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Caffeine Improves Cognitive Performance After Strenuous Physical Exercise

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The effects of three carbohydrate electrolyte solutions (CES) containing different amounts of caffeine on cognitive function and the combined effects of these drinks and exercise on cognitive functions were investigated in a double-blind, cross-over study. On five separate occasions, fifteen endurance trained male athletes (23.3 years) received water placebo, CES placebo (68.8 g/l), and three CES drinks containing low, medium and high dosages of caffeine (150, 225 and 320 mg/l). Each occasion, 8 ml/kg of the drink was consumed before – and 6 ml/kg of the drink was consumed during an all-out 1 hour time trial on a bicycle ergometer. Cognitive (attentional, psychomotor, and memory) tests were carried out immediately before and immediately after exercise. Before exercise, long term memory was improved by CES plus low dose caffeine compared to both placebos. Immediately after exercise, all cognitive functions were improved by CES plus low- and medium-dose caffeine compared to placebo. These results comprise the first practical demonstration of the cognition improving effects of low amounts of caffeine in CES after strenuous physical exercise.

Key words: Physical exercise, caffeine, cognition, athletes, endurance performance test.

Introduction

Caffeine has been shown to have beneficial effects on physical performance. In several studies the endurance performance of trained athletes was improved after caffeine intake ([9,17,30] but see [39]). It has been hypothesized that caffeine exerts at least part of its actions through central neural processes involved in activity and fatigue [17,28].

According to a review by Davis and Bailey (1997) physical endurance exercise induces central dopaminergic and cholinergic deficits. These deficiencies could play an important role in fatigue or the increased perception of effort (and eventual failure) to maintain the required force or power output [7]. Caffeine antagonizes the central adenosine system which results in an increase of the activity of dopamine, norepinephrine, and acetylcholine [28]. Furthermore, caffeine is known to have most apparent effects on cognitive (i.e. attentional, complex psychomotor, and memory) functions during fatigue (e.g. after sleep deprivation) [24,25]. Hence, caffeine, through the reversal of central dopaminergic and/or cholinergic deficiencies, could diminish the perception of effort and fatigue which would result in increased physical output and improved reaction times, precision, and motor coordination [28,34]. These central effects would be expected to be most apparent during and after those types of exercise in which concentration, reaction times, and technical/tactical skills have a major influence on performance, e.g. in most ball game sports or in ultra endurance events [10,13].

In the present study, we investigated the effect of different dosages of caffeine (0–5 mg/kg) in a carbohydrate electrolyte solution (CES), the effect of strenuous exercise (an all-out 1 hour time trial), and the combined effect of caffeine in CES and exercise on cognitive tests in a double-blind, cross-over study with trained athletes. The cognitive tests were administered twice, after warm-up just prior to the exercise time trial and immediately after exercise. Due to technical limitations, it was at present not possible to test the cognitive functions during exercise.

Caffeine has been found to improve memory functions [23, 36,38]. This effect is thought to be mediated by increased vigilance and alertness [24,25]. However, in two earlier studies we found that caffeine positively affected memory without having an intermediate effect on attentional and psychomotor functions [15,33]. Hence, it was hypothesized that before exercise caffeine would enhance memory functions independent of attentional and psychomotor functions.

Although several studies have described a negative effect of strenuous physical exercise on the performance of cognitive tests [12,13,26,35], this has not always been found [1,2,5,10, 14,37]. The results are difficult to compare. Subjects with different levels of fitness were tested with various cognitive tests

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either during or after exercise of a varying duration [26]. Furthermore, perceived exercise-induced deficiencies will not necessarily be followed by a decrease in physical and/or cognitive performance, since trained subjects will first try to invest more effort to overcome deficiencies [7]. For instance, in an earlier study with athletes we found that cycling at 75% W_{max} for one hour on a bicycle ergometer improved performance on attentional and complex psychomotor tests [14]. On the basis of the previous experiment, we thus expected a slight positive effect of exercise on the attentional and complex psychomotor tests. Furthermore, we expected that caffeine, through a decrease in the perception of effort, would additionally enhance performance on the memory, attentional, and psychomotor tests after exercise. Despite the vast amount of literature describing the physical or the psychological effects of caffeine, a combined study has, to the best of our knowledge, never been carried out.

Material and Methods

Subjects

Fifteen healthy male competitive cyclists or triathletes, aged 23.3 ± 3.6 years, participated in the study. All subjects trained on a regular basis (2 h/day and ≥ 4 times/week). Mean weight of the subjects was 72.6 ± 7.5 kg and their mean height was 185 ± 8 cm. None of the subjects had a known caffeine intolerance and all subjects regularly consumed caffeine (148 ± 117 mg/day). Subjects were aware of the risks involved in participation of the study and had signed an informed consent form. This study was approved by the local medical ethics committee at the University Hospital.

Treatment

The treatment consisted of drinking water (14 ml/kg body weight) and four carbohydrate electrolyte solutions (CES) containing: carbohydrates 68.8 g/l, and carbohydrates 68.8 g/l combined with caffeine 150 mg/l, with caffeine 225 mg/l and with caffeine 320 mg/l. The four CES drinks further contained Vitamin C 100 mg/l, Vit E 6 mg/l, Na^+ 690 mg/l, Cl^- 300 mg/l, K^+ 180 mg/l, Mg^{++} 10 mg/l, Ca^{++} 10 mg/l, phenylalanine 70 mg/l, tyrosine 70 mg/l, taurine 70 mg/l, myoinositol 51 mg/l and choline 100 mg/l. Plasma was obtained at baseline, before and after cognitive testing, during the time trial and immediately thereafter. Data on caffeine, electrolytes, and relevant other plasma parameters as well as physical performance results were reported elsewhere [21].

Test design

The experiment was conducted according to an order balanced within subjects repeated measures design. The five drinks were studied according to a double-blind, placebo-controlled, cross-over design: placebo water (Pla-W), placebo carbohydrates (Pla-CES), caffeine 150 mg/l (CES-150), caffeine 225 mg/l (CES-225) and caffeine 320 mg/l (CES-320) respectively. Treatment sequences were drawn at random.

Procedure and apparatus

Each subject came to the laboratory six times with a 1-week interval between separate trials. In the first session, maximal workload was assessed and subjects were trained in the cognitive tests. Subjects were trained on all tests twice to prevent ongoing learning effects during the experimental sessions. Twenty-four hours before testing sessions began, subjects were not allowed any alcohol or caffeine containing drinks (coffee, tea, cola, chocolate, etc.). A standardized breakfast was provided at the laboratory upon arrival. The test procedure, which started 1/2 hour after breakfast, consisted of a warm-up session (5 min 1.5 watt/kg body weight followed by 15 min 2.5 watt/kg body weight), during which the subjects were given 8 ml fluid/kg body weight of one of the test drinks. After 20 min, the first cognitive test session was carried out. This lasted 35 min. After a short warm-up session (5 min 100 W), the subjects took part in a simulated time trial during which they were given 3 ml fluid/kg body weight after 1/3 and again after 2/3 of the time trial task. Immediately after the time trial, the second cognitive test session took place (see Fig. 1).

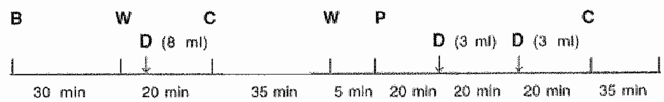

Fig. 1 Schematic representation of the test protocol B = breakfast, W = warm-up, D = drink intake, C = cognitive testing, P = performance time trial.

During the time trial, the subjects were asked to perform a certain amount of work (which required about 1 hour of cycling) as fast as possible. This workload was based on the pretest maximal workload (W_{max}) according to the formula:

Total amount of work = $0.75 \times W_{max} \times 3600$.

The ergometer was set in the linear mode according to the formula: $W = L \times (RPM)^2$, in which RPM is the pedalling rate and L

Table 1 Type of drink, actual mean (SD) body weights, amounts ingested of fluid, of carbohydrates (CHO) and of caffeine, during warm-up (before exercise) and the respective cumulative total amounts ingested

Drink	Body Weight (kg)	Fluid intake before (ml)	Total fluid intake (ml)	CHO intake before (g)	Total CHO intake (g)	Caffeine intake before (mg)	Total caffeine intake (mg)
Pla-W	73.3 (7.6)	586 (61)	1026 (106)	0	0	0	0
Pla-CES	73.6 (7.3)	589 (58)	1030 (102)	40.5 (4.0)	70.9 (7.0)	0	0
CES-150	73.3 (7.3)	586 (59)	1026 (103)	40.3 (4.0)	70.6 (7.1)	87.9 (8.8)	153.7 (15.4)
CES-225	73.3 (7.0)	586 (56)	1026 (99)	40.3 (3.9)	70.6 (6.8)	131.9 (12.7)	230.9 (22.2)
CES-320	73.4 (7.3)	587 (58)	1027 (102)	40.4 (4.0)	70.7 (7.0)	187.8 (18.7)	328.6 (32.7)

is a linear factor. This factor was chosen in such a way that a pedalling rate of 90 RPM would result in 70% W_{max}. In other words, the linear factor was dependent on a subject's W_{max}. This would mean that 75% W_{max} could be achieved at about 100 rpm which appeared to be the preferential pedalling rate of most cyclists [19]. This validated exercise test can be classified as "maximal" or "exhaustive" and subjects usually report maximal values on scales of perceived exertion [35]. The subjects cycled on a magnetically braked ergometer (Lode Excalibur Sport[R], Lode BV, Groningen, The Netherlands) and heart rate was measured continuously with a Sporttester (Polar, Finland©).

Psychomotor and cognitive tasks

Subjects completed a test battery before and after exercise. The attentional, psychomotor, and memory tests are described below. Dependent variables are listed in Table **2**.

Table 2 Description of tests, dependent variables and cognitive functions measured

Test	Dependent variables	Function measured
SCWT	Time to read card III–II (sec)	Visual selective attention
SDT	RT (msec)	Speed of signal detection/ attention shifting
	A' (0–100)	Efficiency of visual signal detection
MCRT	Simple RT (msec)	Simple psychomotor speed
	Choice RT (msec)	Complex decision speed
	S–R incompatible choice RT (msec)	Complex response Preparation speed
VVLT	# of words (0–15)	Storage in long term memory
	RT (msec)	Speed of retrieval from long term memory

The Stroop Color-Word Test (SCWT; [22]) is a visual selective attention test aimed at measuring interference susceptibility and consists of three cards. The test examines the speed at which color names are read (SCWT card I) and the speed at which colored patches are named (SCWT card II). The SCWT card III involves color names again, but the printing ink is different from the color name. The variables are: response times for cards I, II and III. Interference susceptibility as a measure of selective attention is expressed by the percentage of extra time needed for card III, relative to card II. Before the start of each test the subject was allowed to practice one line.

Signal Detection Task (SDT). Visual search requires the shifting of attention. In this visual search task, stimuli (small squares of 3 × 3 mm) are presented on a computer video monitor (640 × 480 pixels resolution). Twenty stimuli are randomly assigned to a 10 × 6 grid, all stimuli being 2.5 cm apart. Every 1000 msec three stimuli are moved to a different location in the matrix. Subjects are seated 60 cm from the monitor and have to respond to targets with their dominant hand by pressing a button as quickly as possible. Targets are defined as four stimuli forming a square of 2.5 × 2.5 cm to which subjects have to respond within 2000 msec. The total number of stimuli presented is 400. With 56 targets, this gives an overall signal probability of 0.14. Seven targets are presented every 50 sec and the same number of stimuli are presented in each quadrant of the inspection area. The task lasts 6'40". Before each actual task is performed there is a practice session consisting of one block in which subjects obtain feedback on task performance. The median reaction time is registered and the perceptual sensitivity A' is calculated. Efficient and rapid visual search (i.e. the rapid shifting of attention) is required to obtain a high signal detection performance. According to the theory of signal detection [32], the proportion of correctly recognized targets (cr) and the proportion of falsely recognized targets (fr) constitute the non-parametric sensitivity measure: $A' = 1 - 1/4\ (fr/cr + [1 - cr]/[1 - fr])$. Because the distribution of A' is skewed due to a ceiling effect, A' was arcsin transformed before being used for statistical analysis.

The Motor Choice Reaction Time Test (MCRT; [16]). Psychomotor speed is assessed by measuring RT's as a function of task complexity. In the simple condition, basic psychomotor speed is assessed. The subject is requested to hold down, with the index finger of the dominant hand, a red home button. When a single target button lights up, the subject has to press this button as fast as possible with the same finger. The complex psychomotor subtests are the following. In the choice condition a decision component is introduced. The subject has to press one of three possible buttons, positioned on a 90° degree arc 5 cm above the central red button. These buttons light up in a random order. In the incompatible condition a response competition component is introduced. The subject has to press the button adjacent to the button that lights up. The inter-stimulus interval of 500 or 1500 msec is randomly varied. Each subtask consists of 40 stimuli, the first 10 of which are practice trials. The measures used for analysis are the median RT's of the simple, the choice, and the incompatible condition.

The Visual Verbal Learning Test with Interference (VVLT). This test is an adapted version of the Rey Auditory Verbal Learning Test [3,22]. The test consists of a list of 15 monosyllabic and concrete nouns in Dutch, which are presented in three trials on a computer screen. To increase memory task complexity and avoid ceiling effects [15], simultaneously, 15 similar but different nouns are presented auditorily. The nouns occur very frequently and are acquired early in life. Items are presented in the same sequence at a rate of one every 2 seconds. Each trial ends with a free recall of the words. Thirty minutes after the third trial, the subject is requested to recall as many words as possible (free delayed recall). A yes/no recognition test, consisting of the 15 former words and 15 new but similar words, is given after the delayed recall test. The reaction times are recorded. The variables used are: the number of correct words on delayed free recall as a measure of storage in long term memory and the median reaction time (RT) of correctly recognized target words as a measure of speed of retrieval from long term memory. For each of the five treatment conditions, a different visual word list with a different auditory list was presented. Parallel lists were order balanced over treatment conditions. The word list was presented only before exercise. Delayed recall and recognition were assessed before and after exercise. Because the distribution of recall is skewed due to a ceiling effect, recall data were arcsin transformed before being used for statistical analysis.

Statistical analyses

Dependent variables were analyzed with separate repeated measures analyses of variance (using the MANOVA module in SPSS 4.0 on MacIntosh), according to a 5 factorial model to test the effect of drink content before and after exercise. The effect of exercise was evaluated by using paired t-tests comparing Pla-W before and after exercise. Separate paired t-tests were performed before and after exercise to assess caffeine-placebo differences. These comparisons were made regardless of the outcome of the corresponding overall F-test. This is a legitimate procedure if the comparisons are built into the design or suggested by the theoretical basis of the experiment [40]. Correction for multiple caffeine-placebo difference testing was accomplished by using the "sequential Bonferroni" procedure for adjusting the alpha-probability criterion [29].

Results

The data of one subject were omitted from analyses because caffeine was detected in the plasma during the CES trial. Therefore all analyses pertain to data for 14 subjects, unless otherwise indicated. During the sessions, subjects were unaware of the content of the drink and were asked to guess the sequence of the five treatment conditions after each test session. Subjects were also asked the reasons for their choice (cycling performance, frequency of urination, subjective feeling, e.g. jittery, or increased concentration). The percentage of correct guesses was (% of guesses based on taste is given between parentheses): CES-150: 22% (13%), CES-225: 38% (19%), CES-320: 41% (38%), Pla-W: 50% (28%) and Pla-CES: 63% (31%). Means and SD of dependent variables and the results of the t-tests before and after exercise are displayed in Table **3**.

Drug effects expressed as caffeine-placebo (Pla-W) difference scores are displayed in Fig. **2**.

There was no main effect of drink content ($F_{4,10} = 1.38$, ns) before exercise on visual selective attention as measured with the Stroop Interference, but there was a main effect of drink content after exercise ($F_{4,10} = 3.88$, $p < 0.05$). Visual selective attention was improved by exercise itself. In addition, visual selective attention performance was significantly enhanced after CES-150, CES-225, and CES-320 compared to Pla-CES.

There was no main effect of drink content on visual signal-detection efficiency (A') before exercise ($F_{4,10} = 1.23$, ns) but there was a main effect of drink content after exercise ($F_{4,10} = 3.88$, $p < 0.05$). Signal-detection efficiency was performed significantly better after CES-225 than after both Pla-W and Pla-CES and also after CES-150 than after Pla-CES. There was no main effect of drink content on the speed of visual signal-detection (RT) before exercise ($F_{4,10} = 1.70$, ns), although signal-detection RT was significantly faster after CES-225 than after Pla-W.

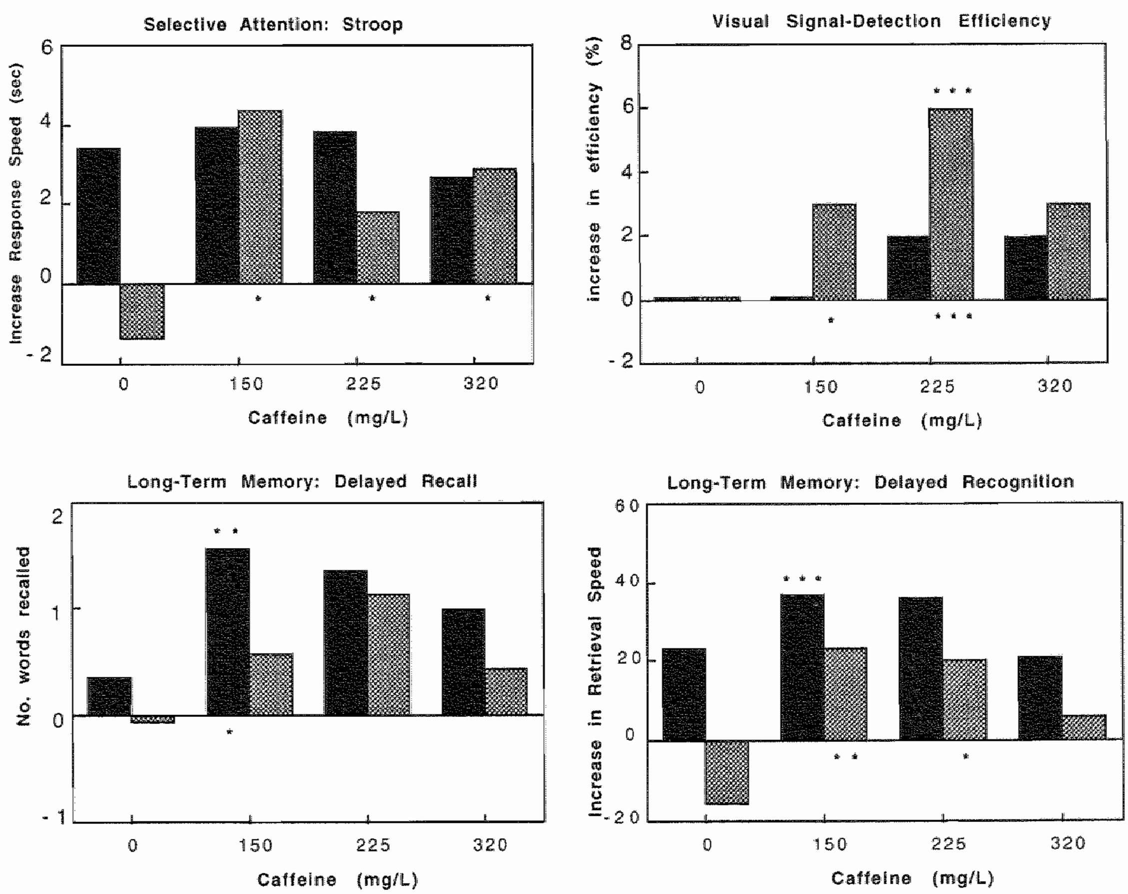

Fig. 2 Cognitive effects of caffeine-containing carbohydrate electrolyte solutions (0 mg corresponds with Pla-CES) before exercise (black bars) and after exercise (grey bars), expressed as deviations from placebo (Pla-W). Height of bars corresponds with degree of improvement. * $p < 0.05$, ** $p < 0.01$; *** $p < 0.005$; Asterisks above bars refer to comparisons with Pla-W and asterisks below bars refer to comparisons with Pla-CES.

Table 3 Means and standard deviations of the dependent variables and results of t-tests comparing the treatment drinks CES-150, CES-225, and CES-320 with the two placebo drinks Pla-W and Pla-CES before and after exercise (n = 14). The effect of exercise (Pla-W before vs. after) is displayed in column 6

Dependent variable	Before exercise	CES 150	CES 225	CES 320	After exercise	CES 150	CES 225	CES 320
Stroop Interf. (III – II)	sec	16 (8)	16 (4)	17 (5)	t = 2.1, **p < 0.05**	14 (3)	16 (6)	15 (4)
Pla-W	20 (10)	–	–	–	18 (10)	–	–	–
Pla-CES	17 (6)	–	–	–	19 (9)	t = 2.2, **p < 0.05**	t = 2.2, **p < 0.05**	t = 2.3, **p < 0.05**
Signal Detection Task	A' (0 – 100)	84 (8)	86 (7)	86 (10)		88 (10)	91 (7)	88 (7)
Pla-W	84 (12)	–	–	–	85 (12)	–	t = 3.4, **p < 0.005**	–
Pla-CES	84 (10)	–	–	–	85 (10)	t = 2.4, **p < 0.05**	t = 3.4, **p < 0.005**	–
Signal Detection Task	RT (msec)	704 (89)	670 (38)	681 (66)		672 (54)	661 (48)	673 (77)
Pla-W	709 (69)	–	t = 2.7, **p < 0.05**	–	691 (80)	–	–	–
Pla-CES	703 (70)	–	–	–	698 (51)	–	t = 3.9, **p < 0.005**	–
MCRT-Simple RT	RT (msec)	349 (24)	350 (23)	350 (29)	t = 4.5, **p < 0.001**	336 (29)	334 (33)	336 (28)
Pla-W	348 (30)	–	–	–	336 (32)	–	–	–
Pla-CES	354 (21)	–	–	–	341 (29)	–	–	–
MCRT-Choice RT	RT (msec)	406 (24)	406 (29)	400 (29)		396 (36)	397 (33)	395 (39)
Pla-W	411 (34)	–	–	–	402 (40)	–	–	–
Pla-CES	411 (24)	–	–	–	408 (33)	t = 3.2, **p < 0.01**	–	–
MCRT-Incomp. RT	RT (msec)	475 (54)	476 (45)	473 (52)	t = 2.7, **p < 0.05**	457 (43)	455 (42)	459 (50)
Pla-W	480 (54)	–	–	–	465 (52)	–	–	–
Pla-CES	480 (44)	–	–	–	475 (42)	t = 2.3, **p < 0.05**	t = 3.1, **p < 0.01**	–
VVLT-Delayed Recall	#words	11.4 (2.4)	11.2 (2.5)	10.9 (3.6)		10.4 (2.2)	11.0 (3.0)	10.3 (3.8)
Pla-W	9.9 (2.8)	t = 3.0, **p < 0.01**	–	–	9.9 (2.7)	–	–	–
Pla-CES	10.2 (2.7)	t = 2.5, **p < 0.05**	–	–	9.8 (3.1)	–	–	–
Delayed Recognition	RT (msec)	563 (62)	564 (44)	579 (63)		557 (44)	560 (47)	574 (56)
Pla-W	600 (64)	t = 3.6, **p < 0.005**	–	–	580 (60)	–	–	–
Pla-CES	577 (56)	–	–	–	596 (51)	t = 3.0, **p < 0.01**	t = 2.6, **p < 0.05**	–

After exercise, there was a significant main effect of drink content on signal-detection RT ($F_{4,10} = 5.35$, $p < 0.05$) with signal-detection RT being significantly better after CES-225 than after Pla-CES.

There were no main effects of drink content on simple psychomotor speed either before exercise ($F_{4,10} = 0.44$,ns) or after exercise ($F_{4,10} = 0.43$, ns). However, after Pla-W simple psychomotor speed was significantly faster after exercise than before exercise. As for the more complex psychomotor speed subtests, there were no main effects of drink content on Choice RT, either before exercise ($F_{4,10} = 1.64$, ns) or after exercise ($F_{4,10} = 2.96$, ns). However, after exercise choice RT was significantly faster after CES-150 than after Pla-CES. Also, there were no main effects of drink content on S-R incompatible choice RT, either before exercise ($F_{4,10} = 1.36$, ns) or after exercise ($F_{4,10} = 1.94$, ns). However, after Pla-W, S-R incompatible choice RT was significantly faster after exercise than before exercise. After exercise S-R incompatible choice RT was significantly faster after CES-150 and after CES-225 than after Pla-CES.

Before exercise, the drink content consumed had a significant multivariate main effect on the delayed recall performance of the subjects on the VVLT ($F_{4,10} = 3.33$, $p = 0.05$). T-tests revealed that significantly more words were recalled after CES-150 than after both placebos. No difference was found between the placebos (Fig. **2**). After exercise the drink content did not have an overall effect ($F_{4,10} = 1.29$, ns). The drink content did not affect delayed recognition RT before exercise ($F_{4,10} = 2.10$, ns). However, t-tests revealed that RT was significantly faster after CES-150 than after Pla-W. After exercise, there was a significant main effect of drink content on recognition RT ($F_{4,10} = 3.52$, $p < 0.05$) which was significantly faster after both CES-150 and CES-225 than after Pla-CES.

Discussion

The aim of the present study was to examine the effects of CES drinks containing caffeine on cognitive functions both before and after exercise. The results show that our hypotheses were confirmed. Before exercise, the drink that contained the lowest concentration of caffeine compared to both placebos improved long term memory performance independent of attentional and psychomotor functions. After exercise, the low and medium dosages of caffeine containing CES drinks improved most of the cognitive functions measured. Exercise itself also improved the speed of performance of certain tasks.

The effects of caffeine before exercise are comparable to those reported by other investigators who studied the cognitive effects of caffeine, whereas the effects of caffeine on cognitive performance after exercise are a new finding. For this reason we will discuss the effects of caffeine on cognitive performance before and after exercise separately.

Before exercise, delayed recall memory performance was significantly improved after the consumption of drink CES-150 compared to Pla-W and Pla-CES. First, since there was no difference beween Pla-CES and Pla-W, this suggests that the observed memory improvement after CES-150 in comparison with Pla-W could not be attributed to the ingestion of 40 g carbohydrates or the other ingredients of the CES which were present in low concentrations. Second, although it is assumed that caffeine acts by enhancing vigilance and alertness and has no direct effect on memory [24,25], the lack of effect of 88 mg of caffeine (see Table **1**) on attentional and speed functions before exercise supports the notion that there was an independent, direct effect of caffeine on memory. The effect of caffeine may be dose-dependent since these results are in agreement with those of other studies which found that the optimal amount of caffeine for improving memory is around 100 mg [23,38]. Again, Smith et al. (1994) also found positive effects of a higher dose of 4 mg/kg caffeine (> 250 mg) on free recall and recognition [36]. The sex of the participants studied could account for varying results since we studied male subjects only. In this respect, acute doses of 2 and 4 mg/kg of caffeine have been found to impair memory performance in females, but not in males [8]. In addition, the differences in habitual use and the possible effects of caffeine deprivation in some subjects could explain some of the discrepancies between studies [15].

However, as to the attribution of our results to the effects of caffeine deprivation, the effects of caffeine withdrawal on cognitive functions are disputed [18]. In the study performed by Warburton (1995) low dosages of caffeine (75 and 150 mg) were seen to improve attention, problem solving, and delayed recall after a minimal caffeine abstinence of 1 h [38]. Hence, even without caffeine deprivation, subjects in the caffeine condition still showed improved cognitive performance. It has been found that withdrawal symptoms occur in subjects that consume as little as 100 mg/day [11]. However, another study, which included subjects that were above average caffeine consumers, did not find effects of caffeine abstinence on cognitive functions such as complex psychomotor speed, working memory and logical reasoning [31]. In the present study subjects were tested after a similar period of caffeine abstinence and also drank relatively little coffee, which may have rendered them even less sensitive to caffeine withdrawal effects.

As expected, exercise itself was seen to improve selective attention, and simple and complex psychomotor functions. This confirmed the findings of our earlier study [14]. In addition, the low and medium dosages of caffeine were seen to positively affect most cognitive functions after exercise. The low caffeine containing drink (CES-150) improved attention (Stroop, SDT), complex psychomotor speed, and recognition memory compared with Pla-CES. Overall, the medium dosed drink (CES-225) had similar effects (see Table **3**) while the drink which contained the highest dosages of caffeine (CES-320 drink) only improved selective attention after exercise.

Curiously, a significant difference in cognitive performance after exercise was only observed when the caffeine-containing CES drinks were compared to CES without caffeine. In general, CES ingested during exercise reduces physical fatigue and improves physical work capacity compared to water alone [4,6, 20]. In addition, we found in the present study that plasma free fatty acids (FFA) were significantly higher after Pla-W than after all other beverages and that Pla-W resulted in the poorest ergometric performance times [21]. This could indicate that subjects were more physiologically challenged after Pla-W compared to the CES containing placebo. It is possible that after Pla-W, subjects have compensated to overcome the effects of perceived fatigue on the mental tests. The decision to invest more effort to overcome the effects of perceived fatigue is especially seen in highly trained subjects [1,7,14,37]. Hypothetically, the increased central activation or arousal due to the physiological stress of prolonged exercise without CES may have aided them in improving their mental performance [12,14,34].

When taking Pla-CES, subjects did not show the exercise-induced increase in speed of performance except on the simple RT. The rather high percentage of correct guesses in both placebo conditions may suggest that the double-blindness of the content of the drinks was not entirely maintained and that expectancy effects may have come into play. The expectancy of participants is thought to influence mental performance after exercise through motivational variables [1,14]. Since drinks with a similar content as Pla-CES are normally consumed during exercise, subjects may have recognized the drink and not have invested the additional effort to improve their mental performance, because they expected no improvement. Caffeine is thought to diminish the perception of effort and hence could have resulted in increased mental and physical output [17,21,24,25,28] which would explain the difference between caffeinated CES and CES without caffeine drinks.

In sum, our results demonstrate, for the first time, that a low and medium dose of caffeine improve complex cognitive functions in athletes after strenuous exercise. This is important because the capacity to concentrate effectively is widely regarded in competitive sport as the key to successful performance [27]. Our results show that these functions can be improved with a relatively low dose of caffeine in the range of 150–225 mg/l and that these effects are not further enhanced by increasing the dosage of caffeine (i.e. 320 mg/l).

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