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Exercise and caffeine improve sustained attention following fatigue independent of fitness status

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Background: Exercise improves cognition, but whether fitness status and caffeine modulate this effect remains unclear. Purpose: To determine if sustained attention is improved following exercise with and without caffeine in endurance-trained vs. sedentary adults. Methods: A continuous performance task (CPT), that is, a 20 min measure of sustained attention to assess accuracy and precision, was used to induce mental fatigue. Following the 20 min CPT, trained (n = 12) and sedentary (n = 12) participants completed either 30-min rest or 30-min moderate-intensity cycling below lactate threshold. Exercise trials were completed with placebo and caffeine (3 mg/kg) followed by cycling to volitional fatigue. Results: Exercise, as compared to rest, improved (p < .05) accuracy and precision after a mentally fatiguing task (CPT) and was not different between endurance-trained and sedentary groups. During the CPT, accuracy and precision declined (p < .05) with placebo, but both were maintained with caffeine following both exercise and cycling to volitional fatigue. Mental energy declined (p < .05) after the CPT with placebo but not caffeine. Cycling to volitional fatigue resulted in lower mental energy/greater mental fatigue as compared to baseline and following moderate intensity exercise, for both caffeine and placebo (p < .05). Conclusions: Exercise improved sustained attention following a mentally fatiguing attentional task independent of fitness status; and, when coupled with caffeine, provided greater benefit on the attentional task for accuracy, precision, and mental energy. Although caffeine’s beneficial effect on sustained attention persisted after cycling to volitional fatigue, it did not prevent a decline in mental energy/increase in mental fatigue.

Keywords: perception; ergogenic aids; cognitive function; brain

Introduction

Fatigue may be manifested by an increased perception of effort to complete a task or the inability to sustain a task. Mental fatigue has previously been defined as a “psychobiological state caused by prolonged periods of demanding cognitive activity” and “characterized by subjective feelings of lack of energy” [1,2]. Surveys conducted within the US workforce [3] indicate a 38% prevalence of fatigue, with 66% of these workers reporting lost productivity time, resulting in an overhead cost to employers of >$100 billion annually. Mental fatigue can be observed by the impairment of

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cognitive function, particularly tasks that require sustained attention or the ability to direct and focus cognitive ability over a period of time.\[1,4,5\]

The acute effect of exercise on cognition and perceived energy appears beneficial \[6–8\] due to increased neural activity,\[9\] arousal, and allocation of neural resources.\[10–13\] Sustained attention, one aspect of cognition that reflects energy and fatigue processes,\[14\] is improved immediately following exercise\[15\] along with self-assessed feelings of energy.\[6\] However, the optimal exercise intensity that elicits greater perceived energy and sustained attention is unclear. High-intensity activity may result in feelings of physical fatigue that persist after exercise, masking potential reductions in mental fatigue or increases in positive affect that have been observed after low-moderate-intensity exercise.\[6,16\]

Fitness status may also influence the emotional or psychological response to exercise of varying intensities.\[12\] About 20–60 min of moderate-intensity exercise near lactate threshold (LT) consistently improves simple and complex cognitive tasks in trained individuals;\[13\] whereas, less fit individuals may experience greater anxiety during or after high-intensity exercise, contributing to lower task performance.\[17,18\] Training status may influence brain hemodynamics and neural activity associated with impairment in certain cognitive tasks in untrained (vs. trained) individuals participating in high-intensity exercise.\[19\] However, the basis to prescribe an exercise intensity that elicits similar efforts across groups of individuals with different fitness status is a design issue that has been primarily addressed by utilizing either relative oxygen uptake or maximum heart rate.\[20\]

In addition to exercise, caffeine may also benefit cognition and perception \[21–24\] through psychological effects serving to enhance task persistence and determination \[25,26\] and physiological effects in the central nervous system (CNS). Caffeine acts as a stimulant potentiating sympathetic activity, may reduce mental fatigue,\[27\] and improves higher order cognitive measures such as sustained attention \[23,24,27,28\] with a concomitant increase in perceived mental energy.

Therefore, acute exercise and caffeine ingestion may each influence the CNS resulting in attenuated mental fatigue and improved attention. The interactions of these and other modulating factors (i.e. fitness status, exercise intensity, and physical fatigue) on mental fatigue, mental energy, and attention remain to be clarified. Thus, our purpose was to determine: (1) the effect of moderate-intensity exercise on sustained attention, using individual LT as the basis for exercise prescription, in comparison to a similar duration of seated rest in endurance-trained vs. sedentary adults; and (2) whether caffeine ingestion provides additional benefit to sustained attention, perceived mental energy, and mental fatigue when combined with exercise.

We hypothesized that moderate-intensity exercise would benefit sustained attention independent of fitness status; however, unlike trained individuals, sedentary subjects would experience impaired attention following exercise performed to fatigue. Furthermore, we also hypothesized that, compared to non-caffeinated placebo, caffeine would maintain sustained attention and, when combined with exercise, would maintain sustained attention and associated perceptual measures (mental energy and mental fatigue) for all subjects.

**Methods**

**Participants**

Twelve endurance-trained males \((n = 10)\) and females \((n = 2)\) and an equal number of healthy sedentary males and females volunteered for this study. Participants provided
written informed consent as approved by the University Institutional Review Board. Physical characteristics of subjects are presented in Table 1. Endurance-trained participants were recruited from the local endurance sports community and reported training ≥ six hours per week. Sedentary participants were recruited from the college campus and spent ≤ 60 min per week in low intensity activity (e.g. riding a bike to class) and did not participate in any regular exercise. Exercise training history via a screening questionnaire and VO\textsubscript{2} peak criteria (< 50 ml/kg-min for sedentary men, < 40 ml/kg-min for sedentary women) stratified participants into groups. One sedentary male was slightly above this cut point for VO\textsubscript{2} peak but his activity status was verified as meeting sedentary criteria.

Typical weekly physical activity was also validated using the Core and Expanded Physical Activity STEPS version 2.0 Instrument.[29] Trained and sedentary individuals were matched pairwise by gender, age (within 3 yr), and Body Mass Index (BMI) (within 2 kg/m\textsuperscript{2}) and, thus, groups differed (p < .05) only in body composition (% body fat), maximal aerobic capacity (VO\textsubscript{2} peak), %VO\textsubscript{2} peak elicited at LT and minutes of exercise per week. Groups were similar in non-exercise physical activity (i.e. transport activities such as walking).

All subjects completed a health-history screening questionnaire and typical caffeine usage questionnaire for a seven-day period [30] to ensure that they met all inclusion criteria. Exclusion criteria eliminated subjects who were either naïve to caffeine or on the “high” range [31,32] of caffeine use (i.e. consuming > 500 mg /day). The trained group tended to have higher reported habitual caffeine intake than sedentary subjects, but the groups were not significantly different (Table 1) and all participants were considered low-to-moderate caffeine users. These classifications also appear to be physiologically valid based on brain activation [32], not just population normative values.

### Research design

Each subject served as his or her own control performing four prolonged exercise trials consisting of a 20 min mental task followed by 30 min moderate exercise (EX) and subsequent to cycling to volitional fatigue. Two of the trials were with caffeine and two with placebo. A “placebo effect” may factor into treatment studies, particularly for individuals who have expectations that caffeine is beneficial. Thus, in order to address placebo effects and minimize potential day-to-day variation in mental fatigue or learning effects, we utilized a double-blind, crossover design with treatment order assigned using a Latin Squares method. Mean scores were averaged across two

<table>
<thead>
<tr>
<th></th>
<th>Endurance-trained (n = 12)</th>
<th>Sedentary (n = 12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>27.7 ± 5.5</td>
<td>26.8 ± 7.0</td>
</tr>
<tr>
<td>BMI (kg/m\textsuperscript{2})</td>
<td>23.1 ± 2.1</td>
<td>23.7 ± 2.9</td>
</tr>
<tr>
<td>Body fat (%)</td>
<td>14.1 ± 5.8</td>
<td>22.6 ± 10.1*</td>
</tr>
<tr>
<td>VO\textsubscript{2} peak (ml/kg-min)</td>
<td>55.6 ± 8.5</td>
<td>38.2 ± 9.1*</td>
</tr>
<tr>
<td>%VO\textsubscript{2} peak at LT</td>
<td>75.7 ± 10</td>
<td>67.5 ± 9.1*</td>
</tr>
<tr>
<td>Weekly physical activity (min/wk)</td>
<td>753 ± 364</td>
<td>44 ± 59*</td>
</tr>
<tr>
<td>Caffeine intake (mg/d)</td>
<td>225.7 ± 183.0</td>
<td>102.8 ± 105.2</td>
</tr>
</tbody>
</table>

*p < .05.
caffeine + exercise and two placebo + exercise trials to reduce variability and bias from either subject or investigator.

In order to compare passive “recovery” following a 20 min mental task, a subgroup of subjects (n = 20) performed a 5th control REST trial with placebo. This control trial (Figure 1, top boxes) was identical to the first portion of the exercise trials through 30 min of moderate exercise with placebo; but, instead subjects sat quietly (performing no mental work) for 30 min. The control trial was not “blinded” or fully counterbalanced among the four exercise trials.

**Preliminary testing and familiarization protocol**

On the first laboratory visit, body mass and height were measured and body composition (% body fat) estimated using the GE Lunar Prodigy Dual X-Ray Absorptiometry scanner (GE Healthcare, Hatfield, UK). Then, participants completed a ramped exercise protocol of cycling to volitional fatigue on an electrically braked Lode Excalibur Sport cycle ergometer (Lode, Groningen, Netherlands) to assess VO$_2$ peak. Participants warmed up for 5 min between 50 and 100 W, followed by workload increases of 25–50 W every 2 min until volitional fatigue. Gas exchange data were obtained using the ParvoMedics True One 2400 metabolic cart (ParvoMedics, Sandy, UT, USA) and rating of perceived exertion (RPE) [33] recorded every min. Subjects met criteria for a maximal test based on similar peak respiratory exchange ratio (1.16 ± 0.05, 1.15 ± 0.11) and RPE (18.3 ± 1.7, 17.7 ± 2.4) for trained and sedentary, respectively. After a cool down, participants were familiarized with the cognitive task.

In order to assign comparable exercise workloads for sedentary and trained individuals, each participant’s LT was determined on the second visit, using a ramped cycling protocol. Participants began cycling at 50 W and workload increased by 25–50 W every 3 min [34] until reaching a RPE of 16–17 (“Hard to Very Hard”). Blood lactate was measured at baseline and following each stage using 0.3 µL blood samples obtained from the ear lobe (Lactate Pro LT-1710 analyzer, Arkray, Japan). Each individual’s LT was determined using the DMax method [34,35] to calculate a
moderate (10% < LT) and vigorous (5% > LT) intensity workload for the 30-min moderate EX and time to cycling to volitional fatigue portions of the protocol, respectively.

After the LT test, participants cooled down before being familiarized with the pre-determined moderate and vigorous workloads for 10 min. If, during familiarization, RPE reached > 16 ("very hard") during moderate and/or > 18 ("extremely hard") during vigorous, or the subject felt uncomfortable with the workload, it was adjusted by 5% until the subject reported a RPE in the target range (below "somewhat hard") for moderate and ("hard") for vigorous. Workload adjustments were made for four trained and three sedentary participants. All pretest instructions (obtaining adequate sleep, hydration, and refraining from caffeine intake and exercise prior to subsequent experimental sessions) were given to subjects. Trained participants continued to engage in their typical endurance training over the course of the study; however, we requested that they refrain from exceptionally strenuous training or racing in the three days prior to experimental sessions, similar to pre-race preparation.

**Experimental protocol**

The next 5 visits (4 exercise visits, 1 resting control visit) were each separated by a minimum of 7 d and scheduled at the same time of the morning following an overnight fast. Before each visit, participants refrained from exercise for 24 h and caffeine for 12 h. Upon arrival to the lab, a 24 h diet recall, 24 h history questionnaire, and visual analog scales (VASs) for rating perceived mental energy and fatigue were completed. Reported hours of sleep prior to each trial was similar between trained and sedentary subjects (7.0 ± 0.6 h and 6.9 ± 0.6 h) and prior to caffeine (6.8 ± 0.6 h) and placebo (7.0 ± 0.7 h) trials. To simulate the practical scenario of the “fed state”, a nutritional bar (PowerBar® Harvest Energy, PowerBar USA, Florham Park, NJ) was given along with treatment beverages. The bar contained 250 kcal, 5 g fat, 42–43 g carbohydrate, 9 g protein, no caffeine, and given in complete packaging so participants could view the nutrition facts label. After the first visit, the 24 h diet recall was copied and returned to the participant to use as a guide for replicating 24 h dietary intake before the subsequent visits.

The schematic of the test protocol is illustrated in Figure 1. In the control trial (Figure 1, top boxes) comparing 30 min REST vs. EX, placebo was given 20 min prior to a continuous performance task (CPT). Following a 20 min CPT, participants completed 30 min of quiet REST or EX before repeating a 5 min CPT. EX consisted of 30 min moderate-intensity cycling (10% < LT) designed to elicit RPEs below 13 or “somewhat hard” which was accomplished (12.4 ± 1.2 and 12.0 ± 0.9 for sedentary and trained, respectively).

In the full exercise experimental protocol (Figure 1, timeline), two caffeine + exercise and two placebo + exercise trials were completed. In order to give sufficient time for caffeine absorption [36,37], participants waited 20 min following treatment ingestion prior to completing the initial CPT. Following the 20 min CPT, 30 min EX was completed and followed by a 5 min CPT. Then, a subsequent cycling task at an intensity 5% > LT to volitional fatigue was completed, eliciting an overall RPE of ~16 or “hard” for both groups. The point of cycling to volitional fatigue was defined as voluntarily termination of exercise at participants’ request and/or the inability to maintain a minimum cadence of 40 rpm. Cycling time to volitional fatigue was typically < 30 min for trained (23.8 ± 8.1 min) and sedentary (24.1 ± 11.3 min) subjects, but mean workload was lower by ~80 W in sedentary. Following cycling to volitional fatigue, participants repeated a final 5 min CPT.
Treatment ingestion

Fruit punch solutions were manufactured and provided (Glaceau Vitaminwater®, Whitestone, NY) in de-identified containers with either 0.34 g/L caffeine or placebo to maintain blinding of the investigators. Fluid volumes were administered based on individual’s body mass to provide ~3 mg/kg caffeine or equivalent placebo (464 ± 85 ml prior to moderate exercise or rest). This amount of caffeine (~218 mg) is similar to the average reported intake of adults in the USA. A dose of 3 mg/kg of caffeine has been observed to be efficacious for mental tasks and ingestion was timed in order to potentially observe caffeine effects toward the latter half of the 20 min CPT (30–40 min after ingestion). During moderate EX, three 25 ml boluses were given (25.5 mg caffeine in caffeine + exercise) and another 25 ml bolus to minimize “dry mouth”, offset sweat loss and ensure a 3 mg/kg caffeine dose prior to starting the ride to cycling to volitional fatigue.

Dependent variables

State-Trait Energy and Fatigue (STEF) Scale

The STEF subjective survey instrument, a 10 cm VAS, assessed the intensity of “state of mental energy and fatigue” [24] when participants arrived to the lab prior to treatments and immediately after each CPT. Mental energy subscales included “energetic, vigorous, and full of pep” items and mental fatigue subscales included “fatigued, exhausted, and worn-out” items. Low and high VAS anchors referred to the absence of a feeling or to the strongest feeling ever felt, respectively. Subscale items were summed and averaged to generate a numerical score for mental energy and mental fatigue.

Continuous performance task

We administered a version of the CPT programmed and presented with MATLAB® v2011 (MathWorks, Natick, MA, USA). This task requires sustained attention, working memory, response inhibition, and error monitoring, and has been used in other motor-related and exercise studies to induce mental fatigue. During the task, a series of letters were visually presented in the middle of a computer screen for 0.6 s and participants were instructed to click a computer mouse upon seeing the target letter “T”. Participants were seated at a standard computer desk with the desktop monitor a fixed length from the chair and consistent lighting for all trials. The task and order of letter presentation was fixed and identical across all trials. The remaining letters of the alphabet served as non-target probes. Attention was required to click on target letters (true positives) while inhibiting response to non-targets. Letters were 1.5 in. in height and appeared in white capital font on a black background at a rate of 1.67 Hz or 100 letters/min. Each 5 min epoch consisted of 500 letters, 127 target letter “T”s of which 59 were preceded by a bait letter “S”, and 373 non-targets of which 14 were preceded by the bait letter “S”. Signal detection sensitivity was 0.81 indicating participants were sensitive to the difference between targets and non-targets.

Dependent variables obtained from the task were true positives (TP), true negatives (TN), false positives (FP), and false negatives (FN). Response accuracy was calculated as = (TP + TN)/(TP + TN + FP + FN) and precision = TP/(TP + FP). Together, accuracy and precision were used as measures of sustained attention. Reduced inhibition and
increased FP would be reflected in lower precision. Although we did not specifically program for reaction time, it is indirectly assessed in this task. Impaired reaction time would result in FN and possibly additional FP, thus lowering accuracy and/or precision. Accuracy and precision were averaged over 5 min blocks but comparisons were ultimately based on: (1) first 5 min of 20 min CPT (Baseline-CPT), (2) last 5 min of 20 min CPT (Post-CPT); and (3) the 5 min CPT after REST or EX; or, after cycling to volitional fatigue. The relative change over two time points was calculated for accuracy and precision using the equation: \((\text{Post} - \text{Pre})/\text{Pre} \times 100\), where “Pre” is the earlier time point; and, “Post” is the later time point.

**Statistical analyses**

Data are reported as mean ± standard deviation (SD) and were analyzed using SPSS 17.0 (Chicago, IL). Three-way (group x condition x time) mixed model repeated measures ANOVA (between-subject factor: trained vs. sedentary group; within-subject factor: REST vs. EX condition) was used to examine differences in accuracy, precision, perceived mental energy and fatigue in control REST vs. a single placebo + exercise trial. Three-way (group x treatment x time) mixed model repeated measures ANOVA (caffeine vs. placebo as the within-subject factor) was used to examine differences in accuracy, precision, perceived mental energy and fatigue in caffeine + exercise vs. placebo + exercise trials. The Greenhouse–Geisser correction was used to account for the sphericity assumption of unequal variances across groups.

If a significant F-ratio was obtained, the Bonferroni post hoc test was used to detect significant differences in pairwise comparisons. Two-way (between factor condition or treatment; within factor time) repeated measures ANOVA with Bonferroni post hoc pairwise comparisons at each time point and between time points were used to examine differences in mental energy, mental fatigue, and, when significant interactions were present, for accuracy and precision. Pearson product moment correlations were used to examine if habitual caffeine intake was associated with dependent variables. Statistical significance was set at an alpha level of \(p < .05\).

**Results**

**Effect of 30 min moderate exercise (EX) vs. REST control on sustained attention**

Changes in accuracy and precision on the CPT in the EX and REST control trial were not significantly different between sedentary and trained groups \((p \geq 0.60)\). There was a significant main effect for time \((F(2,36) = 20.57, p < .001, \eta^2 = .53)\) and, a significant condition x time interaction for accuracy \(F(2,2) = 4.23, p = .02, \eta^2 = .19\). Accuracy declined during the initial 20 min CPT to a similar degree in both sedentary and trained conditions. Accuracy declined \((p < .001)\) from Baseline-CPT to Post-CPT prior to 30 min REST (Relative Δ score of \(-4.5 \pm 4.6\%\)) and prior to EX \((-5.0 \pm 4.7\%\)). Compared to Post-CPT, the improvement in accuracy was higher \((p = .03)\) after EX as compared to after REST (Figure 2), although absolute accuracy score was not different \((p = .41)\) between conditions. EX and REST both restored accuracy to the Baseline-CPT.

There was also a significant main effect for time on CPT precision \((F(2,36) = 12.04, p < .001, \eta^2 = .40)\) and, a significant condition x time interaction \((F(2,23) = 5.52, p = .02, \eta^2 = .24)\). Unlike accuracy, precision declined significantly \((p < .001)\) during
the initial 20 min CPT in the trial preceding the EX condition but not prior to REST ($p = .08$). Compared to Post-CPT, the improvement in precision was higher ($p = .03$) after EX compared to REST (Figure 3, bottom panel). EX and REST both restored precision to their respective Baseline-CPT levels.

**Effect of caffeine combined with EX and cycling to volitional fatigue on sustained attention**

Changes in accuracy and precision on the CPT attentional task in response to caffeine and placebo treatments were not significantly different between sedentary and trained
groups \((p \geq .30)\). Thus, treatment and time effects were analyzed with all subjects combined to compare caffeine vs. placebo on sustained attention before and after exercise (Figure 3).

There was a main treatment effect with caffeine eliciting higher overall accuracy \((F(1,22) = 13.06, p = .002, \eta^2 = .37)\) and precision on the CPT \((F(1,22) = 12.98, p = .002, \eta^2 = .37)\) compared to placebo. There was also a treatment x time interaction for accuracy \((F(3,66) = 8.59, p < .001, \eta^2 = .28)\) and precision \((F(3,66) = 8.40, p < .001, \eta^2 = .28)\). No differences for accuracy and precision were present at Baseline-CPT. At Post-CPT, caffeine maintained accuracy and precision relative to Baseline-CPT; whereas with placebo, accuracy \((p < .001)\) and precision \((p < .001)\) both declined.

Figure 3. Treatment effect (caffeine (CAF) vs. placebo (PLA)) and exercise effect (mean accuracy (top graph) and precision (bottom graph)). *\(p < .05\): difference between CAF and PLA. #\(p < .05\): post-exercise vs. pre-exercise time points for CAF and PLA.
Thereafter, accuracy remained significantly higher (a) with caffeine vs. placebo after EX ($p = .02$) and (b) after cycling to volitional fatigue ($p = .04$). Precision also remained significantly higher (a) with caffeine vs. placebo after EX ($p = .03$) and (b) after cycling to volitional fatigue ($p = .04$). Significant caffeine effects ($p < .002$) were observed for all components of accuracy and precision (TP, TN, FP, and FN) in all subjects. There was also a main effect of time for accuracy ($p < .001$, $\eta^2 = .59$) and precision ($p < .001$, $\eta^2 = .58$). For both caffeine and placebo, accuracy ($p \leq .005$) and precision ($p \leq .006$) were higher after both EX and cycling to volitional fatigue compared to both pre-exercise time points.

Figure 4. Mean ratings for mental energy by group (top graph) and treatment (bottom graph). Top graph, *$p < .05$ Top: trained vs. sedentary groups. #$p < .05$ Top: post-exercise vs. pre-exercise time points for CAF and PLA. Bottom graph, *$p < .05$: difference between caffeine (CAF) and placebo (PLA). #$p < .05$: post-exercise vs. pre-exercise time points for CAF and PLA.
Effect of fitness status, caffeine, and exercise on perceived mental energy

Ratings of mental energy over time were not different between trained and sedentary groups ($p = .09$). There was a significant group x time interaction ($F(2,43) = 3.67$, $p = .04$, $\eta^2 = .14$) (Figure 4, top graph) due to higher pre-treatment mental energy ratings for sedentary ($p = .01$) compared to trained subjects. This group difference remained at Post-CPT ($p = .04$) independent of treatment. For trained individuals, a significant time effect ($p = .03$) indicated that mental energy was significantly higher ($p \leq .01$) after EX and cycling to volitional fatigue compared to both pre-exercise time points. For sedentary subjects, mental energy did not change after EX compared
to pre-treatment and Post-CPT; but, mental energy was significantly lower \((p < .05)\) after cycling to volitional fatigue compared to all previous time points (Figure 4, top graph).

There was a significant treatment x time interaction \((F(3,66) = 4.87, p = .004, \eta^2 = .18)\). Thus, caffeine mitigated the decrease in mental energy from pre-treatment to Post-CPT that occurred with placebo (Figure 4, bottom graph). However, mental energy decreased with both caffeine \((p = .02)\) and placebo \((p = .007)\) between EX and cycling to volitional fatigue.

**Effect of fitness status, caffeine, and exercise on perceived mental fatigue**

Ratings of mental fatigue over time were similar between trained and sedentary participants \((p = .57)\), but there was a significant group x time interaction \((F(3,56) = 5.16, p = .003, \eta^2 = .19)\) (Figure 5, top graph). In comparison to trained participants, sedentary participants reported significantly higher mental fatigue after cycling to volitional fatigue compared to all previous time points \((p < .01)\).

Because there was no between-group difference in ratings of mental fatigue, treatment and time effects were analyzed with all subjects combined to compare the effect of caffeine vs. placebo. There was no treatment effect \((p = .90)\) or treatment x time interaction \((p = .06)\), but there was a time effect \((F(3,66) = 11.75, p < .001, \eta^2 = .35)\). Thus, after cycling to volitional fatigue, mental fatigue was rated significantly higher \((p < .05)\) compared to all previous time points with both caffeine and placebo (Figure 5, bottom graph).

**Potential influence of habitual caffeine intake**

Habitual caffeine intake was not significantly related to accuracy \((r = .02, p = .94)\) or precision \((p = .97)\) at Baseline-CPT or Post-CPT \((p \geq .19)\) when consuming placebo. Habitual caffeine intake was also not related to pre-treatment mental fatigue \((p = .47)\), but the correlation with pre-treatment mental energy approached significance \((r = -.40, p = .05)\). The relationship between habitual caffeine intake and mental energy Post-CPT (with placebo) was not significant \((r = -.34, p = .10)\).

**Discussion**

Our results highlight that 30 min of moderate-intensity exercise below LT restores sustained attention after a mentally fatiguing task faster than 30 min of rest for individuals with either high or low fitness levels. Moreover, sustained attention following vigorous exercise above LT to the point of physical fatigue remained higher compared to pre-exercise and did not differ with the fitness level. Furthermore, compared to placebo, caffeine attenuated the decline in accuracy and precision observed during a mentally fatiguing task and this benefit persisted when coupled with exercise even to the point of physical fatigue, independent of fitness status. However, caffeine could not preserve perceived mental energy at the point of physical fatigue.

These findings contrast with others \([20,42]\) reporting that high-intensity exercise impairs cognitive function in lower fit individuals. This may be due to our exercise prescription using a similar relative intensity based on LT and/or the administration of our cognitive task 10 min after exercise rather than during exercise.\([20,42,43]\)
Acute exercise and cognition

Acute exercise has a small but significant benefit to improve cognition.[12,43–45] However, there are a variety of moderating factors [10,11,45] which influence the magnitude of this effect such as mode of exercise (i.e. smaller effect in running vs. cycling), the type of cognitive task (i.e. smaller effect on processing tasks vs. memory tasks), duration of exercise,[46] and timing of the task following exercise. In addition, research designs that lack a control rest condition [12] result in an overestimation of the exercise effect.[12,47] The present study suggests that, compared to rest, 30 min of moderate-intensity exercise has a moderate ($d = 0.73$, $p = .01$) effect on accuracy during a task requiring sustained attention. This effect has been attributed to exercise-induced arousal and allocation and activation of processing resources in prefrontal brain areas following moderate-intensity exercise. By comparison, decreased brain activation is observed following rest.[48]

The duration of this benefit to restore sustained attention following mental fatigue, however, is unclear since only one post-exercise assessment was performed. The larger effect size in the present study could be due to a more homogeneous setting of the moderate exercise intensity, the nature of the cognitive task (sustained attention), and/or the optimal duration of the exercise bout recently observed to be between 10 and 45 min.[46]

Other factors contributing to the magnitude of the acute exercise effect on cognition include exercise intensity and differences in participants’ fitness status.[12] An “inverted-U curve” has been suggested to describe the relationship between exercise intensity and cognition; specifically, cognitive performance improves with moderate intensities but deteriorates at high exercise intensity.[49] The aerobic vs. anaerobic contribution to energy at different workloads may differ between groups when workloads are based on %HR or %VO$_{2\text{max}}$ (rather than LT), which are likely to influence factors related to fatigue, perception, arousal, and task performance.[12] Therefore, to better understand the interaction between exercise intensity and fitness status on cognitive function, workloads need to be comparable across groups. Since sedentary participants typically reach LT at a lower exercise intensity (based on HR or VO$_{2\text{max}}$) compared to higher fit participants,[50] the use of LT to prescribe exercise intensities across groups is advantageous.

In the present study, we did not observe an “inverted-U” type of phenomenon in either group after exercise intensity on a fixed percentage of the LT. Our findings are in contrast to evidence suggesting that, compared to athletes, untrained individuals experience cognitive decrements, at higher exercise intensity ($>\sim60\%$ HR$_{\text{max}}$).[20,42] A limitation in these studies is that fitness characteristics (i.e. VO$_{2\text{max}}$ and LT) are often not measured,[20] making it unclear if the required perceived efforts between the groups were truly “equivalent”. However, since our participants did not perform the cognitive task during exercise, this may have masked potential impairments in sedentary participants since positive effects are more likely similar across fitness levels when cognitive performance is assessed following exercise.[43] Individuals of lower fitness may require more cognitive resources than physically fit individuals to sustain exercise, leaving fewer neural resources available for the less fit to perform cognitive tasks during high-intensity exercise.[43] Yet, we did not observe this when perceived efforts were comparable across high and low fit groups.
Perceived energy and fatigue related to fitness status

Although the present study observed no impact of fitness status on cognitive performance, the groups differed in their ratings of perceived energy and fatigue in response to exercise. However, trained subjects rated lower mental energy compared to sedentary prior to ingesting treatments or engaging in any tasks. We did not anticipate this difference since chronic aerobic training improves mood and feelings of mental energy and fatigue.[51] This between-group difference is a limitation in evaluating fitness status as a factor that influences perceptions related to mental tasks followed by varying intensities of exercise.

After exercise to physical fatigue, a change in perceived mental fatigue was more pronounced in sedentary compared to trained participants. This appears consistent with investigations indicating that lower fit individuals may require greater mental resources or increased effort to complete mental tasks due to lasting effects of a fatiguing physical task.[13,16,52–54] Other evidence also suggests an emotional response to exercise of moderate vs. high intensity may differ based on training status, possibly affecting cognitive resource allocation, motivation, and effort to maintain engagement in a task during exercise.[13,16,52] It is possible that variable time to volitional fatigue protocols without a definite endpoint may elicit greater perceived mental fatigue and less perceived energy following exercise compared to fixed-length exercise stimuli. The timing of assessments in our design (after the CPT, two of which were immediately preceded by exercise) limits our ability to determine specific effects of exercise vs. specific demands of the cognitive task on perceived mental energy and fatigue. More investigation is needed to understand the optimal exercise intensity that maintains perceived mental energy for sedentary individuals, especially given the recent popularity of high-intensity exercise programs. On the other hand, vigorous exercise, with advantages such as greater energy expenditure and fitness benefits, does not appear to sacrifice cognitive performance in less fit individuals.

Caffeine effects on sustained attention and perceived energy and fatigue

Similar to other studies,[23,24,55,56] we observed moderate caffeine (equivalent to 1–2 cups of coffee) attenuated mental fatigue during a task requiring sustained attention. This was not unexpected since Schmitt et al. [57] suggested that caffeine may be more beneficial to complex, higher order cognitive tasks vs. simple processing tasks by improving concentration. Although exercise restored sustained attention after mental fatigue, caffeine provided additional benefit to sustained attention when coupled with moderate- and vigorous-intensity exercise, possibly due to its CNS actions which appear analogous to exercise effects.[12,27] Our findings are in agreement with previous work indicating 100–150 mg of caffeine improves attention in endurance-trained athletes following fatiguing cycling exercise [58] and extends previous investigations by observing the same effect in those who do not perform regular physical activity.

Although caffeine was able to maintain cognitive performance after physical fatigue, it was not able to mitigate the drop in perceived energy or increase in perceived fatigue. While 6 mg/kg caffeine has been suggested to improve subjective affect dimensions (i.e. increase feelings of pleasure during moderate-intensity exercise), no difference was noted in affective state following exercise.[26] In partial agreement with these results, 3 mg/kg caffeine in the present study improved perceived mental energy following moderate exercise, but not after physical fatigue. A recent systematic
review also indicates that an acute bout of moderate exercise has a similar effect on increasing perceived mental energy as the ingestion of ∼64 mg caffeine (∼1 mg/kg for reference in our study).[6] This suggests that affective state following exercise may be more dependent on exercise duration and/or intensity rather than the dose of caffeine ingested.

Habitual caffeine intake tended to be higher (by ∼ 100 mg/d, equivalent to one cup of regular coffee) in trained compared to sedentary participants, possibly contributing to lower pre-treatment mental energy in trained. However, all participants were classified as low-to-moderate caffeine users.[32] Although mental energy appears sensitive to caffeine dosages between 100 and 200 mg,[23] it is not clear that our trained participants experienced a greater caffeine “withdrawal” effect, since lower mental energy with placebo was no longer significantly correlated to higher habitual caffeine intake following the 20 min cognitive task.

Our study was not designed to determine whether caffeine [27] and exercise [9–13,59] exert distinct and/or synergistic effects. Future studies should include an additional rest control condition with caffeine to understand if caffeine alone restores sustained attention compared to the acute benefit of exercise. Although moderate exercise increases allocation of resources related to complex cognitive tasks, prolonged or exhaustive exercise may decrease this response.[12,17,18] Caffeine may be more effective when attentional control of perceptual functions is low (i.e. fatigued state or when CNS resources are compromised).[27] This could explain our findings that, after physical fatigue, caffeine maintained attention despite lower perceived energy and higher perceived fatigue. Practically, caffeine appears to be an effective countermeasure to fatigue when subsequent mentally and physically fatiguing tasks must be completed intermittently throughout a typical day.

Conclusion
The present study indicates that moderate-intensity exercise improves sustained attention following the induction of mental fatigue in both trained and sedentary individuals. Furthermore, sustained attention was not impaired in either group after exercise to physical fatigue, despite greater perceived mental fatigue. Caffeine acted as a mental ergogenic aid by blunting the decline in sustained attention during a fatiguing cognitive task which persisted after both moderate and vigorous exercise. Caffeine, however, could not maintain perceived mental energy or mitigate mental fatigue at the point of physical fatigue. It is also clear that sustained attention is improved by acute exercise independent of fitness levels. However, more research is warranted to understand the optimal exercise prescription (e.g. intensity) for individuals (sedentary and trained) to maintain mental energy following exercise in order to perform subsequent cognitive tasks and physical activity.

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