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Feeling smart: Effects of caffeine and glucose on cognition, mood and self-judgment

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HIGHLIGHTS

- Caffeine and glucose affect cognitive performance like placebo, water or no treatment controls in a multi-task setting.
- Participants feel preserved mental energy after caffeine and, by trend, coffee placebo consumption throughout a 2-h test.
- These subjective effects were stronger after 24 h caffeine abstinence.

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ABSTRACT

During education and early career, young adults often face examinations and assessment centers. Coffee and energy drinks are convenient and commonly used to enhance or maintain performance in these situations. Whether these macronutrients improve performance in a demanding and drawn-out multi-task situation is not clear. Using double-blind, placebo-controlled studies, we set out to examine the effects of caffeine and glucose in an assessment center-like situation, under natural consumption conditions, in a group of young adults who were heterogeneous with respect to consumption patterns. We measured multi-task performance including logical thinking, processing speed, numeric and verbal memory, attention and the ability to concentrate, and mood over a two-hour period. Caffeine and glucose were administered in common beverages with appropriate placebo controls allowing the assessment of psychological effects of expectancy. Importantly, and in contrast to most previous studies, participants retained their habitual caffeine and sugar intake (studies 1 and 2) as this represents common behavior. Based on the bulk of literature, we hypothesized that (i) caffeine enhances attentional performance and mood, while performance in more complex tasks will remain unchanged, and that (ii) glucose enhances performance on memory tasks accompanied with negative mood. Our results provide evidence that neither caffeine nor glucose significantly influence cognitive performance when compared with placebo, water, or no treatment controls in a multi-task setting. Yet, caffeine and, by trend, placebo improve dispositions such that participants perceive preserved mental energy throughout the test procedure. These subjective effects were stronger after 24 h caffeine abstinence (study 3). Future studies will have to address whether these mood changes actually result in increased motivation during a challenging task.

1. Introduction

How do students make sure they keep their performance at a high level during a long and demanding exam? Some swear by the "awakening effect" of coffee, others seek "food for the brain" by eating something sweet. For many people glucose and/or caffeine are essential and enjoyable aspects of everyday life. However, can these nutrients really enhance cognitive performance? Or do they just have psychological effects? Or is there no effect at all?

Caffeine (1,3,7-trimethylxanthine) is the world's most consumed psychostimulant. It is contained in coffee, tea, energy drinks, and several soft drinks. After oral consumption, caffeine is quickly absorbed in the gastrointestinal tract and the highest blood concentrations are reached after 30–60 min. The half-life time of caffeine in the human body amounts to 3 to 3.5 h on average, but shows high inter-individual

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variation [1]. Similar caffeine concentrations have been found in the blood and in the cerebrospinal fluid, indicating that the blood brain barrier is no obstacle for caffeine [2]. Physiologically, caffeine impedes the binding of adenosine to its receptors in the cell membranes [3], and thus causes a mild dilation of blood vessels and increases in blood pressure, metabolic rate, and urine production [4]. Augmenting effects include increased alertness and reduced fatigue, leading to better performance especially in simple psychomotor tasks demanding fast reactions [5,6]. Transferred to real-life situations, caffeine has been shown to improve, for example, steering accuracy, and reduces the number of incidents in a driving simulator [7,8]. However, for more complex and cognitively demanding tasks, the effects of caffeine appear inconsistent and reports of increased performance in demanding tasks [9] coexist with null findings [10]. It has been suggested that inconsistent effects under high cognitive loads are caused by interactions between baseline arousal state, dose and inter-individual differences (see [11]). For example, moderate doses of caffeine to rested individuals have led to heightened vigilance and faster reaction times while cognitive functions such as memory or learning were unaffected [6]. In contrast, fatigued and exhausted participants showed improvement in working memory after caffeine compared to placebo administration, although the effects were likely attributable to the restored ability to sustain attention during the task rather than to direct improvement in working memory [12]. Subjective effects of caffeine also include increased feelings of wellbeing, mental energy, motivation, and self-confidence [13–15]. According to the withdrawal reversal hypothesis, such benefits for subjective experience and mood merely reflect the restoration to normal levels thereby compensating the detrimental effects of caffeine withdrawal in regular consumers (see [16]). Together, diverse and partly inconsistent findings render a comprehensive view on the beneficial effects of caffeine difficult. Particularly, the use of specific tasks and target groups, e.g. high vs. non-caffeine consumers, places limits on generalization.

The carbohydrate glucose can be found in many of our comestibles, especially sweet ones. Glucose is the major source of energy for the human brain; it is essential for the normal functioning of the central nervous system [17]. The brain relies on a constant blood glucose level, since its energy storage is very small. Although all brain functions are primarily dependent on the availability of glucose, it has been found that especially effortful, controlled, and executive processes are in need of a sufficient supply with glucose [18–20]. When measuring cognitive performance, glucose has been shown to improve attention, speed of processing, and working memory [21–23], for example in solving maze problems, or verbal fluency [18]. However, the most consistent effects of glucose on cognitive functioning have been found for the facilitation of declarative memory [24,25] leading to the hypothesis that the hippocampus plays an important role in the pathway through which glucose acts on cognitive functions in the brain [25]. Also affective mood changes correlated with blood glucose levels [26]. Especially perceived mental energy is reduced as blood glucose levels decrease [27], and elevated when the glucose metabolism in the brain is higher as well [28]. Furthermore, after performing a Stroop task for 30 min, a faster decrease of glucose levels in the blood led to increased ratings of sadness [29]. The existing bulk of studies suggests only a brief time window for beneficial effects of glucose to occur. This is surprising, as, in healthy individuals, plasma glucose concentrations peak within 60 min after glucose ingestion and return to baseline levels only within 2–3 h [30]. Therefore, it remains difficult to infer about glucose effects in multi-task settings that require sustained performance.

During education and early career, young adults face situations that require various cognitive functions, like examination and assessment centers. Coffee and sweetened energy drinks are convenient and popular means to supposedly enhance performance in these situations. The potency of caffeine and glucose to exhibit effects on performance and mood in young adults was investigated with the present series of three studies.

In the first study, we examined the effects of caffeine and glucose in a multi-task setting on a range of cognitive tasks and mood in healthy young individuals. Caffeine and glucose were administered in common beverages with appropriate placebo controls to control for the psychological effects of expectancy, which have been neglected surprisingly often [31]. We hypothesized that (i) caffeine improves attentional performance and mood, while performance in more complex tasks will not be improved, and that (ii) glucose enhances performance on memory tasks, potentially accompanied with negative mood.

Whether the findings of the present study can be explained by a placebo effect (i.e., a psychological effect) or the lack of dietary restraints for the active ingredients, was addressed in studies 2 and 3, respectively. In study 2, we asked whether a placebo treatment compared to plain water is sufficient to enhance mood and/or performance due to psychological expectation-based effects as about the enhancing or activating properties of coffee and energy drink. In study 3, we asked whether (i) caffeine effects occur after a 24-hour caffeine withdrawal and (ii) we compared placebo to no treatment to rule out effects of hydration.

2. Materials and methods

2.1. Ethics Statement

The experimental protocol conformed to the World Medical Association's (WMA) revised Declaration of Helsinki [32] and was approved by the ethics committee of the German Psychological Society (KO-062012). Participants gave their written informed consent prior to participation and received a monetary compensation.

2.2. Study 1

2.2.1. Participants

Healthy male adults were recruited through bulletins at local universities and public places. We recruited only men to avoid confounding interactions of caffeine metabolism with reproductive hormones that vary across the female cycle [33,34]. Seventeen normal weight (body mass index [BMI]: mean = 23.8, $SD = 3$) men aged 19–40 years (mean = 28.5, $SD = 4.4$) completed the study. Participants reported to be healthy. Their quotidian consumption of caffeine and sugary drinks was assessed based on the daily intake of coffee, tea, coke, and energy drinks, and the intake of juice, soda and other sweet drinks, respectively (Table 1). Importantly, participants were allowed to consume their regular amounts of caffeine or glucose up to 2 h prior to testing thereby maintaining their habitual intake behavior and thus avoiding withdrawal symptoms. Then, participants were instructed to refrain from eating and drinking anything but water.

2.2.2. Design and procedure

The effects of caffeine and glucose on cognitive performance and subjective mood were tested in a double-blind, balanced, placebo-controlled within-subjects design. For this, participants received two drinks labeled “coffee” and “energy drink” at the same time. Two versions, one containing an active ingredient (caffeine or glucose) and one without the active ingredient (placebo), were prepared for each drink. Participants were naïve as to the different compositions and unable to discriminate the active and placebo conditions, as we had asked them after completion of the study whether they had noticed any differences in taste or flavor between the respective drinks, which was never the case. These findings are in line with a pilot study (N = 5). The composition of the two drinks differed across treatment conditions as follows: (1) the CAFFEINE treatment consisted of a decaffeinated coffee with added caffeine and an artificially sweetened placebo drink; (2) for the GLUCOSE treatment, a decaffeinated placebo coffee and a glucose drink were administered; (3) in the PLACEBO condition, subjects received a decaffeinated coffee and an artificially sweetened drink. All beverages were based on distilled water. The PLACEBO coffee was prepared using 2 g of decaffeinated instant coffee powder

(Nescafe®, Nestlé, Switzerland) dissolved in 150 ml hot water. The CAFFEINE treatment was created by adding 200 mg caffeine (Sigma Aldrich) to the PLACEBO coffee. The “energy drink” contained 10 ml pure lemon juice (from a local supermarket) in 150 ml water and either 2.25 g artificial sweetener (sucralose, Splenda®, McNeil Nutritionals Ltd., USA) for the PLACEBO version, or 25 g glucose (Sigma Aldrich) for the GLUCOSE condition. Importantly, the main ingredient of the artificial sweetener used to design the placebo, sucralose, does not influence glucose homeostasis [35,36]. In a pilot study ($n = 5$), the two variants of coffee and energy drinks were matched for their sweetness.

Participants were informed that the study investigates the effects of coffee and energy drinks on cognitive performance; they were debriefed after completion of the study. Participants attended three separate sessions that lasted about 2.5 h each and that were separated by at least a week. The sessions started at 9 a.m., 12.30 p.m., or 4 p.m.; subjects were asked to return for the following sessions at the same time. At the beginning of each session, participants rated hunger, motivation and aspects of mood, using 100 mm visual analog scales (VAS) with the anchors “not at all” and “very”. Fourteen aspects of mood were evaluated using adapted PANAS scales [37], including the concepts focused, energetic, happy, satisfied, calm, tired, depressed, lazy, sad, anxious, alert, nervous, and tense. In addition, participants rated how well they thought they would perform during the test (referred to as self-judgment) as a measure of a positive self-judgment bias. Positive biases, for example over-estimating one's degree of control and performance, have a protective function in healthy individuals [38,39]. Then, participants were asked to ingest two beverages, a coffee and an energy drink, within 5 min. During a supervised pause for 25 min to allow the active ingredients reach a significant blood concentration, participants could read magazines or use their cell phones. After that, a series of cognitive tests was performed for approximately 2 h (see below for test characteristics). After testing, participants reported their mood and self-judgment again using the same scales as before. Difference scores (post-minus pre-testing) were computed and used for statistical analyses as a measure of change in mood and self-judgment. To summarize ratings and increase statistical power, ratings of related concepts were pooled to achieve scores for *subjective activation* and *subjective affect* (adapted from [40]):

$$\text{Subjective activation} = [\text{alert} + \text{energetic} + 200 - (\text{tired} + \text{calm})]/4$$

$$\text{Subjective affect} = [\text{happy} + \text{satisfied} + 200 - (\text{sad} + \text{tense})]/4.$$

Table 1
Daily consumption of caffeinated and sugary drinks as well as smoking habits in all three studies.

	Study 1 $N = 17$	Study 2 $N = 18$	Study 3 $N = 20$
Caffeine consumption			
None	7	3	5
Rather low (1–2 units/day)	4	5	5
Moderate-high (3–4 units/day)	4	6	8
High (>5 units/day)	2	4	2
Consumption of sugary drinks			
None	7	5	11
Rather low (1–2 units/day)	6	9	5
Moderate-high (3–4 units/day)	3	2	3
High (> 5 units/day)	1	2	1
Smoking			
None	12	12	16
Light (up to 5 cigarettes/day)	1	1	0
Medium (5–10 cigarettes/day)	2	0	1
Heavy (>10 cigarettes/day)	2	5	3

Note: 1 unit consists of 200 ml.

2.2.3. Test battery

The tests used in this study were chosen to represent a wide and differential selection of cognitive functions, but also to approximate the demands of a real-life exam or an assessment center. In particular, the test battery included the following tests in the order presented in the experiment. *Logical reasoning* was tested using the BOMAT (Bochum matrices test [41]), which requires participants to select geometrical figures according to logical reasoning from a pattern of other geometrical figures in 5 × 3 matrices. After ten practice items, 29 test items had to be completed within 45 min. The outcome measure was the number of correct items. To measure the *speed of information processing*, including visual scanning ability and motor speed, a trail making test variant was conducted (ZVT — “Zahlenverbindungstest”, i.e. number connection test [42]). It requires participants to connect circled numbers from 1 to 90 in ascending order by drawing a line. Participants are asked to connect the numbers as fast as possible; the test score is the amount of connected numbers within 30 s. As a test of *working memory*, we used the Reverse Digit Span Test [43] during which participants were to recall and write down digits presented on a screen in reverse order. Task difficulty increased over time; initial test items consisted of three digits and increased to ten consecutive digits. Outcome variables were (i) the longest number of correctly repeated digits overall (“BackSpan highest”) and (ii) the longest number of digits repeated correctly in a row without making any errors (“BackSpan traditional”). We also measured *verbal memory* capacity and precision with a False Memory Test (adapted from [44]). Subjects were acoustically presented with five sets of 15 words; each set contained words (e.g. apple, orange) belonging to a semantic category (i.e. fruits), which was not presented (critical lure). Participants were to freely recall and write down as many words as possible in 5 min. The outcome measures were (i) the number of correctly recalled words, and (ii) the number of (falsely) recalled critical lures. After the free recall, subjects performed a recognition test on a form which listed some of the words that had been presented in the audio file, as well as the five critical lures and some distractors. Subjects had to fill in whether they remembered the respective word having been presented and whether this was a conscious memory or not. The outcome measure of the word list was the amount of falsely recalled critical lures which were consciously remembered (“Consc. false memory”). *Attention* and the *ability to concentrate* were assessed with the Frankfurter Attention Inventory (FAIR-2) [45]. Here, participants had to accurately and quickly discriminate similar graphical symbols while ignoring irrelevant information. Within 6 min, as many target items as possible had to be discriminated from distractor items by connecting the target items with a line. The FAIR measures (i) performance (“FAIR-L”, the total number of correctly evaluated items), (ii) quality (“FAIR-Q”, the relative ratio of correctly evaluated items to all attended), and (iii) continuity of performance (“FAIR-K”, the mathematical product of Q and L).

Test performance and subjective rating changes (difference scores post–pre) were submitted to separate pairwise Wilcoxon signed-rank tests comparing the placebo condition with the caffeine and glucose condition, respectively. Non-parametric tests were employed for all comparisons because for numerous variables variances were not homogeneous and/or data were not normally distributed as indicated by whisker box plots, Shapiro–Wilks and Mauchly tests. Effect sizes were estimated as $r = Z / \sqrt{N}$. Missing data (0.74%) were replaced by group mean values. The significance level was set a priori to 0.05 for all analyses. Analyses were performed with IBM SPSS 20 (IBM Corporation, Armonk, New York, USA).

2.3. Study 2

2.3.1. Participants

Eighteen healthy, normal weighted (mean BMI = 24.5, $SD = 5.4$) men aged 19–37 years (mean = 27.8, $SD = 5.3$) participated in the study. Table 1 summarizes their daily consumption of caffeinated and sugary beverages and smoking habits. Again, participants were allowed to follow their habitual caffeine and sugar consumption until 2 h prior to testing, during which only water was permitted.

2.3.2. Design and procedure

The effects of PLACEBO compared to WATER were tested in a balanced within-subjects design. During each of two testing sessions, participants received two beverages. In the PLACEBO condition, subjects received a decaffeinated coffee and an artificially sweetened drink labeled "coffee" and "energy drink", respectively. In the WATER condition, subjects received two cups of water. The preparation, procedure and the test battery were identical to those in study 1. Separate Wilcoxon signed-rank tests were used to compare test performance and rating changes (post–pre) between placebo and water treatments.

2.4. Study 3

2.4.1. Participants

Twenty healthy, normal weighted (mean BMI = 24.7, *SD* = 2.4) men aged 22–37 years (mean = 28, *SD* = 3.6) took part in study 3. Table 1 lists their smoking habits and daily consumption of caffeinated and sugary drinks. Notably, participants were asked to refrain from caffeine during 24 h prior to the experiment.

2.4.2. Design and procedure

The effects of CAFFEINE and coffee PLACEBO compared to NO treatment following 24 h caffeine withdrawal were tested in a balanced within-subjects design with a double-blind administration of CAFFEINE and PLACEBO. During each of three testing sessions, participants received CAFFEINE, PLACEBO, or NO treatment. The CAFFEINE treatment consisted of a caffeinated coffee, the PLACEBO treatment of a decaffeinated coffee and no beverage was provided for the NO treatment condition. The preparation, procedure and the test battery were identical to those in studies 1 and 2. Separate Wilcoxon signed-rank tests were used to compare test performance and rating changes (post–pre) following CAFFEINE and PLACEBO treatment to the NO treatment control condition.

3. Results and discussion

3.1. Study 1

3.1.1. Cognitive test battery

Cognitive performance was similar for CAFFEINE and PLACEBO as well as for GLUCOSE and PLACEBO treatment (all $p > 0.16$; see Table 2 for test results and statistics).

3.1.2. Subjective ratings

The changes in subjective ratings (post–pre-treatment) are summarized in Table 3 and significant findings are displayed in Fig. 1. The cumulated score of subjective *activity* showed a significantly higher activity level (or less reduction) after CAFFEINE consumption as compared to the respective PLACEBO treatment ($Z = -2.15$, $p = 0.03$, $r = -0.52$). More specifically, participants felt more *energetic* after CAFFEINE as compared to the PLACEBO consumption ($Z = 2.13$, $p = 0.033$, $r = -0.52$; Fig. 1). Furthermore, participants tended to judge their performance higher after CAFFEINE compared to PLACEBO ($Z = -1.8$, $p = 0.07$, $r = -0.44$). In contrast, changes in mood and self-judgment ratings were similar after GLUCOSE and PLACEBO consumption. Yet, trends toward increased sadness ($Z = -1.46$, $p = 0.15$, $r = -0.35$) or depression ($Z = -1.39$, $p = 0.16$, $r = -0.34$) were observed after GLUCOSE intake compared to PLACEBO intake.

3.1.3. Discussion

In study 1, we tested whether cognitive performance and mood were influenced by CAFFEINE or GLUCOSE ingestion compared to the ingestion of an apparently identical PLACEBO beverage (i.e. without any active ingredients). In contrast to previous studies (see for reviews [11] and [25]), we found that neither CAFFEINE nor GLUCOSE enhanced cognitive performance compared to PLACEBO.

Most previous studies reported caffeine-related improved performance in simple reaction time tasks [5,46] or attention tasks [21,47]. Accordingly, we had expected that enhanced attention, concentration as well as processing and reaction speed would manifest themselves in improved FAIR and ZVT scores after caffeine intake. We cannot exclude that the order of tests contributed to the null findings; the FAIR was the last test of the battery and cognitive capacities may have been depleted by then. It is also feasible that the rather arousing and demanding test situation, caused by the series of challenging tasks to be performed under time pressure, precluded potential beneficial effects of caffeine. It has been shown, in fact, that caffeine improves attention particularly in low arousal situations and in rather simple tasks [6]. Also, the intended mingling of habitual coffee drinkers and non-consumer in our study likely hampered the revelation of potentially diverging effects in regular and non-coffee drinkers. Albeit, the literature provides conflicting evidence about which consumers benefit most: reports of enhancing effects of caffeine in heavy coffee drinkers but not non-drinkers [5] coexist with reports of stronger beneficial effects in non-consumers than regular consumers [48,49].

GLUCOSE was expected to enhance memory performance [25] compared to PLACEBO, yet performance in the numeric memory and verbal memory tasks was unaffected in the present study. As plasma glucose concentrations peak 20–30 min after ingestion [50,51] and return to baseline levels within 2–3 h [30], it is plausible to assume that blood glucose levels were indeed elevated during the entire testing session. While we cannot exclude facilitated depletion of blood glucose due to

Table 2
Means ± *SD* of the outcome scores of the cognitive test battery in study 1 for the three treatment conditions, and significance testing using Wilcoxon signedrank tests for comparing the caffeine and the glucose condition to the placebo condition respectively.

	Placebo		Caffeine		Glucose		Wilcoxon signed-rank test Caffeine vs. Placebo			Wilcoxon signed-rank test Glucose vs. Placebo		
Test	Mean	*SD*	Mean	*SD*	Mean	*SD*	*Z*	*p*	*r*	*Z*	*p*	*r*
BOMAT	19.29	4.12	18.29	4.77	19.06	3.47	−0.88	0.38	−0.21	−0.31	0.75	−0.08
ZVT	51.06	9.74	48.82	10.61	48.47	10.74	−1.07	0.29	−0.26	−1.3	0.19	−0.32
BackSpan traditional	7.47	1.7	7.37	1.83	7.47	1.8	−0.36	0.72	−0.09	−0.37	0.71	−0.09
BackSpan highest	7.76	1.68	8.06	1.85	8.13	1.32	−0.62	0.54	−0.15	−1.24	0.21	−0.3
Free recall correct	28.82	9.59	29.65	8.19	29.18	7.54	−0.41	0.68	−0.1	−0.05	0.96	−0.01
Free recall lures	1.18	0.88	1.53	1.01	1.12	0.99	−1.11	0.27	−0.27	−0.16	0.87	−0.04
Consc. false memory	2.69	1.79	2.81	1.51	2.41	1.66	−0.68	0.5	−0.16	−0.53	0.6	−0.13
FAIR-L	485.12	101.36	459.3	97.6	472.63	94.26	−1.28	0.2	−0.31	−0.52	0.6	−0.13
FAIR-Q	0.95	0.06	0.95	0.04	0.93	0.07	−0.07	0.94	−0.02	−1.42	0.16	−0.34
FAIR-K	457.98	115.09	439.21	104.13	442.68	103.02	−0.69	0.49	−0.17	−0.73	0.46	−0.18

Note: for each test $N = 17$; the effect size is calculated as $r = Z / \sqrt{N}$.

Table 3
Means ± *SD* of the differences (post–pre) between the ratings and the combined subjective activation and affect scores in study 1 for the three treatment conditions, and significance testing using Wilcoxon signed-rank tests for comparing the caffeine and the glucose condition to the placebo condition respectively.

	Placebo		Caffeine		Glucose		Wilcoxon signed-rank test Caffeine vs. Placebo			Wilcoxon signed-rank test Glucose vs. Placebo		
Rating	Mean	*SD*	Mean	*SD*	Mean	*SD*	*Z*	*p*	*r*	*Z*	*p*	*r*
Self-judgment	−5.37	14.69	3.8	10.97	−13.25	13.41	−1.8	0.07	−0.44	−1.16	0.25	−0.28
Focused	−20	34.57	−14.59	31.95	−23	24.32	−1.02	0.31	−0.25	−0.02	0.98	−0.01
Tired	9.12	33.40	9.29	35.39	20.59	30.69	−0.28	0.78	−0.07	−0.69	0.49	−0.17
Sad	−2.06	10.98	−2.88	8.52	8.71	21.2	−0.32	0.75	−0.08	−1.46	0.15	−0.35
Satisfied	−10.47	17.78	−12.88	21.44	−12.76	25.09	−0.55	0.59	−0.13	−0.49	0.62	−0.12
Lazy	12.06	36.72	−0.24	29.89	−1.53	30.76	−1.49	0.14	−0.36	−1.24	0.22	−0.3
Calm	−7.82	30.26	−15.94	17.98	−14.41	25.1	−1.42	0.16	−0.34	−0.31	0.76	−0.07
Happy	−7.88	16.85	−1	20.89	−8.53	23.02	−1.03	0.3	−0.25	−0.41	0.68	−0.1
Anxious	−3.41	7.62	−6.12	15.77	−5.35	8.71	−0.42	0.67	−0.1	−1.28	0.2	−0.31
Alert	−22.53	39.31	−10.06	34.73	−31	25.77	−1.45	0.15	−0.35	−0.81	0.42	−0.2
Nervous	−2.47	17.79	−8.82	17.68	−7.59	27.81	−1.19	0.23	−0.29	−0.97	0.33	−0.23
Energetic	−18.41	31.98	−2.76	33.62	−19	30.86	−2.13	0.03	−0.52	−0.36	0.72	−0.09
Depressed	0.41	9.59	−1.29	8.47	8.41	20.86	−0.51	0.61	−0.12	−1.39	0.16	−0.34
Tense	−7.82	20.83	−2.88	26.81	4.53	23.94	−0.18	0.86	−0.04	−1.05	0.29	−0.26
Subjective activation [alert + energetic + 200 − (tired + calm)] / 4	−10.56	28.6	−1.54	26.53	−14.04	19.22	−2.15	0.03	−0.52	−0.28	0.78	−0.07
Subjective affect [happy + satisfied + 200 − (sad + tense)] / 4	−2.12	9.72	−2.03	12.59	−8.63	18.02	−0.07	0.94	−0.02	−1.16	0.25	−0.28

Note: for each test $N = 17$; the effect size is calculated as $r = Z / \sqrt{N}$.

the cognitive load [23], full depletion (i.e. a drop below the initial fasting level) is unlikely as it is associated with detrimental memory effects [52] which were not observed in the present study. Admittedly, we can only make assumptions about the blood glucose levels in the absence of a blood test, which should be employed in future studies. It seems also reasonable that the potential of glucose to enhance performance in young adults was limited, as age has been shown to be an influential factor [26] and older people benefit particularly from glucose treatments as their glucose regulation is frequently impaired [53,54].

At the mood level, participants preserved subjective feelings of energy and activity after CAFFEINE compared to PLACEBO treatment. Moreover, CAFFEINE, in contrast to PLACEBO, caused participants to judge their own performance higher. Such findings are in accord with caffeine-induced physiological arousal (for a review see [55]) and its potential misattribution to good performance and perceived energy [56,57]. Although caffeine consumption failed to improve cognitive performance, it made participants feel more energetic and even smarter. Thus, a cup of coffee may help to find the energy to get started with or to complete a task, albeit the outcome may be just the same as without coffee. Together, the findings corroborate the notion that caffeine does not enhance cognition per se [11] but it rather enhances vigilance and motivation [58,59].

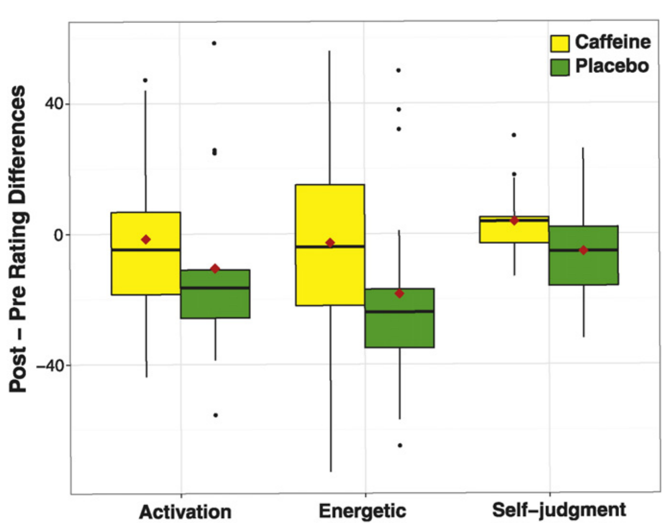

Fig. 1. Ratings of subjective activation, energy, and self-judgment in study 1. Significant differences between rating values (post-minus pre-test) are displayed as Tukey boxplots. Negative scores reflect a perceived loss of the respective trait over time, whereas positive scores indicate a gain. Subjective activation and energy were significantly higher (or less reduced) after CAFFEINE (yellow) compared to PLACEBO (green) treatment (all $p < 0.05$). Self-judgment ratings tended to be larger after CAFFEINE compared to PLACEBO as well ($p = 0.07$). The bottom and top of the box represent the first and third quartiles, respectively. The band inside the box indicates the median and the red diamond the mean. Whiskers are 1.5times the interquartile range.

For GLUCOSE, compared to PLACEBO, no significant effects on subjective mood or performance were observed. Yet, participants tended to feel sadder and more depressed after GLUCOSE compared to PLACEBO consumption. This observation is indicative of reduced levels of blood glucose after 2 h of cognitive performance (cf. [30]).

Together, CAFFEINE and GLUCOSE exhibited no significant effects on cognitive performance compared to PLACEBO. While reports of beneficial effects of glucose are mostly in older adults, the enhancing effects of caffeine have been repeatedly reported also in young adults. Whether the findings of the present study can be explained by a placebo effect (i.e., a psychological effect) or the lack of dietary restraints for the active ingredients was addressed in studies 2 and 3, respectively.

3.2. Study 2

3.2.1. Cognitive test battery

PLACEBO and WATER treatments exhibited no significant difference in cognitive performance (all $p > 0.09$; see Table 4). Interestingly, participants tended toward an increased false memory, i.e., they recalled more lures ($Z = -1.65$, $p = 0.1$, $r = -0.39$) and claimed more often that these memories were conscious ($Z = -1.69$, $p = 0.09$, $r = -0.4$) after PLACEBO compared to WATER consumption.

3.2.2. Subjective ratings

Similarly, changes in mood and self-judgment revealed no significant differences between PLACEBO and WATER (all $p > 0.08$; Table 5). Notably, participants tended to feel less calm ($Z = -1.75$, $p = 0.08$, $r = -0.41$) after consumption of the PLACEBO compared to WATER, and ratings of laziness remained stable after PLACEBO while they increased after WATER treatment ($Z = -1.72$, $p = 0.09$, $r = -0.41$).

Table 4
Means ± *SD* of the outcome scores of the cognitive test battery in study 2 for the two treatment conditions, and significance testing using the Wilcoxon signed-rank test.

	Placebo		Water		Wilcoxon signed-rank test Placebo vs. Water		
Test	Mean	*SD*	Mean	*SD*	*Z*	*p*	*r*
BOMAT	16.67	4.28	17.72	3.86	−1.02	0.31	−0.24
ZVT	49.50	9.48	50.22	11.05	−0.62	0.54	−0.15
BackSpan traditional	6.83	1.34	7	0.97	−0.55	0.58	−0.13
BackSpan highest	7.22	1.48	7.61	1.33	−1.07	0.28	−0.25
Free recall correct	27.94	9.40	28.06	9.4	−0.19	0.85	−0.04
Free recall lures	1.50	1.29	0.94	0.87	−1.65	0.1	−0.39
Consc. false memory	2.44	1.42	1.78	1.59	−1.69	0.09	−0.4
FAIR-L	429.61	77.67	439.5	74.93	−0.44	0.66	−0.1
FAIR-Q	0.95	0.03	0.96	0.02	−1.15	0.25	−0.27
FAIR-K	408.36	74.57	419.8	70.64	−0.5	0.62	−0.12

Note: for each test $N = 18$; the effect size is calculated as $r = Z / \sqrt{N}$.

3.2.3. Discussion

Placebo effects occur as the result of expectations about the effects of the alleged active ingredients, i.e., caffeine and sugar [60–62]. To examine whether the placebo treatment enhances cognitive performance and mood through mere psychological mechanisms we compared PLACEBO with WATER. We hypothesized that water elicits no expectations as of effects on cognitive performance and mood. Hence, a placebo effect would manifest in enhanced cognitive performance and/or mood following PLACEBO compared to WATER treatment. Our findings of similar cognitive performance and subjective mood ratings for PLACEBO and WATER allow two possible interpretations: the absence of a placebo effect or a placebo effect of a similar magnitude as the effect of hydration. The latter scenario is unlikely, despite observations that water consumption alone can affect cognitive performance [63,64], particularly in children [65] who are more susceptible to dehydration than adults, because participants in the present study consumed an equal amount of liquid (two cups) as PLACEBO and as WATER treatment. Also, participants were allowed to consume water ad

Table 5
Means ± *SD* of the differences (post–pre) between the ratings as well as the combined subjective activation and affect scores in study 2 for the two treatment conditions, and significance testing using the Wilcoxon signed-rank test.

	Placebo		Water		Wilcoxon signed-rank test Placebo vs. Water		
Rating	Mean	*SD*	Mean	*SD*	*Z*	*p*	*r*
Self-judgment	−10.67	24.36	−10.94	19.99	−0.35	0.73	−0.08
Focused	−7.56	21.53	−12.5	22.43	−0.61	0.54	−0.14
Tired	7.83	25.67	11.17	26.96	−0.57	0.57	−0.13
Sad	4.44	14.61	4.56	11.78	−0.21	0.83	−0.05
Satisfied	−15.33	22.12	−15.61	21.37	−0.04	0.97	−0.01
Lazy	−1.61	28.83	13.61	24.27	−1.72	0.09	−0.41
Calm	−11.33	17.57	−1	26.32	−1.75	0.08	−0.41
Happy	−8.06	15.7	−13.22	22.59	−0.79	0.43	−0.19
Anxious	−1.78	8.53	4.11	18.32	−0.88	0.38	−0.21
Alert	−17.28	24.31	−27	23.12	−1.13	0.26	−0.27
Nervous	−4.11	17.72	0.89	21.99	−0.76	0.45	−0.18
Energetic	−10.33	26.43	−14.56	20.54	−0.59	0.55	−0.14
Depressed	1.67	20.06	3.33	15.17	−0.31	0.75	−0.07
Tense	2.39	23.68	−3	14.74	−0.73	0.46	−0.17
Subjective activation [alert + energetic + 200 − (tired + calm)] / 4	−6.03	16.39	−12.93	16.13	−1.39	0.16	−0.33
Subjective affect [happy + satisfied + 200 − (sad + tense)] / 4	−7.56	10.75	−7.6	10.99	−0.15	0.88	−0.04

Note: for each test $N = 18$; the effect size is calculated as $r = Z / \sqrt{N}$.

Table 6
Means ± *SD* of the outcome scores of the cognitive test battery in study 3 for the three treatment conditions, and significance testing using Wilcoxon signedrank tests for comparing the caffeine and the placebo condition to the nothing condition respectively.

	Placebo		Caffeine		No treatment		Wilcoxon signed-rank test Placebo vs. No treatment			Wilcoxon signed-rank test Caffeine vs. No treatment		
Test	Mean	*SD*	Mean	*SD*	Mean	*SD*	*Z*	*p*	*r*	*Z*	*p*	*r*
BOMAT	16.6	5.79	16.2	4.66	18	4.9	−0.68	0.5	−0.15	−1.7	0.09	−0.38
ZVT	46.10	11.80	45	12.04	48.55	9.38	−1.18	0.24	−0.26	−1.13	0.26	−0.25
BackSpan traditional	5.74	2.27	5.15	1.76	4.8	2.53	−1.46	0.15	−0.33	−0.55	0.58	−0.12
BackSpan highest	7.89	1.12	7.55	1.5	7.2	2.69	−0.86	0.39	−0.19	−0.16	0.87	−0.04
Free recall correct	33.95	8.11	34.9	8.67	33.25	10.24	−0.52	0.6	−0.12	−0.79	0.43	−0.18
Free recall lures	1.45	1.43	0.95	1.1	1.3	1.42	−0.18	0.86	−0.04	−1.15	0.25	−0.26
Consc. false memory	2.4	1.64	1.9	1.59	2.35	1.76	−0.11	0.92	−0.02	−1.21	0.23	−0.27
FAIR-L	465.61	93.3	426.95	91.98	468.95	115.99	0	1	0	−1.76	0.08	−0.39
FAIR-Q	0.95	0.04	0.94	0.05	0.95	0.03	−0.39	0.7	−0.09	−0.21	0.84	−0.05
FAIR-K	443.72	97.13	402.58	93.88	447.32	120.14	−0.02	0.99	0	−1.72	0.09	−0.38

Note: for each test $N = 20$; the effect size is calculated as $r = Z / \sqrt{N}$.

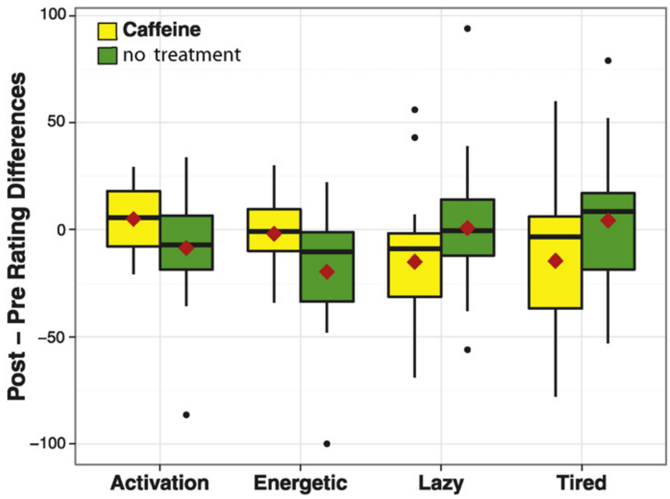

Fig. 2. Ratings of subjective activation, energy, laziness, and tiredness in study 3. Significant differences between rating values (post-minus pre-test) are displayed as Tukey boxplots. Negative scores reflect a perceived loss of the respective trait over time, whereas positive scores indicate a gain. Subjective activation and energy are significantly higher (or less reduced) after CAFFEINE (yellow) compared to NO treatment (green). Similarly, participants felt less tired and lazy after CAFFEINE compared to NO treatment (all $p < 0.05$). Plotting conventions as in Fig. 1.

libitum prior to each testing to minimize dehydration and the concomitant effects thereof. It is therefore plausible that the PLACEBO treatment caused no placebo effects or that the effects were too small or inconsistent across participants with different dietary habits in the present study.

At the most, the PLACEBO treatment tended to change mood such that feelings of laziness and calmness were reduced or remained stable, respectively. These tendencies can be attributed to expectations about the arousing properties of the placebo beverages and may vary based on prior individual experience with the effects of coffee and energy drinks. Nonetheless, the present data suggest that the coffee/energy drink placebo exhibits similar effects on cognition and mood as plain water in a multi-task setting in young adults without prior dietary restriction.

In study 3, we tested whether CAFFEINE exhibits its enhancing action after a 24-h caffeine restriction, thereby probing the withdrawal reversal hypothesis which postulates that caffeine has no direct enhancing effects but it reverses negative effects resulting from withdrawal [16], and whether caffeine PLACEBO influences cognition and mood.

3.3. Study 3

3.3.1. Cognitive test battery

Cognitive performance scores were similar between PLACEBO and NO treatment (all $p \geq 0.15$) as well as between CAFFEINE and NO treatment (all $p \geq 0.08$). Yet, CAFFEINE exhibited trends toward detrimental effects in the BOMAT ($Z = -1.7$, $p = 0.09$, $r = -0.38$) and FAIR performance ($Z = -1.76$, $p = 0.08$, $r = -0.39$) and continuity ($Z = -1.72$, $p = 0.09$, $r = -0.38$) measures. The test results and statistics are shown in Table 5.

3.3.2. Subjective ratings

No significant differences in mood and self-judgment were found between PLACEBO and NO treatment (all $p \geq 0.1$; Table 6). However, participants felt less tired ($Z = -2.11$, $p = 0.04$, $r = -0.47$), less lazy ($Z = -2.38$, $p = 0.02$, $r = -0.53$), more energetic ($p = 0.04$, $r = -0.46$) and subjectively activated ($p = 0.02$, $r = -0.02$) after CAFFEINE compared to NO treatment (Fig. 2, Table 7).

3.3.3. Discussion

In study 3, we investigated i) the effects of CAFFEINE after a 24-hour caffeine withdrawal and we tested ii) whether caffeine PLACEBO influences cognitive performance and mood by comparing it to a NO beverage control.

Caffeine intake after abstinence has been suggested to reverse any deterioration of cognitive abilities from caffeine withdrawal [16] resulting in improved cognitive performance and mood.

PLACEBO and NO beverage treatment yielded similar cognitive performance and mood. Inter-individual differences in expectations and attitudes as to the effects of the coffee may have contributed to the null finding.

When comparing CAFFEINE with NO beverage treatment, we found no significant effects in cognitive performance and, instead, replicated the null finding of study 1. In contrast to study 1, we found trends toward detrimental effects of caffeine on performance in tasks involving reasoning (BOMAT) and attention (FAIR). As reports of unfavorable effects of caffeine on cognition are rare and occur, for example, under high working memory load [66,67] or after high doses of caffeine [68],

Table 7
Means ± *SD* of the differences (post–pre) between the ratings and the combined subjective activation and affect scores in study 3 for the three treatment conditions, and significance testing using Wilcoxon signed-rank tests for comparing the caffeine and the placebo condition to the nothing condition respectively.

	Placebo		Caffeine		Nothing		Wilcoxon signed-rank test Placebo vs. Nothing			Wilcoxon signed-rank test Caffeine vs. Nothing		
Rating	Mean	*SD*	Mean	*SD*	Mean	*SD*	*Z*	*p*	*r*	*Z*	*p*	*r*
Self-judgment	−9.53	14.11	−4.95	16.95	−6.62	16.62	−0.87	0.39	−0.19	−0.04	0.97	−0.01
Focused	0.55	28.61	−3.1	19.14	−2.95	32.33	−0.49	0.63	−0.11	−0.38	0.7	−0.09
Tired	19.25	23.66	−14.6	34.92	4.15	32.36	−1.64	0.1	−0.37	−2.11	0.04	−0.47
Sad	6.85	29.87	0.85	12.31	−0.05	16.26	−0.73	0.47	−0.16	−0.57	0.57	−0.13
Satisfied	−18.2	28.68	−6.8	17.1	−2.35	32.01	−1.25	0.21	−0.28	−0.08	0.94	−0.02
Lazy	0.35	32.41	−15	31.97	0.7	31.8	−0.2	0.84	−0.04	−2.37	0.02	−0.53
Calm	−1.30	31.66	−12.9	23.76	−6.05	37.92	−0.32	0.75	−0.07	−0.43	0.67	−0.10
Happy	−10.1	18.19	−8.85	23.94	−5.1	22.74	−0.84	0.40	−0.19	−0.36	0.72	−0.08
Anxious	−3.35	9.64	−2.4	9.7	−1.1	23.09	−0.51	0.61	−0.11	−0.11	0.91	−0.03
Alert	−11.3	21.59	−5.8	25.95	−17.2	25.03	−1.23	0.22	−0.28	−1.45	0.15	−0.32
Nervous	−1.55	20.62	−10.9	25.55	−3.25	28.34	−0.17	0.87	−0.04	−0.83	0.41	−0.19
Energetic	−9.25	34.73	−2	17.45	−19.6	27.18	−1.07	0.29	−0.24	−2.04	0.04	−0.46
Depressed	11.4	27.74	5.25	16.26	3.8	25.97	−1.11	0.27	−0.25	−0.78	0.44	−0.17
Tense	3.45	25.99	2.65	15.85	1.95	37.16	−0.31	0.76	−0.07	−0.28	0.78	−0.06
Subjective activation [alert + energetic + 200 − (tired + calm)] / 4	−9.63	20.61	4.91	15.67	−8.7	25.77	−0.15	0.88	−0.03	−2.33	0.02	−0.52
Subjective affect [happy + satisfied + 200 - (sad + tense)] / 4	−9.65	19.84	−4.79	11.21	−2.34	20.43	−0.78	0.43	−0.18	−0.08	0.94	−0.02

Note: for each test $N = 20$; the effect size is calculated as $r = Z/\sqrt{N}$.

we can only speculate about the underlying mechanisms at this point. These observations could result from excessive arousal impeding focus and concentration, as is implied by the inverted U-shaped arousal-performance function [69]. Notably, baseline levels of tiredness were similar between treatments in all three studies verifying that caffeine abstinent participants in study 3 were not more (or less) fatigued than participants without dietary restriction in studies 1 and 2 at the beginning of the test session. At the mood level, participants reported significantly increased energy and activation along with reduced tiredness and laziness after CAFFEINE compared to NO treatment. Importantly, these effects cannot be attributed to the restoration of normal levels following caffeine abstinence as activation at baseline was similar for both conditions. Instead, our results support the notion that caffeine exhibits psychoactive effects on mood [70,71], in line with the findings of study 1.

3.4. Conclusions

With the present studies, we investigated the effects of glucose, caffeine, and the respective placebos, water and no treatment on cognitive performance and subjective mood in an assessment center-like situation under natural consumption conditions in young adults with heterogeneous consumption patterns. Together, the results revealed that neither caffeine nor glucose influence cognitive performance differently than placebo, water, or no treatment controls; even a 24-hour caffeine abstinence failed to induce beneficial effects of caffeine or coffee placebo. Previous reports of caffeine-induced effects are inconsistent and likely an indicator for multifaceted inter-individual differences in caffeine responsiveness. These include behavior factors such as consumption habits, physiological traits like susceptibility to dependency and proneness to exhibit withdrawal symptoms, physiological states like baseline levels of arousal [72] and metabolic differences in caffeine elimination rates [1] as well as personality traits [73]. Overall, the existence of universal enhancing effects of glucose and caffeine remains, therefore, questionable. Nevertheless, caffeine consistently improved subjective experiences related to activation: participants preserved mental energy and activation throughout the tests after caffeine intake. Future studies should investigate whether such mood changes are effective in increasing motivation during a challenging task.

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