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The Influence of Different Doses of Caffeine on Visual Task Performance

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Abstract In this study the influence of caffeine as an energy-increasing substance on visual information processing was examined. Subjects were presented with a dual-task consisting of two choice reaction time tasks. In addition, one of the tasks was presented at two levels of difficulty, influencing the decision-making process. Doses of 1.0, 3.0, and 7.5 mg/kg body weight caffeine and 3.0 mg/kg body weight lactose were administered (within-subjects design). The effect of caffeine was expected to be observable in terms of improved performance on measures like reaction time and type and number of errors, as well as in components of the event-related brain potential (ERP). The highest caffeine dose shortened reaction times on both the primary and the secondary task as compared to placebo. Overall there was a linear decline in reaction times on both tasks with increasing caffeine dose. As measured from ERP results, there was an increasing P3 amplitude as caffeine dose increased, indicating that the quantity of information processed was larger under caffeine. There was, however, no evidence of extra energy in terms of more hits and fewer misses or false alarms. Moreover, subjects reported no dose-related differences in amount of effort needed to perform the dual-task. It is concluded that the effect of caffeine, which is supposed to have its impact on both the input and the output stages of information processing, was evident in the output stage in the form of shortened reaction times. However, no effect of caffeine could be observed at the input stage, probably due to a data limited process.

Introduction

Caffeine is generally regarded as a mild stimulant acting on the central nervous system, producing diverse and complex effects, even when consumed in small quantities (for reviews, see Dews, 1984; Garattini, 1993). Although the effects of caffeine on performance have been addressed in many studies, it is difficult to arrive at a coherent account of the cognitive effects of caffeine, even at a descriptive level. Factors that might have contributed to inconsistent findings include for example the individual differences in the pharmacological actions of caffeine, the state of the subject, the amount of caffeine used, and the use of different tasks or test batteries (Gaillard, 1988). In this study, two of these factors are systematically examined; caffeine dose as well as task load were investigated. In addition to subjective measures and reaction times, event-related potentials (ERP) were measured to gain more insight into information processing under the influence of caffeine.

Caffeine and information processing

Previous research (Lorist, Snel, Kok, & Mulder, 1994b; Lorist, Snel, Mulder, & Kok, 1995) has shown that by consuming the amount of caffeine present in two cups of regular coffee, subjects were less easily distracted by irrelevant information, and showed improved sensory perceptual processing of stimuli presented at locations where attention was focused (see also Gaillard, 1988). Based on several studies measuring reaction times and ERPs, Lorist (1995) also found that caffeine improved the detection of visual stimuli and response preparation: in particular the processing of spatial information was facilitated by caffeine. Kenemans and Lorist (1995) and Lorist, Snel and Kok (1994a) studied the response preparation stage and used time uncertainty as a task variable to manipulate motor preparation processes: they found that caffeine facilitates output processes as measured in shorter reaction times. Moreover, using the Lateralized Readiness Potential (LRP) as an electrophysiological index of response preparation, Lorist et al. (1994a) found that caffeine did not influence LRP onset latency, but did shorten reaction times. The conclusion was, therefore, that some effects of caffeine on information processing should have taken place after response preparation, either at the central or peripheral motor execution level. Other studies (Bättig & Welzl, 1993; Daly, 1993; Kenemans & Verbaten, 1998) support this conclusion, and show stimulating effects of caffeine on these late motor processes, predominantly in a dose dependent way. Related to this topic is a possible alteration of strategy under the influence of caffeine, which could be revealed by differences in the number of false alarms or hits. Some studies did not find any alteration although Kenemans and Lorist (1995) did find faster RTs and an increased hit rate as a function of caffeine, which confirmed other reports (see review in Koelega, 1993).

Lorist (1995) concluded that the most pronounced effects of caffeine are to be found at the input stage of information processing, that is, during the identification of incoming information. One plausible explanation for these results is that the normally available amount of energy is enlarged by consuming caffeine. This assumption is supported by the fact that although caffeine has obvious effects on task performance both in fatigued and in normal subjects (Dews, 1984; Frewer & Lader, 1991; Lieberman, Wurtman, Emde, Roberts, & Coviella, 1987; Linde, 1994; Lorist et al., 1994a), it has more impact on information processing in suboptimal conditions, such as tiredness and boredom. In general caffeine effects are more pronounced in those conditions in which the availability of energetical resources is insufficient to meet the demands placed on the human information processing system. Overall, there is evidence for the argument that caffeine has a general arousing effect (Daly, 1993; Phillis, 1991), thereby influencing all the stages of information processing, as well as a more specific effect. The general arousing effect is mainly based on the pharmacological knowledge that caffeine inhibits the binding of adenosine to its receptor sites, thereby reducing the modulating influence of adenosine on the ongoing neural activity, resulting in increases in the function, turnover, and levels of different neurotransmitters (e. g., acetylcholine, noradrenaline, dopamine, and serotonin). Since these neurotransmitters are widely distributed in the brain, caffeine is said to have a non-specific arousing effect. The other viewpoint, mainly based on the work of Lorist et al. (1994a, 1994b, 1995) and Kenemans and Lorist (1995), who studied the possible more specific cognitive effects of caffeine on human information processing is that caffeine has a specific effect on input and output processes, as a function of task demands.

Resource theories

There are many theories concerning multiple-task performance, generally based on the notion that human performers possess one or a few fixed energetic resources with a limited capacity. In this context, a resource is described as a conceptualization of energy, related to mental effort, and can be used to predict changes in task performance. In particular, "multiple resource" theories (e. g., Damos, 1991; Navon & Gopher, 1979; Wickens, 1980) are seen as plausible models of task performance in terms of energy expenditure. Moreover, these theories offer a good explanation for why some tasks can be done almost perfectly simultaneously: the performance of such tasks does not depend on the same energy resource.

Resources are usually distinguished by the type of input and the type of processing they afford. Wickens (1984, 1991) postulated a multiple resource model consisting of three dichotomous dimensions, each constituting a different resource. The dimension of processing *stages* distinguishes two resources, one associated with perceptual-cognitive processes and one associated with response processes. The second dimension distinguishes two *codes* of information processing: spatial versus verbal information processing. The third dimension involves input *modalities*, that is visual versus auditory. The boundaries between different resources seem rigid but should not be interpreted as totally fixed.

Normally, tasks will show more interference if resources have to be shared, because the tasks must compete for the limited amount of available energy from the resources. When two tasks have none of the dimensions above in common it is assumed that they can be performed almost perfectly when carried out simultaneously. However, if this is not the case, timesharing can lead to a situation in which the resources to perform one or two tasks are insufficient, and hence, performance on one or both may deteriorate. Therefore, the number of tasks that are performed simultaneously and the sharing of the same resources are factors that increase demands on resources.

The amount of energy needed from one or more resources to perform a task depends on other factors as well. A generally accepted distinction is that between automatic and controlled tasks (e. g., Schneider & Shiffrin, 1977). Automatic tasks require little energy and can be performed almost without paying attention. In contrast, a controlled task, for example a choice-reaction time task in which the target changes continuously, requires much more energy from the resources. An important difference between automatic and controlled tasks is the amount of practice people have had: some initially controlled tasks can become automatic. The general idea is that through training, the same limited processing resources may be used more efficiently (e. g., Korteling, 1994). That is, less energy is needed to attain the same level of performance.

Apart from limits on performance caused by energetical factors as described above, which Norman and Bobrow (1975) refer to as *resource limited* processing, another factor may influence task performance, which they term *data limited* performance. Data limited performance means that the limits of our sensory system and the quality of the data may prevent performance improvement. Intuitively it is plausible that if people try harder, performance will benefit; to a certain extent this is true. If people are more motivated to do their best, possible performance deterioration can be less or may be even absent (Johnson, Bradley-Johnson, McCarthy, & Jamie, 1984; Vidulich & Wickens, 1984). In cases of data limited information processing, however, trying harder will not lead to better performance, due to the limits of our sensory system or the quality of the data.

The aim of the present study was to assess the influence of three different caffeine doses on the visual input stage of information processing, using two different task load conditions of a complex and demanding dual-task in a within-subjects design. This way, the effect of increasing caffeine doses on overall task performance could be monitored as well as the dose dependent influence of caffeine in different task load conditions. The hypothesis was that by using a dual-task, which was developed in such a way that both tasks were assumed (on the basis of the Wickens 1984, 1991, model) to share the same resource, increasing caffeine doses should improve performance in both the low and the high task load conditions and for the primary as well as the secondary task. A linear relationship was hypothesized between increasing caffeine dose and decreasing reaction times for the primary as well as the secondary task.

In addition, the evaluation of caffeine effects on ERP components should provide information about influences of caffeine on the time course of specific information processing functions and/or on the extent to which these functions are activated or "utilized" during task performance. Following this reasoning, caffeine-induced changes of the early exogenous components in the ERP such as P1 and N1 and changes in reaction time and performance data are interpreted as more specific cognitive effects. In contrast, a caffeine-induced effect on P3 range could possibly point to more general arousing aspects. Based on the theoretical basis of the P3 component as argued by a number of authors (e. g., Johnson, 1986; Polich & Kok, 1995), who state that the amplitude of the P3 is partially based on the amount of information that is processed and by the arousal state of the subject, it was hypothesized that in the present experiment the effects of caffeine could be measured as an increased P3 amplitude as related to dose. Possible shifts in P3 peak latency in relation to dose will be investigated, since this measure is sometimes said to be related to the speed of information processing and is relatively independent of the time required for response selection and execution (e. g., Magliero, Bashore, Coles, & Donchin, 1984; Polich & Kok, 1995; Ragot, 1984).

Task effects

From previous studies (Kenemans, Kok, & Smulders, 1993; Kenemans, Smulders, & Kok, 1995; Previc & Harter, 1982), in which a grating task was presented in a single task situation, specific exogenous and endogenous potentials in the ERP were found for each feature of the grating (low or high spatial frequency, horizontally or vertically oriented). As for the endogenous potentials, they found differences in negativity between relevant and irrelevant dimension levels for spatial frequency (starting 220 ms post stimulus), orientation (starting 230 ms post stimulus), and an interaction between spatial frequency and orientation (starting at 270 ms post stimulus) (Kenemans et al., 1993). The conclusion was that the processing of frequency relevance and orientation relevance were independent. Furthermore, the assumption was that spatial frequency is processed before the orientation feature, given the particular discriminabilities of both dimensions, and that each grating yields its own ERP according to its relevance to the target. To explore whether such single task effects were also present in a dual-task situation the results from the gratings task in the placebo condition were compared with the results of Kenemans et al. (For effects of caffeine on a grating task the interested reader is referred to Kenemans & Lorist, 1995).

Method

Subjects

Twenty healthy, non-smoking subjects (5 males, 15 females) participated in this study. They were all undergraduate students aged 18 to 26 years (M = 20.9, SD = 2.3) and received course credits for their participation. Eighteen subjects were right-handed and two were left-handed. All subjects were regular coffee consumers with a daily coffee ingestion of 3 to 5 cups a day (M = 4.3, SD = 1.3). Subjects did not work night shifts, had a regular sleep rhythm, and normal or corrected to normal vision. Subjects also met several additional criteria, namely they did not work night shifts, did not use prescription medication except for birth control, and did not report having any history of brain damage.

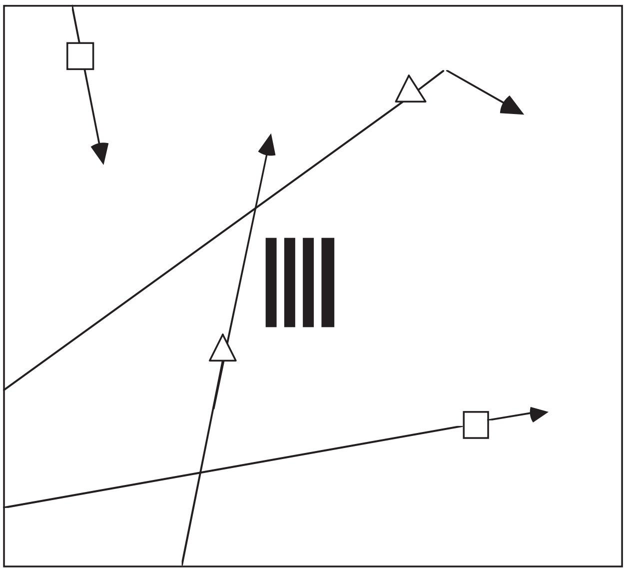

Figure 1 Schematic representation of the dual task that was used. In the center a grating task and at the periphery an adjusted form of an air traffic control task.

Treatment manipulation

All subjects received three doses of caffeine powder: 1.0, 3.0, and 7.5 mg/kg body weight (BW) and a placebo which contained 3.0 mg/kg BW lactose. Doses were dissolved in a cup of decaffeinated coffee (approximately 1.5 dl) and the subjects could add sugar and milk powder if they wished. Treatments were double blind and deceptive as the subjects were led to believe that they were drinking regular coffee (containing a normal amount of caffeine) each experimental session. The order of treatment conditions was balanced across subjects.

Stimuli and apparatus

Subjects were seated in a dimly lit room facing a computer screen at a distance of 80 cm. The experimental task was a dual-task in which a grating task (e. g., Kenemans et al. 1993, 1995; Previc & Harter, 1982) and an adjusted form of the air traffic control task used by Isreal, Wickens, Chesney, and Donchin (1980) were combined. A schematic outline of the dual task is given in Figure 1.

The (primary) grating task consisted of a square filled with square wave gratings built out of bars subtending 1.2° of arc. Stimulus duration was 50 ms and interstimulus interval was 2 s. The width of the bars was either 0.4, 0.3, or 0.2 cm and oriented either horizontally or vertically. This led to six possible grating stimuli of which four were presented (2 horizontal, 2 vertical) in each trial block. As a result a block was either "easy" (the smallest and the widest bars had to be compared) or "hard" (smallest and middle bars). The grating task was presented at the center of the computer screen while the adjusted air traffic control task was presented peripherally. Targets from the primary task changed each block (a conjunction of frequency and orientation). Subjects responded with a button press with the left index finger to the target from this task.

The adjusted air traffic control task, the secondary task, consisted of four continuously moving geometrical forms (two squares and two triangles), approximately 4 mm in diameter, displayed on the computer screen. The forms could either suddenly change their direction by 60 degrees or change in color from black to bright white ("flash up") for 50 ms. These stimuli were presented in black on a white background. All "events" (course changes and flash ups) were displayed in random order, 10 times in each block. The forms entered the display asynchronously at random locations from all sides of the screen and moved at a rate of 2.64 cm/s. An event occurred every 3.5 to 7.0 s. Events could not take place within 4.57 cm of an edge of the display or within a radius of 1.05 cm of the grating figure and could never occur at the same time that a grating was presented. Targets from the secondary task also changed each block (a flash up or course change of a square or triangle). Subjects responded with a button press with the right index finger to the target in the secondary task.

The subjects completed eight blocks of 152 trials (112 gratings and 40 events), of which four blocks were easy and four difficult, randomly assigned. The difference between easy and hard blocks was only determined by a difference in the primary task. Each block lasted about 4 minutes. Both tasks were choice-reaction time tasks in which one of the stimuli was chosen as the target, the subjects were told before each block which were the targets for both tasks. Targets were varied in a balanced way, so that each stimulus category was the target twice and all combinations of targets from the primary and the secondary task could occur.

Subjects were instructed that the grating task was to be perceived as the primary task, on which they should keep their eyes fixated, and the adjusted-air traffic control task as the secondary task.

Stimuli were presented with a Zenith Z-Select 100 PC by the CSSP program of the Psychonomics section against a white background on a Nec Multisync 3FG monitor positioned at 80 cm from the subject's eyes. A small fixation cross was continuously present except during presentation of the central stimulus.

Subjective measures

Questionnaires were used to examine possible differences in mood and state anxiety within subjects as a result of caffeine intake and to examine the task manipulation of an easy and a hard task condition.

- The short version of the *Profile of Mood States* (POMS) (Wald & Mellenbergh, 1990) was used. Subjects indicated how they felt at the moment for each of 32 adjectives on a 5-point scale ranging from 0 (*not at all*) to 4 (*very much*) for the mood states: depression, anger, fatigue, vigor, and tension.
- The *State-Trait Anxiety Inventory* (STAI) (Van der Ploeg, Defares, & Spielberger, 1980) assessed state anxiety on a 4-point scale ranging from 1 *(not at all)* to 4 *(almost always).*
- A subjective workload inventory based on the NASA-TLX inventory (Damos, 1987; Hart & Staveland, 1988) was filled out at the end of each session. The inventory factors represented: overall amount of workload, task difficulty, time pressure, mental effort, physical effort, frustration, stress, fatigue, and type of activity. Subjects could indicate on a 5-point scale how they felt.

Procedure

Subjects first completed an extensive training session, followed by four experimental sessions which were separated by at least one week (within-subjects design). Except for the treatment all experimental sessions were identical. A consent form was filled out at the training session. The subjects were asked to abstain from all caffeine containing foods and beverages for at least 12 hours preceding each experimental session. Their compliance was checked by taking a saliva sample for caffeine analysis at the beginning of each experimental session. All sessions took place between 9.00 a. m. and 1.00 p. m.

After the saliva sample was taken, the POMS and the STAI were completed and the subjects drank their coffee. The subjects' blood pressure was also measured at this time. Next, subjects were prepared for the EEG recording and after that the blood pressure was measured again and the POMS and the STAI were filled out for the second time.

The experimental task started about 45 min after drinking the coffee and lasted for about 45 min, with a short break after each block. After the last trial subjects filled out the STAI, the POMS, and the subjective task load inventory. Then the electrodes were removed and the subjects were thanked for their participation.

Recordings

Reaction times for both experimental tasks were measured, as were the number of misses, the number of correct rejections, and reaction times on false alarms. The electroencephalogram (EEG) was recorded using an electrocap containing pure tin electrodes, from Fz, Cz, Pz, Oz, P3, P4, O1, and O2 (according to the International 10/20 Electrode Placement System) referred to linked earlobes. A ground electrode was placed on the middle of the forehead. For each electrode impedance was kept below 5 kΩ. Bipolar recordings of vertical and horizontal eye movements were made from the outer canthi of both eyes and above and below the right eye. The signals were amplified with a Nihon-Kohden 10 channel polygraph (MME-3100 series) with a low-pass filter set at 35 Hz and a time constant of 5.0 s and continuously digitally sampled and stored at 200 Hz on a Compaq Pro Linea PC with a Keithley A-D converter.

Data reduction and statistical analysis

Reaction times on targets from both tasks were included in the analyses if they met two criteria: reaction times below 200 ms and above 1 s were rejected, as were those which did not fall within a range of 2.5 SD from the mean reaction time. Also commission errors (wrong button presses between 200 ms and 1 s) and omission errors (when no button press was made to a target) were registered. Reaction times for targets on the primary task as well as reaction times for targets on the secondary task were compared between the different treatment conditions. Statistical analyses were performed by fitting a linear contrast on reaction times with increasing caffeine doses, within the multivariate analysis of variance (MANOVA) for repeated measurements procedure (α was set at .05). To test the effects of placebo and the various caffeine conditions, Dunnett's *t*-tests for comparing several treatment conditions against one single control condition was applied.

ERPs were recorded on all stimuli from both tasks, however, to investigate caffeine effects, only ERPs to target stimuli were analyzed. For each subject, the average ERP was computed for each lead, each treatment condition, and each task manipulation. The EEG signal was checked for eye artifacts and corrected accordingly with a method of regression analysis in the frequency domain (Woestenburg, Verbaten, & Slangen, 1983). After EOG correction, intervals containing movement artefacts (change in amplitude of more than 50 μV between two additional samples) or electrical drifts (difference between lowest and highest amplitude more than 150 μV within one trial, 256 samples) were excluded from further analyses. Also trials containing commission or omission errors were rejected from further analysis. The averaging epoch started 100 ms prior to stimulus onset and lasted until 1180 ms post stimulus, using a 100 ms pre-stimulus baseline. For further analysis each ERP was divided into 14 periods of 50 ms, from 50 to 750 ms post stimulus. Overall differences of placebo opposed to the different caffeine conditions as well as the different treatment conditions opposed to each other were analyzed on the basis of the mean area (μV^2) for each 50 ms window. Statistical analyses were performed by means of the multivariate analysis of variance (MANOVA) for repeated measurements procedure. For the overall main tests for the three time windows closest to the P3 peak, α was set at .05. Within these possible overall effects, differences between placebo conditions and the different caffeine doses were analyzed. For these tests α was adjusted according to the Bonferroni procedure. Other possible amplitude differences between treatment conditions were subjected to an exploratory analysis. In addition P3 peak latency and P3 peak amplitude were subjected to a statistical test.

Results

Subjective measurements

All factors from the task-load inventory were analyzed separately. Subjects reported no significant differences between the conditions on subjective effort needed to perform the dual-task. Neither were there differences in mood (as measured with the POMS and the STAI) between the conditions as measured on the arrival of the subjects, or mood differences due to the different caffeine doses as measured at the end of the experimental sessions.

There were no differences between males and females in reported amount of averaged daily caffeine ingestion in mg (484 vs. 452), nor were there differences between the sexes in reported sensitivity to the effects of caffeine.

Performance

In Figure 2, the mean reaction times for both tasks as well as for both levels of difficulty are shown. In regard to a comparison between the easy and the hard condition of the experimental task there were no significant differences on the secondary task. Reaction times on the primary (grating) task did reveal a significant difference ($F(1,19) = 14.21$, $P = .001$) with the easy condition showing faster responses. No other differences between the easy and the hard task conditions were observed. To obtain more statistical power, performance data from the easy and hard conditions were averaged together for all additional analysis.

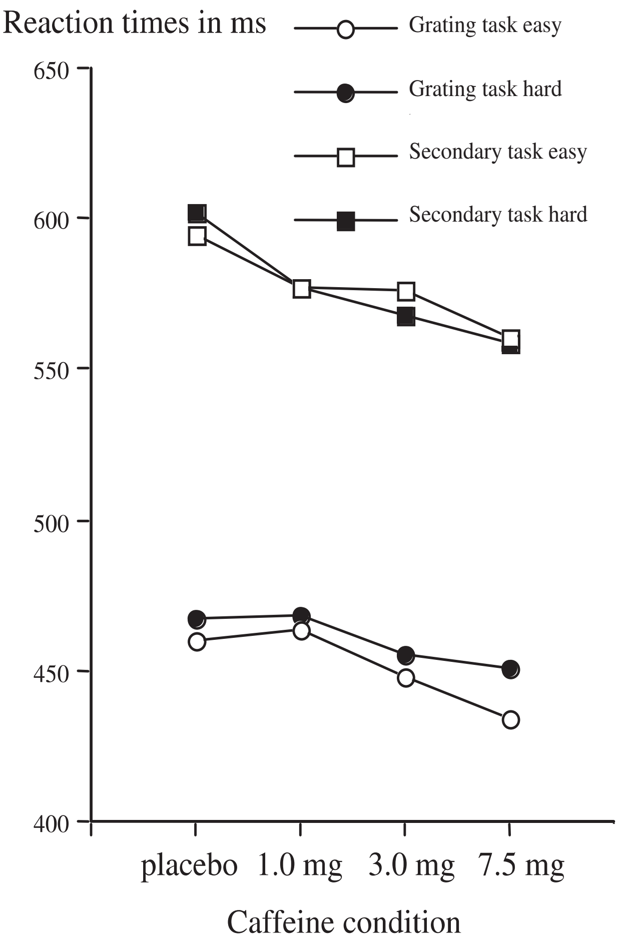

Figure 2 Mean reaction time for targets on the primary and the secondary task, in easy and hard conditions.

Reaction times on both tasks showed a slight decrease with increasing caffeine dose. These decreases in reaction times can be described by a linear contrast for both the primary task ($F(1,19) = 5.24$, $P = .034$) and the secondary task ($F(1,19) = 7.03$, $P = .016$), where higher order contrasts were not significant. Comparing mean reaction times from the placebo condition with reaction times of the different caffeine conditions separately with a Dunnett's *t*-test, the following effect was revealed. Mean reaction times on targets from the secondary task showed a significant difference between placebo and the 7.5 mg/kg BW condition ($t(4,57) = 2.65$, significant at a level of $\alpha = .05$) with the caffeine condition showing shorter mean reactions.

The results concerning the percentage of hits, misses (omission errors), and false alarms (commission errors) are summarized in Table 1. A slight, although non significant, improvement with dose for the number of hits and false alarms can be seen. Compared to the placebo condition, the highest caffeine dose diminished the false alarms from the grating task by an average of 3.1%. In an absolute sense, nearly one stimulus more was correctly rejected in the caffeine condition (from 2.4 false alarms to 1.5). On the secondary task, 2.2% fewer false alarms were made in the 7.5 mg/kg BW condition. The percentage of hits on the grating task improved from placebo to the highest caffeine condition from 86.4% to 90% and the percentage of hits on the secondary task improved from 52% to 55%. Also, there were no differences between the conditions in number of misses, either on the primary task or on the secondary task. What was striking however, was the number of misses on the secondary task. These rates did not differ under the influence of caffeine but indicated that nearly half of all available target stimuli were missed by the subjects.

ERPs

ERP analysis of the targets from the secondary task was not performed because of insufficient statistical power. As can be seen in Table 1, misses on the secondary task were very high, nearly half of the target stimuli were not responded to by the subjects, this means that the corresponding ERP could be averaged over at most 40 stimuli. In addition, this number would be based on the hypothesis that there are no differences in ERPs on “flash ups” and “course changes” from stimuli of the secondary task.

Analyzing the influence of task difficulty revealed two effects: there was a difference in ERP in the 350–400 ms time window ($F(1,19) = 5.12$, $P < .05$) and a further difference in difficulty from 600–750 ms ($F(1,19) = 5.31$–7.45, all *P*s $< .05$), in both cases the difficult condition showing a more positive-going ERP. This early portion of the P3 peak was possibly due to the inter-subject latency variability. The second effect can be interpreted as the ERP of the difficult condition getting back to baseline much slower as compared to the ERP of the easy condition. Since the caffeine effect under investigation was not presumed to be in this time range (> 600 ms), targets for easy and hard conditions were averaged together to obtain more power for statistical analysis.

The grand-average ERPs for targets on the grating task are shown in Figure 3, where the different caffeine conditions are compared to the placebo condition. In Table 2 the P3 peak amplitude measures for all leads and each dose level are presented. On the basis of a peak-picking method for the P3 peak across all leads no differences were revealed in latencies of P3 peak between the different treatment conditions. In addition, no differences in P3 latency across dose levels for any of the

Table 1 Performance data (± SD) averaged over all subjects as a function of task variables and treatment.

Condition:	Placebo	1.0 mg/kg BW	3.0 mg/kg BW	7.5 mg/kg BW
Reaction times (ms)				
Primary task	465 (63.6)	468 (96.3)	450 (86.2)	443 (50.1)
Secondary task	598 (82.6)	577 (75.7)	572 (96.0)	559 (65.6)
Commission errors (%)*				
Primary task	8.5 (2.5)	7.1 (1.8)	5.0 (1.3)	5.6 (1.2)
Secondary task	8.2 (0.8)	7.1 (0.6)	5.4 (0.4)	6.4 (0.5)
Omission errors (%)*				
Primary task	13.7 (2.9)	12.7 (2.4)	10.3 (1.9)	10.5 (1.8)
Secondary task	47.8 (0.7)	46.0 (0.9)	46.2 (0.7)	44.6 (0.7)

Note: *Percentages are expressed relative to the number of trials within the specific stimulus category.

Table 2 P3 peak amplitudes in µV for all leads and for each dose level.

Lead	Placebo	1.0 mg/kg	3.0 mg/kg	7.5 mg/kg
Fz	5.2	6.0	5.8	6.0
Cz	12.9	14.5	13.4	14.3
Pz	16.2	16.6	17.1	17.9
Oz	7.1	7.3	8.8	8.4
O1	7.3	7.3	8.7	8.5
O2	7.3	7.1	8.8	8.5
P3	12.2	12.3	13.0	14.0
P4	13.0	13.6	13.8	14.8
Overall	10.1	10.6	11.2	11.6

separate leads was revealed. P3 peak amplitudes did show a significant main effect of caffeine averaged over all leads ($F(3,57) = 2.78$, $P = .049$); P3 peak being more positive as caffeine dose increased. Separating this effect for midline leads and lateral leads it was revealed that the occipital-parietal leads (O1, O2, P3, P4) did show a dose effect on P3 amplitude ($F(3,57) = 3.58$, $P = .019$) with the P3 peak being more positive as caffeine dose increases, but the midline leads did not show such an effect. Investigating the midline leads one by one the only significant difference in P3 peak amplitude was found on lead Oz ($F(3,57) = 3.87$, $P = .014$). However, in this case the middle caffeine condition (3.0 mg/kg BW) showed the most positive going P3. These results indicate that the effect of treatment on P3 amplitude was especially apparent for the occipital-parietal region.

Analysis of differences between conditions in terms of area (μV^2) over 50 ms windows ranging from 50 ms to 750 ms, averaged over all leads, showed only two windows in which a significant overall effect ($\alpha = .05$) between conditions was present. These were between 400–450 ms ($F(3,36) = 3.00$, $P = .038$), and between 450–500 ms ($F(3,36) = 3.13$, $P = .033$). This was mainly due to the differences in amplitude between placebo and 7.5 mg/kg BW ($\alpha = .05/3 = .017$), see also Table 3 in which the increasing F values can be seen as a function of caffeine dose. The amplitudes in these time windows were larger for the 7.5 mg/kg BW condition as compared to the placebo condition.

Differences in caffeine effects between hemispheres were investigated with an analysis over P3/P4 leads and O1/O2 leads. These analyses showed for the P3/P4 leads that there were no differences in ERPs between hemispheres as brought about by caffeine, nor were there any interactions between caffeine and lead. Analysis for O1/O2 leads showed a main effect of caffeine in three time windows 350–500 ms ($F(3,57) = 3.77–5.07$, all Ps $< .016$), but no interactions between caffeine and lead.

Table 3 F-values averaged over leads, showing the main effect of caffeine on the primary task for placebo versus the different caffeine conditions.

	overall effect	plac vs. 1.0 mg	plac vs. 3.0 mg	plac vs. 7.5 mg
350–400 ms.	2.51	1.55	5.69*	5.26*
400–450 ms.	3.00*	2.26	4.49*	6.89*
450–500 ms.	3.13*	1.47	4.99*	7.37*

Note: plac = placebo condition. *$P < .05$.

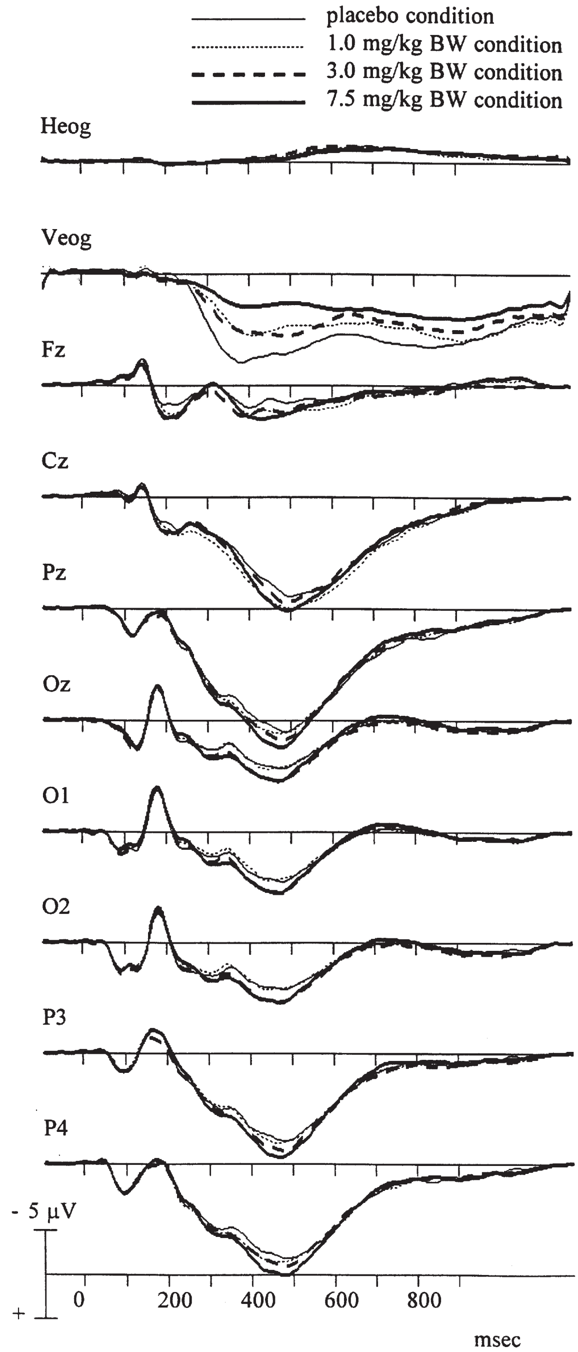

Figure 3 Mean ERPs for the target of the primary task, for the various caffeine conditions.

No effects on exogenous components were revealed for these leads.

Analyzing only the midline leads in 50 ms time windows, there was still a trend towards significant differences in area as a function of caffeine dose, from 400–500 ms ($F(3,57) = 2.53–2.54$, both $Ps < .07$). There were also several interactions of caffeine by lead 200–250 ms and 300–400 ms ($F(9,171) = 1.98–2.19$, all $Ps < .05$). To explore these interactions, midline electrodes were analyzed separately. Pz and Cz did not show any significant effects during the whole time range. Oz showed significant caffeine effects from 350–500 ms ($F(3,57) = 3.38–3.52$, all $Ps < .025$) with increasing area as a function of caffeine, and the Fz lead accounted for the early interaction, namely by a significant main effect of caffeine in the 150–250 ms time window ($F(3,57) = 3.46–6.85$, both $Ps < .025$), with the medium caffeine dose, 3.0 mg/kg BW, showing the greatest area followed by the 7.5 mg/kg BW condition, the 1.0 mg/kg BW and the placebo condition having the smallest area. The Fz lead showed another significant main effect of caffeine in the 400–500 ms time window ($F(3,57) = 2.77–2.89$, both $Ps < .05$). However, the 1.0 mg/kg BW now had the greatest area, followed by 7.5 mg/kg condition, 3.0 mg/kg BW condition and placebo.

Task effects

In this dual-task experiment a main effect of orientation and an interaction effect of orientation and spatial frequency on targets could be seen after 200 ms, however, no main effect of spatial frequency was revealed until 350 ms post stimulus. Another remarkable difference was that between the mean reaction times on the grating task presented in a single task and in a dual-task situation; mean reaction times in a single task situation as reported by Kenemans et al. (1993) were 377 ms as opposed to a mean reaction time of 464 ms in the dual-task situation of the present study. Comparing these results with those described by Kenemans et al. (1993, 1995) and Previc and Harter (1982), it was observed that the grating specific task results were only partially the same.

Discussion

Performance

The influence of caffeine, as an energy-increasing substance, was examined at different doses under different task load conditions. The main hypothesis, that performance on a visual-spatial dual-task would improve with increasing caffeine dose, was supported. Reaction times on both the primary (grating) and the secondary (adjusted air traffic control) task could be described by a linear contrast, with faster reactions as caffeine dose increased. On the secondary task, reaction times were significantly shorter for the 7.5 mg/kg BW caffeine condition as compared to the placebo condition. As far as reaction times are concerned, the present results are in line with earlier research. However, several RT studies have suggested that increases in speed are usually associated with a decrease in accuracy (Pachella, 1974; Wood & Jennings, 1976). Kenemans and Lorist (1995) found faster RTs and an increased hit rate as a function of caffeine, which was in accordance with other reports (see review in Koelega, 1993). The data of the present experiment do not show this relationship. Although reaction speed increases, accuracy neither shows improvement nor a deterioration. This pattern of results could be an indication that caffeine increases the rate at which information about the stimuli accumulates in the processing system (i. e., sensitivity), while leaving the accuracy performances unaltered. This is controversial because when implying more sensitivity as brought about by caffeine, one would also expect a difference in the *amount* of information processed (demonstrated by differences in number of hits, misses, and/or false alarms). One possible explanation for this controversy could be what Norman and Bobrow (1975) described as data limited performance: the limits of our sensory system and the quality of the data that may prevent the performance improving. Apparently, the amount of information that can be processed has a fixed constraint imposed by the human nervous system. In this dual-task study this could mean that the presumed effect of caffeine to mobilize energy could not be found in terms of *more* information processed because this was restricted by the limits of our visual system. This hypothesis is supported by the fact that the subjects reported no difference in the amount of effort necessary to perform the experimental task under different caffeine doses, notwithstanding the finding that under caffeine conditions the subjects reacted faster to targets from both stimulus categories as compared to placebo. Thus, although caffeine did shorten reaction times, probably due to effects at the central or peripheral motor execution level, there was no evidence of differences at the accuracy level, probably due to a data-limited process.

ERPs

As far as the ERP results are concerned, a few remarks must be made. Mean ERP wave forms for the different treatment conditions across all leads showed that the P3 amplitude for the 7.5 mg dose was significantly larger than the P3 amplitude for the placebo condition. This suggests that more caffeine induced spare or reserve processing capacity. In a study by Lorist, Snel, and Kok (1994a) caffeine was also shown to increase P3 amplitude. According to Johnson (1986), one of the variables determining the P3 amplitude is the quantity of information identified by the subject. Donchin, Kramer, and Wickens (1986) demonstrated that the P3 amplitude is related to the processing resource demands of a particular task. In a dual-task situation Sirevaag, Kramer, Coles, and Donchin (1984) showed that P3 amplitude to primary task events increased with the perceptual/cognitive resource demands, whereas P3 response to the concurrent secondary task decreased. Moreover, Polich and Kok (1995) argue that P3 is influenced by cognitive processes as well as by fluctuations in the arousal state of the subject. An enlargement of this component in the caffeine condition might be regarded as an improvement of the signal-to-noise ratio in the information processing system. Thus, on the basis of these P3 results, one could subscribe the caffeine-induced increase in performance measures as brought about by an improvement at the input stage of information processing. However, since there were no interactions between caffeine dose and lead in the P3 peak amplitude windows, one could also argue for the "general arousal" effect of caffeine. Additional support for this point is the fact that the dose related effect on the P3 amplitude could be seen on all leads. There was no evidence for specific caffeine effects on the basis of P1 and N1 components. However, an interesting exogenous effect was found on the Fz lead in the 150–250 ms window, which could point to more specific caffeine effects, but this needs to be explored further in future research. In a review by Van der Stelt (1994) it is argued that caffeine enhances the reflexive aspects of attention and facilitates also the processing of irrelevant information. Hence, both theories could be right in that caffeine does yield a general increase in arousal, and in addition can also show some specific effects as required by certain task demands.

Task effects

An exploratory comparison of the results on the grating task from a single and a dual-task situation revealed that the grating-specific task effects in the ERP as described by Kenemans et al. (1993, 1995) and Previc and Harter (1982) were only partly replicated. For example, the absence of a main effect for spatial frequency in the present study may be due to the addition of a secondary task (Ruijter, 1996). One possible explanation is that by using a dual-task, subjects had to deal with so much visual information at any given point in time that they just had not enough time and energy to consider every aspect of the grating task separately. Thus, in contrast to evaluating all grating features one by one to identify the target, it was suggested from the ERP results that in this case people changed their strategy and delayed the decision about target or non target until later in time and then identified the grating at once. This hypothesis would be in line with a theory of Hockey (1986) who stated that energy is distributed in various ways in the presence of different environmental conditions. For example, subjects adapt a strategy to their need for control and management as brought about by stressors or demands set by the task goals. Taking into account that the information processing stream as seen in the ERPs differed in the dual-task situation as compared to a single task situation, together with a substantial prolonging of RTs, the conclusion could be that subjects did alter their strategy to adapt to the high demands placed on them by the dual-task. In other words, it seemed that by heightening the workload a different distribution of energy was induced. Additionally, these specific task results were independent of caffeine treatment, since these effects were found both in the placebo condition and in the caffeine conditions.

Caffeine was expected to have its largest impact on controlled tasks in which the demands for energy resources were fairly high. To check if subjects still perceived the dual-task as highly demanding and requiring much attention after performing it for nearly four hours, performance in the placebo condition was analyzed as a function of session order (whether placebo was administered the first, second, third, or fourth session). This way practice effects could be revealed and possible automatization of the dual-task investigated. There were, however, no significant differences in reaction times or ERP data between sessions, indicating that there were no significant practice effects and that the dual-task was not completely automatic. This emphasizes the high complexity of the dual-task that was used. The speed-accuracy trade-off was similar in all four conditions; reaction times decreased on both tasks with dose, but the number of false alarms and the number of hits did not change. Moreover, since the subjective work load of the experimental task remained the same in all conditions, it is suggested that the strategy adopted by subjects in performing the dual-task probably did not differ between caffeine conditions. The results found in this dual-task study could, therefore, be attributed to the net effect of caffeine administration.

In conclusion, caffeine's impact on the input and output stages of information processing in relatively simple tasks (e. g., Lorist et al., 1994a) was found in a more complex dual-task in the output stage in the form of shortened reaction times. There was, however, no pronounced dose dependent effect on the input stage of information processing, probably due to higher level, data limited processing, induced by the high complexity of the dual-task.

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