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The Influence of Caffeine on Sustained Attention: An ERP Study

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RUIJTER, J., M. M. LORIST, J. SNEL AND M. B. DE RUITER. *The influence of caffeine on sustained attention: an ERP study.* PHARMACOL BIOCHEM BEHAV **66**(1)29–37, 2000.—The present study investigated the effects of caffeine on sustained attention by measuring concentration and fatigue. Event-related potentials (ERPs) and behavioral measures were recorded from 12 participants who worked continuously for approximately 10 min in a self-paced reaction task under conditions of both caffeine (250 mg) and placebo. The ERP data revealed more positive frontal P2 and parietal P3 components in the caffeine condition. However, a combination of different indices of the behavioral data did not reveal any effects of caffeine intake. These results suggest that caffeine increases arousal, thereby reducing fatigue, as was observed in the ERP results. A probable explanation for the absence of any effects of caffeine in the behavioral data can be found in the demanding properties of the task that was used, thereby supporting evidence for more pronounced effects of caffeine in suboptimal conditions. In addition, these results appeal for an increase in the use of ERPs in drug research, in order to discover possible effects on the brain which do not necessarily result in behavioral changes. © 2000 Elsevier Science Inc.

Caffeine   ERP   Sustained attention   Lapses of attention   Concentration   Fatigue   Bourdon task

THE AIM of the present study was to examine the effects of caffeine on sustained attention. Most studies that examined these effects before, have used long duration auditory and visual vigilance tasks that usually take an hour or more to complete (5,6,13,17,19). These tasks require the maintenance of a high level of attention by the participants in order to detect the occurrence of infrequent target stimuli in the stimulus sequence. The results of most of these studies suggest that caffeine prevents the deterioration of task performance that can usually be found in placebo conditions, and increases absolute alertness levels. When overall task performance is examined, decreased reaction times and an increase in the number of hits by caffeine can normally be observed in comparison to a placebo condition. However, some decline in task performance over time can not be prevented by caffeine.

One of the reasons why caffeine may have a beneficial effect on sustained attention and vigilance decrement (a decline in the detection of targets over time) is its arousal increasing properties. Evidence for this was found in a number of studies (2,9,28), addressing the effects of caffeine on different frequency bands in the EEG. The general conclusion was that caffeine intake leads to a reduction of alpha and delta power and a shift towards faster spectral components, indicating elevated levels of arousal or energy. Additional evidence for an effect of caffeine on sustained attention comes from a different type of studies using ERPs (event-related potentials). For example, it was found (20,30) that the amplitude of the P3 component of the ERP was increased by caffeine. The amplitude of this component is often said to be sensitive to the allocation of available energy (4,10,27). One of the effects of increased energy levels is a reduction in fatigue. In a study (21) with well-rested and fatigued participants, it was found that caffeine counteracted the effects of fatigue: ERPs of fatigued participants displayed a larger P3 amplitude for the caffeine condition compared with the placebo condition, a pattern that was not found for the well-rested participants. It was concluded that the effects of caffeine are most pronounced under conditions of mental fatigue, whereas in well-rested participants it appears more difficult to demonstrate the effects of caffeine.

In contrast to the long duration vigilance tasks that have been used to examine the effects of caffeine on sustained at-

tention, Parasuraman (26) demonstrated that in a no-drug condition an obvious decay in performance could already be observed when using a shorter vigilance task of 10 min. However, the conclusions remain contradictory; although some researchers concluded that beneficial effects of caffeine on sustained attention can only be found in long duration vigilance tasks (5), others have found clear effects of caffeine on different types of shorter vigilance and sustained attention tasks (7,17,18,32). For example, no effects of caffeine were found in different types of a choice reaction task and a continuous performance task, although trends towards such effects were observed (5). In addition, no effects of caffeine were found on a short visual continuous performance test, but positive effects of caffeine were found on a four-choice visual reaction task in which participants had to react to every stimulus that appeared (17). Several factors may be responsible for these discrepancies, such as the amount of caffeine that was used, the task variables, the participant population or interactions with other variables (drugs, for example). However, another possible explanation is that the methods and types of dependent variables that are used may not be sensitive enough for every type of task to reveal the effects of caffeine. Therefore, a different approach was used in the present study. On the basis of previous research (34,36), specific behavioral parameters will be examined in addition to the classical measures that are normally used to determine task performance.

Studies on the effects of caffeine on sustained attention usually concentrate on two aspects, namely, effects on fatigue and concentration. This is assessed by using classical reaction time measurements, signal detection parameters and time-on-task effects, sometimes complemented by ERP measurements. The present study focuses on measuring concentration and fatigue by using uncommon behavioral parameters and a continuous performance task. Although the parameters are mainly based on reaction time variability, similar to the classical measures, more room for improvement in the caffeine condition is obtained by using a short, self-paced continuous performance task, in which a response has to be given to every stimulus. Effects of caffeine on a similar task were found earlier (17).

One of the additional performance parameters that can be determined in a continuous performance task to measure fatigue, is the "mental block," also described as "lapse of attention." The concept of the mental block was first described by Bills in 1931 and refers to the occurrence of incidentally long reaction times increasing in frequency as a function of time-on-task. Furthermore, lapses of attention appear to be unavoidable, rhythmic in nature and sensitive to practice and resting pauses (1,31,34). It was suggested that the frequency and length of lapses of attention form a more sensitive criterion of the onset of fatigue than information obtained from usual reaction time measurements. Moreover, fatigue tends to produce an irregularity in the flow of responses without reducing the actual number of responses per minute for periods up to 1 h (1). Although the cause of the mental block is still not resolved, the general opinion is that it is mainly mental fatigue that causes the blocks to appear. Other parameters that will be examined in the present study include the shortest reaction time of a series, which is considered to be the actual "pure" processing time that is needed to react to a stimulus, and the mean distraction time. One assumption in the theory is that a person is not capable of maintaining absolute attention when performing on a rapid task for a long duration. The observed processing time would thus consist of a combination of the pure processing time and autonomous occurring dis-

traction periods. This, in turn, results in a concentration measure, being a proportion of processing and distraction time.

The present study aims to verify and extend the knowledge about the effects of caffeine on sustained attention. A combination of different indices of behavioral data, such as the lapses of attention, and measurements of ERPs will be used. Based on results from previous studies about the effects of caffeine on vigilance tasks, one prediction is that caffeine would affect the appearance of lapses of attention. That is, by increasing concentration and/or reducing fatigue, a decrease in the number of lapses or in the severity of the lapses is expected under caffeine conditions.

METHOD

Participants

Twelve healthy volunteers, four men and eight women, aged 20 to 25 (M = 22.4, SD = 1.9) participated in this study as a requirement of a psychology course. All participants were right-handed nonsmokers, had normal or corrected-to-normal vision, and were habitual coffee drinkers accustomed to a self-reported daily caffeine ingestion ranging from 3 to 6 cups of coffee a day (M = 4.9, SD = 1.3). Participants did not work night shifts, did not use prescription medication except for birth control, and reported no history of brain damage. The participants in the present study were treated according to university-regulated ethical standards.

Treatment Manipulation

A repeated measurements design was applied in order to use each participant as his/her own control, thereby minimizing the impact of inter individual differences in performance. All participants were asked to maintain a 12-h abstinence of all caffeine containing foods and beverages prior to the experiment. The order of treatment conditions was balanced across participants. Treatment conditions consisted of 250 mg caffeine or lactose dissolved in a cup of normally brewed decaffeinated coffee. To suit their own taste, participants could add sugar and milk powder to the coffee. Treatments were double-blind and deceptive, that is, participants thought that they were consuming caffeine-containing coffee during both experimental sessions.

Physiologic and Subjective Measures

Physiologic and subjective measures were used to examine possible differences in mood and state anxiety within participants as a result of caffeine intake. The questionnaires were also used to examine possible differences in subjective feelings between the two sessions of the same participant. An automatic blood pressure device was used for the blood pressure and heart rate measurements (oscillometric method, boso-Oscillomat).

A general health checklist was used which, among other aspects, assessed to what extent participants were morning or evening types (14). Four questionnaires were used to measure subjective feelings: 1) The short version of the Profile of Mood States (POMS) (37). Participants indicated how they felt at that moment for each of 32 adjectives on a 5-point scale. The five clusters of adjectives represented specific mood states: depression, anger, fatigue, vigor, and tension. 2) The state part of the Dutch version of the State-Trait Anxiety Inventory (STAI) (35) was used to measure the current level of anxiety. Participants reported on 20 items on a 4-point scale. 3) A subjective workload inventory based on the

NASA-TLX inventory (3,8). The inventory items represented overall amount of workload, task difficulty, time pressure, mental effort, physical effort, frustration, stress, fatigue and type of activity. Participants could indicate on a 5-point scale how they felt. 4) A sleep quality inventory (24) was used to measure participants' sleep duration and quality of their sleep on the night before the experimental sessions.

Task

All participants completed three tasks: 1) a color selection task (29), 2) a spatial selection task (in preparation), and 3) a concentration task. Only the concentration task will be discussed in this article. The order in which the participants had to perform these tasks varied according to a rolling Latin square paradigm.

The concentration task used in the present paradigm, is a computer adaptation of the Bourdon test (34). As can be seen in Fig. 1, nine stimuli were used, which differed in their dot positions. Three stimuli consisted of patterns of 3 dots, three stimuli consisted of patterns of 4 dots and three stimuli consisted of patterns of 5 dots. All stimuli were presented as white dots centered against a black background. The screen on which the stimuli were presented was positioned approximately 80 cm from the participants' eyes and subtended a visual angle of 1.27°. A small fixation cross was continuously present except during presentation of the stimulus. All participants were tested individually in a dimly lit, sound-attenuated room, while they were comfortably seated in an easy chair. Participants were instructed to react as fast and accurately as possible to each stimulus by pressing one of the two response buttons. Half of the participants were instructed to respond with the left index finger on a response button located at their left side when stimuli of three and five dots were presented and with the right index finger on the response button located at their right side when a pattern of four dots was presented. The other half of the participants responded with the right index finger to patterns of three or five dots presented and with the left index finger to patterns of four dots. These left and right hand responses remained the same for every participant across the two sessions. By pressing the response button, the next stimulus was presented on the screen with a delay of 324 ms. The task consisted of 30 series of 27 stimuli presented in succession, without pause. In each series the nine stimuli were presented three times in a randomized order, resulting in a pseudo randomized sequence of 810 stimuli. Participants performed a practice run of 54 stimuli followed by a pause. After that they started with the experimental task, which lasted on average approximately 10 min.

General Procedure

Each participant participated in two sessions, with an interval of approximately 1 week. The two experimental sessions differed only in treatment manipulation and that participants completed an informed consent form and a general health questionnaire in the first session. Participants arrived at the laboratory at 0930 h. At this time, they were asked to complete the POMS, STAI, and sleep quality questionnaires and their blood pressure and heart rate were measured. Thereafter, they consumed their coffee, the electrodes were applied and subsequently participants were seated in the experimental room. Approximately 40 min after the coffee consumption participants started with the experimental tasks. The tasks continued for about 1 h, after which participants again completed the POMS and STAI, as well as the subjec-
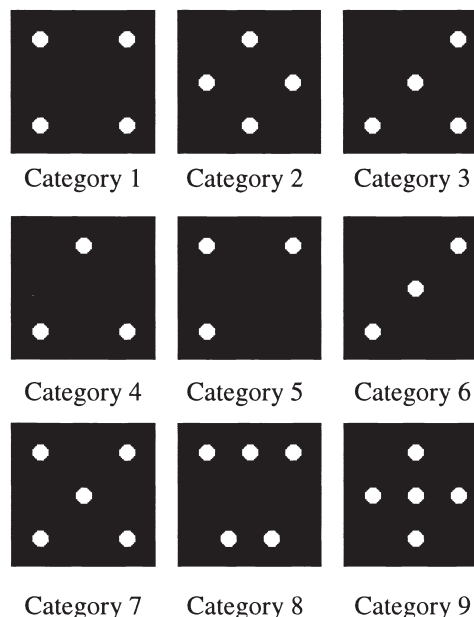

FIG. 1. Schematic representation of the nine stimulus patterns that were used in the sustained attention task.

tive task load inventory, and blood pressure and heart rate were measured a second time. Finally, the electrodes were removed and the participants were thanked for their participation.

Recordings

The EEG was recorded from 30 tin electrodes attached in an electrocap according to the $\frac{10}{20}$ system (American Electroencephalographic Society, 1991). The following electrode locations were used: Fp1, Fpz, Fp2, AFz, F7, F3, Fz, F4, F8, FC5, FC6, T7, C3, Cz, C4, T8, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8, PO3, PO4, O1, Oz, and O2. To monitor vertical and horizontal EOG activity, electrodes were attached above and below the right eye and at the outer canthi of both eyes. The right mastoid was used as a reference electrode and an electrode placed at the right side of the nose was used as ground. The signals were amplified by a Nihon-Kohden Neurotop amplifier (MME-3100 series) with a low-pass filter set at 35 Hz and a time constant of 2.5 s and continuously digitally sampled and stored at 250 Hz on a Compaq Pro Linea PC with the CMSP program developed at the Psychonomics Department.

Data Reduction and Statistical Analyses

Behavioural measurements

Bourdon-Souren analysis. Behavioral measurements were analyzed according to the procedure described by Van Breukelen and Souren (34) and Van der Ven and Smit (36), who studied a paper and pencil version of this task and determined some methods for analyzing behavioral data that proved reliable and useful in addition to the classical behavioral measures to reveal effects on concentration and fatigue. The new variables are based on the "pure" processing time of stimuli, which is represented by the shortest RT, a variable distraction time (the time added to the shortest RT) and the lapses of attention.

The stimulus sequence was divided into "series." Each series contained 27 stimuli and represented progressing time

points. The statistical measures were determined for every series separately, using the reaction times to the stimuli within that particular series. The first series of 27 stimuli was regarded as an extra practice series and was discarded from further analyses, resulting in 29 series for statistical analysis. For each series the following measures were determined: 1) the total reaction time, 2) the mean reaction time, 3) the shortest reaction time, 4) the mean distraction time (derived by subtracting the shortest reaction time from the mean reaction time), 5) a concentration measure (defined as a proportion of processing and distraction time, derived by dividing the shortest reaction time by the mean distraction time), 6) the number of lapses of attention (defined as a reaction time twice or more the mean reaction time), and 7) the number of false alarms (defined as a reaction with an incorrect button press). Statistical analyses for the above mentioned variables (i.e., 1) to 8), were performed using an ANOVA repeated measures, Treatment (2: placebo/caffeine) × Series (29) design, in which linear and quadratic trends were tested. The total number of lapses of attention and the mean reaction times and standard deviations on lapses of attention over all trials were analyzed in an ANOVA, Treatment (2) design.

Classical analysis. Behavioral measures were analyzed using mean reaction times and mean number of hits for each type of the nine stimulus patterns (categories). Button presses were classified as hits if they occurred in a 200 to 1000 ms time period after the onset of the stimulus presentation. A second criterion for a hit was that reaction times had to fall within a range of 2.5 SD from each participant's mean reaction time. Button presses on the wrong button were classified as false alarms. Furthermore, reaction times on trials with rejected EEG measurements (defined below) were excluded from analysis. Overall comparison between reaction times and number of hits for both treatment conditions and the nine categories was done with a MANOVA repeated measurements design, using the exact F-transformations of Hotellings T^2 in the following design: Treatment (2) × Category (9).

Time-on-task analysis. An additional analysis was used to determine the effects of caffeine on the time-on-task effect. Three intervals, each containing 50 trials, were selected for each participant individually to represent the beginning, the middle, and the end of the task, thereby allowing some individual differences in absolute time that had passed since the beginning of the task. Fifty trials were selected from the 50th trial onwards and averaged to time 1. Time 2 consisted of the average of 25 trials before and 24 trials after the trial that represented the middle trial from the total number of trials for that particular participant. Time 3 consisted of the last 50 trials of the task averaged together. Statistical analyses of the mean reaction times were done with a Treatment (2) × Time (3) repeated measurements MANOVA, using the exact F-transformations of Hotellings T^2.

EEG measurements

Classical analysis. Trials with incorrect behavioral responses as defined above were excluded from analysis. Trials containing amplifier blocking or in which the EEG showed flat lines (no voltage fluctuation for a period of more than 40 ms) were detected automatically and omitted from further analysis. Ocular artefact in the EEG was controlled using regression analysis in the frequency domain (39). After EOG correction all intervals containing movement artefacts (change in amplitude of more than 40 μV between two adjacent samples) or electrical drifts (difference between lowest and highest amplitude more than 100 μV within one trial, 256 samples) were excluded from further analyses. For each participant, average stimulus-locked

ERPs were computed separately at each scalp location for each of the nine stimulus categories and for both treatment conditions. The averaging epochs lasted for 924 ms poststimulus, using a 100 ms prestimulus period as a baseline.

The ERP components of interest, shown by earlier research to be sensitive to the effects of caffeine (20,21,29) were the frontal P2 component, and the parietal P3 component. Mean amplitude values for the P2 were determined on leads AFz, Fz, F3, and F4 for a time period of 40 ms (200 to 240 ms poststimulus). Mean amplitude values for the P3 were determined on lead Pz, for two time periods of 100 ms (420 to 516 and 520 to 616 ms poststimulus). Repeated-measures multivariate analyses of variance (MANOVAs) were performed on mean amplitudes for the most prominent ERP peaks, using the exact F-transformations of Hotellings T^2. The MANOVA design for the P2 component was the following: Treatment (2) × Lead (4) × Category (9). The ANOVA design to analyze the P3 component was Treatment (2).

Bourdon-Souren and time-on-task analysis. Due to the diminished numbers of trials for these analysis, ERPs were digitally low-pass filtered at 19.5 Hz prior to subsequent processing and analysis. Mean amplitudes of ERPs on lapses of attention as well as mean amplitudes of ERPs for the different time intervals were computed as follows: ERPs were averaged for 6 time periods of 48 or 52 ms each, from 100 to 412 ms poststimulus and 5 periods of 100 ms each, from 416 to 916 ms poststimulus, for 5 midline leads (Afz, Fz, Cz, Pz, Oz) and both treatment conditions separately. These variables were then submitted to statistical analysis in the following MANOVA design for repeated measurements; for the analysis of lapses of attention: Treatment (2) × Lead (5) × Category (2: lapses of attention/grand average ERPs without lapses) and for the time-on-task analysis: Treatment (2) × Lead (5) × Time (3). When the main design indicated a significant interaction (α = .05) between a variable and Lead, additional analyses were performed for that variable for each midline lead separately. It holds for all ERP analyses that a significance level of α = .05 was used. In addition, possible significant interactions of Treatment with Lead, if present in the multivariate analyses, were followed by a second MANOVA with normalized data (according to the vector length scaling method proposed by McCarthy & Wood (23)) to assess scalp topographic differences. Interactions with location were only reported if the interactions remained significant after normalization. Main effects of Lead will not be discussed here.

RESULTS

Subjective and Physiologic Measurements

Participants reported no differences in their quality of sleep on the night before the experimental sessions. The items from the task load inventory were analyzed separately. Participants reported no significant differences between the caffeine and placebo condition on subjective effort needed to perform the set of tasks. There were neither differences in mood (as measured with the POMS and the STAI) between the conditions as measured at the arrival of the participants, nor differences in mood due to Treatment as measured at the end of the experimental sessions. Averaged over conditions participants felt more fatigued F (1,11) 9.52, $p < 0.010$, and less vigorously F (1,11) 14.49, $p < 0.003$, at the end of the experiment compared with the start of the experiment. There were no significant changes in systole- and diastole blood pressure or heart rate as a result of caffeine intake.

Behavioural measurements

Bourdon-Souren analysis. Analyses of the concentration variable revealed a linear trend for the Series factor F (1,22) = 11.63, p = 0.003, as can be seen in Fig. 2, indicating a decrease in concentration over time. A trend towards a linear effect for the Series factors was found for the distraction variable F (1,22) = 4.22, p = 0.052, indicating an increase in distraction over time. No main effects of linear or quadratic trends for any of the variables were found for the Treatment factor or interactions between Treatment and Series. Behavioral data and ERP data for lapses of attention were analyzed for ten of the participants only, since lapses of attention could not be observed in either one of the two treatment conditions for two of the participants. The number of lapses of attention and the number of false alarms did not reveal any significant effects of Treatment, Series (indicating no differences over time) or interactions between those variables. Mean reaction times and standard deviations to lapses of attention were not significantly different for the treatment conditions. An overview of these results and those from the classical analyses can also be found in Table 1.

Classical analysis. Analyzing the total number of hits and reaction times to all stimuli, it was revealed that averaged over all categories there was no main effect of Treatment, and no interactions between Treatment and Category. There was, however, a main effect of Category on the mean reaction times F (4,8) 45.37, p < 0.001, as well as on the mean number of hits per category F (4,8) 10.29, p < 0.020. Participants reacted fastest on patterns of five dots (M = 494.5, SD = 59.4) and had the most hits on these patterns (M = 74.8, SD = 11.6), patterns of three dots were reacted to with an intermediate level of reaction times (M = 503.2, SD = 53.0) and mean number of hits per category (M = 74.2, SD = 11.0), while the responses to patterns of four dots were the slowest (M = 539.6, SD = 57.2) and had the smallest mean number of hits (M = 68.1, SD = 12.1). There were no significant differences in reaction times between the two hands.

Time-on-task analysis. A representation of the time-on-task effects can be seen in Fig. 3. Mean reaction times showed a main effect of time-on-task F (2,10) 13.30, p < 0.002, with the beginning of the task showing intermediate reaction times (M = 513.0, SD = 56.8), slower reaction times during the middle of the task (M = 519.3, SD = 59.9) and the fastest reaction times at the end of the experimental task (M = 506.0, SD = 60.8). No main effect of Treatment and no interaction between Treatment and Time was observed.
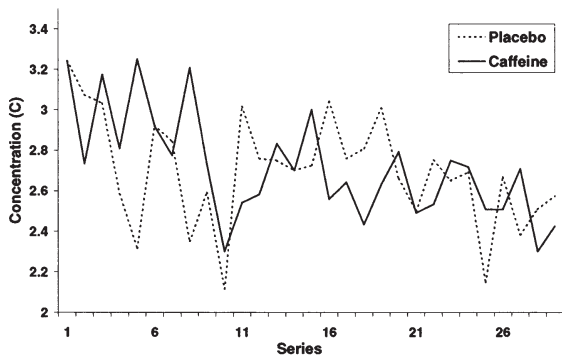
TABLE 1
PERFORMANCE DATA (± SD)

	Placebo (SD)	Caffeine (SD)
Mean RT (n = 12)	514.2 (76.6)	510.7 (47.4)
Mean number of hits per category (n = 12)	71.2 (12.0)	73.6 (13.7)
Mean number of false alarms per category (n = 12)	36.3 (32.6)	34.7 (17.9)
Mean RT to lapses (n = 10)	1367.5 (252.5)	1313.2 (246.8)
Mean number of lapses (n = 10)	7.3 (9.6)	7.0 (8.1)

ERP measurements

Classical analysis. Fig. 4 depicts the grand average ERPs for the Afz, Fz, F3, and F4 leads for the placebo and caffeine condition superimposed, averaged over Category. The early frontal positive wave form (200 to 240 ms) showed a significant effect of Treatment F (1,11) 6.12, p < 0.031, with the wave form being more positive in the caffeine condition compared with the placebo condition. Although it might seem that the effect in this time-interval is part of a broader positivity that is longer in duration, additional analysis of other time-intervals did not reveal any significant treatment effects, probably due to increasing standard deviations.

In Fig. 5 the late positive parietal complex is shown on lead Pz for the placebo and the caffeine condition superimposed, averaged over Category. A main effect of Treatment was observed for the 520 to 616 ms time period F (1,11) 5.82, p < 0.034, with the caffeine condition showing a more positive going wave form compared with the placebo condition. In this time period a main effect of Category was observed as well F (4,8) 75.64, p < 0.000, as can be seen in Fig. 6. Results showed that the amplitudes on Category 1, 2 and 3 (stimuli presenting 4 dots) were more positive compared with amplitudes on the remaining categories, which were more comparable in amplitude. No interactions between Treatment and Category were observed.

Analysis of lapses of attention. A total number of 73 and 70 lapses of attention were observed for the placebo and caffeine condition, respectively. Although this number is not very high, it is enough to obtain reliable ERPs, especially for the later, more robust components such as the P3. A signifi-

FIG. 2. Mean concentration scores for the placebo and caffeine conditions as a function of time (Series).
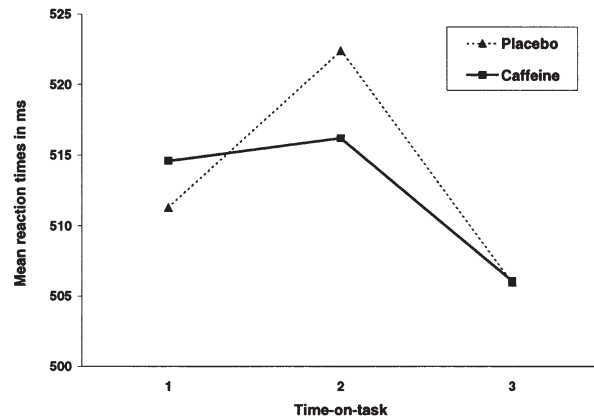

FIG. 3. Time-on-task effects expressed in mean reaction times for the placebo and caffeine conditions.
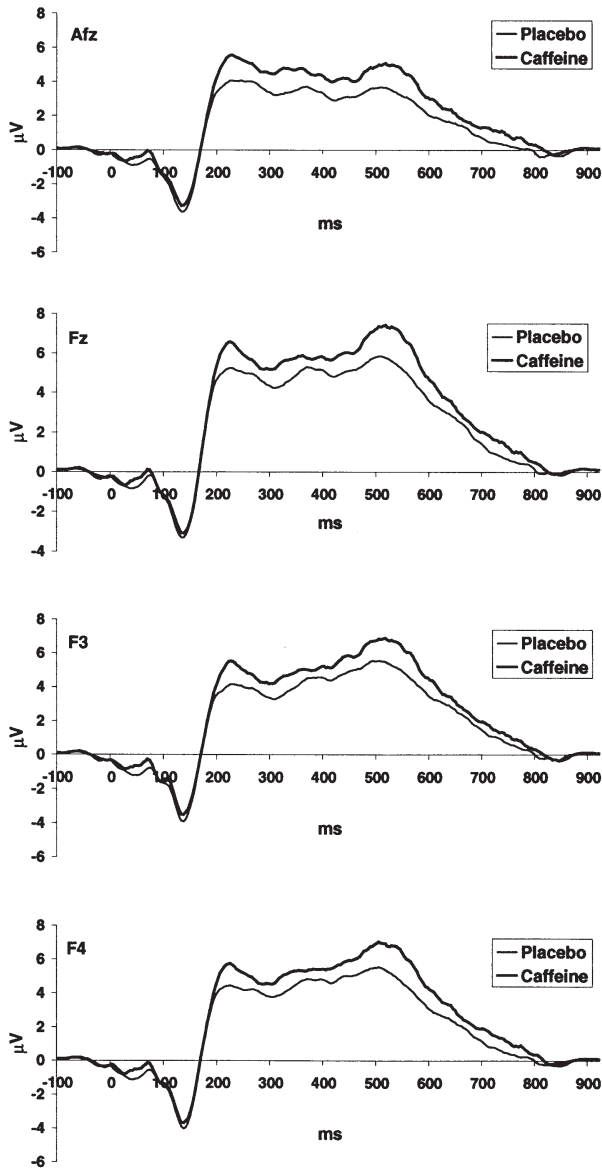
FIG. 4. Grand average ERPs for the Afz, Fz, F3, and F4 scalp locations. Superimposed are ERPs for the placebo and caffeine condition, averaged over Category.
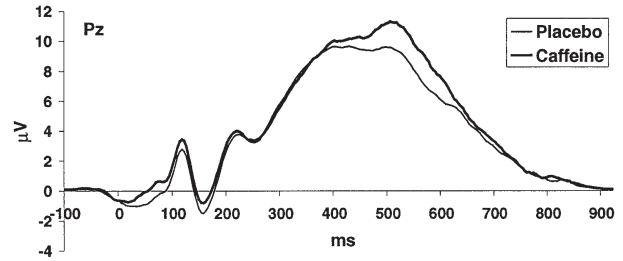

FIG. 5. Grand average ERPs for the Pz scalp location. Superimposed are ERPs for the placebo and caffeine condition, averaged over Category.

0.084, while effects of Category did not show trends towards significant effects on other midline leads. No interactions of Treatment with Lead were observed.

Time-on-task analysis. Statistical tests of mean amplitudes of ERPs to the different time intervals, Leads and both Treatment conditions revealed three main effects for Time, from 156 to 204 ms $F(2,10)$ 4.54, $p < 0.040$, and from 312 to 360 and 364 to 412 ms after stimulus presentation $F(2,10)$ 4.95 to 5.67, $p < 0.032$ to 0.023. The time-on-task effects for the ERPs can be seen in Figs. 8 (placebo condition) and 9 (caffeine condition). Averaged over conditions, this effect displayed the largest amplitude for time 1 (the beginning of the task), the smallest amplitude for time 2 (the middle of the task) and an intermediate amplitude for time 3 (the end of the task) for the time intervals of 156 to 204 and 312 to 360 ms. For the 364 to 412 ms time period this effect was somewhat different, with the beginning of the task showing the largest amplitude, followed by the middle and the end of the task. A trend towards a significant effect of Treatment (averaged over time) was observed in the 416 to 516 ms time period $F(1,11)$ 4.51, $p < 0.057$, with the caffeine condition showing a more positive going ERP compared with the placebo condition. However, this effect may reveal an extension of the observed influence of caffeine on the parietal P3 component, which was found to have a very broad scalp distribution. No interactions of Treatment or Time with Lead were observed.

DISCUSSION

The present study examined the effects of caffeine intake on sustained attention. A self-paced reaction time task was used in both a placebo and a caffeine condition, followed by a broad spectrum of analyses of the behavioral results and ERPs.

cant effect of Treatment was found in the Treatment (2) × Lead (5) × Category (2: lapses of attention/grand average ERPs without lapses) design, but no effects of Treatment were found in an added post hoc analysis involving only the ERPs to lapses of attention (Treatment × Lead). A main effect of Category was found from 100 to 152 ms poststimulus $F(1,9)$ 5.90, $p < 0.038$, as can be seen in Fig. 7, with the ERPs to lapses of attention showing a more negative going mean amplitude compared with the grand average ERPs (averaged over treatment conditions). In addition, a significant interaction of Category and Lead was found from 520 to 616 ms $F(4,6)$ 4.90, $p < 0.042$. Analyzing the effects of Category in this time period for the Leads separately, it was revealed that lead Afz accounted for the observed difference $F(1,9)$ 3.78, $p <$
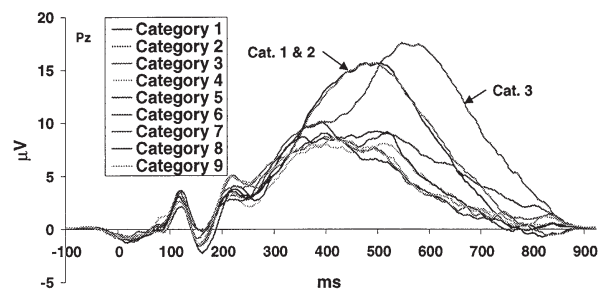

FIG. 6. Grand average ERPs for the Pz scalp location. Superimposed are ERPs for the different categories (stimulus patterns), averaged over treatment conditions.
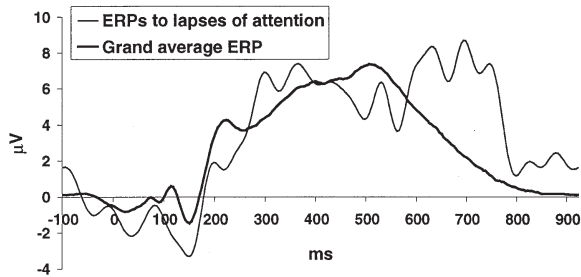
FIG. 7. Averaged ERPs over five midline leads and both treatment conditions. Superimposed are grand average ERPs and ERPs to lapses of attention.

FIG. 9. Averaged ERPs over five midline leads for the caffeine condition. Superimposed are ERPs to the different time intervals.

ERP results showed the expected effects of caffeine on mean amplitudes. The frontal P2 and the parietal P3 component were both more positive under caffeine conditions than under placebo conditions. The effects of caffeine on the parietal P3 component that were found in the present study are similar to results that were previously found. For example, it was found that the P3 amplitude for a 7.5 mg/kg dose (30) and for a 200 + 50 mg dose (20) of caffeine was significantly larger than for the placebo condition. The parietal P3 component is thought to be influenced by fluctuations in cortical arousal level (4,10,27). An increase of this component by caffeine could therefore suggests more caffeine induced activity for information processing, which is in accordance with the statement from another study that an increased positivity of the P3 component reflects heightened information processing (12).

An increase in frontal P2 amplitude by caffeine has also been found in some other studies (21,29,30). Based on results obtained from CSD and spline maps (29) the authors concluded that the probable generator area for this caffeine effect in the brain could be a frontally based source. The prefrontal cortex is said to be related to working memory and to higher level control- and co-ordination mechanisms (for an overview see (38)). The present study may appeal to these mechanisms via the need for rapid decision making, regarding which hand should be used to react with (on the basis of stimulus information) and to switch from hand to hand to execute the correct motor response.

Remarkable is the fact that the caffeine effects on the ERPs were not supported by the behavioral data. Neither the
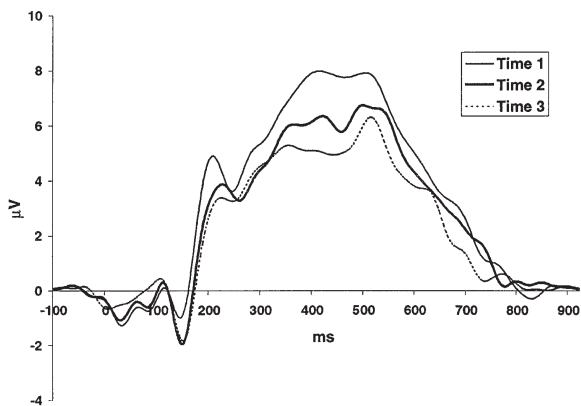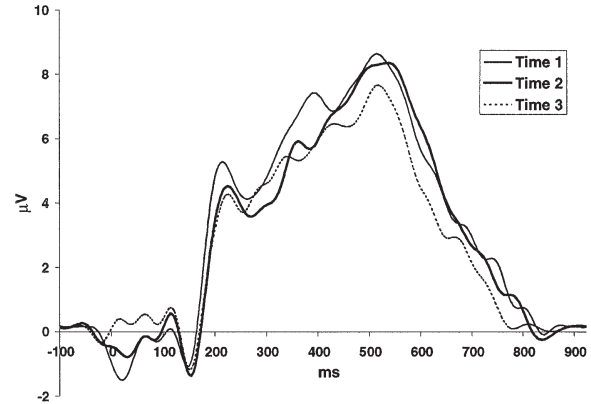
analyses according to the Bourdon-Souren methods, the lapses of attention and the time-on-task effects, nor the classical analyses revealed any significant Treatment effects. Multiple factors may influence the performance deterioration in vigilance tasks, one of those being the capacity limitations (25,26). As stated in the introduction, this may explain why caffeine normally improves vigilance performance. However, other authors argue that the absolute overall performance in vigilance tasks is mainly determined by the difficulty of the task (15). The task used in the present study was probably more difficult and demanding than normal vigilance tasks, because of the fact that a reaction had to be given to every stimulus and a rapid decision had to be made regarding which hand to respond with. The effects of caffeine may more easily be assessed on simple tasks, where it prevents performance degradation by keeping up the motivation and/or counteracting the effects of fatigue (5). In contrast, when task demands are sufficiently energizing, caffeine may have no additional influence on performance. This may explain why no improvement in performance levels were found in the present study. More support for this hypothesis comes from a study (22) in which no effects of caffeine were found on reaction times in a high display load condition, while a low display load did reveal significant differences. In addition, decrements in primary task performance may not always be observed due to the so-called "performance-protection strategy" of participants (11). In the present study the behavioral data from both treatment conditions point to the same strategy; no differences in number of false alarms or concentration levels were observed, while the pattern of lapses of attention over time is comparable for both conditions. However, secondary patterns of degradation might be observed (11). One of those, applicable to sustained attention tasks, is the fatigue-after effect. In the present study, caffeine may have influenced these after-effects: participants may have been less tired after task performance than in the placebo condition. However, no effects of caffeine ingestion were found in the answers to the questionnaire measuring subjective effort to perform the tasks. But this may have been caused by the fact that the participants filled out the questionnaire after completing a 1-h set of tasks rather than immediately after performance on the sustained attention task.

In sum, fatigue can be manifested in different ways. With caffeine counteracting the effects of fatigue, the effects on

FIG. 8. Averaged ERPs over five midline leads for the placebo condition. Superimposed are ERPs to the different time intervals.

task performance may be expressed in various ways as well. In the present study the effects of caffeine were absent in the behavioral measurements, but were manifest in the ERP data. These results support the hypothesis that effects of caffeine on behavioral measures are probably easier to discern in suboptimal conditions, for example with fatigued participants or when using less arousing tasks.

The mean reaction times and the mean number of hits differed significantly between the different stimulus patterns that were used. Participants reacted fastest and had the highest number of hits on patterns of five dots. Intermediate levels were found for patterns of three dots, whereas the reaction times were longest and the number of hits was lowest to patterns of four dots. These effects were independent of the hand with which the participants had to react to the different stimulus patterns. Based on these results, a probable assumption might be that the patterns of four dots were the most difficult to process. In the ERP results, differences between stimulus patterns were also observed: in the P3 peak area, a more positive amplitude for stimuli of four dots was found compared with amplitudes of patterns of three or five dots. However, in contrast to the conclusion based on the behavioral results, many researchers have observed smaller P3 amplitudes as task conditions become more difficult (16), indicating that the patterns of four dots were the easiest to process. Smaller P3 amplitudes were observed, for example, in conditions with a smaller target probability, a higher memory load or with the addition of a secondary task. However, alternative explanations for these observations were also presented (16), such as "data-limitation" (a sensory limitation) or the possibility that difficult tasks activate processes that could interfere with target identification. Support for these alternative explanations comes from a study in which equiprobable stimulus categories were used (33). In this study, an increase in P3 amplitude was found with increasing difficulty of the stimulus categories and a positive correlation was observed between the subjective feelings of effort that were needed to perform the task and the degree of difficulty of the stimulus categories. Following this rationale, the P3 amplitudes that were observed in the present study in reaction to the different dot patterns, may also represent the degree of difficulty of processing, indicating that the patterns of four dots were the most difficult. In addition, category three might be even more difficult than categories one and two (see Fig. 6). Although it is known that patterns of less than 6 dots are usually processed "automatically," it cannot be ruled out that pattern recognition and perceptual organization was more difficult for certain patterns as compared with the others. One might argue that the most dissimilar ERP wave form (Fig. 1, category 3) belongs to the pattern that intuitively also seems the most difficult to recognize. In addition to the P3 amplitude, the P3 latency also supports this hypothesis. The latency of this component is often said to represent the speed of stimulus evaluation. Although the P3 latencies were not separately calculated for all stimulus categories, it can be speculated from Fig. 6 that the latencies of the patterns with three and five dots are earliest and more or less comparable, followed by the P3 latency to categories one and two and an even longer latency for category 3. This would confirm the same pattern of difficulty: patterns of three and five dots are easiest to recognize and process, followed by categories one and two of four dots, while category three of four dots seems the most difficult.

The conclusion from the ERP results might be that caffeine increases arousal, thereby reducing fatigue or counteracting boredom, as can be seen in the more positive going amplitudes of the P2 and P3 components of the ERP. However, the benefit of the extra processing capacity could not be observed in the behavioral data because the task was probably arousing enough in itself. These results support evidence that the arousal increasing effects of caffeine are probably more easily demonstrated in suboptimal conditions. In addition, these results appeal for an increase in the use of ERPs in drug research, in order to determine possible effects on the brain which do not necessarily result in behavioral changes.

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