Effects of caffeine on visual attention
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General discussion
Effects of caffeine on visual attention

Introduction

The primary objective of the studies described in this thesis was to assess the effects of caffeine on the perception and processing of visual information, and more specifically, to gather more information about the influence of caffeine on different aspects of visual attention. Lorist (1995) studied the effects of caffeine on different stages of information processing and used, for example, a search task (spatial selection), and a nonspatial selective attention task. The overall results from her studies revealed that especially the input and output stages of information processing were susceptible to the effects of caffeine, while the central processing stage was not affected. Moreover, the results suggested that the effects of caffeine may be more pronounced for spatial attention conditions compared to other types of attention. The studies in this thesis aimed to verify this suggestion, and to assess the effects of caffeine on tasks that appeal for types of attention that were not used in the studies of Lorist. Based on the conclusions from Lorist, an additional aspect of interest was to study the interactions between caffeine and the perceptual and output processes under different types of attention. The first study in this thesis (chapter 2) examined the effects of increasing caffeine doses (1, 3 and 7.5 mg/kg body weight) on divided attention (a dual-task). Three other studies (chapters 3, 4 and 5) examined the effects of 250 mg caffeine on the following aspects of attentional processing: spatial selective attention, nonspatial selective attention to colour (both studies were designed to measure attention to one type of stimuli while ignoring another), and sustained attention (a concentration task). In the current chapter, the results of these studies will be summarised, and an interpretation of the results is given. After that, some remarks concerning this type of research, and some suggestions for future research, will be discussed.

Overview of results

To examine the effects of caffeine on different aspects of attention, several types of dependent variables were used: subjective measures, behavioural measures and event-related potentials (ERPs). The ERP measures were used as the basis for spline maps and current source density (CSD) maps, which can reveal more specific information about the distribution of brain activity over the scalp. The results of the subjective measures did not differ between the placebo and caffeine conditions in any of the studies. Therefore, the observed effects on behavioural and ERP measures might be regarded as "pure" effects which are not due to, or contaminated by, changes in subjective feelings or mood.

An overview of the treatment-related effects that were found in all the studies is presented in Table 1. Other main or interaction effects, such as those of attention, time,
or task, will not be discussed in this chapter, since those results are not related to the primary hypothesis and research questions concerning the effects of caffeine. An overview and discussion of the results that were not treatment-related can be found in the separate chapters.

**Table 1** What happened under the influence of caffeine?

<table>
<thead>
<tr>
<th>Tasks:</th>
<th>Effects: Behavioural measures: Reaction Times</th>
<th>Behavioural measures: Accuracy</th>
<th>ERPs: exogenous frontal P2 amplitude</th>
<th>ERPs: parietal P3 amplitude to targets</th>
<th>Other ERP results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual-task</td>
<td>decreased on both tasks</td>
<td>-</td>
<td>increased</td>
<td>increased</td>
<td>-</td>
</tr>
<tr>
<td>Colour-selection task</td>
<td>decreased</td>
<td>-</td>
<td>increased</td>
<td>increased for the P3 to irrelevant targets</td>
<td>N2b attention component increased</td>
</tr>
<tr>
<td>Spatial-selection task</td>
<td>-</td>
<td>number of hits increased, sensitivity A' increased</td>
<td>increased</td>
<td>not investigated</td>
<td>Interaction between treatment and attention for occipital P2 and N2 components</td>
</tr>
<tr>
<td>Concentration task</td>
<td>-</td>
<td>-</td>
<td>increased</td>
<td>increased</td>
<td>-</td>
</tr>
</tbody>
</table>

**Behavioural results**

A combination of speed and accuracy of the responses usually assess the quality of behavioural results. A positive shift in this speed-accuracy trade off curve (increased speed and higher accuracy) can usually be interpreted as a structural effect, because the efficiency of all processes increases. In contrast, a negative shift in the speed-accuracy trade off curve can probably be attributed to a change of the strategy that is followed by the participant. One could argue whether a change in value of one of these aspects, either accuracy or speed, that is accompanied by a change in the opposite direction or no change at all of the other aspect, is the result of structural or strategic effects. Leaving the origin of this effect aside, it can be said that such an effect is normally interpreted as reflecting a change in the quality of task performance. Following this reasoning, the decrease in reaction times that was observed in the dual-task and the colour-selection task by caffeine, that was not accompanied by a change in accuracy, can be interpreted as representing an improvement in the quality of task performance by caffeine. In addition, an increase in the quality of task performance was also found in
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the spatial-selective attention task, in which the intake of caffeine resulted in more hits and an increased perceptual sensitivity A', while no differences in reaction times were observed. The fact that in two studies speed increased while in another study accuracy improved could indicate that the influence of caffeine on perceptual processes is differential for spatial attention conditions. However, these effects could also be related to other task requirements such as the difficulty of the task. The verbal comments of the participants suggested that the distinction between target and nontarget stimuli was much more difficult to make in the spatial-selection task than in the colour-selection and dual-tasks. In the concentration task, no differences in behavioural responses between the placebo and caffeine conditions were found. However, this does not necessarily mean that caffeine does not influence sustained attention at all. It could also be the result of specific task requirements, such as the aspect that participants had to react to every stimulus in this task, while in the other tasks only infrequent target stimuli were presented on which the participant had to react. Summarising, an increase in the quality of task performance was observed in three out of the four studies that are described in this thesis. It also became clear that the amount of caffeine that is administered affects the results. In the dual-task, the effects of multiple doses of caffeine on performance and information processing were studied besides the general effects of caffeine on divided attention. Concerning the behavioural results, it was revealed that for both tasks of the dual-task a decreasing linear trend in reaction times was observed with increasing caffeine doses. This indicates that the amount of caffeine that is used plays an important role in determining the results. Using multiple doses of caffeine seems informative and may improve the reliability of generalising the results beyond the doses that were studied.

The fact that caffeine decreased reaction times in the selective attention to colour task and the divided attention task (dual-task) could point to a specific influence of caffeine on the perceptual processes. However, alternatively, these results could reflect an influence of caffeine on the output-related processes in the information-processing stream. A decrease of reaction times by caffeine is a fairly robust and often replicated finding for a range of different tasks. Lorist (1995) reached the conclusion on the basis of her studies, that faster reactions are the result of the influence of caffeine on the motor-responses. More specifically, Kenemans and Lorist (1995) found faster reaction times to targets in the caffeine condition, but no differences in the onset of the lateralized readiness potential (LRP) between the caffeine and the placebo condition. This may mean that the speeding up of processes took place after initial response preparation had begun, probably at the central and/or peripheral motor execution stages. From another study by Kenemans and Verbaten (1998), that was specifically designed to reveal the influence of caffeine on visuo-spatial perception, it was concluded that the faster responses by caffeine were the result of an improvement in preparation and execution of the motor responses, rather than the result of improved perception or processing of information.
A general conclusion may be that the improvement in the quality of task performance after caffeine seems to be fairly robust. The perceptual processes may be influenced by caffeine, as was observed in the spatial-attention task, but this possibly depends on specific task requirements. Taking into account the results of previous studies, a more probable interpretation for the decrease in reaction times by caffeine may be that the locus of this improvement is the output process of information processing, namely, the motor-responses. It can be concluded that the behavioural effects of caffeine that were found in the studies of this thesis do not seem to be restricted to particular attention conditions. The interpretation of the complementary ERP results will probably contribute to a better understanding of the locus of the effects of caffeine on the behavioural responses.

**ERP results**

**P3 component**

The amplitude of the parietal P3 component to targets was, in general, enlarged after caffeine. In the colour-selection task a more specific effect was found, namely, a P3b irrelevant target effect of caffeine. The amplitude of the P3 component is often said to reflect the amount of "energy" that is used for the processing of information, or the effectiveness with which the stimulus information is processed (Donchin, Kramer & Wickens, 1986; Johnson, 1986; Polich & Kok, 1995; Sirevaag, Kramer, Coles & Donchin, 1984). In addition, as stated in chapter 1 of this thesis, caffeine usually increases cortical arousal levels as measured with the EEG, which has been interpreted as a reflection of elevated levels of energy (e.g. Bruce, Scott, Lader & Marks, 1986; Hasenfratz & Bättig, 1994; Rall, 1990). Therefore, the interpretation of the observed effects of caffeine on the P3 amplitude, that the stimulant caffeine increases energy, is in agreement with a combination of these two generally accepted viewpoints.

The observed effects on the P3 component indicate that the central, higher cognitive processes are also influenced by caffeine. Increased activity at this stage could be the result of increased activity for information processing at the input stages, or it can be a more independent effect, in which case it could lead to behavioural effects such as a decrease in reaction times. Since the effect of caffeine on the P3 was found for several different tasks that were used in this thesis, a probable conclusion may be that this effect is non-specific and independent of the perceptual- and input stages of information processing. In addition, since no differences in P3 latencies were found between placebo and caffeine conditions, the observed effects of caffeine on the behavioural measurements are probably the result of output-related stages of information processing.

With the task demands remaining the same, the P3 amplitude to targets was found to be larger in the caffeine condition than in the placebo condition in the dual-task and concentration task, indicating the increase of energy by caffeine. In the colour-selection task, a P3b irrelevant target effect of caffeine was found, suggesting increased
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processing of this stimulus type, as compared with the irrelevant target in the placebo condition and the standard stimuli of both conditions. This effect may also point to increased energy, in this case used to evaluate the second-most important stimulus type, since the detection of the relevant target was already completed. This leads to the conclusion that caffeine increases the available energy for general task performance, and not merely for the processing of relevant target stimuli. Support for elevated energy levels by caffeine also comes from a study by Lorist, Snel, Kok and Mulder (1994) who found that a reduced energy level, induced by fatigue and which was observed as a smaller P3 component, was counteracted by caffeine. Thus, as can be observed in a larger P3 amplitude, caffeine seems to increase the available energy, independent of the different types of visual attention conditions that were studied.

P2 component
In all studies described in this thesis, the P2 component had a larger amplitude in the caffeine condition as compared to the placebo condition. The amplitude of this exogenous component, peaking in a range of 180-240 ms after stimulus presentation, at Afz and Fz leads, was independent of the manipulation of the different aspects of visual attention. In the colour-selection task, spline- and CSD maps were calculated for this effect, pointing to a fronto-central source of activation. On these maps, a general increase of brain activity was also visible, which was distributed equally over the scalp and could be reflecting either the same P2 effect or a different overlapping effect. It has been argued that the P2 reflects basic perceptual processing (Csisbra, Czigler & Ambrò, 1994). Thus, the enlargement of the P2 amplitude by caffeine could indicate modified basic perceptual processing. However, for the colour-selection task, the P2 effect seemed to originate from the fronto-central brain areas, and since these brain areas are not known to play an important role in perceptual processing, this suggests that this interpretation is less likely to describe the effect in the present studies. An alternative explanation might be that the P2 amplitude effect reflects increased activity of the fronto-central brain areas in the caffeine condition. Speculating further, one could hypothesise that it is the prefrontal cortex, assumed to be related to working memory and a higher level control- and co-ordination mechanism (see for example Wickelgren, 1997), that is influenced by caffeine. The tasks that were used might have called upon a higher level of information processing. For example, in the sustained attention task, an appeal to these mechanisms might have been made by the prolonged need for rapid decisions making about the hand with which to react (on the basis of stimulus information) and to switch from hand to hand to execute the correct motor responses. In the dual-task higher processing might be used to be better co-ordinate the division of attention between tasks and to initiate the right hand response for each task.

Additional ERP effects of caffeine on attention
In the colour-selection task an interaction of caffeine with the amplitude of the central N2b component (240-280 ms poststimulus) was found, demonstrating a main effect of
attention in the caffeine condition but not in the placebo condition. In other words, the effects of caffeine became apparent in this instance by the ability of participants to differentiate between relevant and irrelevant non-target stimuli: something they were not able to do in the placebo condition. The N2b is sometimes described as a "covert orienting response", or is said to be related to "selection for action", indicating that the observed effect of caffeine on this component might improve these features of information processing in the colour-selection task. In addition, this component has been interpreted as being sensitive to the state of the participant and to the allocation of energy (Gunter, van der Zande, Wiethoff, Mulder & Mulder, 1987). A comparable effect of caffeine on the N2b component was found by Lorist, Snel, Kok, and Mulder (1994) who used a spatial diagonal-selection task, but not by Kenemans and Lorist (1995), who used a nonspatial grating task. A possible factor that might be responsible for this discrepancy may involve the time between caffeine administration and actual task performance. In the colour-selection study described in this thesis, as well as in the study of Lorist et al. the interval between caffeine intake and task performance was about one hour, while in the Kenemans and Lorist study this time was about two hours. It is known from pharmacological studies (e.g. Daly, 1993) that caffeine reaches its peak plasma concentration in about 45 minutes to one hour. If the metabolic elimination time of caffeine is also taken into account, the conclusion may be reached that after two hours the level of caffeine in the brain could be substantially lower than after one hour. Another factor that might influence the variation in results, is the difficulty of the task that is used. The behavioural results of the colour-selection task and the task by Lorist et al. show no improvement by caffeine in the number of hits and false alarms. In contrast, the number of hits did increase by caffeine in the Kenemans and Lorist study. In addition, reaction times were faster in this study as compared to the two other studies. Although the pursuit of comparing the difficulty of tasks between studies is always a complex matter, these results may indicate that the colour-selection task and the diagonal selection task, in which modulations of the N2b component were found, were indeed more difficult than the grating task in which no modulation of the N2b component by caffeine was found. This suggests that task difficulty might be one of the factors that influences the effects of caffeine on the N2b ERP component. Furthermore, based on the speculation that the influence of caffeine on the frontal P2 component could be an indication that the higher level control-mechanisms are more active in caffeine conditions, one could hypothesise that the frontal control mechanisms can coordinate the use of the extra available energy that becomes available by caffeine intake, in a flexible way. One of the factors determining the use of the extra available energy may be the difficulty of the task. If the tasks that were mentioned before were indeed more difficult, it seems plausible that some of the extra energy may be directed towards the central stages of information processing. As far as the studies in this thesis are concerned, an influence of caffeine on the N2b component was only found in the colour-selection task, which in itself could indicate that this caffeine effect is specific for nonspatial selective attention. However, since this effect was not found in another
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nonspatial attention task (Kenemans & Lorist, 1995), and alternative factors that may influence this effect have been proposed and can not be ruled out yet, the conclusion at this point is that the effects of caffeine on the N2b component are not restricted to nonspatial selection, but are more general and could depend on the time between caffeine administration and task performance or task difficulty.

In the spatial-selection task, interactions between caffeine and attention were found for the occipital P236 and N284 components. The P236 component showed larger amplitudes for stimuli at the unattended location by caffeine, while in the placebo condition larger amplitudes were found for stimuli at the attended locations. Since initial perceptual processes, visible on the occipital leads, already took place, this effect might indicate that the energy increasing effect of caffeine was flexibly used to perceptually process the irrelevant information. In contrast, in the placebo condition the system was possibly more rigid and continued to further process the information at the relevant location. The interaction of caffeine with the occipital N284 component was similar to that with the N2b component in the colour-selection task: the effect of attention was apparent in the caffeine condition, but not in the placebo condition. Again, this indicates that the differentiation between relevant and irrelevant non-target stimuli became apparent in the caffeine condition, but not in the placebo condition. These interaction-effects could be interpreted as an enlargement of the amount of information that can be processed, or as a differentiation in the type of information that is preferred for processing under caffeine conditions. Moreover, these effects might be specific for spatial attention, but replication of these findings need to confirm this.

Conclusion

The effects of caffeine intake on different aspects of visual attention were observed as the following differences in behavioural and ERP data in comparison to a placebo condition: first, an improved perceptual sensitivity and an increase in the number of hits was apparent in the spatial-selection task due to caffeine. Next, an increase in the amplitude of the frontal exogenous P2 component by caffeine was found, followed by an enlarged central N2b amplitude in the colour-selection task, and interactions of caffeine and attention in the occipital region for the spatial-selection task. After that, an increase in amplitude of the parietal P3 amplitude was observed, and a decrease in reaction times by caffeine.

Based on her work, Lorist (1995) suggested that the early stages of information processing of spatial information might be more sensitive to the effects of caffeine than the processing of nonspatial information. Although an increase in the number of hits and sensitivity by caffeine was found in the behavioural results of the spatial-selection task used in this thesis, which could indicate an effect of caffeine on spatial attention, this was not confirmed by the ERP results. Caffeine did not affect the early P1 and N1 components of the ERP that are said to be specifically involved in spatial attention. Therefore, the observed behavioural results probably represent improved perceptual
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processes by caffeine that are not specifically related to the spatial attention condition. Interactions between caffeine and attention were found for this task in later time intervals of the ERP, but it remains to be determined whether these later interactions depend on specific task requirements, or are possibly specific for spatial attention after all. In general, behavioural and ERP data of these and other studies do not seem to yield an unequivocal pattern of results concerning the effects of caffeine on the perceptual processes. For example, using a stimulus degradation task, Lorist, Snel and Kok (1994) found an enlarged N1 component that was accompanied by fewer omission and commission errors in the caffeine condition. In addition, using a Stroop task, Hasenfratz and Bättig, (1994) and Kenemans (1998), found decreased Stroop interference by caffeine, indicating improved perceptual processing by ignoring distracting information. On the other hand, in a diagonal-selection task (Lorist, Snel, Kok & Mulder, 1994), no differences in the number of hits, misses, or false alarms due to caffeine were observed. Also, no effects of caffeine on perceptual processing were found in a grating task (Kenemans & Lorist, 1995), and in a spatial-selection flanker task (Kenemans & Verbaten, 1998).

Summarising, it can be said that the effects of caffeine do not seem to be specifically sensitive to conditions of spatial selective attention. Moreover, the enlarged amplitudes of the P2 and P3 components by caffeine and the decrease in reaction times found in several of the studies, also do not seem to be related to particular attention conditions. In addition, it was argued that the influence of caffeine on the N2b amplitude in the colour-selection task is probably not specific to nonspatial attention conditions. The only effects that might suggest a possible specific effect of caffeine in spatial attention conditions, are the interactions between caffeine and attention on the occipital leads in the spatial-selection task, but more research is needed to confirm this.

While the detailed interpretations of these effects differ, the common idea is that they can all be explained by an increase of available energy by caffeine, that is implemented in different ways. It becomes clear from the studies in this thesis, as well as from other studies, that the effects of caffeine on visual information processing sometimes vary. The diversity of the results mainly seems to be brought about by the range of different independent variables that are used. For example: the task variables (e.g., the difficulty of the task, central or peripheral presentation of the stimuli, focused or divided attention conditions, occasional targets or each stimulus as a target), the method of data analysing, and of course the independent variables such as the amount of caffeine that was used, the selection of participants and the research design, to name a few. Even within one set of studies (as in the studies from this thesis, but also within the studies of Lorist), in which most independent variables remain fixed, the diversity of the effects is large, suggesting that especially the task variables may play a critical role in the effects of caffeine.

As far as the influence of different doses of caffeine are concerned, it can be concluded that for the participants in the dual-task study, the amount of caffeine that was administered played an important role in determining the effects. Both the decrease
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in reaction times and the enlargement of the P3 amplitude showed a linear relation with increasing caffeine doses, indicating that the results that were observed are dose-dependent. Moreover, the most pronounced differences between conditions for these effects were observed when comparing the 7.5 mg/kg body weight condition to the placebo condition. In some studies deteriorating effects on mood and cognitive performance are found with higher doses of caffeine (in the range of 400 to 600 mg) (Frewer & Lader, 1991; Hasenfratz and Bättig, 1994; Loke, 1990) but this was not observed in the divided attention study. A possible explanation for this might be the habitual caffeine consumption of 499 mg per day ($SD = 137$ mg) for the participants in the present study. Since they were used to higher doses than average of caffeine, the level at which performance usually starts to deteriorate might be shifted for our participants, and not be reached by a dose of 7.5 mg/kg body weight. Thus, for the pre-selected participants in the dual-task study, more caffeine seemed better.

In conclusion, one might say that the effects of caffeine that have been studied in this thesis in general seem to be beneficial to information processing and task performance. Although the ERP results confirm this conclusion, the beneficial effects of caffeine were not always visible in the behavioural results. This might be related to other factors such as task requirements, the state of the participants, or the more subtle nature of certain effects that may therefore be more difficult to observe. The effects of caffeine intake seem to be flexible and not restricted to specific attention conditions. However, caffeine does seem to influence certain information processing stages, such as the perceptual- and output processes, more than others. The human information processing system is a dynamic and highly complex system. Based on the results in the present studies, the conclusion might be drawn that the extra energy that becomes available by caffeine intake can affect many different processes. However, it mainly seems to be implemented there where it is most needed or most useful, which may be one of the reasons why coffee continues to be such a popular drink.

Remarks

A couple of remarks will be made in this section concerning the generalisation of results of this type of (drug) research, and those of the studies in this thesis in particular. The first remark concerns the group of participants that was studied in the experiments. The groups were selected by meeting certain including and excluding criteria, to minimise the possible range of responses and thereby increasing the possibility of finding treatment effects (see also Chapter 1). However, at the same time, these selection criteria limit the generalisation of the findings to the general population. For example, nicotine speeds up the clearance rate of caffeine, while taking the birth-control pill, certain types of asthma drugs or some heart and ulcer drugs, and pregnancy delay the clearance of caffeine (Arnaud, 1993; Dicum & Luttinger, 1999; Sawynok &
Yaksh, 1993). In addition, the effects of caffeine also seem to depend on the amount of caffeine a person is used to (Jarvis, 1993; Kuznicki & Turner, 1985; Nehlig, Daval & Debry, 1992; Snyder, 1981). These are just a few variables that can be readily found in the general population but have been excluded or restricted for the studies in this thesis. It is impossible to say how these variables could have influenced the effects of caffeine that were found in the present studies.

The amount of caffeine used in the present experiments: 250 mg in three studies and 1, 3 and 7.5 mg/kg body weight in another study, is a topic that should also be taken into account. The dose of 250 mg was chosen because it represents a habitual amount of caffeine for the regular coffee drinkers in our studies, and thus may be representative for the effects of moderate caffeine consumption in the general population. The results of the study in which different doses of caffeine were used indicate that the effects of caffeine are highly dependent upon the amount of caffeine consumed. This should be taken into account in the interpretation of caffeine effects. Results obtained using a specific caffeine amount cannot be generalised without limitations. Using multiple doses of caffeine, as in the dual-task study, may definitely improve the reliability of generalising the results beyond the doses that were used. It has been shown that multiple doses of caffeine should be used more often, if a carefully designed and well-established paradigm is available.

A third remark is that for this thesis, the researchers were interested in the average effects of caffeine. That is, all results and conclusions are based on the averaged results over all participants. However, that does not necessarily mean that indeed all individual participants showed this particular effect. In the present studies, where participants were selected to form a homogenous group, there were participants who displayed so called "paradoxical effects" in comparison to the average effect (for example, slower responses instead of average faster responses). Even though this has been found before (e.g. Lorist, Snel and Kok, 1994), the reason for this remains unclear up till now. A possible explanation could be that the observed effects of caffeine are more state dependent than we presumed up till now. For example, hyperactive children sometimes seem to benefit from caffeine intake, in that they are better able to focus (Harvey & Marsh, 1978; Reichard & Elder, 1977). Also, people seem to drink coffee to relax, and as a social event in normal situations or in situations of stress or over-arousal (Cines & Rozin, 1982). Furthermore, high doses of caffeine have been known to induce sleepiness in rats (Jaffe, 1975), and humans (Regestein, 1989) emphasising that caffeine intake can display paradoxical effects. Three possible explanations were given for these sleep inducing effects of caffeine: the nocturnal withdrawal of caffeine, a direct sedative action of caffeine as has been reported for small doses (Snyder, 1981) or specific arousal characteristics as have been shown for amphetamine. Although questionnaires were used in the present studies to measure subjective mood aspects like anxiety, anger, vigour and fatigue, a possible feeling of under-arousal or over-arousal is difficult to reveal. The point is that besides being careful with generalisation of the
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results, one should also be careful not to individualise the general results from these and other studies.

**Future research**

Several leads for future research emerge from the studies described in this thesis. According to this author, the main point of interest for future research should be the larger amplitude of the frontal exogenous P2 effect by caffeine that was found in all the studies of this thesis. It would be interesting to definitely locate this effect in the brain and to know whether this effect is indeed an indicator for the activity of the frontal control mechanisms, or that it merely displays the general arousal increase by caffeine. One way to study this would be by a combination of measurement tools. Combining ERPs and fMRI (functional magnetic resonance imaging), a method that produces anatomical maps indicating the active brain areas, could provide information about the active brain area in the time frame of interest: 200 milliseconds after stimulus presentation. It could also be examined whether this effect also appears in tasks of other modalities, such as the auditory modality.

Another point of interest would be to try to find out how robust the effects of caffeine that were found in this thesis really are. To examine this, a within-subjects research design could be used in which every participant is tested three times: once in a placebo condition (coffee without caffeine) and twice in a caffeine condition, in which the same fixed amount of caffeine is used. To the best knowledge of the author this has not been done before. Also, one should try to keep all independent variables as fixed as possible and present the participants with a more extensive and detailed range of questionnaires to be able to check on differences in subjective feelings between sessions. The possibility that an additional variable is responsible for the observed effects should be studied as extensive as possible. The main question of course will be whether the effects of caffeine, as observed with behavioural and ERP measures, are similar or if they differ between the two caffeine conditions, and if so, to what extent. If the effects of caffeine would significantly differ in the two caffeine conditions, that could mean that the human information processing system is extremely flexible and even reacts to the smallest uncontrollable changes in variables. On the other hand, if the effects would be similar, it would be an indication that patterns of results can be replicated, and that it should be possible to formulate some general rules concerning the effects of caffeine, given that all the predetermined variables are comparable enough among studies. Extending this topic even further, it would be interesting to add a fourth condition to examine the expectancy effects of drinking coffee: a baseline condition, without association to coffee drinking, could be added. This has been done before by Keister and McLaughlin (1972) who did not find any differences in performance on a vigilance task between a no-drug group and a placebo group. However, by using
different groups for these conditions instead of a within subjects design, the absence of any effects may have been the result of a lack of power.

It seems clear now from the studies described in this thesis as well as from previous research that some of the effects of caffeine on human information processing seem pretty robust. However, other results seem to be less stable, for example, the increase of energy by caffeine seems to be implemented there where it is most needed. Laboratory research is very valuable to teach us about the fundamental effects of caffeine, but trying to generalise these findings to daily-life situations might be a problem because of the unpredictable influence of mediating variables in daily-life situations. Therefore, we should be very careful generalising laboratory findings to daily-life situations. Alternatively, it could be tried to study the daily-life situations in which coffee is enjoyed, instead of only using laboratory studies that are always an approximation of the normal situation. Doing field studies in addition to laboratory studies will help to increase the reliability of the results in that particular situation.