Does coffee make you reason smarter? The effect of caffeine on executive functioning and dual-process reasoning.

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Abstract

In a setup based on the Masicampo and Baumeister (2008) lemonade study, the effects of caffeine on dual-process reasoning were explored. Participants in this double-blind study were divided into a caffeine and a caffeine-free control group. Participants had to solve several classical dual-process paradigms. Participants in the caffeine group were expected to perform better on analytic reasoning trials. In a follow-up experiment participants were also given an unexpected implicit recollection task to see whether caffeine has an affect on conflict monitoring, an executive function underlying dual-process reasoning. Even though the paradigms being used proved to be appropriate for dual-process testing, no effects of caffeine on dual-process reasoning or on conflict monitoring were found.

Keywords: Dual-process reasoning, conflict monitoring, executive functions, caffeine

Literature

On average, people drink about 148 liters of coffee each year. Although reasons for drinking coffee vary between different people, an often recurring reason is a subjective feeling of better cognitive performance. For example, a student in the middle of an exam period or an employee with a high workload may think they will perform better after a couple cups of coffee. In our study, we found out whether or not dual-process reasoning is influenced by those cups and whether coffee is the elixir many people take it for.

Research in thinking and reasoning repeatedly concluded that human reasoning is supported by two distinctive systems and can be considered dual-process reasoning. Two very easy-to-use and neutral terms for these two Systems were proposed by Stanovich (1999) and Stanovich and West (2000), System 1 and System 2. System 1, which can be described as an instinctive System, that is formed by associative learning processes, works rapidly, parallel, and automatically, and is based on heuristic reasoning. System 2 on the other hand is capable of abstract hypothetical thinking. It requires more mental resources and works much slower. System 1 is believed to do the primary reasoning whereas System 2 has the ability to override, inhibit or correct the default responses produced by System 1. System 2's location in the brain has repeatedly been explored and one of its main locations is believed to be the prefrontal cortex (Goel, Buchel, Frith, & Dolan, 2000; Goel & Dolan, 2003; De Neys & Goel, 2011). Reasoning researchers increasingly believe that System 2 has a high inhibitory role and thus will be supported by the central executive System. For an extensive review on dual-process reasoning, see Evans (2008). In our current study, we looked at the effects of caffeine on these dual-process reasoning Systems.

In 2008, Masicampo and Baumeister found that the ingestion of sugar enhanced the reliance on System 2 reasoning. They tested whether more blood glucose is needed for the highly demanding System 2 processes than is needed for System 1. They found that when participants had to complete highly demanding tasks, which relied on executive functioning, their blood glucose levels dropped. Not enough glucose remained available after these tasks for System 2 to operate optimally. As a result, System 2's influence in subsequent tasks decreased. The low levels of glucose had a diminishing effect on dual-process reasoning tasks, which participants performed later on. When the blood glucose levels were restored by administering sugar-holding lemonade, System 2 regained functionality and performances on the dual-process tasks recovered to normal. The participants performed better in the dual-process reasoning tasks compared to the control group which was depleted but received sugar-free lemonade and the control group which was not depleted in the first place. Pocheptsova, Amir, Dhar, and Baumeister (2009) found that depleting participants of their limited resource of glucose by giving them self-regulating tasks, influences their performance on reasoning tasks afterwards. The resource depletion decreased the ability to rely on effortful and deliberative reasoning. After the System 2 performance decline, only the System 1 automatic and intuitive processes remain available for the participant to rely on. From these studies we can conclude that glucose is necessary for optimal System 2 reasoning performance. Gailliot and Baumeister (2007) explained that not all psychological processes, such as System 1 and System 2 reasoning, have the same high energy requirements. More specifically, the rational and intelligent decision making of System 2 requires more energy and thus more glucose. This is in contrast to the automatic information processing of System 1, which still needs energy, but only in low quantities. In our current research, we investigated whether the effects of caffeine on dual-process reasoning are comparable to the effects of glucose administration.

Experiment 1

In 1984, Nehlig, Lucignani, Kadekaro, Porrino, and Sokoloff studied the effects of acute administration of caffeine to certain brain regions of the rat. Even after the administration of small doses of caffeine (0.1 mg/kg and 1.0 mg/kg), they were able to find increased levels of glucose utilization in certain regions of the brain. When they increased caffeine dosages up to 10 mg/kg, caffeine produced a widespread increase in glucose utilization throughout the brain. An increase of 15% in the average rate for the whole brain was determined. These results imply that not only will the metabolism be able to extract more glucose from the blood; these elevated levels of glucose will also be used more effectively. When these results are linked to the results of Masicampo and Baumeister (2008), we would expect the increased glucose utilization caused by caffeine administration to result in improved System 2 reasoning and thus in better logical reasoning.

In their experiment, Masicampo and Baumeister (2008) used the asymmetrical dominated alternative choice dilemma to test dual-process reasoning. Although this paradigm has proven to be an adequate method to test dual-process reasoning, it is used only occasionally in the field. Paradigms that are more straightforward to the dual-process framework by producing a clear distinction between analytic and heuristic reasoning might be more adequate. Therefore, in our experiment we not only used the alternative choice dilemma used by Masicampo and Baumeister (2008), we also used several more widely accepted testing paradigms, complemented by another less known paradigm.

First of all, we included the probably most commonly used dual-process reasoning paradigm: syllogisms with content. Evans, Barston, and Pollard (1983) initially introduced syllogisms into the dual-process literature. Evans et al. argued that syllogisms create a conflict between two different responses, produced by, respectively, System 1 and System 2.

We also used the Wason selection task. We included two versions: one abstract indicative version and one more realistic and heuristic problem (Johnson-Laird and Tagart, 1969; Griggs and Cox, 1982) .

A third task used in this study was originally developed by Huber, Payne, and Pluto (1982), the asymmetrical dominated alternative choice dilemma. In this task participants are faced with a decision between two options with several relevant dimensions on each option given and a third option, which is added as a decoy. The decoy option resembles one of the two other options, but is inferior to it in on all relevant dimensions. Studies show how participants do not choose the decoy option, but favor the option lying closest to a decoy option, which is called the attraction effect. Dhar and Simonson (2003) explained this phenomenon by postulating that the attraction effect is mainly based on the intuitive and perceptual System 1 processes, excluding the logical System 2.

Another type of task used in our study is the classical base-rate neglect problems, introduced by Kahneman and Tversky (1973). Participants are confronted with two statements made about a person in a description and are asked to pick to one that is most likely according to the description. Participants should give their answers based on a mentioned sample distribution, but instead they often choose their answers based on the heuristic beliefs cued by the short description. They intentionally ignore the normative System 2 response and rely on the heuristic System 1 resolution.

Tversky and Kahneman (1983) also developed the conjunction fallacy task. A conjunction fallacy task gives a description of a person, followed by three statements about that person. It is the participant's task to order these three statements based on their probability. The theoretical rule behind this type of problem is that the probability of a conjunction of two items can never be greater than the probabilities of its constituents. We used both the famous Linda problem and the Bill problem, translated into Dutch.

Finally, a relatively new task was used to research the dual-process framework. In 2009, Gillard, Van Dooren, Schaeken, and Verschaffel used simple proportional and non-proportional denominator neglect problems. They declared that proportional mathematical reasoning is the result of System 1 heuristic reasoning. They believe that non-proportional mathematical reasoning is the result of System 2 reasoning. Therefore, errors are made on non-proportional problems as a result of System 1 interfering and solving the problems proportionally.

In the present study, we looked at the effects of caffeine on dual-process reasoning performance. Using several commonly accepted dual-process reasoning paradigms, we first looked at the general distinction between analytic and heuristic trials. We expected to find a main effect for the analytic-heuristic distinction. We expected to replicate the general findings of the literature that accuracy is the highest when the analytic and the heuristic response are in correspondence to each other but lower when they are in conflict. Next, we looked at the effects of caffeine and the interaction of caffeine with the analytic-heuristic distinction.

We expected to find a significant interaction between caffeine condition and the distinction between analytic and heuristic trials. More specifically, we predicted accuracy levels on the heuristic items to remain unchanged, and accuracy levels on the analytical items to increase as a result of caffeine intake. Finally, we also expected to find a main effect of task type, as a result of the different accuracy rates expected for each different task.

Method

Sixty-four University students (11 men and 53 women) took part in the experiment (*M* = 18.8, *SD* = .9). They received course credit for participation and they had low to moderate caffeine consumption habits (mean cups/day = .81, *SD* = .94). We did not use participants that consumed more than four cups daily avoid possible tolerance effects.

The study had two different conditions: an experimental caffeine condition and a placebo control condition. Participants were randomly divided into the two groups, with 29 participants in the experimental condition. The participants were told the study dealt with caffeine and reasoning. They all received a cup of decaffeinated coffee at the beginning of the session. 200 mg of caffeine was dissolved in the cups of the experimental group and all participants were allowed to add milk to their cup. Participants agreed to refrain from all caffeine consumption during the morning of the experiment. After drinking the coffee, participants completed several irrelevant tasks for 40 minutes, since that is the time it takes caffeine to get absorbed from the gastrointestinal tract and get distributed throughout all tissues of the bodies (Fredholm, Bättig, Holmen, Nehlig, and Zvartau, 1999). After the filler tasks, participants started on the seven different dual-process reasoning tasks. They began with eight syllogisms, followed by an abstract Wason selection task, three attraction effect tasks and a realistic Wason selection task. Next, they completed four base rate-neglect problems, two conjunction fallacy problems and finally two denominator neglect problems. The Departmental Ethical Committee approved all experimental procedures.

Results

The scores on the tasks are summarized in Table 1. Four of our tasks had a clear distinction between problems that could be solved heuristically and problems that had to be solved analytically. These were Wason selection tasks, syllogisms, base-rate neglect tasks and the denominator neglect problems. For the analysis, we used a repeated measures analysis of variance design. We created a 2 (caffeine vs. placebo) by 2 (analytic vs. heuristic) by 4 design (task type). The analyses for the attraction effect and the conjunction fallacy problems were done separately.

For the first four tasks, a significant difference was found between analytic versus heuristic trials, $F(1, 1) = 225.29$, $MSE = 30.70$, $p < .001$. We were able to replicate the classical dual-process reasoning experiments. This means that accuracy on items that could be solved correctly using heuristics was higher than for items that had to be solved analytically. We also found a significant main effect for the four different tasks, $F(1, 3) = 18.82$, $MSE = 2.33$, $p < .001$. This means there is a significant difference in the results for the different tasks. This is as we would expect, based on the different accuracy rates on the different tasks found in previous research. We expected, for example, that accuracy rates for the denominator neglect problems would be much higher than for the Wason selection tasks. We did not find a main effect of caffeine condition ($F(1, 1) = .06$, $MSE = .00$). This implies that there is no difference in dual process reasoning between participants who took in caffeine before testing and those who did not. The interaction between caffeine condition and the distinction analytic-heuristic, which was the subject of our main research question, was not significant. This means that accuracies on the analytical and heuristic items were independent of the caffeine condition. ($F(1, 3) = .05$, $MSE = .01$). The interaction between caffeine conditions and task type was not significant either. We did find a significant interaction between the different types of task and the distinction between analytic and heuristic ($F(1, 3) = 4.78$, $MSE = .55$, $p = .003$). This is congruent with what can be found in literature and can be explained by the unequal input by System 1 and System 2 for the different tasks.

We did a separate analysis for the attraction effect. Here again we could not find an effect of caffeine condition on performance ($F(1, 1) = .17$, $MSE = .01$). We also could not find a main effect of caffeine condition for the conjunction fallacy task ($F(1, 1) = .52$, $MSE = .04$).

Discussion

From our results, we conclude that there are no effects of caffeine on dual-process reasoning. When looked at the results more closely, we found a clear distinction between the analytic and heuristic items. This means that the used experimental paradigms were appropriate to test dual-process reasoning. For each separate paradigm results were in agreement with existing literature. In every paradigm, accuracy was highest when the heuristic response was in accordance with the logical response and lowest when they were in contrast. If anything, we found even lower accuracy rates for the items that required analytic reasoning compared to the ones found in previous research. Accuracy for the analytic version of the Wason selection task was no higher than 9 percent. The non-proportional word problems had accuracy rates up to 40 percent, while original literature predicted accuracy rates up to 68 percent. Yet, the administered amount of caffeine did not elicit improved accuracy for the analytic responses compared to the placebo condition.

Experiment 2

From an executive functioning perspective, dual-process processing is assumed to be based on three executive functions. First of all, Sloman (1996) and Epstein (1994) assume a process of conflict monitoring is at work during dual-process reasoning. The central executive is triggered when a conflict arises between a System 1 and a System 2 response. A second executive function that seems necessary for good dual-process reasoning is response inhibition (De Neys & Everaerts 2008). Once a conflict between System 1 and System 2 is detected, our central executive is supposed to inhibit the System 1 response. For a participant with a properly working central executive system, dual-process reasoning is assumed to follow a pattern. When the participant is confronted with a dual-process task, the central executive will get triggered because of a conflict between the System 1 and System 2 response. Next, the inhibition function will suppress the System 1 response. As a result, the System 2 response will have a clear pathway and the participant will report this System 2 response. Thirdly, working memory capacities have been repeatedly linked to System 2 reasoning, where individual differences in capacities predict differences in dual-process reasoning (Handley, Capon, Beveridge, Dennis, & Evans, 2004; Stanovich, 1999).

The effects of caffeine on numerous executive functions have been studied. We will only discuss those executive functions that are relevant for dual-process reasoning. Caffeine does not appear to have the same effect on all executive functions relevant to System 2 reasoning. In one study, Tieges, Ridderinkhof, Snel, and Kok (2004) showed how caffeine improves the action of conflict monitoring. Tieges, Snel, Kok, and Ridderinkhof (2009) indicated how response inhibition was not influenced by caffeine. Working memory was also not affected by caffeine, as shown in a study by Smith, Clark, and Gallagher (1999).

The work of De Neys and colleagues can bring more clarity on the matter. Based on the interplay between these executive functions and caffeine, some conclusions can be made. In an fMRI-study, De Neys, Vartanian, and Goel (2008) showed that the conflict monitoring area in the brain is always activated when the participant is confronted with a conflict between a System 1 and a System 2 response. This activation was present even when the participant reasoned according to System 1. The inhibition area, on the other hand, was activated mainly when the participant's response was based on logic and the stereotypical response was avoided. Another study by De Neys and Franssens (2009), indicated that a failure to produce a logical response is not the consequence of a failing conflict monitoring System. These erroneous answers result from a failure to complete the inhibition of the System 1 response, even when the conflict is noticed by the central executive in the first place. This annotation by De Neys and colleagues could be a possible explanation as to why we did not find an effect of caffeine on dual-process reasoning tasks. It is possible that the only effect caffeine had, was on conflict monitoring. It is likely that caffeine lead to even more brain-activation at the conflict-monitoring level, but the caffeine did not stimulate the inhibition in the same way. As a result, the participants were not able to bring out the System 2 response, making them stay with the default System 1 response.

Our hypothesis for the second experiment is that with implicit measurement, we will find a positive effect of caffeine on conflict monitoring. With the knowledge of De Neys and colleagues and their implicit measurements and tasks used in the previous research, we made a test battery including explicit dual-process tasks and an unannounced implicit recollection task. For the recollection tasks we were not as much interested in the exact remembered numbers, as we were in the ratios of the remembered numbers. We hypothesize that when the conflict monitoring in used in a conflicting item, participants would implicitly direct more focus on the ratios in the stimuli. This unconscious focus would lead to a deeper processing and consequently a better recollection for the conflict items, compared to the non-conflict control items. We hypothesize that under the influence of caffeine, the conflict monitoring is stimulated, which would lead to a better recollection of the rates of conflict items.

Method

Fifty-three students (9 men and 44 women) took part in the experiment (M = 19.96). All participants had low to moderate caffeine consumption habits with an average of no more than two cups of coffee a day.

The experiment procedure was equal to Experiment 1 but the test-battery was reduced. The experiment can be roughly divided in two parts, the explicit reasoning part and the implicit recollection part. Participants completed a denominator neglect problem and a base-rate neglect problem. After these two task, we presented the participants with an unannounced recollection task. Participants were asked to recollect the ratios of the presented denominator neglect items and the base-rates for the base-rate neglect task. The denominator neglect problems were slightly altered to make them suitable for a recollection task. In the figures for the different items the dots were changed to small figures like flowers or clocks (see Figure 1). We also used different colors in each items. This allowed us to differentiate between the items easier and allowed the participants to better remember each item separately.

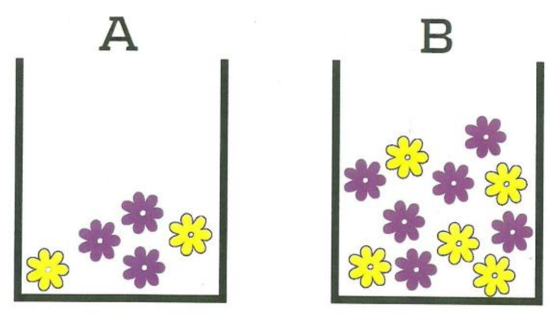

Figure 1. Example of a stimuli in the denominator neglect problem.

Results

The data from four participants was deleted due to bad performance on the control items. This resulted in a total of

53 participants, 26 in the non-caffeine group and 27 participants in the caffeine group.

For this statistical analyses, The Mann-Whitney U test, a non-parametric test for the comparison of a (semi-) continuously variable between two independent groups, was used.

For the denominator neglect problems, we didn't find any significant differences in correctness between the congruent and incongruent items. In a within group comparison, none of both item-types was significantly solved better than the other. There were not more or less errors made on the incongruent items compared to the congruent items in the whole group. 90,57% of the congruent items and 83,96% of the incongruent items was solved correctly. The results does not show any statistical differences between analytic or heuristic items you would expect in a reasoning task to test the dual process theory, which is in contrast to Experiment 1. In a between group comparison, where we compare the results of the caffeine group against the non-caffeine group. The effect of caffeine did not provide any significant enhancements on the performance on the task, not even on the conflicting, incongruent items.

For the base-rate neglect problems, accuracy was highest on congruent (100%) and neutral analytic (100%) problems, the lowest on the incongruent items (only 54% correct) with the neutral heuristic problems (90,56%) somewhere in between. Only about 46% of the incongruent items were solved heuristically, which is much lower than what Kahneman and Tversky (1974) published. However, this number is still significantly different from all the other item-types.

The sum of the correctly solved items is distributed significantly different between the two caffeine conditions. Whereas the caffeine group solves about 80% of the items correctly, the non-caffeine group manages this in only 71% of the items. An in-between group comparison on the incongruent items reveals an important significant effect. Incongruent conflicting items are answered significantly better than non-conflicting items (U= 243.0, z= -1.79, p= 0.04). The caffeine group performed better on the incongruent items and solved almost 12% more items correctly compared to the non-caffeine group. This observation is again in contrast to the results from Experiment 1.

For the recollection part of the denominator neglect problem, we compared the ratios given by the participants against the actual ratios of the stimuli. We found a significant effect between the congruent and incongruent items ($t(51) = 422$; p= .02). It seems that the recollection of incongruent items was much better than the recollection of the congruent items. There was however no difference in recollection between the two caffeine groups.

A vast majority (68.5%) of recollected base-rates were exactly the ones that were presented in the task. There were no significant differences between the different item types. Performance on all the different items, congruent and incongruent, was equal. This is in contrast to the results from the works of De Neys and colleagues. There was however a marginal difference between the two caffeine groups (U= 284.5, n1= 27, n2= 26, Z= 1.5726, p= .0579). Participants that had consumed caffeine were barely better at recollecting the base rates of the incongruent items.

Discussion

The results from the second experiment were mixed. First of all, we were not able to replicate the explicit results for the denominator neglect problems. There was a significant effect of item in the implicit recollection task afterwards. The main idea in De Neys and Glumicic (2007) of the presentation of an implicit recollection task is that when people successfully detect a conflict within an item they must have incorporated the analytical information as well as the heuristic. This extra processing time leads to a better imprinting of the information and eventually to a better recollection. Even though participants were equally good in answering the explicit items, it seems that more effort was put into the conflict items and conflict monitoring was stimulated, which led to a better recollection afterwards. No effects of caffeine were found in these tasks though.

Several reasons for the lack of a main effect of caffeine in the denominator neglect problems can be argued. One on the reasons that seems obvious, is the task alterations. The task features were altered to make the task suitable for a implicit recollection task. We also wanted to make this task as similar as possible to the base-rate neglect task. The test battery from Experiment 1 was very divers which made task comparison very hard. It is possible that these task alterations made the task just too different from the original to replicate the results.

Another possible explanation for the lack of an effect could be the number of items that were presented. Only two incongruent and two congruent items were presented. However, increasing the number of items would be disastrous for the recollection task. For each item, four values had to be recollected. This gives a total of 16 values to remember, which in our opinion was sufficient enough to remember implicitly. Increasing the number of items would only lead to very limited recollection.

The base-rate neglect worked better. Performance on conflict items was more heuristic than on the non-conflict items and caffeine administration reduced this effect. This finding confirms the hypothesis that caffeine strengthens conflict monitoring. But this difference in performances does not continue in the implicit part of the experiment. Participants did not recollect the base-rates of the incongruent items more accurately. This is against our expectations and a opposition to the work done by De Neys and colleagues. Again, caffeine had no clear effect on the recollection task.

General discussion

In sum, we did not find a clear effect of caffeine on dual-process reasoning, nor on the executive function of conflict monitoring. Even though we did find an effect in the base-rate neglect task of the second experiment, this result needs to be interpreted with caution due to the deviation of performance on this task to previous research. However, this effect and the marginally significant effect on the implicit part give enough reason to further explore the area of research. It would also be interesting for further research to look at the effect of depletion before the administration of caffeine, congruent to Masicampo and Baumeister (2008). Still, it seems that all those daily cups of coffee consumed by millions of people worldwide do not make them reason exceptionally better and that caffeine is not the elixir many people take it for.

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