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Experimental investigation on effects of odor types, concentrations, and release frequencies on cognitive performance

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ABSTRACT

Previous studies have demonstrated that aromatic environments have the potential to improve cognitive performance. However, there is a lack of continuous exposure experiments relevant to real-world office settings, and insufficient research on the impacts of different affecting factors on cognitive performance. This study recruited 44 participants who were exposed to different odors (rosemary, lemon, and peppermint), various concentrations (odorless, low, and high), and different release frequencies (stable release, 20-min-cycle, and 60-min-cycle) for a duration of 2 h Subsequently, participants completed neurobehavioral ability tests and self-assessments of workload. Electroencephalographic (EEG) data were measured and recorded during the cognitive tasks. The results indicated that different odor types improved cognitive test scores to varying degrees and impacted the relative power spectral density (PSD) of EEG. Test scores and EEG activity generally exhibited consistent trends. Relaxing and soothing aromatic environments were found to improve short-term memory and logical reasoning task scores, while environments that increased brain excitement and alertness improved perceptual task scores. No significant impacts of aromatic environments on subjective workload were observed.

1. Introduction

Indoor air quality (IAQ) is considered to have a significant association with perceived productivity, satisfaction and health outcomes [1]. IAQ within a workplace can have a notable impact on work performance [2], subsequently impacting social and economical outcomes to organizations and the community [3]. An aromatic environment is characterized by an IAQ that is improved by the introduction of fragrances through the release of aromatic compounds from natural plants into the air.

Extensive research has demonstrated that essential oils have cognitive-enhancing properties [4–7]. Previous studies on the impacts of aromatic substances have mainly focused on the direct inhalation of scents. With developments in the fragrance industry and the introduction of intelligent indoor furniture, the practice of creating aromatic environments to improve IAQ is becoming more prevalent. This trend has led to further investigations into their impacts, extending beyond direct inhalation. In recent years, some scholars have begun to explore the potential of using plant-based essential oils to create aromatic environments in indoor spaces as a means to improve cognition. Du et al. [8] conducted a study where participants were exposed to lemon- and grapeseed- scented environments for about 30 min, revealing variations in cognitive performance based on the type of task compared to a control group not exposed to the scents. Choi et al. [9,10] examined the learning performance of students who were exposed to rosemary, lemon, and peppermint environments released stably for 90 min, as well as the sweet orange environments released intermittently for 70 min. Wang et al. [11] exposed participants to a sweet orange environment for 70 min and noted that this environment improved cognitive task performance during exposure and notably reduced emotional stress, as indicated by heart rate variability (HRV).

Past studies have indicated that different types of odors have varying effects on improving cognitive performance, which can be attributed to the distinct physicochemical properties and biological activities of the components present in different essential oils [12–15]. Du et al. [8] found that lemon and grapeseed environments exhibited similar effects on cognitive performance, suggesting that these two odors may share common mechanisms in influencing cognitive processes. Choi et al. [9] observed that the effects of rosemary, lemon, and peppermint environments on cognitive performance varied, with lemon showing a more pronounced improvement in memory-related tasks. The investigation into the differences in effects between various types of odors is

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considered a promising and valuable research topic.

Further, the exposure dose plays a critical role in determining the impact of aromatic environments on human physiology, especially in clinical studies. If the dosage is too small, it may fail to produce the desired effects, while an excessive dosage could lead to adverse reactions [16,17]. Similarly, there should be an appropriate dosage range for enhancing cognitive performance. While previous research has delved into the mechanisms underlying the physiological and psychological impacts of aromatic concentrations [18–20], research on indoor aromatic environments has predominantly focused on the effects of scents themselves, overlooking the importance of odor concentration [8,9,11]. Fragrance products designed to establish aromatic environments typically utilize intermittent release strategies to prevent overpowering or lingering odors, thereby ensuring a pleasant and comfortable olfactory experience. This suggests that the concentration of aromatic compounds in real-world scenarios may vary due to the intermittent release patterns, rather than remaining constant. In a similar vein, existing studies have predominantly focused on the impacts of intermittent release on sensory perception [21,22]. Choi et al. [10] compared cognitive performance between the aromatic conditions with 10-minute release intervals and the odorless conditions but found no significant differences, which differs from previous studies with similar scent components but stable release mode [9,11].

As discussed, the types of odors, their concentrations, and release frequencies are critical variables that shape the effects of aromatic environments on cognitive performance. Different odors have distinct effects on cognition, while concentration levels and release frequencies may potentially influence the strength of these effects, which have been largely overlooked in previous research. A comprehensive examination of these factors is essential to fully understand the mechanisms by which aromatic environments affect cognitive performance. The primary objective of the study was to elucidate the impacts of these factors, as well as their interactions, on cognitive performance. The results of this research can offer valuable insights for creating aromatic environments in offices and other settings that demand improved cognitive abilities.

2. Method

2.1. Experimental design

This study designed an experiment aimed at examining the impacts of various types of odors, concentrations, and release frequencies on cognitive performance. Workload self-assessment is a commonly employed technique in cognitive performance studies [23], where an increased workload often signifies heightened attention in response to uncomfortable environments to maintain performance levels [24]. Electroencephalographic (EEG) activity is a crucial indicator of the human body's reactions to the built environment, with changes in power spectral density (PSD) across different frequency bands reflecting alterations in arousal, stress, and other psychological states closely linked to cognitive performance [25]. In our experiment, participants were exposed to aromatic environments for a period of 2 h to replicate prolonged exposure in office or educational settings. Apart from cognitive task scores, EEG activity was also monitored and recorded during the tasks, while their self-assessed workload was gathered post-task completion.

The study examined the impacts of 3 variables related to aromatic settings, including types of odors, concentrations, and release frequencies. For odor types, we selected rosemary, lemon, and peppermint. Rosemary has been shown to enhance cognitive task accuracy and reduce response time [26], improve short-term memory [12,14], and positively impact reading performance [27]. Lemon odor promotes memory performance [9,28,29], and alleviates anxiety during cognitive tasks [30]. Peppermint odor boosts memory [15], alertness [15,31], attention [31], and performs better in more challenging tasks [32]. Additionally, these three odors are recognized for their invigorating and pleasant qualities and have a high level of subjective acceptance [33]. They also encompass the odors most frequently examined in studies of indoor aromatic environments and cognitive performance [8–11] (lemon and sweet orange are similar, with d-limonene being the highest content compound in both).

These essential oils were sourced from Aroma Plant Research Center at Shanghai Jiao Tong University. The type of odor was considered a between-subject factor, with each participant being exposed to a single type of odor exclusively during the experiment.

The study considered 2 within-subject factors: concentration and release frequency. Concentration levels were classified as high and low, while release frequency was classified as stable release, 20-min-cycle, and 60-min-cycle. Participants were exposed to all concentration levels and release frequencies within a single specific odor as part of the within-subject design.

Participants were also involved in an odorless scenario, which functioned as a reference point for contrasting with the scented scenarios in subsequent analyses.

The aromatic substance concentration pertains to the calculated theoretical concentration based on the substance release rate and ventilation rate. A low concentration is defined at 2.5 μg/L, indicating the threshold of perception, while a high concentration is set at 15 μg/L, representing the maximum acceptable level [33]. Due to the lack of previous research on concentration levels, we selected two extreme concentrations based on studies of olfactory perception to preliminarily explore the direction and size of concentration effects, providing a reference for future studies for additional concentration levels.

The release was classified into 2 categories: stable release and intermittent release. In a stable release scenario, the aromatic substance was emitted at a constant rate. With a consistent ventilation rate, the concentration of the aromatic substance in the air remained constant. Intermittent release, on the other hand, involved a rapid emission for 5 min to achieve the desired concentration, followed by the cessation of release and continuous ventilation to allow the concentration to gradually decrease. This cycle was repeated multiple times during the exposure period. Intermittent release was further divided based on the duration of each release cycle: the 20-min-cycle and the 60-min-cycle. Specifically, the 20-min-cycle comprised 5 min of emission followed by 15 min of decay, while the 60-min-cycle consisted of 5 min of emission followed by 55 min of decay.

2.2. Participants

A priori power analysis was conducted to determine the minimum sample size by PASS 15.0 software. The repeated measures analysis of variance (RMANOVA) and Bonferroni corrected T test are main statistical methods to examine the effects of aromatic factors. More details about statistical procedure and priori parameters can be found in Section 2.6.3. The minimum sample size for RMANOVA is 42, and 43 for Bonferroni corrected T test. Finally, a total of 44 individuals finished the experiment except fallen samples. Section 2.6.3 shows the actual statistical power of 44 participants. Before the commencement of the study, the participants were furnished with a plain language statement and duly signed a consent form. The demographic characteristics of the participants are outlined in Table 1. The participants were exclusively college students who had not previously used any fragrance products. They were required to be in good physical condition, devoid of respiratory ailments, anosmia, and allergic responses. Furthermore, they were advised to refrain from engaging in high levels of emotional stress,

Table 1
Demographic information of participants.

Number	Gender	Age	Height	Weight	BMI
22	Male	21.6 ± 2.8	175.7 ± 5.9	68.0 ± 7.9	22.0 ± 2.0
22	Female	21.9 ± 2.2	162.4 ± 5.1	52.6 ± 4.8	19.9 ± 1.3

vigorous physical exertion, and the consumption of medications, alcohol, and caffeine before the experiment.

2.3. Instrument and environmental control

The study was conducted in a climate chamber designed to resemble a private office (Fig. 1), with a floor area of 13.2 m^2 and a volume of 36.96 m^3. A computer was provided in the chamber for participants to undertake neurobehavioral tests and complete questionnaires. To maintain uniform ventilation, a fresh air fan and an exhaust fan were positioned on opposite sides of the chamber. The air exchange rate within the room, assessed using CO_2 tracer method [34], was calculated to be 2.326 exchanges/h. A fragrance diffuser was utilized to establish an aromatic ambiance. The laboratory was furnished with 2 identical chambers, facilitating concurrent experimentation with 2 participants.

The thermal, lighting, and acoustic conditions in the climate chamber were controlled variables and were continuously monitored using environmental measurement devices. Air temperature, relative humidity, and air velocity were assessed using Swema 03+ and HC2A-S instruments, with a measurement range of 10–40 °C for temperature, 0–100 %RH for humidity, and 0.05–1.00 m/s for air velocity. The accuracy of these measurements was ± 0.2 °C for temperature, ± 0.8 %RH for humidity, and ±0.03 m/s for air velocity. The average and standard deviation recorded values were 25.8 ± 0.2 °C for temperature, 54 ± 3 % for relative humidity, and less than 0.2 m/s for air velocity. Illumination and color temperature were measured using an HPC-1 color temperature meter, with a measurement range of 0–200,000 lx for illumination and 1500–20,000 K for color temperature. The accuracy of these measurements was ±4% for illumination and ±1 K for color temperature. The average and standard deviation recorded values were 279 ± 15 lx for illumination and 5785 ± 26 K for color temperature. Acoustic levels were measured using a Testo 815 sound level meter, with a measurement range of +30–130 dB(A) and an accuracy of ±1.5 dB(A). The average and standard deviation recorded 46.5 ± 1.3 dB(A).

The determination of aromatic substance concentrations in the air involved sampling and component analysis. Air samples were obtained from the exhaust fan of a chamber, with a sampling duration of 5 min and a flow rate of 0.2 L/min. These samples were subjected to analysis by Gas Chromatography-Mass Spectrometry (GC–MS). Table 2 presents the primary components of 3 odors at both low and high concentrations. The theoretical concentrations of 2.5 μg/L for low concentration and 15 μg/L for high concentration (Section 2.1) were calculated based on the release rate of the aroma diffuser and the air exchange rate. However, actual measured concentrations were observed to be lower than the theoretical values due to variations in the proportions and volatility of the main components. Additionally, the relative proportions of components differed between the low and high concentrations.

Table 2
Mean concentrations of aromatic substance in air.

Odor	Conc. of main components (μg/l)		Proportion of main components		
	Low conc.	High conc.	Compound	Proportion in low conc.	Proportion in high conc.
Rosemary	1.619	10.468	1R-.alpha.-Pinene	67.8%	64.4%
			Camphene	9.9%	10.5%
			Eucalyptol	19.8%	22.1%
			D (+)-Camphor	2.6%	3.1%
Lemon	0.484	4.908	D-Limonene	95.7%	89.9%
			Citral	4.3%	10.1%
Peppermint	0.600	4.549	1R-.alpha.-Pinene	17.7%	12.2%
			D-Limonene	18.7%	20.9%
			Menthol	21.8%	27.7%
			Menthone	26.7%	34.0%
			(1S)-(-)-Beta-Pinene	15.2%	9.7%

2.4. Testing, subjective questionnaire and EEG recording

The quantitative evaluation of cognitive task performance was carried out through computerized testing. Lan [35] developed a neurobehavioral test application that includes various cognitive tasks. For this study, 8 tasks from Lan's online application were chosen for their relevance. Tasks such as digital breadth, meaningless figure recognition, and signal-code test predominantly evaluate short-term memory, which pertains to the capacity to retain and retrieve a limited amount of information and is closely associated with cognitive aptitude [36]. Number calculation and overlapping tasks mainly assess logical reasoning and thinking abilities, which are connected to encoding and matching processes [37] and are typically necessary for handling complex tasks. The Stroop test, visual reaction task, and letter search task primarily evaluate information perception and processing skills, which depend on the distribution of attentional resources and are vital for executive functions [38].

To facilitate data processing and analysis, a code (T1 to T8) was allocated to each task. With the exception of the digital breadth task, which was assessed based only on accuracy, all other tasks were evaluated considering both accuracy and response time. The cognitive tasks' names, codes, and evaluation criteria are listed in Table 3.

NASA-TLX questionnaire was employed to assess the workload experienced by participants upon task completion. Harts et al. conducted a comprehensive study and identified 6 key factors that encapsulate workload: mental demand, physical demand, temporal demand,

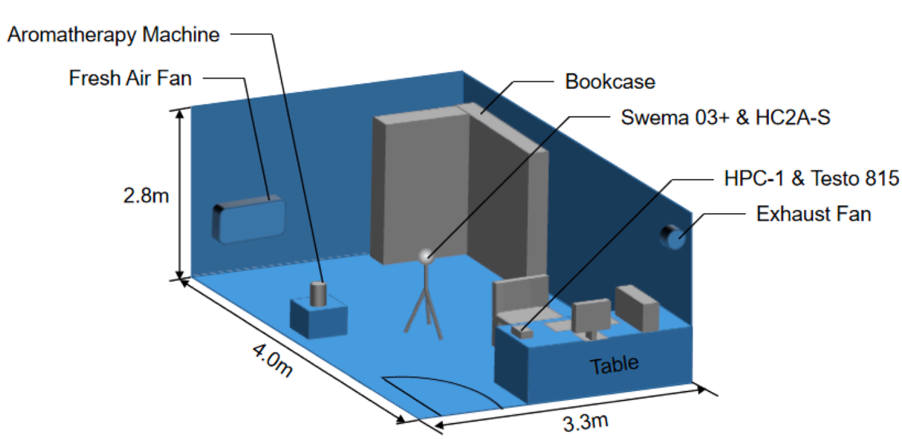

Fig. 1. Laboratory layout.

Table 3
Cognitive tasks and performance indicators.

(Code) Task	Evaluating indicator	
	Accuracy	Response time
(T1) Digital breadth	√	N/A
(T2) Number calculation	√	√
(T3) Meaningless figure recognition	√	√
(T4) Signal-code test	√	√
(T5) Stroop test	√	√
(T6) Visual reaction	√	√
(T7) Overlapping	√	√
(T8) Letter search	√	√

self-evaluated performance, effort, and frustration [39]. Participants were required to rate each type of load on a scale ranging from 0 to 100 in the questionnaire, with higher scores indicating a higher level of workload. The average score across these 6 factors was utilized to gauge the workload during cognitive tasks. Given that NASA-TLX questionnaire assesses workload across multiple dimensions, an evaluation of its reliability and validity becomes imperative. The analysis of the collected questionnaires revealed a Cronbach's α coefficient of 0.707 for the 6 factors and a Kaiser-Meyer-Olkin (KMO) value of 0.681, suggesting that the questionnaire's reliability and validity were acceptable. In addition to workload, the questionnaire included an investigation of environmental perceptions. Specifically, it assessed participants' perceived intensity of odors and their evaluation of air quality. Odor intensity was rated using a six-point scale ranging from 1 to 6, where 1 represented "no odor" and 6 indicated "strong odor". Perceived air quality was evaluated using an eleven-point scale from −5 to 5, where −5 represented "unacceptable" and 5 indicated "acceptable".

EEG is a non-invasive method employed for monitoring brain activity through the recording of electrical signals. These signals are produced by the dendrites of neurons in proximity to the electrodes used for measurement. Fluctuations in activity across different frequencies have been observed to be associated with various cognitive processes [40]. Aromatic compounds have the potential to impact brain function through several pathways: they can activate the olfactory cortex via the olfactory system, interact with receptors in the central nervous system by crossing the blood-brain barrier, or directly impact physiological parameters, resulting in notable alterations in EEG patterns. EEG recordings are frequently employed in studies investigating the impact of environmental factors on cognitive function. By comparing the relative PSD in diverse settings, researchers can gain insights into how different indoor conditions impact cognitive performance [41]. Therefore, the analysis of EEG data obtained from individuals engaged in cognitive tasks can offer valuable information on the neural and physiological mechanisms that underlie the impact of aromatic environments on cognitive performance.

The participants utilized Emotiv Epoc X for the acquisition of EEG data. Emotiv Epoc X is a portable wireless EEG measurement device (Fig. 2). It comprises 16 EEG channels, consisting of 2 reference electrodes and 14 measurement electrodes. In this study, the 14 measurement electrodes were positioned on specific brain regions: the frontal lobe at AF3, AF4, F3, F4, F7, F8, FC5, and FC6; the parietal lobe at T7, T8; the temporal lobe at P7, P8; and the occipital lobe at O1 and O2 (Fig. 3).

Fig. 2. Appearance of EEG headset.

2.5. Procedure

The experimental procedure in Fig. 4 involved participants entering the chamber and subsequently taking a seat. Research aimed at enhancing cognitive function through improved IAQ often concentrates on office workers or students, who spend extended periods in indoor settings [42,43]. In general, office workers' 8-hour workday is typically divided into two continuous 4-hour sessions in the morning and afternoon. Therefore, we are more concerned with performance during the middle of the continuous 4-hour work period (around the 2-hour mark). As such, before the cognitive testing begins, participants are required to engage in self-arranged work, such as reading and writing, for approximately two hours. At 115 min into the session, the experimenter entered the room to equip the participants with EEG measurement device before exiting. 5 min later, at the 120-min mark, the participants commenced the neurobehavioral tests on the desktop. Throughout the testing phase, EEG data was wirelessly transmitted and recorded on the experimenter's computer. The testing period typically lasted between 20 and 30 min. Upon completing the tests, participants were instructed to fill out the questionnaire to report their environmental perception and workload of the cognitive tasks. Subsequently, they were allowed to remove EEG headset and exit the chamber. Notably, participants were continuously exposed to the aromatic environment from the moment they entered the chamber until they left.

16 participants were exposed to rosemary, 14 to lemon, and 14 to peppsermint. Each participant underwent 7 experimental trials, consisting of 2 concentrations multiplied by 3 release frequencies, plus one odorless trial. To mitigate order impacts, the sequence of trials for each participant was determined using a randomly generated number table ranging from 1 to 7. Wu et al. [44] observed that with 3 repetitions of tests, participants' performance showed gradual improvement, reaching stability after 4 or more repetitions. Therefore, prior to the experiment, participants completed the tests 3 times to acquaint themselves with the procedures and prevent learning impacts. Each participant conducted the experiment on different days, but at the same time each day, to minimize potential circadian rhythm impacts on the results [45].

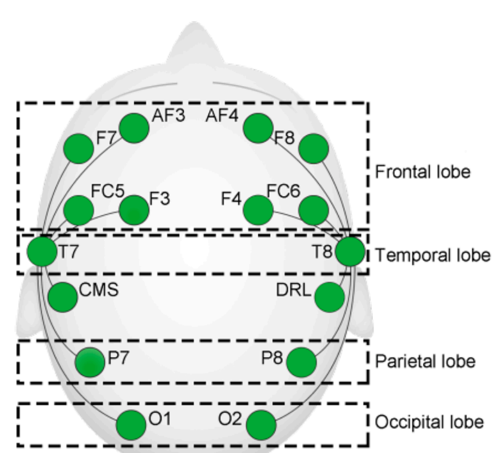

Fig. 3. Channels of EEG headset.

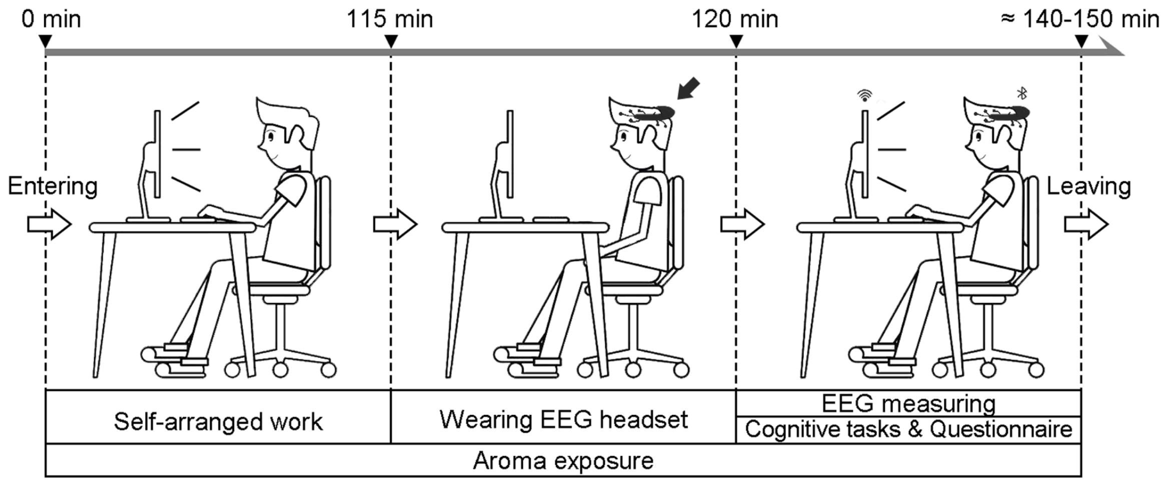

Fig. 4. Experimental procedure.

2.6. Data Processing and analysis

2.6.1. Task performance data

The online test application has the capability to record the accuracy and response time of each test. For every participant's test, the accuracy and response time under the experimental condition x are recorded as $\textit{Original Accuracy}_x$ and $\textit{Original Response Time}_x$, respectively.

The standardized accuracy $\textit{Accuracy}_x$ (A) can be determined as follows:

$$\textit{Accuracy}_x = \frac{\textit{Original Accuracy}_x}{\textit{Original Accuracy}_{max}}$$

where $\textit{Original Accuracy}_{max}$ represents the maximum accuracy achieved among the 7 cases encountered by participant. A higher value of A indicates greater accuracy and cognitive performance.

$\textit{Original Response Time}_x$ represents the time at which the participant completed the test. A higher value signifies a faster response from the participant and indicates superior cognitive performance. To maintain coherence between response time and accuracy, a higher score should reflect improved cognitive performance. Standardizing response time involves applying the reciprocal of $\textit{Original Response Time}_x$. The standardized response time $\textit{Response Time}_x$ can be calculated as follows:

$$\textit{Response time}_x = \frac{\frac{1}{\textit{Response Time}_x}}{\left(\frac{1}{\textit{Response Time}}\right)_{max}}$$

where $\left(\frac{1}{\textit{Response Time}}\right)_{max}$ represents the minimum response time achieved among the 7 cases encountered by the participant. A higher RT value indicates a quicker response by the participant and reflects greater cognitive performance.

2.6.2. EEG data

The raw EEG data were preprocessed quality assurance. The noisy data was eliminated using a high-pass filter, preserving the data within the 0.5–30 Hz range. Fast Fourier transform (FFT) technique and a Hamming window were employed to compute the absolute PSD in μV^2/Hz. In line with previous studies on cognitive performance and EEG [46], the power spectrum was segmented into different frequency bands: θ (4–8 Hz), α (8–14 Hz), and β (14–30 Hz). The relative PSD (%) was calculated by dividing the absolute PSD of each frequency band by the total absolute PSD within 4–30 Hz band.

2.6.3. Statistical analysis

This study primarily used RMANOVA and *t*-tests to analyze the data. As each group has a sample size greater than 30, the data are assumed to meet the requirements of normality and homogeneity. Since the main focus is on whether the presence of aromatic environments impacts cognitive task scores, the hypothesis testing also includes *t*-tests comparing each aromatic group with the odorless group, with *t*-test results serving as a basis for reporting RMANOVA results. Specifically, RMANOVA was applied to test for main effects and interaction differences among different aromatic environments, and independent or paired *t*-tests were used to assess differences between main effects groups and odorless groups. If the *t*-test result between a main effect group and odorless group is significant, then post-hoc tests of main effects and interactions based on RMANOVA results can be reported. If the *t*-test between the main effect group and the baseline is not significant but RMANOVA shows significant interactions, this may indicate that the interactions have masked significant and non-significant effects. In this case, further *t*-tests can compare 2-way sub-groups and odorless groups, and interactions can be reported if the *t*-test results are significant.

For subjective questionnaire and EEG activity, RMANOVA was directly applied, with post-hoc and interaction results reported as indicated by the RMANOVA findings. The odorless groups are shown as references in result figures only. The statistical procedures and corresponding figure numbers are illustrated in Fig. 5.

To investigate the impact of the aromatic environment on cognition, a detailed analysis was conducted to assess how odor type, concentration, and release frequency impact test scores. A RMANOVA was employed to explore the main effects and 2-way interactions of these 3 factors. In cases where a main effect was found to be statistically significant, pairwise comparisons between different levels of that factor were conducted using Bonferroni-corrected two-tailed *t*-tests. The covariance matrix for the repeated measures was assumed to have an independent structure (nonsphericity correction $\varepsilon = 1.0$), with a conservative correlation coefficient of $\rho = 0.1$. The significance level was set at 0.05, with an medium effect size of $d = 0.5$ [47]. In instances where interactions were significant, they were further elucidated through plots for comparison. The same variance analysis and post-hoc testing procedures were applied to both EEG and workload data. The statistical power, calculated based on the sample size in Section 2.2, is presented in Table 4.

3. Results

3.1. Subjective questionnaire

The descriptive statistics pertaining to the participants'

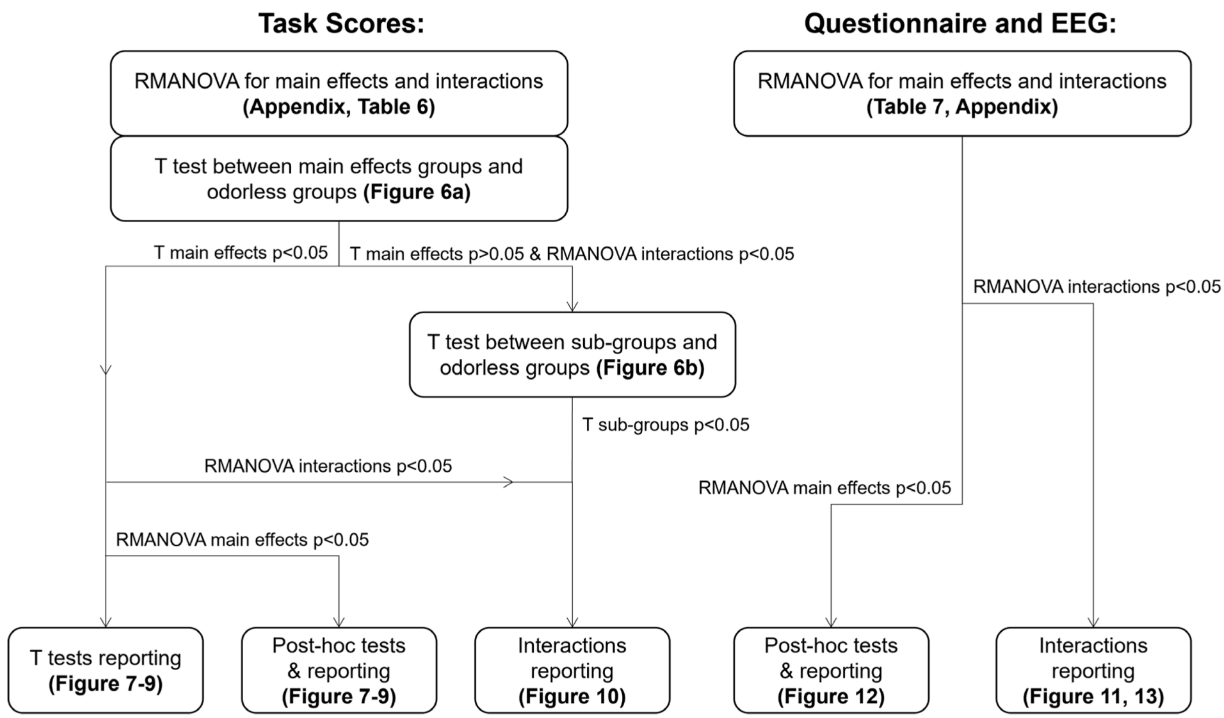

Fig. 5. Process for determining which tasks were affected by aromatic environments.

Table 4
Statistical power for RMANOVA and post-hoc analysis.

Statistical method	Term	Statistical power
RMANOVA	Odor	0.83
	Concentration	0.99
	Release cycle	0.97
	Odor * Concentration	0.97
	Odor * Release cycle	0.94
	Concentration * Release cycle	0.97
T test (Bonferroni corrected)	Odor	0.81
	Concentration	1.00
	Release cycle	0.99

environmental perception and workload in various aromatic environments are detailed in Appendix Table B0. The main effects and interactions of the 3 environmental factors were examined using RMANOVA, and the results are displayed in Appendix Tables B1-B3.

Appendix Table B1 indicates that the perceived intensity differences between various concentrations were significant. However, no significant differences were found in perceived intensity across different release frequencies or odors, and the interactions between these factors were also nonsignificant. According to Appendix Table B2, significant differences in perceived air quality were observed between different odors and concentrations, whereas no significant differences were found between different release frequencies. Additionally, no significant interactions were detected among these factors. Therefore, pairwise comparisons of perceived intensity at different concentrations and perceived air quality at different odors and concentrations are presented in Fig. 6.

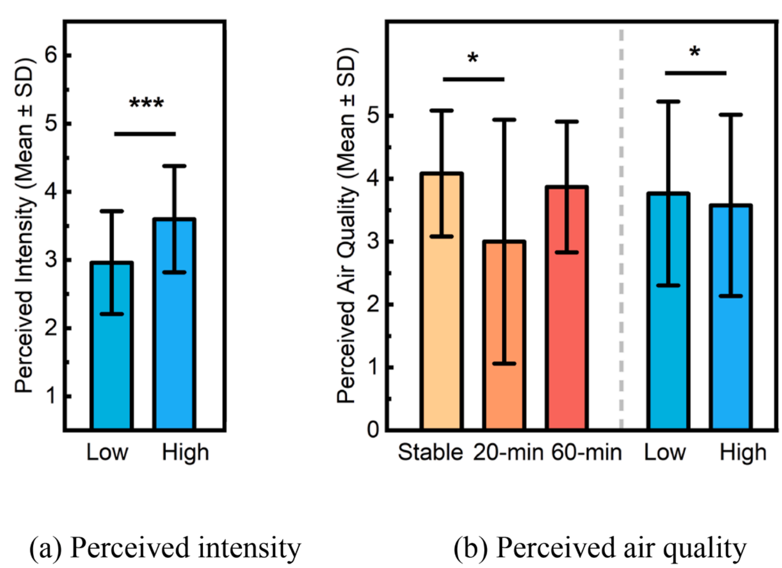

Fig. 6. Pairwise comparison of environmental perception. (*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$).

Fig. 6(a) shows that participants were able to clearly perceive differences in odor intensity across environments with varying concentrations. Fig. 6(b) indicates that participants rated the air quality of the lemon-scented environment as poorer, which might be attributed to a higher standard deviation in their evaluations of the lemon scent—suggesting that only some participants, rather than the majority, provided particularly low ratings. Additionally, Fig. 6(b) also shows that participants perceived better air quality in low-concentration environments compared to high-concentration ones, albeit with a small effect size.

As for workload, the results of Appendix Table B3 suggests that the impact of odor type, concentration, and release frequency on workload is not statistically significant. However, a notable interaction was observed between odor type and concentration, whereas other interactions did not yield significant results. The analysis of the interaction between odor type and concentration is depicted in Fig. 7. Variations in concentration do not have a significant impact on workload for lemon and peppermint. Conversely, for rosemary, cognitive workload escalates as concentrations increase.

In Section 2.4, the questionnaire demonstrated satisfactory reliability and validity, affirming NASA-TLX's efficacy in capturing the participants' workload. Section 3.2 highlights that variations in the aromatic setting resulted in significant differences in test scores. However, this section indicates that the aromatic environment did not exert a substantial impact on participants' subjective self-assessed workload. This discrepancy suggests that self-assessed workload may not provide an accurate reflection of how the aromatic environment impacts cognitive performance. To delve deeper into the impacts of the aromatic environment on cognitive performance from diverse perspectives, the subsequent section will undertake an analysis and comparison of EEG activity in various aromatic environments.

3.2. Task scores

The descriptive statistics for the test scores in various aromatic environments are detailed in Appendix Table A0. The main effects and interactions of the 3 environmental factors were examined using RMANOVA, and the results are displayed in Appendix Tables A1-A29. Table 5 provides a summary of the environmental factors that had a significant impact on the test scores.

While different aromatic environments may have diverse impacts on test scores, this diversity does not always lead to improved test performance compared to the absence of odor. When test scores in aromatic environments are classified by primary impacts and compared to those in odorless environments, the results are presented in Fig. 8(a). The symbols "+" or "-" scores in aromatic environments are significantly higher or lower than those in the odorless environment ($p < 0.05$).

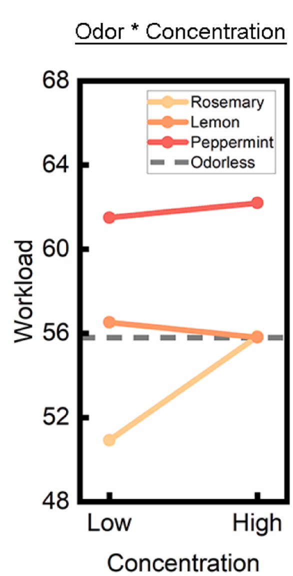

Fig. 7. Impacts of interactions on workload.

Table 5
RMANOVA results on impacts of aromatic environments on task performance.

Task and indicator		RMANOVA p ("*" represents <0.05)					
		Main effect [a]			Interaction [b]		
		M1	M2	M3	I1	I2	I3
T1	A						*
T2	A			*		*	*
	RT			*			
T3	A		*	*			
	RT			*		*	
T4	A		*	*			*
	RT			*	*		
T5	A						*
	RT	*					
T6	A			*			
	RT	*					
T7	A		*				
	RT		*				*
T8	A						*
	RT			*			*

[a] "M1" represents Odor, "M2" represents Concentration, and "M3" represents Release cycle.
[b] "I1" represents Odor * Concentration, "I2" represents Odor * Release cycle, and "I3" represents Concentration * Release cycle.

While no significant differences were observed in the accuracy of T1 to T3 and T5 to T8, and response time of T2 and T8 between aromatic environments and the odorless environment when analyzed based on main effects, Table 6 indicates the presence of interaction effects on T1-A, T2-A, T5-A, T8-A and T8-RT. These interaction effects may lead to non-significant differences following the combination of factors. To examine whether it is meaningful to report the interactions above, *t*-tests between aromatic sub-groups and odorless groups were conducted, and the results are shown in Fig. 8(b). With the exception of T1-A and T2-A, the subgroups exhibit significant differences in T5-A, T8-A and T8-RT when compared to the odorless group. Therefore, the *t*-tests results and post-hoc results the tasks which show significance in Fig. 8(a) will be reported, and the interactions on the tasks which show significance in Fig. 8(a) and Fig. 8(b) will be reported. Additionally, Fig. 8 demonstrates that both the main effect groups and the 2-way subgroups consistently showing higher test scores than the baseline (odorless group) in all instances. This consistency suggests a positive impact of aromatic environments on cognitive performance.

If Fig. 8 presents the improvement of test scores due to a specific factor and Table 6 indicates the statistical significance of the RMANOVA results, subsequent pairwise comparisons of the main effects at various levels of this factor were undertaken. The results of these comparisons are illustrated in Figs. 9–11.

Fig. 9 depicts the variations in test scores among different types of odors. In comparison to the baseline, all 3 odors demonstrate the ability to improve the response time for the meaningless figure recognition task (T3-RT). Rosemary exhibits a capacity to improve the accuracy of the signal-code test (T4-A), while peppermint accelerates the response time for the visual reaction task (T6-RT). Notably, the significant differences in the aforementioned cognitive tasks are observed between the aromatic groups and the baseline, rather than among the different odors. In the Stroop test, both lemon and peppermint are shown to accelerate the response time (T5-RT) and exhibit a significant variance when compared to rosemary. This suggests that lemon and peppermint odors have a more pronounced impact on enhancing performance in Stroop test.

Fig. 10 illustrates the variations in test scores between different concentrations. Low concentrations demonstrate the ability to expedite response times in meaningless figure recognition and Stroop tests (T3-

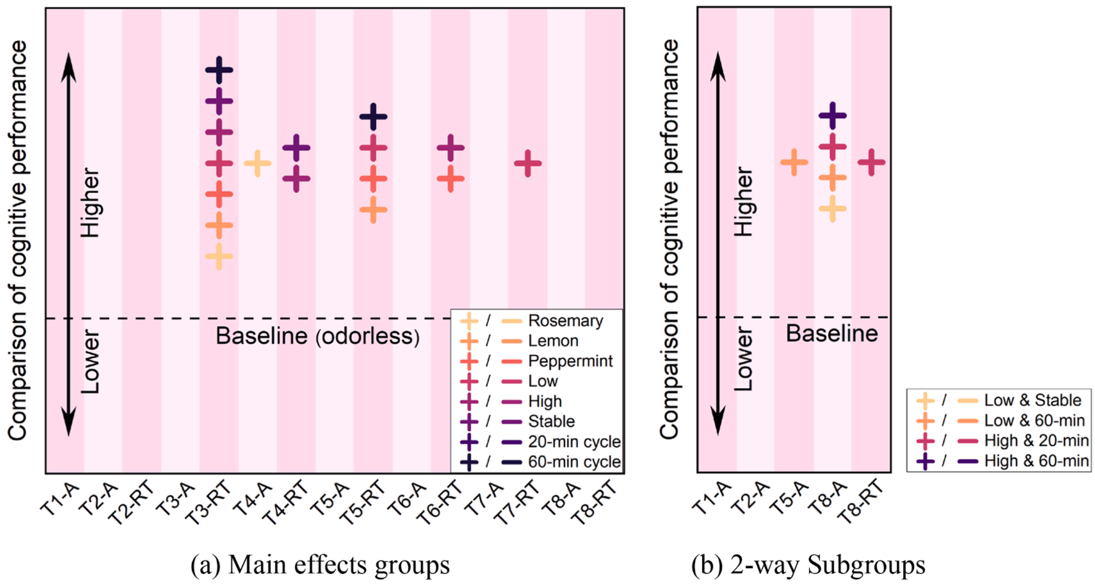

Fig. 8. Independent *t*-test results comparing aromatic groups and odorless groups.

Table 6
Aspects significantly affected by aromatic environmental factors.

Factor	Cognitive task	Workload	EEG activity
Odor	T3, T4, T5 and T6	N/A	θ of temporal lobe
Concentration	T3, T4, T5, T6 and T7	N/A	θ and β of all lobes
Release cycle	T3, T4, T5, T6 and T7	N/A	θ and β of frontal and parietal lobes
Odor * Concentration	T4	Appl.	θ of all lobes, α of frontal and temporal lobes, and β of parietal and temporal lobes
Odor * Release cycle	T3	N/A	θ of frontal lobe, andα of parietal and occipital lobes
Concentration * Release cycle	T4, T5, T7 and T8	N/A	N/A

RT and T5-RT) compared to the baseline. On the other hand, high concentrations accelerate response times in meaningless figure recognition and signal-code tests (T3-RT and T4-RT) in comparison to the baseline. Notably, significant differences in the aforementioned cognitive tasks are observed primarily between aromatic groups and the baseline, rather than among different concentrations. In the visual reaction task, high concentrations lead to faster response times (T6-RT) and exhibit a notable difference from the results at low concentrations. Conversely, in the overlapping task, low concentrations result in quicker response times (T7-RT) and display a significant difference from the results at high concentrations. These results suggest that while aromatic environments generally improve cognitive performance, optimal improvement is achieved only at specific concentrations. Furthermore, the ideal aromatic concentration varies across different cognitive tasks.

Fig. 11 presents the variations in test scores resulting from different release frequencies. In comparison to the baseline, the stable release demonstrates the ability to improve response time in the Stroop test (T5-RT), with a significant difference observed only between the stable release group and the baseline. In the task of meaningless figure recognition, both the stable release and the 60-min-cycle intermittent release exhibit accelerated response times (T3-RT), with a notable difference between the stable release and the 20-min-cycle intermittent release. In the signal-code test, the stable release accelerates response time (T4-RT) and displays significant discrepancies when compared to both intermittent release modes. These results suggest that the stable release contributes more effectively to improving cognitive performance, while the 20-min-cycle intermittent release has a comparatively lesser impact on cognitive performance.

In addition to examining the main effects, an examination was conducted to determine if there were any interactions between factors impacting test scores. The results of RMANOVA for these interactions

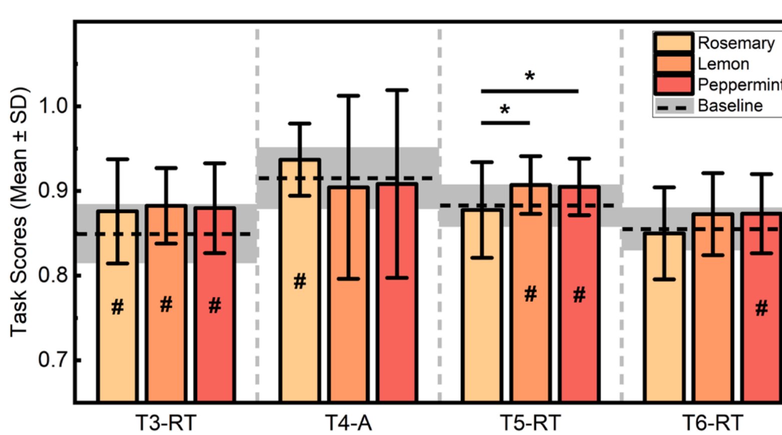

Fig. 9. Pairwise comparison of task scores across different odors. (*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.005$; #: significantly different from baseline with $p < 0.05$).

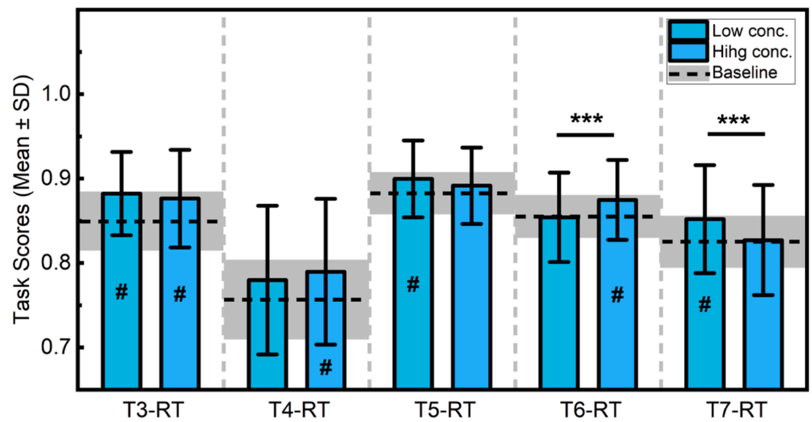

Fig. 10. Pairwise comparison of task scores between different concentrations. (*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.005$; #: significantly different from baseline with $p < 0.05$).

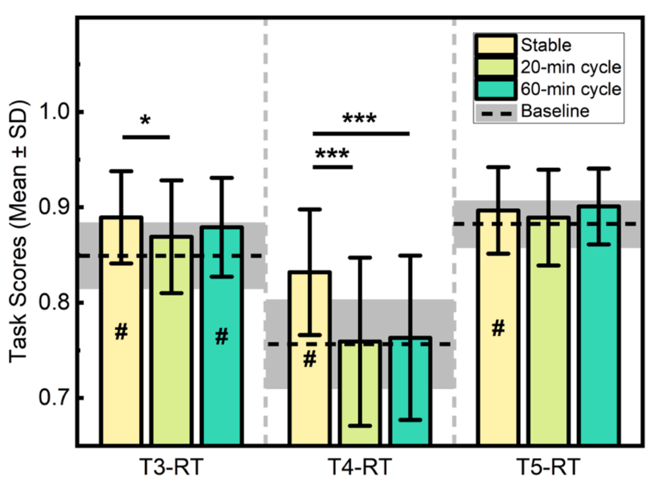

Fig. 11. Pairwise comparison of task scores across different release cycles. (*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.005$; #: significantly different from baseline with $p < 0.05$).

are detailed in Appendix Tables A1-A29. The results reveal significant interactions for the following pairs: Odor*Concentration on T4-RT, Odor*Release frequency on T3-RT, and Concentration*Release frequency on T4-A, T5-A, T7-RT, T8-A, and T8-RT. These interactions are represented in Fig. 12.

While Fig. 12 illustrates that a high concentration results in a more pronounced acceleration in the response time of the signal-code test (T4-RT), the interaction analysis for T4-RT reveals that this impact is statistically significant only for the lemon odor. In contrast, for rosemary and peppermint, a low concentration demonstrates a more noticeable acceleration in comparison to a high concentration.

Fig. 12 depicts that the stable release leads to a notable acceleration in the response time for the task of meaningless figure recognition task (T3-RT). This conclusion is further supported by the results of the interaction analysis for T3-RT. Additionally, main effects results indicate that the intermittent release in 60-min-cycle has a more significant enhancing impact compared to 20-min-cycle. However, the interaction analysis reveals that this main effect is specifically observed in the case of rosemary and lemon, while for peppermint, the 20-min-cycle intermittent release demonstrates a greater improvement compared to the 60-min-cycle.

Besides the aforementioned interactions, the study primarily focuses on the relationship between concentration and release frequency. Notably, interactions were predominantly observed in T4-A, T5-A, T8-A, and T8-RT, with no significant differences detected in the main effects analysis. This suggests that the presence of interactions hinders the isolation of impacts related to individual factors. While the RMANOVA results for T5-A indicate a significant interaction between concentration and release frequency, the effect size is low, thereby not warranting further discussion. Noteworthy is the observation that in cases of stable release, the impact of concentration on test scores is magnified. This can be attributed to both concentration and release frequency representing the extent of exposure to aromatic substances. In comparison to intermittent release, stable release leads to heightened exposure levels, resulting in more pronounced improvements or hindrances in cognitive performance in response to changes in concentration under stable release conditions.

3.3. EEG power spectrum density

An increasing number of studies focusing on indoor cognitive performance utilize EEG activity analysis to evaluate cognitive performance. A traditional research approach entails conducting cognitive task assessments concurrently with EEG signal detection within a controlled setting [48]. Variations in EEG activity can serve as a direct indicator of the management of cognitive resources such as attention and cognitive load, and can also furnish empirical evidence for investigating the relationship between test results and EEG activity. This study scrutinizes and contrasts the frequency domain indicators most frequently employed in such investigations.

Descriptive statistics detailing the relative PSD in various aromatic environments are available in Appendix Table C0, while the results in Tables C1-C117. In cases where the p-value of an ANOVA factor is below 0.05, additional pairwise comparisons of the primary impacts across different levels of that factor will be performed, and the results are presented in Fig. 12.

Fig. 13 initially presents the results from 14 EEG channels. The colored channels signify that PSD of a particular waveform at one level of the environmental factor is notably higher compared to another level of the environmental factor (t-test $p < 0.05$). Subsequently, the investigation was broadened to encompass 4 brain lobes. Colored brain lobes indicate ANOVA $p < 0.05$, with the associated bar graphs illustrating the results of the pairwise comparisons.

Fig. 13 illustrates the main effects of odor on relative PSD, indicating notable variances associated with the type of odor. Particularly, the impact of peppermint is prominent when contrasted with the other two odors. Peppermint demonstrates a significant improvement of β waves, whereas rosemary and lemon exhibit a notable increase in θ waves. The contrast between rosemary and peppermint is particularly striking and is consistent across all 4 brain lobes. Although less prominent than the contrast between rosemary and peppermint, the differentiation between lemon and peppermint is still discernible in the parietal, temporal, and

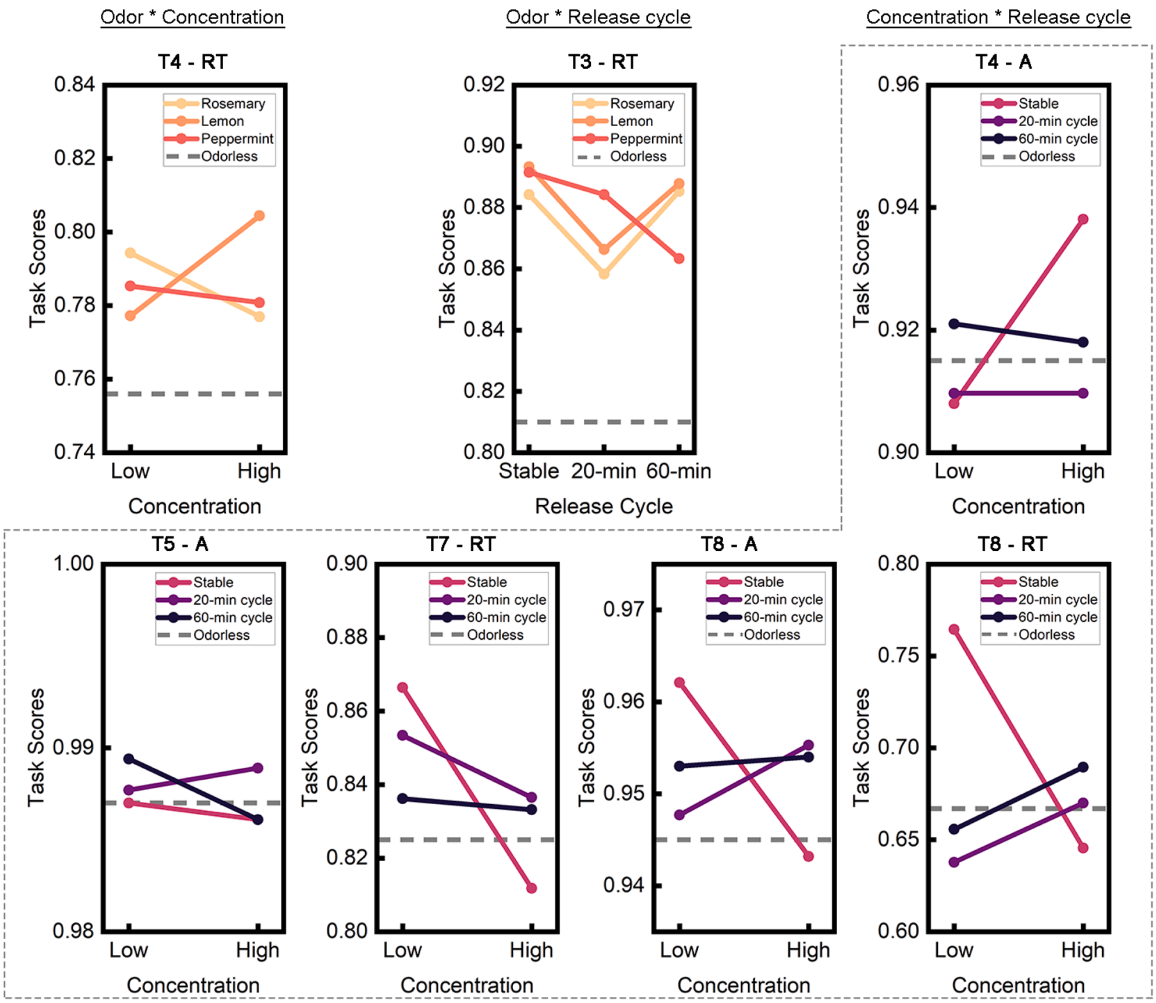

Fig. 12. Impacts of interactions on task scores.

occipital lobes.

The main effects of concentration reveal that low concentration levels lead to a significant increase in β waves, while high concentration levels result in a significant increase in θ waves. The impact of concentration on relative PSD is predominantly observed in the frontal and parietal lobes.

The main effects of release frequency indicate that significant variances are observed in select channels. Specifically, at the brain lobe level, the relative PSD of stable release and intermittent release in 20-min-cycle predominantly exhibit notable distinctions in the temporal lobe. Stable release is associated with an increase in the proportion of θ waves and a corresponding decrease in α waves.

A subsequent analysis was performed to assess the presence of significant interaction impacts on the relative PSD of the brain lobes. The results for these interactions are detailed in Appendix Tables C90-C117. The results reveal significant interaction impacts between odor and concentration on the relative PSD across the 4 brain lobes. Furthermore, notable interaction impacts between odor and release frequency were observed in the frontal, parietal, and occipital lobes. Conversely, no significant interaction was identified between concentration and release frequency. The interaction impacts displaying significant variances are illustrated in Fig. 14.

The results of the interaction analysis between odor and concentration reveal that the observed pattern of low concentration leading to an increase in β waves and high concentration leading to an increase in θ waves is predominantly impacted by the lemon odor. This consistent pattern is evident across all 4 brain lobes. In contrast, the impact of concentration on rosemary and peppermint odors shows an opposite trend. Exposure to rosemary and peppermint environments resulted in a higher concentration correlating with a rise in the proportion of θ waves and a decline in the proportion of α and β waves, particularly notable in the temporal lobe.

The interaction results of odor and release frequency indicate that the release frequency of rosemary and lemon consistently impacts the relative PSD in a manner that is diametrically opposed to the impacts observed with peppermint odor. Specifically, in the presence of peppermint odor, intermittent stimulation leads to an increase in β waves and a decrease in α waves. Conversely, for rosemary and lemon odors, intermittent stimulation results in a decrease in β waves and an increase in α waves. These contrasting interaction impacts elucidate the limited number of significant differences detected when examining the main effects of release frequency across different odor types.

4. Discussion

4.1. Aromatic Environments: Beneficial to task performance, irrespective of their relaxing or stimulating nature

Previous studies on aromatic environments and cognitive performance have mainly focused on the effects of odor types. Du et al. [8] investigated the effects of lemon oil but did not report the concentration. They found that a lemon environment increased accuracy in simple tasks and sped up responses in complex tasks, but at the cost of reduced accuracy in the complex tasks. This phenomenon was explained by

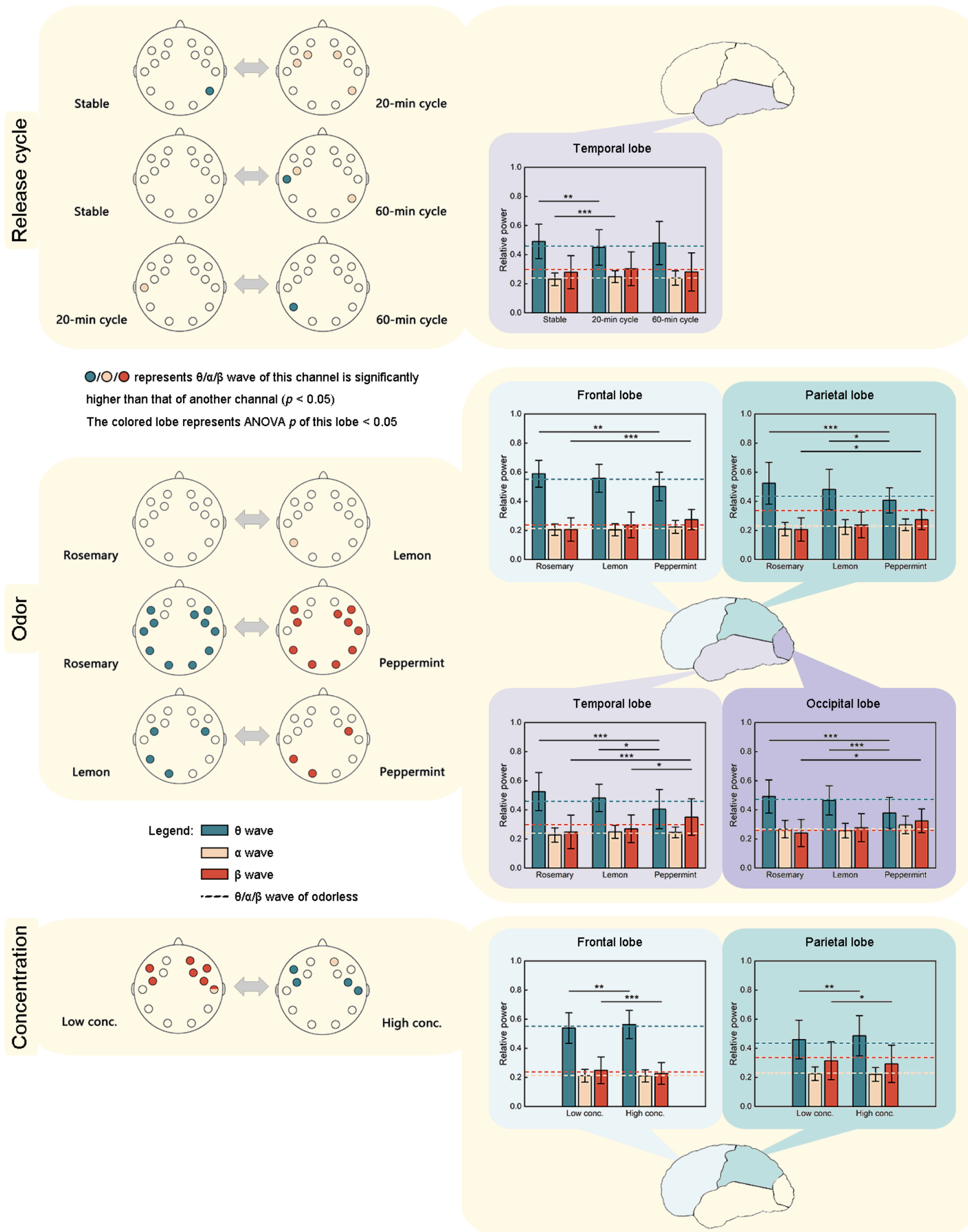

Fig. 13. Pairwise comparison of EEG power spectrum density of θ, α, and β wave across different channels and lobes.

suggesting that the lemon environment made participants more impulsive. In our study, we also observed faster responses, but unlike Du et al., we did not observe a decrease in accuracy. In fact, Choi et al. [9] did not find any decline in accuracy either. Choi et al. found that the lemon environment improved performance in memory tasks, though they did not report odor concentration or find significant effects. This could be due to the fact that the effect of lemon on response time enhancement was greater than its impact on accuracy. Wang et al. [11] reported only the concentration of d-limonene in their sweet orange study, suggesting that their environment closely resembled the low and stable concentration used in our study. Wang et al. found that aromatic environments could speed up responses and improve accuracy, which aligns with our

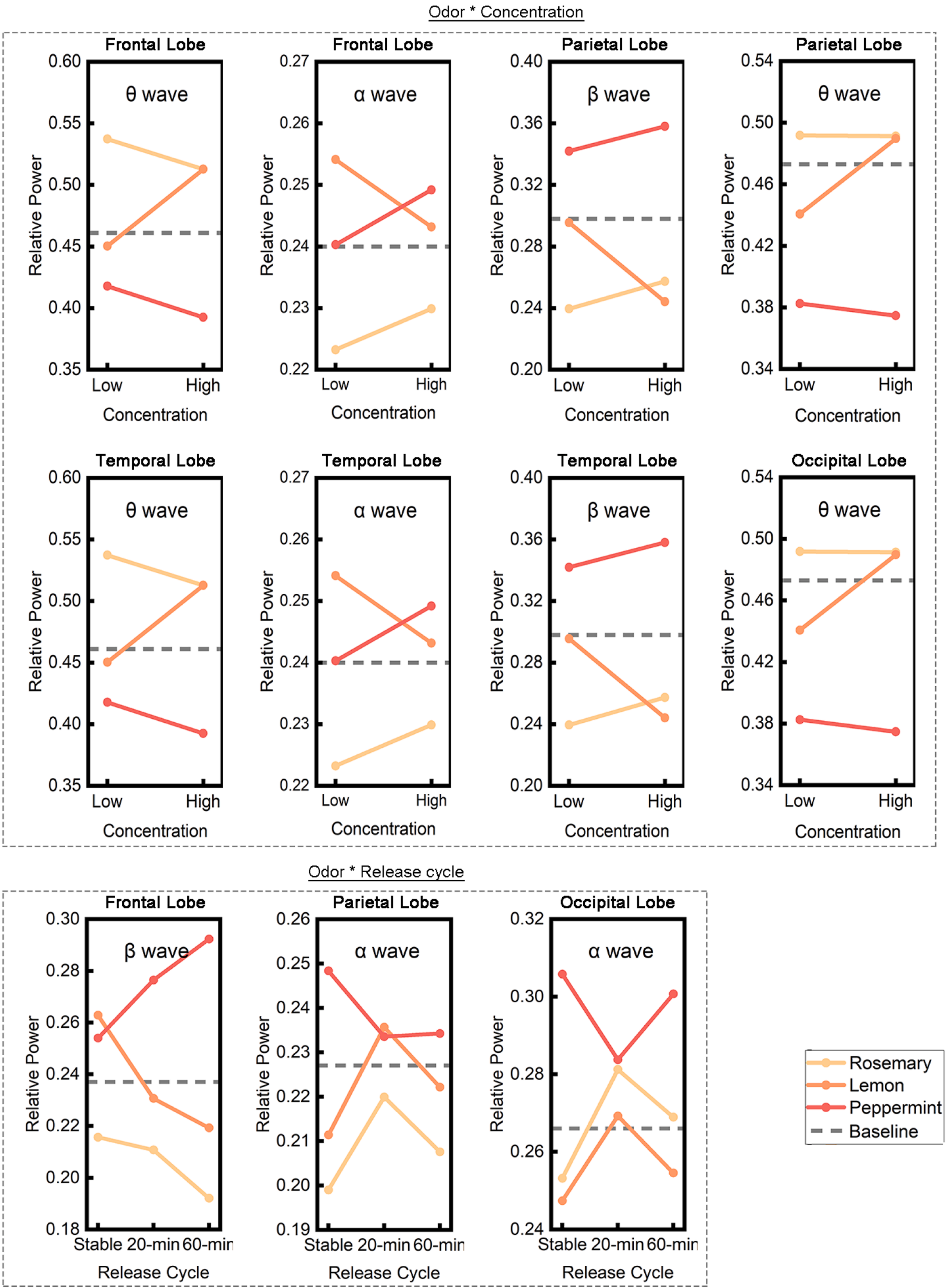

Fig. 14. Impacts of interactions on EEG power spectrum density.

results. However, most of their results were not significant, likely due to their small sample size (only 10 participants). In other words, the cognitive effects of the odor were not as pronounced as they had predicted. Additionally, Choi et al. [10] studied a sweet orange environment with 10-minute interval releases but only reported the theoretical concentration. We speculate that the peak concentration in their experiment was close to our low concentration level. Choi et al.'s study found an impact on perception but no cognitive effects, which could also be due to their insufficient sample size (21 participants). Our study shows that intermittent release in an aromatic environment can improve cognition, but with a lower effect size compared to stable concentrations. Therefore, when studying intermittent release, the sample size should be larger than in studies with stable concentrations. To summarize, our study employed more comprehensive experimental conditions and provided a sufficient statistical power, effectively validating previous research results while offering more in-depth findings.

The characteristics of smells have been traditionally viewed as falling into 2 categories: relaxation and stimulation. Smells that are often associated with relaxation include sweet orange [11], lavender [49], and cinnamon [50]. These fragrances are widely believed to aid in stress reduction, improve mental health, and evoke a sense of tranquility and calm. In contrast, scents such as peppermint [51] and sage [52] are typically classified as stimulating, capable of eliciting excitement or alertness to certain degree. EEG analysis conducted in this study revealed different relaxation-stimulation properties for rosemary, lemon, and peppermint. In cognitive research, θ waves are generally seen as indicative of fatigue [53]. Recent studies in the field of indoor environmental science have suggested that an increase in θ waves may be linked to relaxation, possibly triggered by a feeling of comfort in the surroundings [54,55]. α waves are associated with heightened wakefulness [25], while β waves are considered markers of excitement, tension, stress, and alertness [56]. The results of this study demonstrated that in the presence of peppermint scent, participants experienced a significant decrease in θ waves and a notable increase in β waves, indicating that peppermint may improve feelings of excitement and alertness while performing tests. In contrast, exposure to rosemary and lemon scents resulted in higher θ waves and lower β waves, with rosemary showing more pronounced differences compared to the baseline. These results suggest that these 2 fragrances, particularly rosemary, may have calming and relaxing properties.

Baccarani et al. [18] presented a challenge to the conventional perspective by proposing that the relaxing or stimulating properties of a scent are not only determined by its type but are closely linked to its concentration. The study suggests that lower concentrations of scents tend to induce relaxation, while higher concentrations may lead to stimulation. While this study did observe significant impacts of concentration changes on EEG activity, these results do not completely align with the perspective put forth by the aforementioned study. The research results indicate that the impact of concentration changes on EEG is not simple but rather interacts with the types of odors. Through interaction analysis, specific mechanisms were revealed regarding how odor types and concentrations impact EEG. In a lemon-scented environment, an increase in concentration notably raised the proportion of θ waves and reduced α and β waves, indicating that higher concentrations of lemon improve its soothing and relaxing properties. Conversely, in rosemary and peppermint environments, higher concentrations resulted in a decrease in the proportion of θ waves and an increase in α and β waves in the temporal lobe, suggesting that increased concentrations of rosemary and peppermint may hinder relaxation or improve alertness to certain extent. This discovery highlights the complex relationship between odor type and concentration, demonstrating that the impacts of concentration on EEG activity differ across various odor types. Therefore, when discussing the relaxing or stimulating impacts of aromatic environments, it is essential to consider both the type of odor and its concentration to gain a comprehensive understanding of the underlying mechanisms.

Despite the varied impacts of different aromatic environments on EEG activity, all aromatic environments generally improved cognitive task performance compared to an odorless environment. Previous research has presented conflicting results on the contributions of relaxation and alertness to the improvement of cognitive abilities [11, 49,51]. This study revealed that even when a specific aromatic environment did not lead to improved test scores in a particular type of task, it did not have a significantly detrimental impact on cognition. Essentially, both relaxation and alertness induced by aromatic environments have a positive impact on cognitive performance. It is important to highlight that many studies sought to establish correlations between EEG frequency domain characteristics and cognitive task performance [57,58], but these associations may only be applicable to the specific environmental stimuli examined, lacking robust evidence for generalizability to other settings. The research indicates that while aromatic environments may have dual impacts on subjective experiences or physiological conditions, as evidenced by variations in relative PSD, their impact on cognitive task performance consistently yields positive results.

4.2. Impact of aromatic environments on task performance potentially mediated by EEG activity

Since the aromatic environment could significantly affect task scores and PSD, there may be some potential correlations between the two. According to the results of the experiments, specific tasks, workload and brain waves that significantly affected by aromatic environmental factors are listed in Table 6. EEG analysis reveals that rosemary has a calming impact, enhancing performance on the signal-code test (T4) that evaluates short-term memory. On the other hand, peppermint boosts alertness and improves tasks related to perceptual abilities, such as Stroop test (T5) and the visual reaction test (T6). High concentration levels induce relaxation and improve performance on the signal-code test (T4), while low concentration levels increase alertness, leading to improved performance on the visual reaction test (T6) and the overlapping test (T7) assessing logical reasoning abilities.

The results also indicate that the frequency of release can have an impact on test performance. Consistent levels of concentration are more favorable for enhancing scores, especially in assessments related to short-term memory, such as the meaningless figure recognition test (T3) and the signal-code test (T4). The impact of release frequency on EEG activity is predominantly noticeable in the temporal lobes. A stable release of aromatic compounds in the environment leads to an increase in the ratio of θ waves and a decrease in the ratio of α waves, thereby facilitating relaxation, which is in line with the requirements of cognitive tasks involving short-term memory.

The study reveals consistent patterns in the impacts of odor type interactions with other factors on EEG activity and test scores. When examining the interaction between odor type and concentration, it was noted that as concentration levels rise, lemon tends to promote relaxation, while rosemary and peppermint lead to increased alertness. This trend is evident in the signal-code test (T4), where test scores improve with higher concentrations of lemon, but decrease with rosemary and peppermint. A similar trend is observed in the interaction between odor type and release frequency. In comparison to a 60-min-cycle of intermittent release, rosemary and lemon exhibit higher proportions of α and β waves under a 20-min-cycle, while peppermint shows lower levels of α and β waves. This pattern is also reflected in the meaningless figure recognition test (T3). Specifically, rosemary and lemon demonstrate better performance under 20-min-cycle intermittent release conditions, while peppermint performs better under a 60-min-cycle release. These results suggest that changes in EEG activity correspond to the cognitive demands of the tasks, indicating that improvements in task performance in aromatic settings are linked to the optimization of brain cognitive function systems.

4.3. Limitations and futural works

In this research, improvements in test performance primarily manifested as quicker response times, with only sporadic occurrences of improved task accuracy. Numerous studies propose that aromatic settings might induce higher impulsivity [59,60], potentially hastening response times. Another explanation could be that the cognitive assignments employed in this research were not particularly demanding for the subjects, leading to elevated levels of accuracy that hindered the detection of statistical variances in precision. Furthermore, certain results suggest that EEG activity does not entirely explain variations in test results. For instance, the impacts on test scores mainly revolve around the interplay between concentration and release frequency, but no notable impact on EEG activity. In fact, this study only observed a few results where release frequency was associated with EEG activity. However, we cannot rule out the possibility that we may have overestimated the effect size of release frequency on EEG activity prior to the start of the experiment.

Prior research has indicated that indoor environmental elements could also impact cognitive performance through environmental perception, physiological parameters, and psychological health. Studies have shown that cognitive performance was correlated with odor preference [9]. Observations of HRV suggested that the odors could improve cognitive performance by modulating emotional states during work [11]. Anatomical and pharmacological studies suggest that odors may have the potential to improve health, thereby enhancing cognition. For example, rosemary has been shown to increase deoxygenated hemoglobin levels and oxygen extraction [61], as well as inhibit acetylcholinesterase, which could enhance cognitive function [62]. Similarly, lemon has been found to inhibit acetylcholinesterase [63], and possesses antioxidant properties that help prevent oxidative stress and related cellular damage. Peppermint has been shown to enhance memory by increasing brain-derived neurotrophic factor levels in brain tissues and plasma, as well as doublecortin in the dentate gyrus of hippocampal tissue [64]. However, the health effects of odors are complex, and improper use can lead to certain risks. Indoor air studies have long considered essential oils as air pollutants [65,66]. The toxicity of essential oil components can cause mucous membrane irritation, allergies, and symptoms such as nausea and headaches [67]. These potential negative aspects suggest that indiscriminate application of scents should be avoided. Du et al. [8] argue that in aromatic environments, both odor effects and pollution effects coexist, and distinguishing between these two health effects presents a challenging task in cognitive research. Therefore, our subsequent studies will encompass a wider array of subjective and objective metrics in the experimental framework to delve into the mechanisms by which aromatic environments impact cognitive abilities.

5. Conclusion

This study examined the cognitive task scores, self-assessed workload, and EEG activity results of 44 participants exposed to various aromatic environments. The conclusions are outlined as follows:

1) Exposure to aromatic environments can significantly improve cognitive task scores. The impacts of odor type and concentration on cognitive performance vary across different tasks. Compared to intermittent release, a stable aromatic environment results in more pronounced improvements in performance. There is an interaction between concentration and release frequency impacting test scores, with stable release amplifying the positive impacts of concentration. No negative impacts of aromatic environments on cognitive tasks were observed.
2) Aromatic environments significantly impact the relative power spectral density of EEG during cognitive tasks. Exposure to rosemary and lemon scents increases the proportion of θ waves, while peppermint scent increases the proportion of β waves. The interaction between odor type and concentration indicates that increasing the concentration of lemon scent further increases θ waves while decreasing α and β waves. In contrast, increasing the concentration of rosemary and peppermint scents reduces θ waves and increases α and β waves. Additionally, there is an interaction between concentration and release frequency, with peppermint's release frequency impacting EEG activity differently compared to the other two odors.
3) Differences in self-assessed workload across various aromatic environments are not significant. Test scores and EEG activity generally exhibit consistent patterns of change, making EEG an effective indicator for evaluating the impact of aromatic environments on cognitive performance. Aromatic environments that promote relaxation and calmness improve short-term memory and logical reasoning task performance, while environments that increase brain arousal and alertness improve performance on perceptual tasks.

CRediT authorship contribution statement

Yongxiang Shi: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Junmeng Lyu:** Writing – original draft, Visualization, Data curation. **Christhina Candido:** Writing – review & editing. **Julie Tian Miao:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Zhiwei Lian:** Writing – review & editing, Supervision, Software, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.buildenv.2024.112456.

Data availability

The available data was provided in the supplementary materials

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