Caffeine Improves Physical and Cognitive Performance during Exhaustive Exercise

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ABSTRACT

HOGERVORST, E., S. BANDELOW, J. SCHMITT, R. JENTJENS, M. OLIVEIRA, J. ALLGROVE, T. CARTER, and M. GLEESON. Caffeine Improves Physical and Cognitive Performance during Exhaustive Exercise. *Med. Sci. Sports Exerc.*, Vol. 40, No. 10, pp. 1841–1851, 2008. Caffeine is thought to act as a central stimulant and to have effects on physical, cognitive, and psychomotor functioning. **Purpose:** To examine the effects of ingesting a performance bar, containing caffeine, before and during cycling exercise on physical and cognitive performance. **Methods:** Twenty-four well-trained cyclists consumed the products [a performance bar containing 45 g of carbohydrate and 100 mg of caffeine (CAF), an isocaloric noncaffeine performance bar (CHO), or 300 mL of placebo beverage (BEV)] immediately before performing a 2.5-h exercise at 60% $\dot{V}O_{2max}$ followed by a time to exhaustion trial (T2EX) at 75% $\dot{V}O_{2max}$. Additional products were taken after 55 and 115 min of exercise. Cognitive function measures (computerized Stroop and Rapid Visual Information Processing tests) were performed before exercise and while cycling after 70 and 140 min of exercise and again 5 min after completing the T2EX ride. **Results:** Participants were significantly faster after CAF when compared with CHO on both the computerized complex information processing tests, particularly after 140 min and after the T2EX ride ($P < 0.001$). On the BEV trial, performance was significantly slower than after both other treatments ($P < 0.0001$). There were no speed–accuracy tradeoffs ($P > 0.10$). T2EX was longer after CAF consumption compared with both CHO and BEV trials ($P < 0.05$), and T2EX was longer after CHO than after BEV ($P < 0.05$). No differences were found in the ratings of perceived exertion, mean heart rate, and relative exercise intensity (% $\dot{V}O_{2max}$; $P > 0.05$). **Conclusion:** Caffeine in a performance bar can significantly improve endurance performance and complex cognitive ability during and after exercise. These effects may be salient for sports performance in which concentration plays a major role. **Key Words:** COGNITION, CONCENTRATION, ATHLETES, CYCLING, ERGOGENIC AID

Caffeine is considered to be an ergogenic "drug" with beneficial effects on both physical and mental performance and minimal side effects (6,23). Oral caffeine ingestion was found to have a positive effect on time to exhaustion trials and in prolonged exercise lasting up to 2 h (5,7,24,28). Although caffeine was reported to have no effect on power output after repeated bouts of very short term intense exercise, such as a 4 × 30-s Wingate sprints with 4-min rest intervals (8,9,30), a 2 × 60-s maximal cycling bouts (4), or a single 30-s Wingate test (19,20), others have found positive effects on exercise performance with exercise durations as brief as 4–6 min (3,14,30).

Caffeine is thought to act as a central stimulant and to have effects on cognitive and psychomotor functioning, particularly during mental and physical fatigue, by enhancing alertness and vigilance (16,19,21,22,30,32). These findings could suggest that the performance-enhancing effects of caffeine are due to altered central nervous system function, possibly related to the attenuation of central fatigue effects (15,25). Caffeine may therefore have an important role in all types of exercise in which concentration, reaction times (RT), and technical/tactical skills have a major influence on both physical and mental performance (e.g., cycling/mountain biking, skiing, most ball game and racquet sports, golf, orienteering, Formula 1, or in ultraendurance events).

There are many studies relating caffeine to physical performance, or relating caffeine to cognitive performance, but only few that investigated the interactions of exercise and caffeine on cognitive performance. Without caffeine, exercise itself can improve cognitive performance (10). For instance, one study found that a cycle ergometer endurance test at approximately 70% $\dot{V}O_{2max}$ improved cognitive performance in athletes, particularly on more complex cognitive tests, such as the Stroop Color–Word test, which requires inhibition of overlearned automatic responses (12). Another study (13) revealed an additive effect of caffeine on the activating and cognition-enhancing effects of exercise. Approximately 150 $mg \cdot L^{-1}$ of caffeine in a beverage (8 $mL \cdot kg^{-1}$ of the beverage was consumed before exercise and 6 $mL \cdot kg^{-1}$ was consumed during exercise)

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improved memory, concentration, and complex RT in athletes after exercise and also improved exercise performance itself (an all-out 1-h time trial on an ergometer at approximately 75% W_{max}). Larger dosages of caffeine (225 and 320 $mg \cdot L^{-1}$) had no additional effects in this study (13). Others (18) also found that caffeine (5 $mg \cdot kg^{-1}$) improved psychomotor performance (a multiple-choice RT test) during exercise (multistage incremental cycling to volitional exhaustion). However, this effect, observed in nine trained soccer players, was only seen in thermoneutral (22°C) but not cold (4°C) environments. Others reported no effects of a higher dose (6 $mg \cdot kg^{-1}$) of caffeine on RT and number recall in a mixed sex study group after two 60-s maximal cycling bouts (4). In fact, caffeine ingestion was associated with higher blood lactate and a slower time to peak power and was suggested to have detrimental effects on anaerobic exercise performance.

Differences between the type of participants tested (sex, suboptimal training levels, caffeine habituated, or caffeine naive, etc.), exercise protocols (anaerobic exercise bouts or endurance exercise/time to exhaustion trials or time trials vs time to exhaustion), caffeine dosages, and the sensitivity of the cognitive tests used (simple RT tests and number recall vs more complex information processing tests) may explain differences in outcomes between studies. As far as we are aware, there are no studies that have examined the effects of caffeine on both time to exhaustion and cognitive performance during and after exercise, and there are relatively few studies that have investigated whether the combination of caffeine with carbohydrate (or other macronutrients) has greater effects on physical performance and cognitive function during exercise compared with carbohydrate alone. It is well established that carbohydrate ingestion during exercise improves cognitive and endurance performance (29).

The primary aim of the present study was to examine the effects of the ingestion of performance bars containing carbohydrate with or without caffeine before and during prolonged exercise on different aspects of cognitive performance during (at 70 and 140 min) a moderate-intensity cycling exercise task (60% $\dot{V}O_{2max}$) lasting 150 min and after a subsequent time to exhaustion trial at a higher exercise intensity (75% $\dot{V}O_{2max}$). To limit the number of treatments (taking into account the time investment interfering with training programs) and the fact that most athletes will use some form of supplement during or just before prolonged exercise, a CHO-only true placebo was used, whereas the beverage placebo acted as a baseline measurement of cognitive and physical performance without any supplements.

METHODS

Participants. Male-only subjects were recruited through personal contacts, advertisements in local sports clubs and the student pool of the University of Loughborough (UK), and/or by word of mouth. Subjects were enrolled after having fulfilled all inclusion criteria and presenting none of the exclusion criteria (determined by both questionnaire and interview). All participants were fully informed about the rationale for the study and of all experimental procedures to be undertaken. Participants provided written consent to participate in the study, which had earlier received the approval of Loughborough University ethical advisory committee.

Participants could be included if they were healthy, endurance-trained male volunteers, had cycling as one of their main sports, preferably with some competitive practice, and were moderate habitual caffeine users.[1,2] Participants were between 18 and 35 yr of age, trained at least three times a week for more than 2 $h \cdot d^{-1}$, and had been involved in endurance training for at least 2 to 4 yr. Each potential subject's aerobic capacity ($\dot{V}O_{2max}$) was determined (as described below) during the first visit to the laboratory, and subjects were only included in the study if their $\dot{V}O_{2max}$ was at least 50 $mL \cdot kg^{-1} \cdot min^{-1}$.

Subjects representing one or more of the following criteria were excluded from participation: smoking or use of any (in particular, psychoactive) medication that could interfere with test performance or use of illicit drugs; experienced or had a history of cardiac, hepatic, renal, pulmonary, neurologic, gastrointestinal, hematological, or psychiatric illness or with any sensory or motor deficits that could be expected to affect test performance; and objected to the prescription of diet (recall of diet, alcohol abstention), exercise, and resting regimens or those who will not be expected to comply with treatment.

Before the study, power analyses were performed on the basis of our earlier work (13) using the Stroop Color–Word test as a primary outcome measure, which indicated that $n = 24$ were needed to obtain 80% power. Twenty-four healthy trained men [age = 23 ± 5 yr, body mass = 73.8 ± 8.1 kg, $\dot{V}O_{2max}$ = 56.6 ± 4.7 $mL \cdot kg^{-1} \cdot min^{-1}$, power output at $\dot{V}O_{2max}$ = 316 ± 32 W (means ± SD)] were included in the present study. During the study, one participant dropped out after the first session because of time constraints and was subsequently replaced by another participant using the same order. On completion, participants were paid £100 per subject, and we also offered a prize of £100 for the best overall cognitive performance and the best endurance performance (average of the three trials) to encourage subjects to try their best.

[1]As derived from estimated caffeine contents in beverages and foods consumed on a weekly basis: http://www.ameribev.org/industry-issues/healthy-balanced-diet/beverage-ingredients/caffeine/index.aspx.

[2]Because of time constraints, we had to include four participants who were caffeine-naive but were subsequently asked to increase their daily caffeine intake before the study (which was reflected by their increased resting salivary caffeine concentrations during the study). Two participants reported an equivalent intake of more than six cups of coffee per day, but all others consumed the equivalent of less than four cups of coffee per day.

Subjects were assigned to the treatment groups in a double-blind, placebo-controlled, randomized, cross-over, single-center, clinical trial design. All participants completed five exercise bouts: two preliminary trials ($\dot{V}O_{2max}$ determination and habituation trial) and three main trials. All trials were separated by at least 1 wk.

Treatment composition. The two types of performance "energy" bars used in this study were commercially available coconut-flavored PowerBar® Performance bars and consisted of protein (5.4 g), carbohydrate (44.9 g), fat (3.2 g), fiber (4.0 g), sodium (0.6 g), and vitamins and minerals in amounts intended for nutritional support of athletes. The two bars were a noncaffeine (CHO) and a caffeine-containing (CAF) version. The latter (ActiCaf® bar) contained 100 mg of slow-release caffeine. The placebo beverage (BEV) consisted of artificially sweetened and flavored water (Vittel Raspberry flavor) and was not intended to provide energy or nutritional ingredients.

Study design. Participants exercised under three different conditions: BEV trial, CAF trial, or CHO trial. The order in which each participant undertook each condition (BEV, CAF, or CHO trial) was randomized and counterbalanced, where subjects were randomly assigned to one of the six sequences in a balanced way (CAF CHO BEV, CHO BEV CAF, BEV CAF CHO, CAF BEV CHO, BEV CHO CAF, and CHO CAF BEV). Randomization was performed by TrialBalance (Nestlé program for randomization) in blocks to ensure balance (each treatment was applied equal times at each period). No form of stratification was applied.

Blinding. Four different codes were created for the performance bars (*Y*, *Z*, *X*, and *W*, where CAF = *Y* and *W*, and CHO = *Z* and *X*), and subjects and investigators were blinded about the content of each bar until after completion of the study. Participants were told that any of the beverages/bars could or could not contain caffeine. However, the beverage was not blinded for the investigators who were responsible for buying and measuring quantities before administrating the blinded drinks to the volunteers. Both subjects and investigators were not allowed to discuss the experimental treatments in any format during the trials. At the end of each trial, participants completed a questionnaire to try to guess which treatment they had been given (e.g., caffeine bar, noncaffeine bar, and caffeine or noncaffeine beverage) to check adequacy of blinding procedures.

Protocol before the treatment trials. Participants completed a food record diary for the 48-h period before habituation trial and were required to follow the same diet during the 48 h before each of the three main trials. Participants were required to abstain from alcohol, chocolate, and heavy exercise for 24 h before each trial and to have a quiet day on the day immediately before each trial. It was also stipulated that participants should not consume any caffeine-containing foods or drinks from 2100 hours the night before the trial.

During the first visit, an incremental cycle exercise test to volitional exhaustion was performed to determine the individual $\dot{V}O_{2max}$ and maximal work rate (W_{max}, the power output at $\dot{V}O_{2max}$). These results were used to set the workload (60% $\dot{V}O_{2max}$) for the submaximal cycle ride during the habituation and subsequent main trials. The incremental exercise test was performed on a cycle ergometer (Lode Excalibur, Groningen, The Netherlands), modified to the configuration of a racing bicycle with adjustable saddle height and handlebar position. Subjects began with a 3-min warm-up at 95 W, followed by an incremental exercise protocol of 35 W every 3 min until exhaustion. These results were used to set the workloads in the experimental trials. Expired gas samples (1-min collection period) were collected into Douglas bags during the final minute of each stage for the determination of oxygen consumption and carbon dioxide production. A Polar heart rate (HR) monitor (Vantage NV; Polar, Kempele, Finland) was used for continuous recording of the HR. Standard measures of height and body mass were also performed during this visit.

A week before the actual trial, a habituation trial was carried out, which was similar to the main trials, except that no treatments were given during this trial, only water. The purpose of this habituation trial was threefold: first, to familiarize the participants with the physical stress of the exercise and with the methods involved in the trial; second, to ensure that the participants were able to maintain the selected intensity for 150 min after an overnight fast; and third, to ensure that the selected work rate actually did elicit a relative intensity of 60% $\dot{V}O_{2max}$.

Protocol during treatment trials. Volunteers arrived at the laboratory at 0830 hours in the morning of the main trials after an overnight fast (>10 h). After a 5-min seated rest, a blood sample was obtained from an earlobe, using an autoclick lancet, and the blood glucose concentration was analyzed using an Accutrend GC (Roche, Mannheim, Germany) blood glucose analyzer. After that, unstimulated saliva samples were obtained by having subjects dribble saliva into a collection tube for 3 min.

Participants were asked to go to the toilet and empty their bladder, and after that, they had their body mass measured. After that, participants performed a series of cognitive tests [immediate recall of the memory, Visual Search, Stroop Color–Word, and Rapid Visual Information Processing (RVIP) tests] and completed a caffeine side effect questionnaire while seated on the cycle ergometer, with the computer screen not more than 1 m away from them. To minimize potential external noise, a pair of earplugs was used during all cognitive tests batteries in all trials. Participants then consumed their first experimental product (performance bar or beverage) within 5 min and performed 150 min of exercise at 60% $\dot{V}O_{2max}$ immediately after the consumption of the product. Further experimental supplementation of either CAF, CHO, or 300 mL of BEV was given at 55 and 115 min. In addition, 200 mL of water was

consumed at the onset and every 20 min during the exercise bout for all trials.

During exercise, the following measurements (as illustrated in Fig. 1) were taken: A caffeine side effect questionnaire and the cognitive performance tasks (Stroop Color–Word and RVIP tests) were administered at 70 and 140 min. The caffeine side effect questionnaire was developed on the basis of common and known side effects after administration, withdrawal, and overdosing of caffeine, which were categorized as nervous system, gastrointestinal, pulmonary, and cardiovascular effects. The questionnaire was computerized and presented before each cognitive test trial. The total number of side effects per trial was reported. Rating of perceived exertion (RPE) was assessed during exercise every 20 min using a paper version of the 0–20 Borg scale (2). Earlobe blood drawing (for glucose analysis as described above) and saliva sampling (before cognitive test sessions) were carried out at 65 and 125 min. Oxygen uptake, carbon dioxide production, and respiratory exchange ratio (RER; during exercise at 30, 90, and 115 min) were assessed using a Douglas Bag collection system, Servomex gas analyzer, and Harvard dry gas meter, and HR (every 10 min) was monitored using a Polar HR monitor (Vantage NV; Polar).

At the end of the 150-min exercise, subjects were given a 5-min break, immediately followed by a time to exhaustion trial at 75% $\dot{V}O_{2max}$. Participants were instructed to maintain a pedal cadence of more than 50 rpm while cycling to remain seated at all time and to attempt to cycle for as long as possible. However, no external encouragement was given during the trial. No music was played and no clues about elapsed time, power output, and HR were given during the ride to exhaustion. HR was recorded unobtrusively every 5 min during the ride to exhaustion. Immediately after completion of the exercise to exhaustion trial, a saliva sample and an earlobe blood sample (for glucose analysis) were collected. Then, the caffeine side effect questionnaire was completed, and cognitive performance tasks (delayed recall of the memory, Visual Search, Stroop Color–Word, and RVIP tests) and subjective rating scales and questionnaire assessments were carried out. Finally, participants were weighed again to determine their weight loss. Sweat loss was estimated on the basis of weight loss corrected for fluid intake and any urinary losses. All saliva samples collected were stored frozen at −20°C before analysis of caffeine concentration (Emit caffeine assay kit; Dade Behring Ltd., Milton Keynes, UK).

Definition of cognitive measures. Subjects were asked to complete a cognitive test battery that lasted for approximately 15–20 min. The cognitive tests were selected on the basis of their proven sensitivity to the effects of exercise in combination with caffeine (13).

Stroop Color–Word test. This test was the primary outcome measure. The test measures the sensitivity to interference and the ability to suppress an automated response (time needed to read the color words rather than the time it takes to name the color of the letters) (27). The baseline level contained 15 stimuli (reading color names printed in white on a black background), the color-interference level (naming the font color rather than reading the printed color name, which was always incongruent) comprised 40 stimuli. Each color word was placed on the center of the screen with the target and distractor presented at random on the left or right side of the stimulus word, with target position counterbalanced for the left and right side within each test level. The participant was required to press the left or right arrow key as quickly as possible to indicate the position of the target word. Correct response times were recorded in milliseconds. Errors were also recorded for error analysis and to assess speed–accuracy tradeoffs. Both tests started with five learning trials that included feedback.

Rapid Visual Information Processing task. The RVIP (11) is a continuous performance test lasting 5 min, where subjects are required to monitor a continuous stream of digits (100 digits·min^{-1} or 600 ms·digit^{-1}) for target sequences, which were defined as three consecutive odd or even numbers (e.g., 3–5–7 or 2–8–4). The test had 8

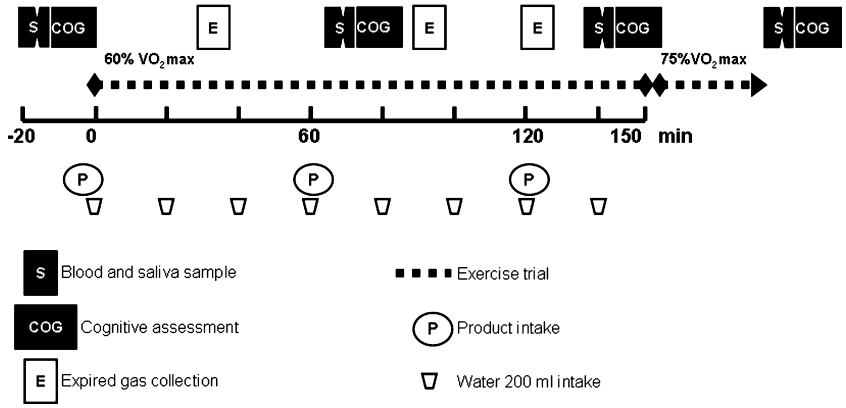

FIGURE 1—Schematic representation of a test day, showing exercise protocol, key assessments, and product administration. See text for full description.

targets·min^{-1} with 5–30 digits between each target, and the screen was updated with a new digit every 600 ms. Subjects responded to target strings by pressing a button box linked to the parallel port. Correct detections ("hits") of target strings could be registered during the last digit of a sequence and in the subsequent 1500 ms. RT in milliseconds, correct detections and omission errors (missed responses to targets), and commission errors (false alarms to nontarget) were recorded. Analysis was performed on RT for correct responses, true positive rate [TP / (TP + FP)], and miss rate [FN / (FN + TP)].

Visual search test. The computerized visual search and detection test required the disengagement from one focal area of attention to locate the next target (a triangle formed from constantly moving dots). Participants were instructed to press a key as soon as they could detect a triangle on the screen. The baseline level contained 15 stimuli, which were drawn in solid green lines on a black background. In the 40 complex-level stimuli, moving random dots covering the entire screen served as background distractors. New target triangles were initially drawn with just a few visible dots of each line, and the density of these points increased linearly with time until a key press response was registered. The screen was redrawn every 250 ms. After each response, new targets appeared with random delays of at least 500 ms. Visual search results were recorded with RT (in ms) and the number of true and false positives (1). This test was only performed before and after exercise (after the time to exhaustion trial).

Word learning test. This test consisted of four parallel (including one training version) word learning lists that were on the basis of modified versions of the Hopkins, Rey, and Californian Auditory Verbal Learning Tests. Each test consisted of a list of 16 monosyllabic words, which were presented in three trials on a computer screen. Items were presented in the same sequence at a rate of 0.5 s^{-1} (presentation time of 1 s, interstimulus interval of 1 s). Each trial ended with a free immediate recall of the words, which was done before exercise. The main outcome variables of this test were the number of words correctly recalled after exercise, constituting a measure of consolidation efficiency. Forgetting rate was calculated as the maximum number of words immediately recalled in one trial—the delayed recall.

Data analysis. Overall, treatment effects (including treatments BEV, CAF, and CHO) were analyzed via repeated-measures ANOVA that included the main effect of treatment, time, visit day, and treatment × time interactions. All analyses were performed with R (version 2.5; www.r-project.org). If a significant treatment × time interaction was found, the responses at 70, 140, and 180 min were analyzed using mixed-effects models. These models contained fixed main effects of treatment, fixed main effect for mean scores at time 0 (to adjust for baseline speed), and a fixed main effect for visit day (to account for learning between visits). The nlme package was used to build linear mixed-effect (lme) models for the normally distributed RT data. The lme4 package was used to build the same models for binomial data such as the proportion of correct answers, which were modeled via the binomial distribution. The resulting adjusted *P* values for the contrasts CAF–CHO, BEV–CAF, and BEV–CHO are listed in Figures 2–4 as CCO, CAF, and CHO, respectively. Significance codes of the *post hoc* comparisons (adjusted for three comparisons at each time point) are as follows: $*P < 0.05$, $**P < 0.01$, and $***P < 0.001$. For these *post hoc* tests, the correlations between BEV, CHO, and CAF samples were found to be approximately 0.5; hence, the adjusted Bonferroni-corrected alpha level for three comparisons used was 0.03.

To compare the physiological and other responses (HR, maximum HR, RPE, blood glucose concentration, time to exhaustion, sweat loss, and % $\dot{V}O_{2max}$) between the three different treatments (CAF, CHO, and BEV), repeated-measures

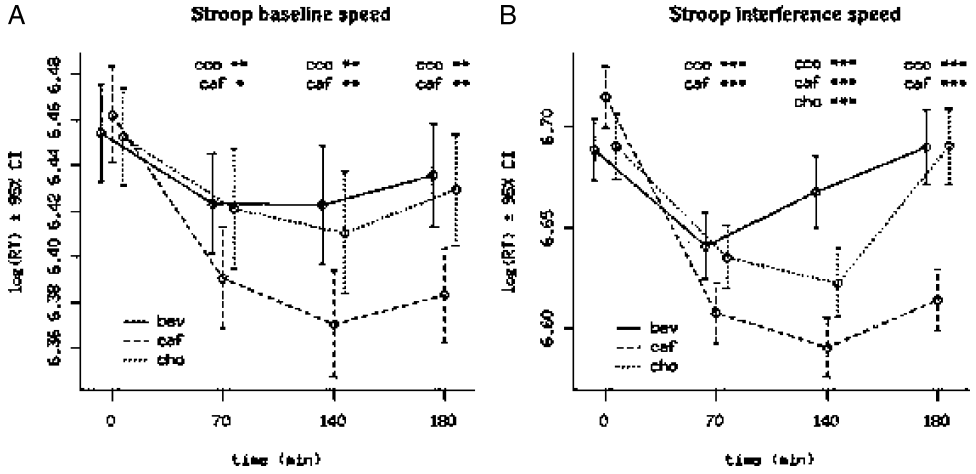

FIGURE 2—Treatment and time effects on speed (A) and accuracy (B) on both Stroop test levels. The adjusted *P* values for the contrasts CAF–CHO, BEV–CAF, and BEV–CHO are shown as CCO, CAF, and CHO, respectively. Significance codes of the *post hoc* comparisons (adjusted for three comparisons at each time point) are as follows: $*P < 0.05$, $**P < 0.01$, and $***P < 0.001$.

general linear models were used. *Post hoc* analyses were carried out, where appropriate, using Bonferroni corrections. All statistical analyses were carried out blinded to treatment by the onsite investigators (caffeine in saliva was analyzed last).

RESULTS

Caffeine Consumption

On the basis of self-report, habitual caffeine consumption (including coffee, tea, chocolate, cola, etc., using standard estimate tables; (see footnote 1) was estimated to be, on average, 170 $mg \cdot d^{-1}$ (median = 121 $mg \cdot d^{-1}$, SD = 167), indicating that most participants were low to moderate caffeine consumers, ingesting the equivalent of one to three cups of coffee per day.

Stroop Color–Word Test

The RT were log-transformed to approximate a normal distribution more closely, and the means and 95% confidence intervals (CI) of these log-transformed response latency and accuracy, split for time, treatment, and test type are displayed in Figures 2A and B.

In the ANOVA of the log-transformed RT data, there was a main effect of treatment [$F(2, 46) = 45.7$, $P < 0.0001$], a main effect of time [$F(2, 46) = 60.9$, $P < 0.0001$], and an interaction between time and treatment [$F(2, 46) = 46.8$, $P < 0.0001$]. However, the three-way interaction between treatment, time, and test type (Reading speed vs Color-Naming speed) was not significant ($P = 0.13$). Thus, the treatment effect occurred similarly on the baseline and the color-interference level of the Stroop test (compare Figure 2A with Figure 2B), implying that treatment effects were not specific to the interference component. Nevertheless, we found a trend toward significance for the two-way interaction between test type and the CCO treatment contrast at 180 min [$t(23) = 2.13$, $P = 0.03$] and a trend toward significance for the interaction between test type and the CAF treatment contrast [$t(23) = 1.84$, $P = 0.07$]. Although these significance levels do not survive the correction for two comparisons, the trends indicate that the caffeine effect was more pronounced on the complex interference RT than the baseline test RT.

Post hoc testing revealed that participants were significantly faster after treatment of CAF when compared with both other treatments at times of 70, 140, and 180 min on both levels of the test (Fig. 2). RT after treatment of CHO were significantly faster than after placebo (BEV), only on the interference level and only at 140 min (Fig. 2). Performance with CAF maintained its fast response times after the time to exhaustion trial, indicating improved response latencies to complex stimuli with caffeine during and after endurance exercise. When the mean differences between the treatments were retransformed into milliseconds via the exponential function, we found that after correcting for baseline speed, the effect size on the color-interference test level of the CAF–CHO (CCO in Fig. 2) contrast was 79 ms, and the effect size of the BEV–CAF (CAF in Fig. 2) contrast was 80 ms, with responses after CAF always being faster. On the baseline level of the Stroop test, the effect sizes of the CAF–CHO and CAF–BEV contrasts were 34 and 37 ms, respectively.

The overall ANOVA model of Stroop accuracy (proportion of correct responses) revealed no significant main effect of treatment ($P = 0.12$), no significant treatment × time interaction, and no significant three-way interaction between treatment, time, and test type (both $P > 0.5$). Because treatment effects were absent, no *post hoc* testing was performed on the accuracy data. There was thus no speed–accuracy tradeoff where athletes would have sacrificed accuracy for faster speed of performance.

Rapid Visual Information Processing Task

The RT were log-transformed to approximate a normal distribution more closely, and the means and 95% CI of these log-transformed response latencies and accuracy [misses and true positive (TP) rate], split for time and treatment, are displayed in Figures 3A–C.

In the ANOVA of the log-transformed RT data, there was a main effect of treatment [$F(2, 46) = 23.3$, $P < 0.0001$], a main effect of time [$F(2, 46) = 59.2$, $P < 0.0001$], and an interaction between time and treatment [$F(2, 46) = 16.8$, $P < 0.0001$]. The TP rate also showed a significant main effect of treatment [$F(2, 46) = 10.0$, $P < 0.0001$], no significant main effect of time ($P = 0.12$), and a significant interaction between time and treatment [$F(2, 46) = 3.4$, $P = 0.03$]. Finally, the miss rate showed a significant main effect of treatment [$F(2, 46) = 30.2$, $P < 0.0001$], a significant main effect of time [$F(2, 46) = 26.1$, $P < 0.0001$], and a significant interaction between time and treatment [$F(2, 46) = 26.6$, $P < 0.0001$].

Because all outcomes showed significant treatment × time interactions, *post hoc* testing was performed on all measures, the results of which are displayed in Figures 3A–C. These findings are in line with those of the Stroop mentioned previously, in that caffeine improved complex and RVIP during and after exercise.

On all parameters of this test, performance was better with CAF than both CHO and BEV. This effect emerged after 70 min of exercise for TP rate and miss rate and after 180 min for the RT latencies (CAF–CHO; see Fig. 3A). This indicates improved performance on RVIP both during and after time to exhaustion exercise with caffeine.

Visual Search Test

The RT for correct responses were log-transformed to approximate a normal distribution more closely. The ANOVA of the log-transformed RT data revealed a significant

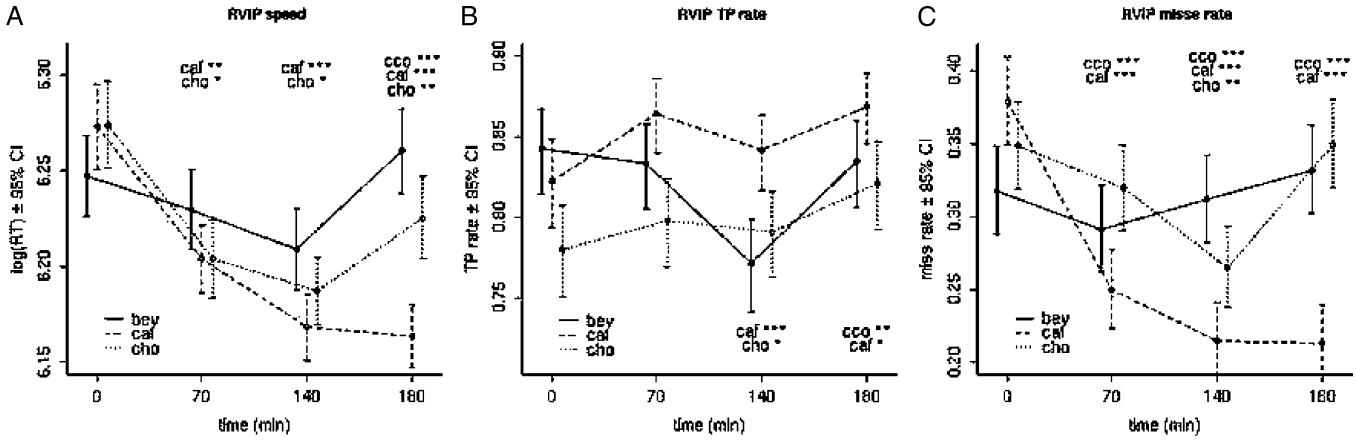

FIGURE 3—Treatment and time effects on speed (A), TP rate (B), and miss rate (C) on the RVIP test. The resulting adjusted *P* values for the contrasts CAF–CHO, BEV–CAF, and BEV–CHO are shown as CCO, CAF, and CHO, respectively. Significance codes of the *post hoc* comparisons (adjusted for three comparisons at each time point) are as follows: *$P < 0.05$, **$P < 0.01$, and ***$P < 0.001$.

interaction between time and treatment [$F(2, 46) = 5.4$, $P = 0.004$]. No significant treatment effects were found on the visually simple level of this test, implying that treatment effects were specific to the visual complexity component. The means and 95% CI of these log-transformed response latencies and proportion of correct responses on the complex level of the Visual Search test, split for time and treatment, are displayed in Figures 4A and B.

Post hoc testing revealed significant treatment effects on the complex level of the Visual Search test. Significant response speed improvements were found at 180 min for CAF compared with BEV and CHO (but not for CHO compared with BEV; Fig. 4A). These findings indicate that the caffeine-related improvements on the Visual Search test are related to improved processing of complex visual scenes and not just simple motor-related response speed.

The overall ANOVA model of Visual Search test accuracy (proportion of TP) revealed a significant treatment × time interaction [$F(2, 46) = 6.8$, $P = 0.001$] and a significant three-way interaction between treatment, time, and test type [$F(2, 46) = 3.1$, $P = 0.04$]. This indicates that TP rates were affected by treatment on the complex level of this test only. *Post hoc* analyses revealed no significant treatment effects on the simple test level and significant accuracy improvements on both bars (CHO and CAF) compared with BEV (Fig. 4B). However, there was no significant difference between CHO and CAF at 180 min.

It thus seems that for all outcome measures on the complex level of Visual Search test, CAF improved performance significantly compared with BEV, and that for accuracy, there was also a significant improvement with CHO compared with BEV. Furthermore, CAF produced significant response speed improvements compared with CHO.

Word Learning Test

The delayed recall component of this test was only performed after exercise. For these analyses, repeated-measures

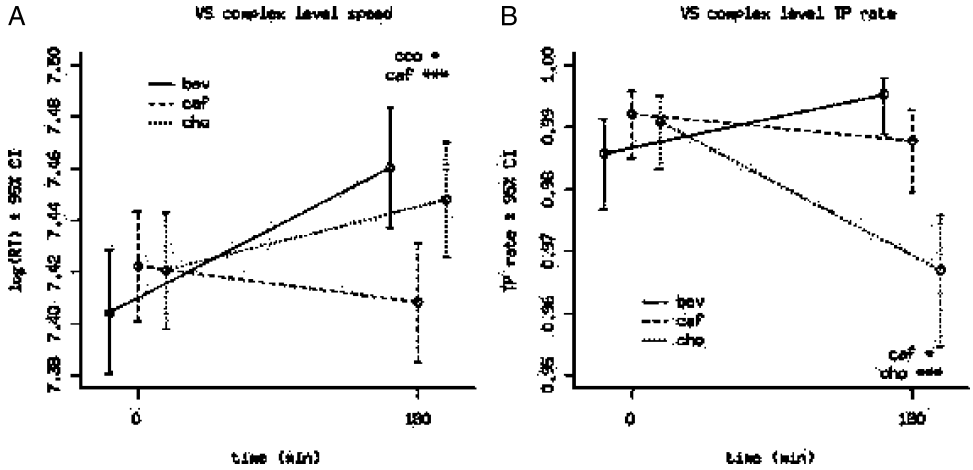

FIGURE 4—Treatment and time effects on speed (A) and accuracy (B) on the complex level of the Visual Search test. The resulting adjusted *P* values for the contrasts CAF–CHO, BEV–CAF, and BEV–CHO are shown as CCO, CAF, and CHO, respectively. Significance codes of the *post hoc* comparisons (adjusted for three comparisons at each time point) are as follows: *$P < 0.05$, **$P < 0.01$, and ***$P < 0.001$.

TABLE 1. Mean ± SD HR (beats·min^{-1}) during 60% $\dot{V}O_{2max}$ and after time to exhaustion trial.

	HR at 60% $\dot{V}O_{2max}$	Maximum HR at Exhaustion
CAF	144 ± 13	179 ± 12*
CHO	143 ± 12	176 ± 10
BEV	141 ± 12	172 ± 11

* Significantly different from the BEV trial ($P < 0.05$).

general linear models were used with Bonferroni-corrected pairwise comparisons. Overall, within subjects, effects showed no main effect of treatment [$F(2, 46) = 1.52$, $P = 0.22$]. Delayed recall after exercise was nonsignificantly higher after CAF (10.0 words recalled on average, SD = 3.55) compared with treatment with BEV (8.9 words recalled, SD = 4.07; noncorrected paired *t*-test, $P = 0.08$; Bonferroni-adjusted comparisons, $P = 0.23$) with performance after consumption of CHO having an intermediate position (9.8 words recalled, SD = 3.65) between placebo BEV and CAF. The power for these secondary analyses, however, was insufficient (31%). There was no difference in immediate recall before exercise ($P > 0.55$).

Caffeine Side Effects

There were no serious side effects reported after any of the treatments. Most complaints were probably related to the effects of exercise itself, as there was no significant difference [$F(2, 46) = 1.49$, $P = 0.24$, power = 26%] between the total number of side effects reported between treatments. For CAF, an average number of 2.1 (SD = 3.3) side effects was reported; for CHO, 1.2 (SD = 2.2) side effects; and for BEV, 1.9 (SD = 3.1) side effects. For all trials, the most common complaints were having the following: a stuffy nose (20×), a dry mouth (15×), tiredness (15×), muscle trembling (12×), weakness (11×), hunger (8×), shakiness/jitters (8×), and drowsiness (7×). Less common were as follows: the urge to urinate (4×); loss of appetite, dehydration, and irritability (all 3×); belching, dizziness, and headache (all 2×); and confusion, increased pain sensitivity, restlessness, cold sweats, feeling bloated, nauseous, and stomach upset (1×).

Physiological Parameters

Heart rate. There were no significant differences in the mean HR between trials [$F(2, 46) = 2.05$, $P = 0.14$, power = 40%; Bonferroni-corrected comparison between CAF and BEV, $P = 0.17$] during the 150-min rides at 60% $\dot{V}O_{2max}$. However, a significant difference was found in the maximum HR achieved in the time to exhaustion trial, comparing CAF and BEV treatments [$F(2, 46) = 8.13$, $P = 0.001$, power = 95%] (see Table 1).

Rating of perceived exertion. No significant difference in the RPE was found between treatments ($P > 0.05$). Thus, caffeine did not affect mean RPE during the 150-min rides at 60% $\dot{V}O_{2max}$. The means of the RPE were 12 ± 1, 12 ± 1, and 13 ± 1 for CAF, CHO, and BEV trials, respectively (means ± SD). Power for these analyses was insufficient at 36%. As expected, a significant effect of time was found with RPE increasing across time in all three trials ($P < 0.05$), but no differences in the RPE between trials were found at any time point ($P > 0.05$).

Sweat loss. An average sweat loss (weight loss after correction for fluid intake and any urinary losses) of 2.6 kg (SD 0.5), 2.4 kg (SD 0.5), and 2.5 kg (SD 0.5) was found in the CAF, CHO, and BEV trials, respectively. However, no significant differences in sweat losses were found between trials.

Time to exhaustion. Performance time in seconds was assessed using a time to exhaustion protocol at 75% $\dot{V}O_{2max}$, which was introduced after a 5-min break after having cycled for 150 min at 60% $\dot{V}O_{2max}$. There was a significant effect of treatment on time to exhaustion [$F(2, 46) = 12.06$, $P < 0.001$, power = 99%], with CAF showing the best results. Time to exhaustion in both the CAF and CHO trials was significantly longer than the BEV trial ($P = 0.001$ and $P = 0.031$, respectively). Overall, caffeine improved the time to exhaustion by 354 s, a 27% improvement in performance compared with ingesting the bars without caffeine [$t(23) = 2.36$, $P = 0.03$, which remained significant after Bonferroni–Holm correction] and a 751-s (84%) improvement compared with taking a liquid beverage containing no energy source (Fig. 5). Time to exhaustion was 397 s (44%) longer on the CHO trial than on the BEV trial ($P < 0.01$).

Relative exercise intensity. No differences in the relative exercise intensity (% $\dot{V}O_{2max}$) were found between trials ($P = 0.15$, power = 39%), and therefore all trials were done at an intensity of approximately 60% $\dot{V}O_{2max}$ (CAF = 60.0 ± 2.4% $\dot{V}O_{2max}$; CHO = 59.0 ± 2.5% $\dot{V}O_{2max}$; and BEV = 59.0 ± 2.3% $\dot{V}O_{2max}$).

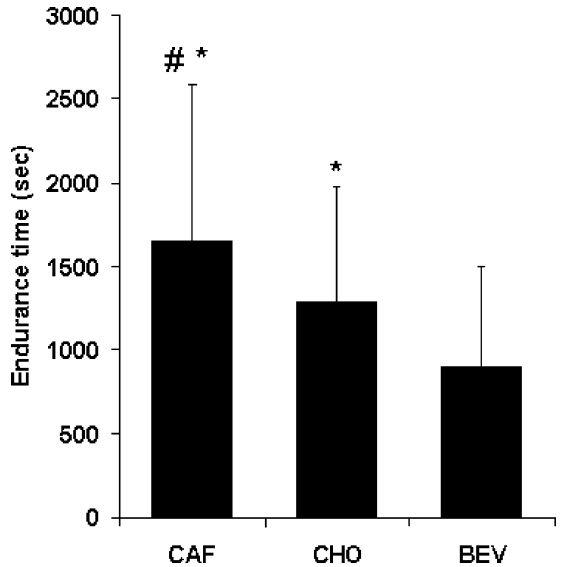

FIGURE 5—Time to exhaustion (s) according to trials. *Significantly different from the BEV trial. #Significantly different from the CHO trial ($P \leq 0.05$).

Respiratory exchange ratio and estimated rate of carbohydrate oxidation. Although rates of oxygen uptake were not different between the two performance bar trials (with and without caffeine), the RER and the calculated rate of carbohydrate oxidation (Table 2) were higher at 30 min of exercise in the CAF trial compared with both CHO and BEV trials ($P < 0.05$). At 90 and 115 min of exercise, the RER and rate of carbohydrate oxidation were both lower in the BEV trial compared with the CAF and CHO trials ($P < 0.05$).

Blood glucose concentration. Significant main effects of trial ($P = 0.01$), time ($P < 0.001$), and a trial × time interaction ($P = 0.015$) were observed for blood glucose concentration (Table 3). Both CAF and CHO trials were significantly different from the BEV trial. There was no difference in the glucose concentration at preexercise between any of the trials. However, glucose concentration was significantly higher at 65 min in the CHO trial compared with the BEV trial ($P = 0.015$) and at 125 min in both CAF and CHO trials compared with the BEV trial ($P < 0.05$). In addition, glucose concentration increased at the end of the time to exhaustion test in the CAF and CHO trials compared with the BEV trial ($P = 0.001$). Analyzing the trial × time interaction, the glucose concentration in the CAF trial showed a significant difference at time to exhaustion compared with rest and with 65 min ($P = 0.046$ and $P = 0.009$, respectively). No difference was found in glucose levels between any time points for the CHO trial. In the BEV trial, glucose concentration was significantly lower at 65 and 125 min of exercise ($P = 0.015$) compared with preexercise, but this was not significantly different from rest at the end of the ride to exhaustion ($P > 0.05$; Table 3).

Saliva caffeine concentration. Caffeine concentrations in saliva were substantially increased in the CAF trial (rest = 0.25 ± 0.32 to 5.93 ± 2.84 $\mu g \cdot mL^{-1}$ at the end of the ride to exhaustion) compared with rest values, whereas no changes from rest values were found in either the CHO or the BEV trials (rest = 0.14 ± 0.22 to 0.03 ± 0.03 $\mu g \cdot mL^{-1}$ and 0.26 ± 0.41 to 0.06 ± 0.06 $\mu g \cdot mL^{-1}$ in CHO and BEV trials, respectively) at any time point.

Unblinding. Blindness checks were made after exercise. After consumption of CAF, 83% ($n = 20$) of the participants were under the impression of having received caffeine in the bar. Comments made by participants after the trial suggested that it was the mental alerting effect ("It feels like I had my morning cup of tea"; "I feel more awake"; "I am more concentrated"; "I felt like I could cycle forever") that rendered these results and not the taste. Only 12.5% ($n = 3$) thought that the beverage contained caffeine. Comments made were "I have no energy"; "I feel weak"; "It takes a long time"; "This surely has no caffeine in it", etc., suggesting that this placebo was insufficiently blinded. Approximately 50% ($n = 12$) of those having consumed CHO thought it had contained caffeine, suggesting that this was well blinded.

TABLE 2. Mean ± SD respiratory gas exchange variables.

	30 min	90 min	115 min
Oxygen uptake, $L \cdot min^{-1}$			
CAF	2.43 ± 0.23	2.52 ± 0.24	2.52 ± 0.24
CHO	2.41 ± 0.26	2.46 ± 0.25	2.48 ± 0.22
BEV	2.38 ± 0.21	2.48 ± 0.24	2.50 ± 0.23
RER			
CAF	0.941 ± 0.047*	0.920 ± 0.042	0.921 ± 0.043
CHO	0.919 ± 0.032**	0.918 ± 0.041	0.915 ± 0.040
BEV	0.911 ± 0.037**	0.876 ± 0.026***	0.882 ± 0.034***
Carbohydrate oxidation rate, $g \cdot min^{-1}$			
CAF	2.65 ± 0.53*	2.50 ± 0.51	2.55 ± 0.50
CHO	2.39 ± 0.35**	2.42 ± 0.51	2.40 ± 0.47
BEV	2.26 ± 0.38**	1.96 ± 0.33***	2.04 ± 0.42***

* Significantly different from CHO at same time point ($P < 0.05$).
** Significantly different compared with CAF at same time point ($P < 0.05$).
*** Significantly different from both CHO and CAF at same time point ($P < 0.05$).

TABLE 3. Mean ± SD blood glucose concentration ($mmol \cdot L^{-1}$).

	Rest	65 min	125 min	Immediately after Ride to Exhaustion
CAF	4.2 ± 1.0*	4.0 ± 0.9*	4.4 ± 0.8**	4.8 ± 0.8**
CHO	4.5 ± 0.7	4.4 ± 1.0**	4.1 ± 0.9**	4.5 ± 0.9**
BEV	4.3 ± 0.7	3.5 ± 0.8***	3.4 ± 0.7***	3.8 ± 0.6

* Significantly different from time to exhaustion point ($P < 0.05$).
** Significantly different compared with BEV trial at same time point ($P < 0.05$).
*** Significantly different from resting values ($P < 0.05$).

DISCUSSION

The present study showed better concentration, faster response speed and detection, and improved complex RVIP with caffeine given in a performance bar both during moderate-intensity cycling exercise (150 min at 60% $\dot{V}O_{2max}$) and after a time to exhaustion trial at 75% $\dot{V}O_{2max}$ in trained athletes compared with a performance bar without caffeine. These alerting, focusing, and vigilance-improving effects are vital in most competitive sports. Memory was not improved, but our earlier study (13) had included a more complex memory test that had an interference component added to this. Pure effects of caffeine on memory performance are controversial (26). In all likelihood, effects of caffeine will only occur when complex memory tests are used, which require inhibition of interference and are thus mediated by the caffeine's effects on concentrational ability (26). In addition, performance of the time to exhaustion trial itself was improved and, accordingly, maximum HR achieved during the time to exhaustion trial was higher after consumption of the caffeine-containing bar. However, perceived effort was not altered, and there were no significant differences between the CAF, CHO, and BEV trials in relation to most of the physiological measurements, such as HR during exercise, RPE, oxygen uptake, and sweat loss. Importantly, there were no significant or major side effects after consumption of the bar containing caffeine.

An earlier study also showed improved physical and mental performance after 150 $mg \cdot L^{-1}$ of caffeine in a carbohydrate solution (13). The present study indicates that caffeine given in a performance bar shows comparable effects. Similar to the earlier study (13), effects were most clearly observed on the more complex cognitive tests and

less so on tests using simple response times, indicating centrally mediated and not merely peripheral sensorimotor improvements. Some cognitive tests are thus more sensitive to the effects of caffeine with carbohydrates than others. In the same vein, two other studies (16,32) also found improved performance on the RVIP test using low-dose caffeine (33 mg and 1 $mg \cdot kg^{-1}$, respectively) in combination with carbohydrates. It is unclear whether similar effects occur when caffeine is taken without carbohydrates. However, one of these studies (32) suggested that reversal of withdrawal effects was the major effect of caffeine on cognition and mood, as that study could not show caffeine effects when moderate caffeine consumers were no longer caffeine-deprived (i.e., after they had been given a second dose of caffeine). In the present study, 100 mg of caffeine was given three times at regular time intervals during the trials but cognitive performance continued to improve over time. These findings would indicate that results are not primarily explained by caffeine withdrawal alleviating effects.

Lower blood glucose concentration was found during and after exercise in the BEV trial compared with other two trials. This suggests that the consumption of an energy bar containing carbohydrate helped maintain blood glucose concentration during exercise, which otherwise falls in the absence of carbohydrate intake. Although blood glucose concentrations were not different between the two performance bar trials (with and without caffeine), the rate of carbohydrate oxidation was higher at 30 min of exercise in the trial with the caffeinated bars. A recent study indicated that the presence of caffeine in a glucose beverage increased the rate of exogenous carbohydrate oxidation, most likely via a stimulatory effect of caffeine on intestinal glucose absorption (31) and a similar effect may account for our observation in the present study.

Other measures such as RPE, respiratory parameters, and sweat loss were similar to those observed in other similar studies. For example, Kovacs et al. (17) reported no changes in sweat loss with caffeine compared with non caffeine trials during 1 h of cycling at 70% $\dot{V}O_{2max}$. A review from Magkos and Kavouras (23) stated that studies have found no significant effects of caffeine on oxygen uptake during exercise at a given fixed work rate. Findings suggest that effects may have occurred through the reduction of central fatigue mechanisms. This findings are similar to several earlier studies (5,6).

Limitations of the present study are that blinding of the caffeine containing bar may have failed. However, discourse analyses revealed that the central alerting effects rather than physical characteristics of the treatment were conducive in this and were probably only recognized at the end—or during the later stages—of the trial.

In conclusion, caffeine in a performance bar can significantly improve physical and mental ability during and after endurance exercise. It is notable that the improvement in cognitive performance with caffeine was still present after the ride to exhaustion, although participants exercised for longer in the trial with the caffeinated bars. Caffeine is no longer on the prohibited list of the World Anti-Doping Agency, but its use in competition is monitored. Its use in professional sport is not banned. Thus, the results of the present study have important implications for all endurance sports performance in which concentration, complex information processing, and vigilance play a major role.

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