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The effect of caffeine on cognitive task performance and motor fatigue

Hiske van Duinen, Monique M. Lorist, Inge Zijdewind

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Abstract

In everyday life, people are usually capable of performing two tasks simultaneously. However, in a previous study we have shown that during a fatiguing motor task, cognitive performance declined progressively. There is extensive literature on the (positive) effects of caffeine on cognitive and motor performance. These effects are most pronounced under suboptimal conditions, for example during fatigue. However, little is known about the effects of caffeine on cognitive performance during a fatiguing motor task. We aimed to investigate whether a moderate dose of caffeine could attenuate the decline in cognitive performance during a fatiguing motor task. The study consisted of a placebo and a caffeine (3mg/kg) session; 23 subjects completed these sessions in a semi-randomized and double blind order. In each session, subjects performed maximal voluntary contractions of the index finger, a choice-reaction-time task (CRT) and a dual task that consisted of a fatiguing motor task concomitantly with the same CRT-task. After the fatiguing task the CRT was repeated. Caffeine improved cognitive task performance, in both the single and dual task, as was seen by decreased reaction times together with unchanged accuracy. Cognitive performance in the dual task deteriorated with increasing fatigue. However, the decrease in cognitive performance in the beginning of the dual task, as seen in the placebo condition, was partly prevented by caffeine administration (i.e., no increase in reaction-times). We found no effects of caffeine on motor parameters (absolute force, endurance time or EMG amplitude). In conclusion, caffeine improved cognitive performance, also in demanding situations such as the performance of a dual task and in the situation of progressive fatigue.

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Introduction

Coffee is a widely used beverage and it is estimated that about 90% of Dutch adults drink coffee regularly (Hameleers et al., 2000). Coffee contains caffeine that is known to have stimulatory effects on the central nervous system. The stimulating effects of caffeine are predominantly caused by an antagonistic action on adenosine receptors. Hence, caffeine increases the levels of several neurotransmitters such as dopamine, acetylcholine and serotonin (for review see Fredholm et al., 1999). In daily life, caffeine is commonly used to suppress feelings of fatigue. Furthermore, after caffeine consumption, subjective feelings as increased alertness, energy and ability to concentrate are often mentioned. The effects of caffeine are most pronounced when subjects perform under suboptimal conditions, such as during fatigue or tediousness, or in tasks placing high demands on the information processing system (Lieberman et al., 1986; Lorist et al., 1994; Ruijter et al., 1999). The execution of two tasks simultaneously is a condition that places high demands on the processing system. Several studies showed that in a cognitive dual-task condition caffeine has a positive effect on the performance (Brice and Smith, 2002; Ruijter et al., 1999).

By using a dual-task paradigm we previously showed a mutual interference between motor- and cognitive-performance during a protocol that induced progressive amounts of muscle fatigue (Lorist et al., 2002). In this study, subjects performed a submaximal contraction until they could no longer maintain the contraction at the desired force levels. Concomitantly with this fatiguing motor task, the subjects had to execute a choice reaction time task (CRT). The reaction times and the number of errors served as a measure of cognitive performance. The growing amount of fatigue was accompanied by an increase in both reaction times and number of errors. We attributed the progressive decline in cognitive performance to an increasing demand on central resources by the motor task. Thus, fewer resources were available for the cognitive task performance. As caffeine seems to have an effect on the availability of central resources, the investigation of this interference – between motor fatigue and cognitive task performance – seems to be a logical direction for further research.

Besides beneficial effects on cognitive performance, caffeine is also known to affect motor performance. The effects of caffeine on short-term exercise, however, are not consistent. Some studies show an increase in endurance time after caffeine consumption (Jackman et al., 1996; Kalmar and Cafarelli, 1999; Plaskett and Cafarelli, 2001), while others show no effect (Lopes et al., 1983; Williams et al., 1987). In addition, the effects of caffeine consumption on muscle force are contradictory. Several studies

fail to show significant ergogenic effects (Lopes et al., 1983; Williams et al., 1987); however, in two well-controlled studies, Cafarelli and co-workers (Kalmar and Cafarelli, 1999; Plaskett and Cafarelli, 2001) found an increase in muscle force after caffeine administration.

The usage of caffeine in studies is not very consistent. There are differences in duration of caffeine abstinence, dose, and manner of administration. In some studies, subjects have to abstain from coffee for just one hour before the experiment, while other studies demand abstinence from caffeine for several days. As it has been shown that caffeine has a positive effect in subjects that had only been minimally deprived of caffeine (Christopher et al., 2005; Warburton, 1995; Warburton et al., 2001), we decided to allow subjects to drink their morning cup of coffee. In this way, detrimental effects of caffeine withdrawal symptoms were prevented and the daily ritual of subjects would not be affected (Lane and Phillips-Bute, 1998; Rogers et al., 2003). In previous studies, the doses of caffeine used vary from a single dose of 32 mg (Lieberman et al., 1987) up to 1400 mg of caffeine (Streufert et al., 1997), or bodyweight related doses of 1 (Yeomans et al., 2002) to 13 mg/kg (Pasman et al., 1995). According to Graham (2001), the optimal dose of caffeine is between 3 and 6 mg/kg bodyweight. To mimic everyday life as much as possible, we used a dose of 3 mg/kg (equivalent to about two cups of coffee) and dissolved the caffeine in decaffeinated coffee.

It was the aim of this study to investigate the effect of a moderate dose of caffeine on the performance on a cognitive task and the motor parameters, force and endurance time. Furthermore, we have used a dual-task paradigm to investigate whether a moderate dose of caffeine could attenuate the decline in cognitive performance that was observed during a fatiguing motor task.

Methods

Participants

Twenty-four healthy adults (mean age 24 ± 6 years, 11 males, 13 females) participated in this study. All subjects were right-handed, non-smokers; they usually drank 3-6 cups of coffee per day (or an equivalent of that amount of caffeine in other dietary sources). The subjects had normal or corrected-to-normal vision and intact hearing. Each subject signed written informed consent prior to the study. All procedures were undertaken with the approval of the local ethics committee (METc, Academic Hospital Groningen) and were performed with the standards set out in the Declaration of Helsinki.

Experimental set-up

Subjects sat at an experimental table; their lower arms rested on the table with the elbows in an angle of 135 degrees. Their right hand was fixed in the experimental set-up in a position halfway between pronation and supination. Furthermore, hand and lower arm were immobilized with pressure plates and Velcro tape. We measured the abduction force of the first dorsal interosseous muscle (FDI) of the right hand. Therefore, the proximal interphalangeal joint of the right index finger was inserted (slightly abducted) in a snugly fitting ring that was rigidly connected to an isometric force transducer (for detail see Zijdewind and Kernell, 1994). Electromyographic (EMG) recordings were obtained from the FDI of both hands with a surface electrode (4mm diameter) placed over the muscle belly and a reference electrode placed at the metacarpophalangeal joint of the index finger. A band-shaped earth electrode was placed around the right wrist. EMG and force recordings were amplified, filtered (EMG: 10Hz-1kHz; force: DC-500), and sampled using a PC equipped with a data-acquisition interface (1401+, Cambridge Electronic Design, Cambridge, UK). The sampling rates were 2000 and 500 Hz for EMG and force recordings, respectively. Off-line analysis was performed with custom-made scripts (Spike2, Cambridge Electronic Design, Cambridge, UK).

Tasks

In this study, subjects had to perform three tasks: a motor-task, a cognitive-task, and a dual-task.

The motor task consisted of voluntary abductions of the right index finger. The contractions could either be maximal (MVC) or submaximal (30% cMVC). At the start of the experiment, subjects performed three maximal voluntary contractions (MVCs; 4s) of the index finger (abduction) at approximately 1-minute intervals (Enoka et al., 1989; Fuglevand et al., 1993; Zijdewind and Kernell, 1994). If the difference between the peak forces of two consecutive MVCs exceeded five percent, a subsequent trial was performed. The strongest contraction was used as the 'control MVC' (cMVC). During the cognitive tasks (see below), subjects executed an MVC after each 60-second-period (see Fig. 1).

The *cognitive task* involved an auditory choice reaction time task (CRT). The stimuli (500 or 900 Hz pure tones; duration: 50 ms, intensity: 70 dB) were presented binaurally through speakers. Random sequences of 'frequent' (70% occurrence; high-probability) and 'infrequent' (30%; low-probability) stimuli were presented in blocks of 50 stimuli (a period lasting approximately 60 s). The inter-tone interval varied randomly

between 1100 and 1300 ms. Subjects responded to the auditory stimulus by pressing one of two response-buttons with the middle or index finger of their left hand, as fast and accurately as possible. Half of the subjects were instructed to respond with their middle finger to frequent stimuli and with their index finger to infrequent stimuli. The other subjects received opposite instructions. For half of the subjects in each group, 500 Hz tones were 'frequent' stimuli; for the other half of the subjects these tones served as 'infrequent' stimuli. As a result, there were four different versions of the CRT: 1) frequent stimuli 500 Hz, middle finger response; 2) frequent stimuli 900 Hz, middle finger response; 3) frequent stimuli 500 Hz, index finger response; and 4) frequent stimuli 900 Hz, index finger response. The presentation of stimuli and the collection of the subjects' responses were controlled by Micro Experimental Laboratory Professional Software (MEL v2.0; Schneider, 1988) in conjunction with the MEL Serial Response Box.

The *dual task* consisted of a motor task at 30% cMVC (right index finger) that was performed in combination with the cognitive task (left hand; see Fig. 1). The subjects looked at a dual-beam oscilloscope in front of them; one beam continually displayed the isometric force production of the subject, and the second beam indicated the desired level of contraction force (30% cMVC). The task started with: 1) the submaximal contraction at 30% cMVC maintained for 60s, followed by 2) an MVC for 4s and 3) 4s-rest. Concomitantly with the submaximal contraction, the subjects had to execute the same CRT that is described above. This sequence (1-3) was repeated until the subject could no longer maintain the target force.

Caffeine administration

Subjects completed a placebo and a caffeine session in a semi-randomized and double-blind order. In the placebo condition, subjects received decaffeinated coffee. In the caffeine condition, subjects received decaffeinated coffee in which caffeine (3mg/kg bodyweight) was dissolved. Subjects were allowed to use milk and/or sugar, and they could not distinguish between caffeinated and decaffeinated coffee. As there is evidence that withdrawal effects may play a role in the observed caffeine effects (Rogers et al., 2003), subjects were allowed to consume one cup of coffee before 10 a.m. If they drank their morning coffee, they had to do so on both experimental days.

General procedure

Figure 1 shows a schematic drawing of the procedure that was followed throughout both experimental sessions. These sessions were identical except for the caffeine treatment;

the sessions were at least one week apart. Each session started at 1.30 p.m., and lasted 1.5 to 2 hours; a session started with drinking a cup of coffee (with or without caffeine, see 'Caffeine administration').



Figure 1. Schematic representation of general procedure. Practice and MVC measurements, which precede the single CRT pre-fatigue, are not shown. During the single CRT pre-fatigue, an MVC is produced once every minute. After this task, the dual task is executed: a contraction at 30% cMVC in combination with the CRT, followed by an MVC and 4-s rest. The dual task is followed by the single CRT post-fatigue.

In order to attribute the influence of performing a concurrent motor task on CRT-performance, we started with a single CRT task. The difference in performance between the single task and the start of the dual task give an indication of the additional demands of the motor task. The long-term effects of fatigue were studied by repeating the single CRT. The difference in performance between the pre- and post-fatigue CRTs gives an indication of these long-term effects. Hence, the order of the executed tasks was as follows:

- 1) Practice; one block of 150 CRT stimuli was followed by three blocks of 50 CRT trials (ca. 60s), each block was followed by an MVC;
- 2) Three MVC measurements; this part started approximately 45 minutes after caffeine administration;
- 3) Single CRT (pre-fatigue); fourteen blocks of 50 stimuli, each block was followed by an MVC;
- 4) Dual task; a submaximal contraction combined with the CRT, continued until the subject failed to maintain the target force level for more than 2s.
- 5) Single CRT (post-fatigue); fourteen blocks of 50 stimuli, each block was followed by an MVC (see 3).

Since accurate force measurements require fixation in the experimental set-up, which would be uncomfortable for long time periods (>1.5 hour), we did not perform baseline measurements before coffee consumption.

Data reduction and statistical procedure

Force and EMG data were analysed with Spike2 for Windows. EMG data were rectified and smoothed over a time-constant of 100 ms. Peak values of force and EMG were determined for the MVCs, while mean amplitudes of force and EMG and force variability (SD/mean) were determined for the submaximal contractions.

To study time-on-task effects, we grouped the behavioural data into three equal time periods (begin, t1; middle, t2; and end of task, t3) per task (dual task, and single CRTs). We calculated the mean force and EMG values for each time period. In the CRTs, the first two stimuli of each block were regarded as practice trials, and they were therefore excluded from the analysis. For each subject, we determined mean accuracy percentages and trimmed mean (20%) reaction times (RTs) of correct responses per time period. Trimmed means were used to prevent large effects of outliers, without losing too much data (in contrast to the median; Wilcox et al., 2000). The 20% trimmed mean refers to a situation in which the fastest 20% and the slowest 20% of the reaction times are removed; the remaining reaction times are averaged.

The cognitive data were analysed using ANOVAs for repeated measurements using the statistical package SPSS 10 for Windows. For reasons of clarity we have separated the statistical analysis for the single task and the dual task. Thus, in the single task condition both pre- and post-fatigue data were combined, resulting in 6 time-periods (t1-t3 for the pre-fatigue values; and t4-t6 for the post-fatigue values). Since the caffeine was administered in a semi-randomized order (in session 1 or 2), we used session (two levels), frequency (two levels: frequent stimuli and infrequent stimuli), and time-on-task (three: t1-3 or six: t1-6) as within-subjects factors and session of caffeine administration as between-subjects factor. Although subjects underwent a practice trial still training effects could be induced by repeating the experiment. The interaction between session and session of caffeine administration shows the effect of caffeine on this possible training effect.

We also used ANOVAs for repeated measurements to analyse the motor parameters. For MVC data, within-subject factors were session (two levels), and time-on-task (three levels); between-subjects factor was session of caffeine administration. For the absolute force and the endurance time the within-subject factor was session and the between-subjects factor was session of caffeine administration. If the main analysis indicated a significant effect of a factor or an interaction between factors, follow-up analyses were performed, with adjustments of the significance level for multiple

comparisons according to Bonferroni. In text data are reported as means \pm SD and in Figures as means \pm SE.

Results

Table 1 shows the mean age, weight, and caffeine amount for all subjects who were used for analysis. In one (female) subject the recording of cognitive data failed at the start of the dual task; therefore, data of this subject were excluded from the analysis.

Table 1. Physiological data and caffeine consumption for male and female subjects. For each parameter mean \pm S.D. and range (between brackets) are given.

Subjects	11 Males	12 Females
Age (years)	25.6 \pm 7.0 (19 – 42)	21.3 \pm 2.1 (18 – 24)
Weight (kg)	78.8 \pm 9.5 (63 – 97)	65.5 \pm 11.4 (48 – 84)
Caffeine (mg)	236.5 \pm 28.5 (189 – 291)	196.5 \pm 34.1 (144 – 252)

No significant differences were found between CRT performance in the different test versions (frequent stimuli 500 or 900 Hz, middle or index finger response; RT: $F_{(3,19)}=1.32$, $p=0.297$; accuracy: $F_{(3,19)}=0.22$, $p=0.881$). Therefore, data were pooled across the four CRT versions. Neither did we find a significant interaction between gender and caffeine on the various cognitive and motor parameters (RT: $F_{(1,21)}=0.36$; accuracy: $F_{(1,21)}=1.38$; cMVC: $F_{(1,21)}=0.80$; endurance: $F_{(1,21)}=0.35$; all values are n.s.). Therefore, we have pooled the data of male and female subjects. Figure 2 shows reaction times (RTs) and accuracy of the three tasks (pre-fatigue single CRT, fatiguing dual task, and post-fatigue single CRT).

In both the single CRTs and the dual task, the reaction times were significantly shorter in the second session ($F_{(1,21)}=28.10$, $p<0.001$). To investigate the effect of caffeine on the reaction times we have used session of caffeine administration as a between-subject variable. Significant interactions between session and session of administration were found for reactions times of both frequent and infrequent stimuli ($F_{(1,21)}=9.48$, $p=0.006$). This interaction suggests that caffeine has an additional effect on the effect of session. Overall subjects responded faster in the second session. However, subjects who received caffeine in the second sessions were significantly faster, while subjects who received caffeine in the first session did not show an improvement in their

reaction times. That is, in those subjects the effect of session (faster in session 2) and the effect of caffeine (faster in caffeine session: 1) have contradicting effects on reaction times. Since we are interested in the effect of caffeine, we will discuss the interaction between session and session of caffeine administration in more detail in the following paragraphs.

Single-task performance

As can be seen in Figure 2, caffeine consumption significantly affected the difference in reaction times between session 1 and 2 ($F_{(1,21)}=8.08$, $p=0.010$; for frequent and infrequent stimuli together), but not accuracy ($F_{(1,21)}=0.25$, n.s.). Subjects reacted significantly faster in the caffeine condition (290 ± 51 versus 299 ± 52 ms), without decreasing their accuracy (92.6 ± 7.7 versus $92.4 \pm 7.9\%$). We found no interactions between caffeine and frequency and/or time-on-task.

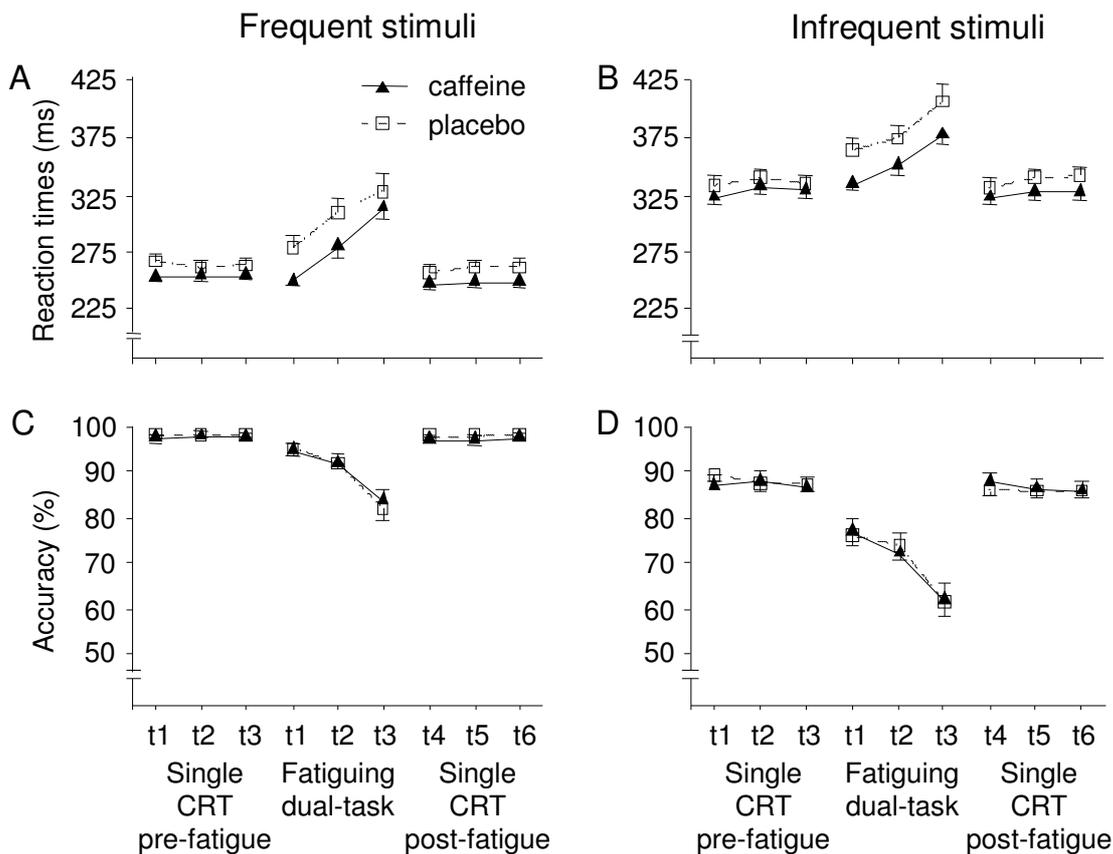


Figure 2. Reaction times and accuracy data. Reaction times are shown for both frequent (a) and infrequent (b) stimuli; accuracy data are shown in c (frequent) and d (infrequent stimuli). Data of both the caffeine (▲) and placebo (□) condition are shown, during the single task before fatigue, the dual task and the single task after fatigue.

We also found that stimulus frequency had a significant effect on both reaction times and accuracy (RTs: $F_{(1,21)}=286.16$, $p<0.001$; accuracy: $F_{(1,21)}=121.83$, $p<0.001$). In line with previous research (Lorist et al., 2002), subjects responded faster and more accurately to frequent stimuli ($257 \pm 32\text{ms}$, $97.8 \pm 1.7\%$) compared to infrequent stimuli ($333 \pm 38\text{ms}$, $87.2 \pm 7.9\%$). Besides stimulus frequency, time-on-task also had a significant effect on reaction times; this effect was caused by the reaction times of t4, which were significantly faster than the reaction times in t2 and t3 ($F_{(5,105)}=3.40$, $p=0.007$). Accuracy levels did not change with time-on-task ($F_{(5,105)}=1.546$, n.s.). Furthermore, there was a significant interaction between the effect of stimulus frequency and time-on-task for reaction times ($F_{(5,105)}=6.43$, $p<0.001$). Post-hoc tests revealed that this interaction was due to data of the single CRT pre-fatigue (t1-t2: $F_{(1,21)}=19.27$, $p<0.001$; t2-t3: $F_{(1,21)}=6.28$, $p=0.021$). From t1 to t2 reaction times of frequent stimuli slightly decreased, while reaction times of infrequent stimuli slightly increased; conversely, from t2 to t3 reaction times of frequent stimuli slightly increased, while those of infrequent stimuli slightly decreased from t2 to t3 (as can be seen in Figs. 2A&B).

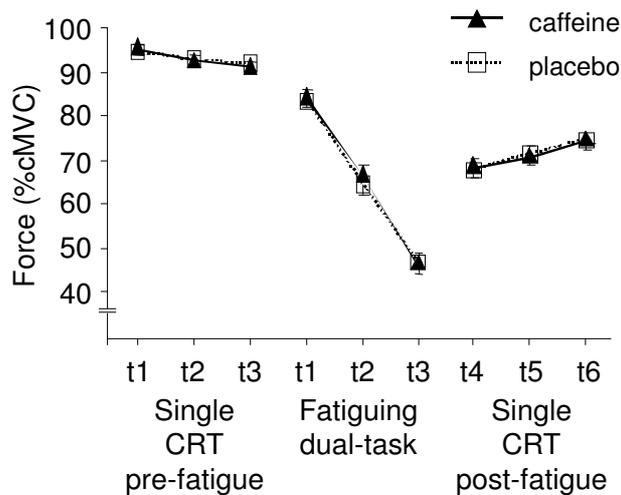


Figure 3. MVC-values (%) during pre-fatigue single task, dual-task and the post-fatigue single task. Mean values were calculated for three equal time-periods per task. The MVC-values in both the caffeine (\blacktriangle) and placebo (\square) condition are shown.

During the single CRTs, subjects performed an MVC after every block of 50 stimuli. Figure 3 shows the change of MVC-values with time. During the single CRT before the fatigue test, a small decline in MVC values could be observed (t1: $95.0 \pm 3.3\%$ -cMVC, t3: $91.1 \pm 5.5\%$ -cMVC; $F_{(2,42)}=30.55$, $p<0.001$). During the single CRT after the fatigue test MVC values increased approximately by 6%, indicating a small recovery from fatigue (t4: $67.7 \pm 7.3\%$ -cMVC, t6: $74.1 \pm 8.9\%$ -cMVC; $F_{(2,42)}=53.63$, $p<0.001$). Caffeine affected neither the cMVC ($F_{(1,21)}=0.18$, n.s.), nor the MVC values during the CRTs ($F_{(1,21)}=0.018$, n.s.). In addition, no effect of caffeine was found on the time-course

of the MVC values (interaction caffeine × course of MVCs: $F_{(5,105)}=0.17$, n.s.), nor the accompanying EMG values (during MVCs: $F_{(1,21)}=0.22$, n.s.; interaction caffeine × course of EMG during MVCs: $F_{(5,105)}=0.97$, n.s.).

Dual-task performance

During dual-task performance the MVC values declined significantly as can be seen in Figure 3 (t1: $84.0 \pm 6.3\%$ cMVC, t3: $46.1 \pm 11.1\%$ cMVC; $F_{(2,42)}=147.10$, $p<0.001$); this indicates that fatigue was indeed induced by the submaximal motor task. Moreover, in accordance with previous research (Lorist et al., 2002), subjects showed a significant decrease in cognitive performance with increasing fatigue: reaction times increased and accuracy decreased progressively with time-on-task (RT: $F_{(2,42)}=23.14$, $p<0.001$; accuracy: $F_{(2,42)}=30.08$, $p<0.001$). However, a significant interaction effect between session and session of caffeine administration was found for the reaction times ($F_{(1,21)}=5.52$, $p=0.029$). This result implies that caffeine administration improved the cognitive performance significantly in the dual task; in the caffeine condition subjects showed faster responses (319 ± 67 ms versus 343 ± 78 ms) without a change in response accuracy (80.7 ± 17.2 versus $80.1 \pm 16.9\%$; $F_{(1,21)}=0.27$, n.s.). We found no significant interactions between caffeine and stimulus frequency and/or time-on-task.

As expected, stimulus frequency significantly affected reaction times and accuracy. Subjects reacted faster and more accurately to frequent than to infrequent stimuli (RT: 294 ± 64 ms versus 369 ± 62 ms; $F_{(1,21)}=148.06$, $p<0.001$; accuracy: $90.1 \pm 10.0\%$ versus $70.7 \pm 17.0\%$; $F_{(1,21)}=112.84$, $p<0.001$).

No significant effect of caffeine on the motor parameters was found; caffeine did not affect the amplitude of the MVC values ($F_{(1,21)}=0.94$, n.s.). Neither was the decline in MVC values affected by caffeine consumption ($F_{(2,42)}=0.44$, n.s.), nor the accompanying EMG values ($F_{(1,21)}=0.037$, n.s.; interaction caffeine × time: $F_{(2,42)}=0.28$, n.s.). However, in the caffeine condition subjects had the tendency to produce slightly more force (30.93% vs 30.21% cMVC) during the submaximal contraction ($F_{(1,21)}=3.35$, $p=0.081$). Although this effect was small and not significant, it could influence the time that subjects could maintain the fatiguing task. As shown in Figure 4, a significant negative correlation could be observed between absolute force at the start of the dual task (t1) and the endurance time ($r= -0.378$; $p=0.010$). The endurance time and the absolute force at the start of the dual task, however, were not affected by caffeine ($F_{(1,21)}=1.20$, n.s., $F_{(1,21)}=0.15$, n.s., respectively).

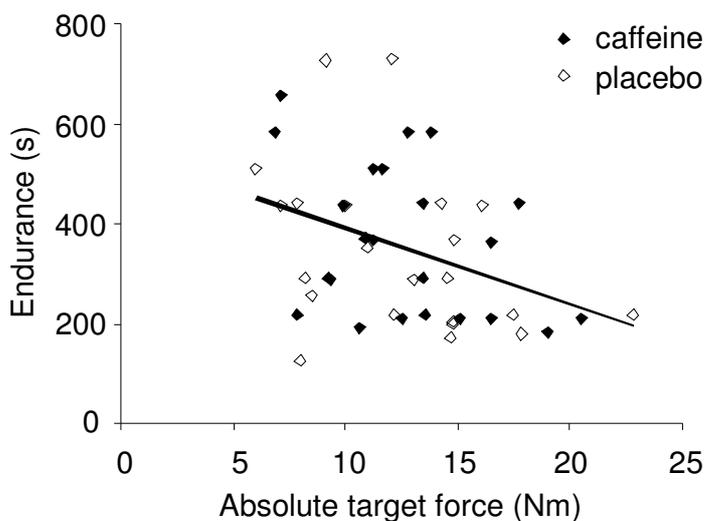


Figure 4. The relation between the (produced) target force (Nm) during t1 of the dual-task and the endurance time (s). Each point represents data of a subject in the caffeine (◆) and placebo (◇) session. The correlation between force and endurance was -0.397 , $p=0.006$.

Single- versus dual-task performance

Overall, cognitive performance in the dual task was inferior compared to performance in the single CRTs: reaction times were longer and the accuracy was lower in the dual task (effect of task: RT: $F_{(2,42)}=45.87$, $p<0.001$; accuracy: $F_{(2,42)}=43.15$, $p<0.001$). Post-hoc tests revealed that the dual task differed significantly from the single CRTs (for both RTs and accuracy: single CRT pre-fatigue versus dual task: $p<0.001$; dual task versus single CRT post-fatigue: $p<0.001$). However, in the dual task, performance was also influenced by fatigue. Since fatigue has a deteriorating effect on dual-task performance, the difference between the single CRTs and the dual task might have been caused by fatigue. To exclude this effect of fatigue, we have also compared t3 of the single CRT pre-fatigue versus t1 of the dual task. For reaction times, we found a significant interaction between task and caffeine ($F_{(1,21)}=6.46$, $p=0.019$); that is, reaction times increased in the placebo condition but not in the caffeine condition, as can be seen in Figure 2 (increase in reaction times: 1 ms in the caffeine condition, 22 ms in the placebo condition). For accuracy, there was a main effect of task ($F_{(1,21)}=19.90$, $p<0.001$). This implies that, both in the caffeine and placebo condition, accuracy was lower in the dual task than in the pre-fatigue CRT (decrease of 6.6%), without an interaction between task and caffeine ($F_{(1,21)}=0.32$, n.s.).

Discussion

In everyday life, motor and cognitive performance generally occur together. Deterioration of cognitive functions, provoked by motor fatigue, might lead to sub-optimal functioning in, for example, work situations. As caffeine can improve both cognitive and motor performance, we studied whether caffeine also positively affects cognitive performance

during a fatiguing motor task. We indeed showed that caffeine improved cognitive performance, also in a situation of motor fatigue. However, no effect of caffeine on the motor parameters (maximal force and endurance time) was found.

We found that subjects responded faster in the second session than in the first session. Thus, repeating the same test resulted in an improved performance; subjects respond faster without increasing their number of errors (see also Klapp, 1995; Rabbit and Banerji, 1989). This training effect was seen despite the fact that we did not find a time-on-task effect in the first single task (single CRT t1-t3). However, the fact that subjects responded faster on t4 (the first measurement after the dual task) showed that subjects could still improve their performance. Thus, despite lack of improvement during the experiment a significant improvement was seen while repeating the test.

The decrease in reaction times between the first and second experiments was influenced by caffeine consumption. Subjects who consumed caffeine in the second session were much faster in this session than in the first session, while subjects who received caffeine in the first session did not improve their reaction times. In the latter subjects, the accelerating effects of caffeine (first session) were obscured by the accelerating effect of practice in the second session. In contrast, for the first group of subjects the accelerating effects of caffeine were added to the accelerating effects of practice in the second session. Overall, this interaction between session and session of caffeine administration showed that cognitive performance was more efficient in the caffeine condition than in the placebo condition. The positive effects of caffeine were observed for both frequent and infrequent stimuli. In general, the effect of caffeine is most robust on tasks associated with attention or alertness (Brice and Smith, 2002; Lieberman et al., 2002; Warburton, 1995). The accelerating effect of caffeine on reaction times is consistent with this observation. In a dual-task paradigm higher demands are placed on the information processing system (Wickens, 2000). Since the capacity of the information processing system is limited, performance in one or both tasks of the dual-task paradigm would be expected to deteriorate. In our experiment, we have instructed our subjects to consider the motor task as the primary task and therefore we expect to find changes in the cognitive performance as an indication of increasing demands. In the placebo condition, we found a decline in cognitive performance in the beginning of the dual task (t3 of single CRT pre-fatigue versus t1 of dual task), indicating that the demands placed on the information processing system in the dual-task condition indeed exceeded the available capacity. However, in the caffeine condition this decline was partially prevented, as there was no increase in reaction times in the beginning of the dual task, indicating that caffeine did have an influence on the information processing

capacity. This result indicates that caffeine has an effect on the efficiency of the information processing system and/or the allocation of the available capacity. This result is consistent with the finding of enhanced performance in a caffeine condition in experiments using a cognitive dual-task paradigm (Brice and Smith, 2002; Ruijter et al., 1999). In our study, the dual task consisted of a fatiguing motor task in combination with a cognitive task. If the demands of the motor task increase during the development of fatigue, the performance on the secondary cognitive task declines. However, positive effects of caffeine persisted, since no interaction effect between caffeine and time-on-task was observed.

Despite the effect of caffeine on the cognitive performance, we did not find an effect on the different motor parameters: absolute force, time course of the MVCs or endurance time. A complication is the fact that in the caffeine condition subjects tend to produce more force compared to the placebo condition. As was shown by Rohmert (1960) subjects tend to fatigue faster at higher force levels (see also Hunter and Enoka, 2001). This could imply that in the caffeine condition subjects fatigue faster and this would reduce the endurance time. However, the difference in force levels between the two conditions was extremely small (0.72%); therefore, it is more likely that other factors are of importance for explaining the lack of effect of caffeine on motor parameters. In our study we have used 3 mg/kg, which is within the range of optimal dosages as suggested in the review by Graham (2001). Moreover, it is a realistic amount of caffeine that equals the amount of caffeine that is present in approximately two cups of brewed coffee in the Netherlands. Some of the studies that show an effect of caffeine on force and endurance used a dose of 6 mg/kg (Kalmar and Cafarelli, 1999; Plaskett and Cafarelli, 2001). However, in several other studies that used higher doses of caffeine no effects were found. For example, in a recent study by the group of Cafarelli (Kalmar and Cafarelli, 2004), no effect of caffeine (6 mg/kg) was found on maximal voluntary force or endurance time in an index finger abduction task. Furthermore, Williams and colleagues (Williams et al., 1987) used 7 mg/kg, and did not find an effect on force and endurance during a hand grip task either. Moreover, Lopes and colleagues (Lopes et al., 1983) applied 500 mg of caffeine, but also they did not find an effect on maximal force and endurance time of a thumb-adduction task. In summary, none of the studies on hand muscles found an effect of caffeine on the muscle force. On the other hand, studies using large muscle-groups such as leg muscles did show an effect of caffeine on force or endurance time (Bell et al., 2001; Doherty, 1998; Greer et al., 2000; Jackman et al., 1996; Kalmar and Cafarelli, 1999; Plaskett and Cafarelli, 2001; Tarnopolsky and Cupido, 2000). Hence, maybe intrinsic properties of the exercised muscle (-group) or the motor

task are of importance for the effect of caffeine. For instance, the load upon the cardiovascular system is significantly greater during exercise of large muscles (or - groups) compared to small hand-muscles. In addition, the metabolic stress (e.g., lactate) after exercising hand muscles will be much lower. Furthermore, evidence also suggests that muscles differ in the ease with which they are activated maximally by the central nervous system (Behm et al., 2002; Belanger and McComas, 1981). Data obtained by Kalmar (Kalmar and Cafarelli, 1999) suggest that the force increase after caffeine consumption could (partly) be explained by an enhancement of the central drive to the muscles. The fact that muscles differ in the ease with which they are driven maximally implies that the effect of a potential enhancing stimulant, such as caffeine, also varies across muscles. Since caffeine has an effect on several systems within the body (e.g., muscle, brain, and cardiovascular system) it is uncertain which effect could be responsible for the apparent difference across various muscles.

Furthermore, data suggest that the effect of caffeine consumption can vary with the time of day (Miller et al., 1995b). We have measured all our subjects in the beginning of the afternoon starting at 1.30 p.m. Data obtained by Miller and colleagues (1995b) showed a significant effect of caffeine on force production in the morning while no such effect was observed in afternoon or evening sessions. This may also explain why we did not find an effect of caffeine on force production. In most of the other experiments the investigators did not indicate at what time the experiments were performed.

In conclusion, caffeine can positively affect cognitive performance, also in the situation of fatigue. This indicates that drinking coffee (or other caffeine-containing beverages) might prevent unfavourable situations caused by deterioration of cognitive performance as a result of fatigue. This positive effect of caffeine is of importance for sports and working situations in which subjects have to make imperative decisions, also in situations in which they are fatigued. The effects of caffeine could be due to an enhancement of the availability and/or the allocation of the information processing capacity.