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Effect of Coffee Aroma on Cerebral Activity during Concentration Tasks

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Abstract

Caffeine has been shown to reduce various health risks, such as diabetes, obesity, and vascular diseases, and it may provide health benefits when consumed in moderate amounts, such as three to four cups per day. However, caffeine may exhibit harmful effects depending on the dose. Although the health benefits and disadvantages of caffeine intake have been studied, the effects of caffeine's aroma have hardly been studied. This study aimed to examine the impact of caffeine scent on brain activity during cognitive tasks using electroencephalography (EEG). This study included 30 healthy young adults. We investigated cerebral activity using EEG during the concentration tasks. Participants performed tasks under pre- and post-conditions, including drinking coffee, smelling coffee, or drinking water. The number of correct responses and reaction times were calculated for each task, and mean power levels were analyzed. A linear mixed model was applied with "performance", "ROI", and "wave band" to examine the effects of conditions and timing. Significant differences were observed in left-frontal θ power (coffee < smell and water) and in right-frontal α power (coffee < smell) during the post-task phase ($P < 0.05$). No significant differences were observed during the pre-task phase between conditions. Also, there were significant differences in left-occipital θ between pre- and post-task during water conditions (pre < post). Although there was a trend toward improved correct performance reactions, this was not statistically significant. Lower α on the frontal lobe and higher θ are associated with improved arousal and cognitive functions. Drinking coffee reduced α power, whereas smelling coffee or drinking water increased θ power. Therefore, drinking coffee, smelling coffee, and drinking water may affect cerebral activities and enhance cognitive performance.

Keywords

Coffee, Caffeine, Concentration, Electroencephalography, Brain Function, Neuroimaging

1. Introduction

Caffeine is a central nervous system stimulant and is likely the most widely used psychoactive substance worldwide [1]. A review article suggested that caffeine is the world's most frequently consumed psychostimulant [2]. Its usage is increasing worldwide, primarily driven by its benefit in improving concentration, memory, and physical performance [1]. In addition to its primary use as an additive in numerous beverages, it also has clinical applications, such as in treating apnea of prematurity, serving as an adjuvant in pain therapy, and a regulatory-approved use for short-term fatigue treatment [2]. Caffeine has been shown to reduce health risks such as diabetes, obesity, and vascular diseases, providing health benefits when consumed in moderation, typically three to four cups per day. Caffeine improves alertness, attention, concentration, and reaction time [3] [4], particularly in sleep-deprived individuals. Moreover, it may improve endurance performance and muscle strength. Intoxications with caffeine are relatively rare but can be fatal. Within typical doses, caffeine use is generally considered safe [2]. Coffee and caffeine-containing products affect the cardiovascular system through positive inotropic and chronotropic effects and the central nervous system by stimulating locomotor activity and producing anxiogenic-like effects. Thus, it is of interest to examine whether these effects could be detrimental to health [1]. Low-dose caffeine intake selectively enhances cognition and brain activity compared to medium- and high-dose caffeine, improving executive function and prefrontal cortex activity [5].

On the other hand, it has been suggested that caffeine may have harmful effects depending on the dose. Caffeine abuse and dependence are becoming more and more common and can lead to caffeine intoxication, which puts individuals at risk for premature and unnatural death [1]. Acute caffeine intake can attenuate homeostatic sleep pressure and worsen sleep quality [6]. It also exhibits characteristics of addictive substances, including withdrawal symptoms and tolerance [2]. Interestingly, a randomized, double-blind, placebo-controlled trial reported that compared to placebo, participants showed a higher error rate and a longer reaction time on working memory (WM) tasks in the caffeine condition. Building on the earlier evidence highlighting increasing cerebral metabolic demands for WM function after acute caffeine intake, this finding suggests that such demands might be impeded over daily intake and may worsen performance [7].

As mentioned above, although the health benefits and disadvantages of caffeine intake have been studied, no substantial attention has been paid to the effects of caffeine's aroma. Furthermore, a recent review article stated that future studies must provide continued evidence on the effect of caffeine on various types of cognitive functions [8]. Therefore, the purpose of this study was to examine the effect of caffeine scent on brain activity during cognitive tasks using electroencephalography (EEG). Furthermore, the results of this study will provide new insight into whether it can serve as a complementary substance to promote rehabilitation for patients with central nervous system disorders, such as dementia.

2. Materials and Methods

2.1. Participants

This study enrolled 30 healthy young adults (10 women and 20 men; age: 20.4 ± 1.70 years). All prospective participants were provided with a comprehensive explanation of the study's safety protocols and were assured that their personal identifying information would remain confidential; thereafter, they provided written informed consent for study participation. Additional informed consent was obtained from all participants whose identifiable information was included in the study. None of the participants had a history of major physical disorders, including neurological illnesses, brain injuries, or psychiatric conditions. This study was approved by the Ethics Committee of Nishikyushu University (approval no. 23XQB18) and conformed to the principles of the Declaration of Helsinki [9] and its subsequent amendments.

2.2. Task

The AX task from the Continuous Performance Test (CPT), part of the Clinical Assessment for Attention (CAT, Japanese Society for Higher Brain Dysfunction), was used to evaluate participants' concentration. Numbers from 1 to 9 were randomly presented 400 times on a computer. The only target was the number seven, which appeared immediately after three and was set to appear 40 times. Participants were asked to press the enter key on the computer as quickly as possible only when a seven appears after a three. The average time required was approximately 16 minutes and 40 seconds. Then, the number of correct reactions and reaction time to the targets were automatically determined.

2.3. Experimental Protocol

All 30 participants were randomly allocated to three groups: coffee group (participants drank coffee), smell group (participants smelled coffee aroma), and water group (the group drank water). Participants were seated in a quiet room on a chair with a backrest and placed their forearms in a relaxed position on a table. They were asked to perform the task in pre- and post-condition settings, which consisted of drinking coffee, smelling coffee, or drinking water. Each drink including smell condition was 200 ml at room temperature, and regarding coffee, coffee beverage (containing caffeine 63 mg/100ml) was used for both smelling and drinking. In drinking conditions, the post-task was performed after 15 minutes of consuming. In smelling condition, the post-task was performed over 15 minutes of smelling coffee. Participants were instructed to abstain from caffeine-containing drinks for at least a day before the experiment. Additionally, they were instructed to perform the tasks without any additional movements, such as head movement, and maintain the same posture throughout the experiment. EEG measurements were recorded during the tasks using Polymate Pro MP6100 (Miyuki Giken, Tokyo, Japan). Before electrode placement, the skin was cleansed with alcohol, and the electrodes were affixed to an elastic cap using a holder. Based on the international 10/20 EEG placement system, 19 gold-coated active EEG electrodes were placed at specific cortical locations: Fp1 (left frontal pole), Fp2 (right frontal pole), F3 (left frontal), Fz (middle frontal), F4 (right frontal), F7 (left inferior frontal), F8 (right inferior frontal), C3 (left central), Cz (middle central), C4 (right central), P3 (left parietal), Pz (middle parietal), P4 (right parietal), O1 (left occipital), O2 (right occipital), T3 (left mid temporal), T4 (right mid temporal), T5 (left posterior temporal), and T6 (right posterior temporal). The EEG recorded at the scalp level represents the aggregate currents of the electrical fields generated by neural activity in cortical neural circuits [10].

2.4. Data Analysis

EEG data were sampled at a rate of 1000 Hz and filtered within the 1 - 60 Hz range using a bandpass filter. Artifacts caused by eye blinking or muscle movement were excluded. Power spectrum analysis was conducted using the Electro Magnetic Source Estimation Data Editor (Cortech Solutions, Wilmington, NC). The nine regions of interests (ROI) were set as L-frontal (Fp1, F3, F7, and Fz), R-frontal (Fp2, F4, F8, and Fz), L-temporal (T3 and T5), R-temporal (T4 and T6), central (C3, C4, and Cz), L-parietal (P3 and Pz), R-parietal (P4 and Pz), L-occipital (O1), and R-occipital (O2). EEG rhythms were categorized into six wave bands according to their frequency ranges: δ (0 - 4 Hz), θ (5 - 8 Hz), α (9 - 13 Hz), β (14 - 30 Hz), and γ waves (31 - 60 Hz). These classifications were based on previous studies [11] [12]. The mean power level of each wave band was calculated for each task.

2.5. Statistical Analysis

The Linear mixed model was utilized to analyze "performance" (number of correct reactions and average reaction time), "ROI", and "wave band" to examine the effects of conditions and timing. Moreover, statistically significant different spots were analyzed by Kruskal-Wallis's test or Wilcoxon's signed rank test to examine differences between conditions and task timing, respectively. EZR software for medical statistics [13] was used for statistical analyses. Statistical significance was set at $P < 0.05$.

3. Results

Table 1 shows the comparison of outcomes between conditions. No significant main effect was found, although significant interactions were found at six spots (†). After the Kruskal-Wallis test, there were significant differences observed during the post-task period ($P < 0.05$) on the (i) left-frontal θ (coffee < smell and water) and (ii) right-frontal α (coffee < smell). However, no significant differences were observed during the pre-task between conditions. Also, Wilcoxon's signed rank test showed a significant difference in left-occipital θ between pre- and post-task during water conditions (pre < post). Moreover, there was a significant trend toward differences observed in correct reactions of performance, although there was no significant difference was found.

Table 1. Comparison of outcomes between conditions.

	Condition	Coffee		Smell		Water	
Outcome	**Timing**	**pre**	**post**	**pre**	**post**	**pre**	**post**
Performance:							
Correct reactions (n)		38.30	39.20	39.80	38.50	38.10	38.30
Average reaction time (seconds)		448.61	441.94	441.61	436.22	477.07	458.45
EEG power levels: (μV^2)							
Left-frontal	δ†	47.50	3.99	225.54	16983.03	77.28	257.77
	θ†	6.81	0.83	52.48	1186.62	17.43	71.81
	α	2.47	0.40	26.17	290.63	6.17	20.71
	β	0.79	0.14	8.39	46.91	1.70	5.92
	γ	0.18	0.09	1.61	1317.70	0.36	0.89
Right-frontal	δ†	258.08	9.59	223.03	19223.21	77.88	525.59
	θ	28.49	1.64	51.85	1429.12	17.88	188.54
	α†	8.56	0.61	25.79	319.81	6.20	43.21
	β†	2.35	0.19	8.27	50.08	1.70	12.53
	γ	0.47	0.21	1.66	2067.70	0.42	1.66
Left-temporal	δ	26.57	6.01	21.12	11329.76	7.58	59.04
	θ	8.33	1.79	5.08	521.35	1.74	21.86
	α	3.85	0.89	2.70	152.11	0.73	5.00
	β	1.39	0.29	0.95	25.92	0.23	1.45
	γ	0.31	0.12	0.31	1257.99	0.11	0.21
Right-temporal	δ	16.62	1.58	1.02	11163.19	1.81	125.03
	θ	2.46	0.45	0.38	581.25	0.84	49.12
	α	1.16	0.44	0.54	134.71	0.41	15.24
	β	0.49	0.27	0.44	19.22	0.15	3.87
	γ	0.26	0.23	0.36	1726.90	0.17	0.66
Central	δ	51.25	8.69	8.39	11178.41	3.99	59.01
	θ	17.50	2.84	2.33	502.96	1.25	23.89
	α	8.23	1.31	1.24	145.33	0.55	5.64
	β	3.09	0.47	0.53	24.55	0.17	1.58
	γ	0.72	0.16	0.28	1348.35	0.14	0.25

Continued

Left-parietal	δ	36.29	5.48	3.28	1577.38	1.66	54.09
	θ	10.58	1.34	0.93	123.92	0.53	21.69
	α	4.59	0.64	0.57	30.15	0.29	5.93
	β	1.61	0.20	0.19	6.63	0.07	1.56
	γ	0.30	0.09	0.09	287.93	0.08	0.22
Right-parietal	δ	562.27	84.07	18.70	2671.33	5.21	12.10
	θ	180.72	17.84	6.12	133.21	1.01	4.55
	α	77.64	7.22	3.15	43.38	0.50	1.52
	β	27.74	2.47	1.17	8.77	0.12	0.40
	γ	4.63	0.50	0.28	316.26	0.07	0.08
Left-occipital	δ	48.94	8.03	2.60	533.90	1.42	23.71
	θ †	15.70	1.77	0.87	51.41	0.46	8.93
	α	7.04	0.95	0.70	17.77	0.38	2.60
	β	2.52	0.33	0.18	5.49	0.14	0.70
	γ	0.49	0.13	0.06	47.96	0.13	0.13
Right-occipital	δ	25.39	4.70	2.51	12602.16	2.09	78.56
	θ	7.73	1.10	0.76	578.87	0.75	31.02
	α	3.73	0.83	0.87	150.60	0.58	9.32
	β	1.28	0.26	0.17	21.72	0.20	2.39
	γ	0.31	0.16	0.11	1721.27	0.22	0.40

Significant differences are indicated (†$P < 0.05$ by Linear mixed model).

4. Discussion

This study examined the effect of caffeine scent on brain activity during cognitive tasks using EEG. Post-task analysis revealed the following: the left-frontal θ showed a significantly reduced power level with the coffee condition than smell and water conditions, and the right-frontal α showed a significantly reduced power level with the coffee condition than smell, although there was no significant outcome difference during pre-task between conditions. Also, the power level of left-occipital θ significantly increased during post- than pre-task with water condition. Moreover, there was a notable trend toward condition timing interaction difference on correct performance reactions, although no significant differences were found. Notably, drinking coffee reduces power levels of θ and α waves on the frontal lobe, and drinking water increases θ wave power on the occipital lobe than drinking or smelling coffee. However, no specific EEG features were identified with the smell condition. These EEG changes might affect cognitive task performances and concentration.

A randomized controlled trial suggested that a 50 mg caffeinated drink significantly reduced the percentage changes from baseline of α wave activity over the midline electrodes, *i.e.*, frontal, central, and occipital areas after drinking during a 5 min eyes-closed resting state. Cognitive function test results, such as the trail-making test and digit span forwards, significantly improved after drinking. A significant inverse correlation between the diminished α wave activity over the midline central and occipital cortical regions and the Trails B positive scores was observed [14]. Previous studies have suggested that a reduced α power may correlate with increased cognitive flexibility and arousal, while an increased θ power correlates with greater cognitive control and decision-making under pressure [15]. In the speed game, caffeine had a significantly greater number of target shots post-dose than pre-dose. However, it also exhibited slower reaction times post-dose compared to pre-dose. EEG data collected concomitantly with game playing showed that better performance in the speed game resulted in significantly reduced α power and increased θ activity, consistent with enhanced cognitive processing [15]. Moreover, a previous study reported that the EEG showed that power density in the θ during waking was increased for at least two days after a single dose of caffeine, revealing long-term effects of a single dose of caffeine on vigilance states, EEG, and neuronal activity in the lateral hypothalamus [16].

Consistent with previous studies, drinking coffee containing caffeine induces lower α and higher θ power. Specifically, reduced α activity in the frontal lobe relates to improving cognitive functions such as executive function, attentional function, cognitive flexibility, and arousal. Higher θ relates to greater cognitive control and vigilance states. Therefore, these two phenomena are important to improve cognitive performance. In the present study, lower α was observed after drinking coffee. However, higher θ was observed after smelling coffee or drinking, without significant cognitive performance difference. Hence, drinking coffee affects concentration performance, but smelling coffee and drinking water may also affect cerebral activities and induce better concentration performance. To seek the best way to induce the best cognitive performance, it is imperative to conduct further experiments incorporating various condition settings such as caffeine content control, amount of drinking, or time of smelling.

This study has some limitations. First, it focused solely on healthy young adults; therefore, it is unclear whether our results can be generalized to older patients or those with neurological disabilities. Second, the concentration task was limited to the CPT; therefore, whether Cerebral activities during other concentration tasks are comparable to those observed during the CPT remains unclear. Third, the amount participants drank was a cup of coffee/water. Thus, the effects of different amounts of coffee/water or various beverages remain unclear. Finally, our study included only a small number of participants. To address these limitations, future studies should include more participants under varying conditions, diverse concentration tasks, and investigate cerebral activity.

In conclusion, a reduced α on the frontal lobe and an increased θ are associated with improving arousal and cognitive functions. Drinking a cup of coffee reduces α power, whereas smelling a cup of coffee or drinking water increases θ power.

Not only does drinking coffee affect cognitive performance, but smelling coffee and drinking water may also affect cerebral activities and induce better cognitive performance.

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Authors' Contributions

MM: Conceptualization, methodology, investigation, software, resources, data curation, visualization, supervision, project administration—original draft preparation, and writing—review and editing.

TI, SH, and RT: Conceptualization, methodology, investigation, writing, and editing.

TH: Validation, formal analysis, and review.

All the authors have read and agreed to the published version of the manuscript.

Institutional Review Board Statement

The study was approved by the Ethics Committee of Nishikyushu University (approval no. 23XQB18).

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Data Availability Statement

The datasets generated and analyzed in the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Abbreviations

EEG	Electroencephalogram
CPT	Continuous Performance Task
θ	Theta wave
α	Alpha wave
COF	Coffee condition
SME	Smell condition
WAT	Water condition
CNS	Central Nervous System
RFT	Right Frontal Theta
LFO	Left Frontal Alpha
LOO	Left Occipital Theta
CFA	Cognitive Flexibility and Arousal
RCT	Randomized Controlled Trial