*SE*) maximal exercise performance to exhaustion and sessional rating of perceived exertion as a function of group (iBET and control) and test session (pre and post) in study 2.

performance compared with physical training alone and, moreover, enhanced novel dynamic exercise performance. We also found that BET improved novel response inhibition cognitive task performance but not novel nonexecutive function cognitive task performance. Accordingly, the current findings add to those of previous studies showing that *prior*, *current*, and *post* BET improved endurance exercise performance and demonstrate near transfer of training in both physical and mental performance domains. Our key findings are discussed in detail below.

Our first study purpose was to investigate the effects of BET on subsequent endurance exercise performance. The pretest to posttest improvement in performance was consistently greater

Table 2

Mean (*SD*) novel cognitive task performance as a function of group (iBET and control) in the posttest in study 2.

Task/measures	iBET	Control	*F*(1, 27)	η_p^2
Switched attention				
Speed (responses/s)	2.42 ± 0.26	2.19 ± 0.25	5.55*	0.171
Accuracy (% correct)	96.60 ± 1.92	96.14 ± 3.21	0.22	0.008
Variation (%)	20.40 ± 7.20	25.07 ± 9.30	2.31	0.079
Choice reaction time				
Speed (responses/s)	2.21 ± 0.21	2.14 ± 0.24	0.76	0.028
Accuracy (% correct)	99.20 ± 0.94	97.07 ± 8.44	0.95	0.030
Variation (%)	14.53 ± 5.33	14.64 ± 8.71	0.00	0.000
Mackworth clock				
Speed (responses/s)	1.64 ± 0.47	1.68 ± 0.50	0.05	0.002
Accuracy (% correct)	55.80 ± 28.44	57.29 ± 30.56	0.02	0.001
Variation (%)	11.33 ± 6.16	17.29 ± 20.90	1.12	0.040
Rapid visual information processing				
Speed (responses/s)	2.25 ± 0.47	2.64 ± 0.63	3.63	0.119
Accuracy (% correct)	82.73 ± 11.08	78.86 ± 9.01	1.06	0.038
Variation (%)	102.00 ± 85.91	119.86 ± 45.64	0.48	0.017

*$p < 0.05$.

after BET than physical training alone: press-ups (study 1: 53% vs. 32%; study 2: 27% vs. 15%), burpees (30% vs. 7%), jump squats (25% vs. 6%), leg raises (26% vs. 5%), plank (study 1: 46% vs. 40%; study 2: 10% vs. 8%), and wall sit (131% vs. 89%). In partial support of our first hypothesis—that BET would improve performance of calisthenic exercises compared with control—we found that BET improved exercise performance more than physical training alone for press-ups, burpees, jump squats, and leg raises but not for plank or wall-sit. In sum, BET enhanced dynamic exercise performance but not static exercise performance compared with physical training alone. This evidence for the physical performance benefits of *intermixed* BET adds to previous evidence, showing self-paced endurance exercise performance is further improved by *prior* BET (9), *concurrent* BET (3,10,18), and *post* BET (25,26). Collectively, this evidence establishes that cognitive loading combined with physical training is a countermeasure that can be used by athletes to improve their self-paced endurance exercise performance. Finally, it is worth noting that externally paced endurance exercise was also improved by *post* BET (25).

It is important to explore the reasons why *iBET* improved most but not all exercises. First, it is possible that BET only enhances self-paced tasks, such as burpees and press-ups. Most previous BET studies (see above) only used self-paced tasks, including cycling, running, and rhythmic handgrip tasks. Evidence suggests that decision making, a key feature of pacing, can be impaired by mental fatigue and exertion (21). Accordingly, BET may improve self-paced dynamic exercise by making decision making (e.g., pacing strategy) resistant to interference from central fatigue and exertion. For instance, BET may have reduced the time-under-tension when performing the exercises, thereby reducing muscular fatigue and allowing participants to complete more dynamic exercises until failure (28). Second, BET may only enhance performance for tasks that are improved relatively little by physical training alone. The relative improvements for the exercises in both studies provided limited support for this explanation. Therefore, the possibility that BET may be more effective for more demanding and well-practiced tasks must await further investigation. Third, it is possible that BET only benefits physical tasks that are vulnerable to mental fatigue. There is mixed evidence regarding the effects of mental fatigue on calisthenic exercise tasks (1,7). We found that exercise performance was worse after completing the 20-minute cognitive tasks for press-ups, wall-sit, and plank (study 1) and burpees, leg raises, and plank (study 2). It also tended to be worse after the cognitive tasks for jump squats and press-ups (study 2). Accordingly, because this necessary condition was satisfied for all the calisthenic exercise tasks, the finding that BET improved press-ups, burpees, jumps squats, and leg raises but not plank and wall sits cannot be accounted for by this factor. However, there is evidence to suggest that maximal isometric exercises, such as wall-sit and plank, are relatively unaffected by mental fatigue (19), and thus, a potential reason why BET only improved the performance of the dynamic exercises is because they represent a submaximal form of exercise. In conclusion, the current findings point to a key role played by pacing during exercise and its improvement by BET. Nevertheless, the extent to which BET can benefit performance of other physical tasks remains to be established by further research studies.

Our second study purpose was to explore changes in perception of the physical tasks as a function of training. Contrary to our second hypothesis—that BET would reduce perceived exertion associated with performance of calisthenic exercises compared with control—we noted that the rating of perceived exertion associated with performing the calisthenic exercises was not different after iBET compared with standard training (cf Ref. 23). Specifically, perceived exertion did not change with training in study 1 (it was 2% lower for iBET and 2% higher for control), whereas sessional perceived exertion unexpectedly increased with training in study 2 (it was 3% higher for iBET and 2% higher for control). Based on the ratings of perceived exertion at pretest and posttest (Figures 1D and 2F), participants in both the iBET and the control groups perceived that the calisthenic exercises required exertion that was "*very strong*" (study 1) and "*hard*" (study 2) (18) (Borg, 1982). The lack of substantive differences in perceived exertion between groups (and tests) may be explained by the nature of the exercise, with all being maximal tests to failure and with all participants willing to exert the same level of effort. It has been suggested that perceived exertion is a key limiting factor in endurance exercise performance (17). Based on this premise, we expected that improvements in exercise performance after iBET would be accompanied by reductions in perceived exertion. However, the current studies provide no evidence to support this putative mechanism underlying improved performance with BET. In line with the current evidence, past studies have also noted that performance improvements after BET were not accompanied by lower ratings of perceived exertion (9,10). It is worth mentioning that when exercising at a fixed workload at the start of a maximal cycle time to exhaustion or time trial, the BET group reported lower ratings of perceived exertion compared with a control group (18,25). Moreover, perceived exertion increased similarly during the maximal test in both groups, peaking earlier in the control group than the BET group. Another concurrent BET study reported lower perceived exhaustion during the cycling task (3). It is also worth noting that mental fatigue is a transient state that can be reduced by exercise; undertaking physical activity can increase the peripheral level of dopamine concentration (4), which has been proposed to negate the effects of mental fatigue (2). Because the current studies and some of the previous BET studies (9,10) assessed perceived exertion upon completion of the maximal exercise tests, it is possible that perceived exertion played a contributory role *during* exercise, as more dynamic calisthenic exercises were performed in the BET groups, for the same level of exertion, as in the control groups. This possibility must await the findings of BET studies that assess perceived exertion before, during, and after exercise in the posttraining assessments. Nonetheless, the interpretation of subjective self-reported measures of mental exertion remains ambiguous without corroboration from (neuro)physiological measures.

Our third study purpose was to explore changes in performance of cognitive tasks as a function of training. In support of our hypothesis—that BET would improve cognitive performance compared with control—we found that response speed was faster and variation lower on the repeated 2-back memory updating task and the novel AX CPT vigilance task after iBET than control in study 1. Contrary to our hypothesis, we found that responses did not differ between iBET and control on the novel switched attention (attention), choice reaction time (decision making), Mackworth clock (vigilance), and rapid visual information processing (attention) tasks. The former evidence adds to previous research findings showing that BET improves cognitive performance on a variety of cognitive domains find broad agreement with previous studies showing improved memory updating after concurrent (10) and prior BET (9). In sum, the current studies provide evidence that BET facilitates transfer of learning to a novel cognitive task, when the novel task shares core elements with the cognitive tasks used during training (i.e., the tasks involve the same executive function—response inhibition) but not when the novel task does not share such core elements (i.e., train on executive function tasks but tested on nonexecutive function tasks). In other words, there is near transfer but not far transfer with BET. In line with our hypothesis—that BET would reduce mental fatigue elicited by the cognitive task compared with control—we found that the iBET group reported less mental fatigue after the novel 20-minute cognitive tasks in posttesting compared with control (study 2). This finding provides partial evidence that BET improved mental fatigue resistance. However, this interpretation must be tempered by our unexpected finding, contrary to our hypothesis, that the iBET group reported more mental fatigue after the 20-minute cognitive task in posttesting compared with control (study 1). The latter unexpected result may have been because the improved cognitive performance of the BET group came at a cost of greater mental fatigue because of their greater response processing.

Our fourth study purpose was to investigate whether BET improved novel endurance exercise performance. The iBET group performed 34% more repetitions to failure of the mountain climber exercises than the control group. In support of our hypothesis—that BET would improve performance of a novel calisthenic exercise task compared with control—we found that the iBET group completed more repetitions until failure of mountain climbers, a whole-body calisthenic exercise, compared with the control group. This evidence extends the physical performance benefits of BET to the near transfer of learning to other forms of endurance exercise performance. This is the first such evidence, to our knowledge, that BET can be used to improve the performance of exercises that were not included in the exercise training program.

The current studies have given us some important new insights regarding BET. However, interpretation of the findings should consider potential study limitations. First, ours are the first study to evaluate *intermixed* BET and therefore direct comparison with the findings of other research studies must await replication. Second, training lasted 4 weeks and comprised a dozen 30-minute sessions. It is possible that *iBET* over an extended training period, with longer sessions, and with longer bouts within each session may improve exercise performance on static tasks such as the wall-sit and plank. Third, performance on the exercise tasks was assessed shortly after completion of training. It is therefore the extent to which the benefits of BET persist remains to be determined by studies that incorporate follow-up assessments. Fourth, we assessed exertion and fatigue using self-report measures, which, despite being practical (22), do not provide any physiological insights. Future studies could supplement these ratings with neurophysiological measures, such as heart rate variability, eye movements, and brain oscillations, to corroborate the self-report assessments. Finally, we did not record the weight of our subjects. It is possible that changes in weight could have influenced changes in exercise performance.

In conclusion, the current studies, which were the first to investigate the effects of completing brief mentally fatiguing cognitive tasks after and before bouts of calisthenic exercise, showed that intermixed brain endurance training (*iBET*) improved subsequent physical endurance performance of familiar and unfamiliar dynamic exercise tasks but not static exercise tasks relative to physical training alone.

Practical Applications

Athletes and sports science support staff (e.g., strength and conditioning coaches), looking to further improve self-paced dynamic exercise performance should consider the addition of mentally demanding cognitive tasks interleaved between sets during their physical training. The novel information yielded by our studies could help strength and conditioning coaches to better understand the impact of mental fatigue on exercise performance and, moreover, help guide their training sessions to consider the utility of BET as a training method to help their clients practice and ultimately perform better.

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