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Olfactory Environment Design in Office Buildings: A Study on the Recovery Effect of Specific Fragrances on Work Fatigue Based on Multimodal Measurement

Mizhi Feng [1,2], Chengmin Zhou [1,2,*], Fangfang Yuan [1,2] and Jake Kaner [3]

[1] College of Furnishings and Industrial Design, Nanjing Forestry University, Nanjing 210037, China; fengmizhi@njfu.edu.cn (M.F.); yuanfangfang@njfu.edu.cn (F.Y.)
[2] Jiangsu Co-Innovation Center of Efficient Processing and Utilization of Forest Resources, Nanjing Forestry University, Nanjing 210037, China
[3] School of Art and Design, Nottingham Trent University, Nottingham NG1 4FQ, UK; jake.kaner@ntu.ac.uk
* Correspondence: zcm78@163.com

Abstract

The office environment significantly influences employees' work efficiency and health. With the increasing prevalence of modern, enclosed and monotonous office settings, employees often work under high-intensity conditions for extended periods. This situation leads to physiological and psychological fatigue, which in turn affects work efficiency and overall well-being. This study explores how olfactory stimulation influences physiological and psychological fatigue in office environments. It also examines its effects on cognitive recovery. Through market research and user surveys, three types of scents were selected as experimental materials (floral, fruity, and forest scents). Utilizing multi-channel fatigue identification technology and wearable biosensors, the study monitored in real-time the physiological responses of employees to different olfactory stimuli, such as pupil diameter, heart rate variability (HRV), electromyography (EMG), and electroencephalogram (EEG) signals. Additionally, subjective evaluation questionnaires were used to comprehensively assess the effects of olfactory stimulation on psychological fatigue. The results showed that all three olfactory interventions to some extent alleviated employee fatigue and improved cognitive abilities. Among them, the floral intervention had a better effect on the recovery of physiological fatigue, the fruity intervention had a better effect on the recovery of psychological fatigue and cognitive abilities, and the forest intervention had a slightly inferior recovery effect but could effectively reduce time load. This research aims to provide new ideas for the design of sustainable office working environments. Introducing appropriate olfactory stimuli can effectively alleviate employees' office fatigue, enhance their work efficiency and overall well-being.

Keywords: restorative olfactory environment; workplace fatigue; psychophysiological recovery; cognitive recovery; olfactory intervention; employee well-being

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1. Introduction

Today, people generally spend about 80 to 90% of their daily lives in indoor environments. Prolonged indoor living away from nature can lead to physical and mental exhaustion [1]. In the fast-paced office environment, employees often work long hours and experience high levels of stress, leading to severe physiological and psychological fatigue. Physiologically, this fatigue manifests as bodily tiredness and muscle soreness;

psychologically, it is characterized by low mood and difficulty concentrating [2]. Long-term exposure to this state of fatigue not only adversely affects work efficiency and quality of life [3,4] but may also induce a series of health problems, including anxiety, depression, insomnia [5,6], musculoskeletal disorders [7], and chronic fatigue syndrome [8].

With the growing awareness of healthy office concepts, the importance of improving the office environment to alleviate work fatigue has become increasingly prominent. Numerous studies have shown that various aspects of the office environment, including layout, office furniture, lighting, temperature, greening, control, noise, and aesthetics, all have a significant impact on the physiological and psychological health of office workers as well as their work performance [9–12]. In the study by Fang et al. [13], improving the lighting and correlated color temperature (CCT) of the work environment reduced computer-work fatigue, with the lowest fatigue level observed at 4000 K + 500 lx. In another study, Ojala et al. [14] investigated the alleviating effects of brief virtual natural breaks in the office environment, and the results showed that natural sounds and videos help relieve stress. Mattila et al. [15] also found that after watching forest videos, there was an increase in positive emotions and a decrease in negative emotions, as well as an increase in perceived recovery.

Research on the brain has shown that olfaction (sense of smell) is closely related to the limbic system, which is responsible for instinctive functions. An increasing number of studies have shown that olfaction can affect human alertness, fatigue levels and cognitive abilities through mechanisms such as emotional regulation, neural modulation, cognitive processing and physiological responses [16–19]. Moreover, olfactory intervention, as a method to improve fatigue, is gaining attention due to its minimal interference with daily activities and work [20]. Various olfactory stimulants include floral, fruity, herbal, and woody scents, all of which directly or indirectly affect human psychological and physiological conditions [21].

Hasheminia and Sho'ouri's [22] research demonstrated that inhaling musk aroma during neurofeedback training can improve training efficiency. Among different types of scents, mint aroma is quite popular, and research has shown that it can enhance attention, boost cognitive abilities [23], and improve memory [24]. It has also been shown to improve sleep quality in patients with fatigue and anxiety and to increase alertness under monotonous work and relaxation conditions [25]. The aroma of rosemary can also enhance the vigilance of drivers [26]. Exposure to floral scents can improve emotional states and may promote brain functions related to memory, speech, and movement, thereby potentially improving emotional health, depression, and memory disorders [27]. Studies have shown that the scent of lavender can alleviate fatigue, and its essential oil aromatherapy can reduce fatigue in patients with heart disease [28] and effectively decrease depression, anxiety, and stress in elderly community members [29]. Xiong et al. [30] studied the natural aroma of Pink Jasmine flowers and found that it has physiological and psychological recovery effects. Research has also shown that the aroma of citrus fruits has multiple effects [21]. Citrus fruits and their essential oils have a pleasant scent and can have relaxing, calming, invigorating, mood-enhancing, stress-relieving, and fatigue-reducing effects [31–34]. Empirical studies have shown that sensory contact with natural wood and woody materials induces physiological relaxation in humans [35]. After olfactory stimulation with the natural aroma of wood or volatile essential oils from wood, participants showed increased parasympathetic nerve activity and increased levels of salivary dehydroepiandrosterone sulfate [36,37]. This olfactory stimulation promoted physiological relaxation and reduced participants' emotional anxiety, depression, and fatigue [38].

However, previous studies have already pointed out several significant limitations. Firstly, most experiments only focused on a single outcome domain, usually an emotional

state or a physiological indicator such as heart rate or skin conductance. At the same time, office fatigue is a multi-dimensional construct involving cognitive efficiency, musculoskeletal stress, and psychological stress. Therefore, it is not clear how olfactory stimulation affects the overall recovery of these different fatigue dimensions. Secondly, previous work often studied only one type of fragrance or compared different fragrances across different experimental protocols, making it difficult to draw reliable conclusions about the differential effects of floral, citrus, and woody fragrances under the exact task requirements. Thirdly, although many papers concluded that certain fragrances "have a relaxing effect" or "have a stimulating effect", they rarely translated these findings into design-oriented guidelines, that is, clearly indicating which fragrance types are most suitable for different office tasks and workload conditions.

To address these deficiencies, this study developed a standardized office fatigue assessment paradigm and combined multiple measurement methods to systematically evaluate the recovery effects of three typical fragrance types compared with a control group. We further comprehensively assessed the fatigue-relief effects of different fragrances for office workers, with the aim of providing new ideas and methods for alleviating office fatigue. This study aims to answer the following research questions:

1. What is the impact of different scent olfactory stimulations on cognitive abilities?
2. What is the impact of different scent olfactory stimulations on physiological fatigue?
3. What is the impact of different scent olfactory stimulations on psychological fatigue?
4. Which type of olfactory intervention is appropriate for the office scenario?

2. Materials and Methods

2.1. Participants

The experimental subjects were recruited from a group of young workers over the age of 25. The participants were recruited through online channels (such as the school's email list and the experimental announcement platform), based on an a priori power analysis, conducted in G*power 3.1.9.7, (α = 0.05, β = 0.80, medium to high effect size based on ANOVA: Repeated measures, within factors), 40 participants were recruited. Based on the pre-existing power analysis, we initially recruited 40 young office workers to participate in the experiment. They were all assigned to complete three fragrance conditions and a control group without any odor. All selected participants were required not to stay up late before the experiment and to be in good physical and mental condition; they had no color weakness or color blindness, were right-handed, had no physical disabilities, had natural vision or corrected to normal vision, did not smoke, and had no known history of perfume allergies. The 40 recruited participants were aged between 25 and 30 years old (mean $\pm$ standard deviation = 27.05 $\pm$ 1.93 years old), with an equal gender ratio (20 males and 20 females). After excluding the participant data that were incomplete in some experimental stages or had quality issues, a total of 20 participants provided complete and valid data under all three fragrance conditions and the odorless air control condition. These 20 participants were included in the final analysis. This predetermined sample size is comparable to those used in previous studies on olfactory intervention research [18,39,40]. Table 1 summarizes the demographic characteristics of the recruited sample and the final analysis sample.

Table 1. Basic demographic information of all participants.

		Age	Height	Weight	Upper Arm Length	Forearm Length	Shoulder Height	Hip Height	Knee Height
Male	Mean	27.2	177.4	77.5	26.55	25.65	144.6	97.75	47.5
	SD	2.15	4.7	2.82	2.03	1.49	7.14	5.4	2.72
	Max	30	187	92	30	27.5	158	106	53
	Min	25	172	68	24	23	132	89	44
Female	Mean	26.9	165.3	48.4	25.75	23.85	135.9	99.45	47.35
	SD	1.79	6.45	4.45	2.8	1.51	6.73	4.16	3.48
	Max	30	178	53	30	26	148	110	53
	Min	25	160	42	21	22	127.5	96.5	43.5

2.2. Materials

2.2.1. Material of Stimulation

In this experiment, 49 floral scents, 34 fruity scents, and 50 woodsy scents were collected based on market research. To maximize olfactory stimulation and monitor users' physiological changes during the experiment, we initially selected 27 scents from each category based on sales rankings. Subsequently, we conducted a fragrance preference survey among 40 office workers aged 25 to 30 with higher education. Using a 5-point Likert scale (1 = least preferred, 5 = most preferred) and incorporating commonly preferred fragrances in olfactory studies, we ultimately identified six highly preferred fragrances. Their mean preference scores and standard deviations are as follows: Floral (Jasmine: 4.45 ± 0.60, Lavender: 4.2 ± 0.77); Fruity (Lemon: 4.4 ± 0.68, Orange: 4.2 ± 0.83); and Forest (Tea Tree: 4.1 ± 0.91, Cedarwood: 4.15 ± 0.75).

Previous studies have demonstrated that controlled short-duration administration at a fixed distance in front of the nose for approximately 1–2 min can induce immediate psychophysiological responses while limiting olfactory fatigue [41]. This experiment employed a 90 s olfactory stimulation duration. The literature indicates that inhalation dilutions of 5–10% (v/v) are widely used [42,43], with 10% concentrations demonstrating comparable efficacy to higher concentrations (e.g., 30% peppermint) for certain outcomes [44]. This suggests that moderate concentrations can yield detectable effects while balancing safety and comfort. The concentration of the olfactory stimulus in this experiment was set at 10%.

2.2.2. Experimental Equipment

The equipment used for user physiological signal recognition includes the following: (1) Ergo LAB sEMG wearable surface electromyograph (Beijing, China): The Ergo LAB sEMG wearable surface electromyograph can collect surface electromyography and perform motion, posture, and fatigue analysis. The sampling rate is 1024 Hz, the collection range is $\pm$1500 µV, and the collection accuracy is 0.183 µV. (2) Tobii Pro Spectrum eye tracker (screen type—S series) (Beijing, China): The Tobii Pro remote eye tracker uses binocular infrared tracking technology with adaptive collection for both bright and dark pupils. The maximum sampling frequency can reach 1200 Hz, the accuracy of the gaze position is 0.06°, the delay time is less than 2.5 ms, the subject's head movement distance is 55–75 cm, and the head movement range is 65 × 34 × 26 cm. (3) Ergo LAB human–computer environment synchronization cloud platform (Beijing, China); (4) Bitbrain hydro-electrode wireless portable electroencephalograph (Beijing, China): It can record 8–64 EEG channels in real-time, and this experiment recorded 16 EEG channels in real-time. The single-channel sampling rate is 256 Hz, and the amplitude range is $\pm$100 mV; (5) Ergo LAB ECG wireless electrocardiograph: The collection range is $\pm$1500 µV, and the accuracy is 0.183 µV.

Other equipment includes a Logitech HD webcam C930c (California, USA) and a Dell OptiPlex 7000 desktop computer (Texas, USA), among other recording devices. The entire experimental environment is an indoor space with air conditioning control, good temperature and humidity, good lighting, and no noise. Participants are tested in a natural sitting position.

2.3. Experiment Design

This study was approved by the Experimental Animal Welfare and Ethics Committee of Nanjing Forestry University (approval No. 2024-12-20-08) and conducted in accordance with the Declaration of Helsinki. Participants were fully informed about the research process, their rights, and the objectives of the experiment before the experiment, with assurances given to maintain the confidentiality of their personal information. Written informed consent was obtained from all participants.

The experiment lasted for 20 days. The participants were required to avoid smoking, drinking alcohol and using perfume for at least 24 h before each experiment. All experiments were conducted in the same similar office-like laboratory, and the non-olfactory environmental conditions inside were strictly controlled. The walls of the room were pure white, and all experiments were carried out under artificial lighting to avoid the influence of sunlight changes. The horizontal illuminance on the workbench surface was maintained at 500 lux, and the relevant color temperature was 4000 K. The experiments had been calibrated before, and the participants indicated that they felt comfortable with the lighting conditions. The indoor temperature was maintained at 24 °C, and the relative humidity was maintained between 50% and 60%. A mechanical fresh air system and humidifier were used to ensure the cleanliness and stability of the indoor air. The background noise level in the laboratory was kept below 30 decibels to reduce external auditory interference. The seats, screens and diffusers were arranged according to a fixed layout scheme (Figure 1), which provided a unified initial visual stimulus and a stable physical environment for the experiment, thereby minimizing environmental interference or visual distraction factors that might affect the experimental results.

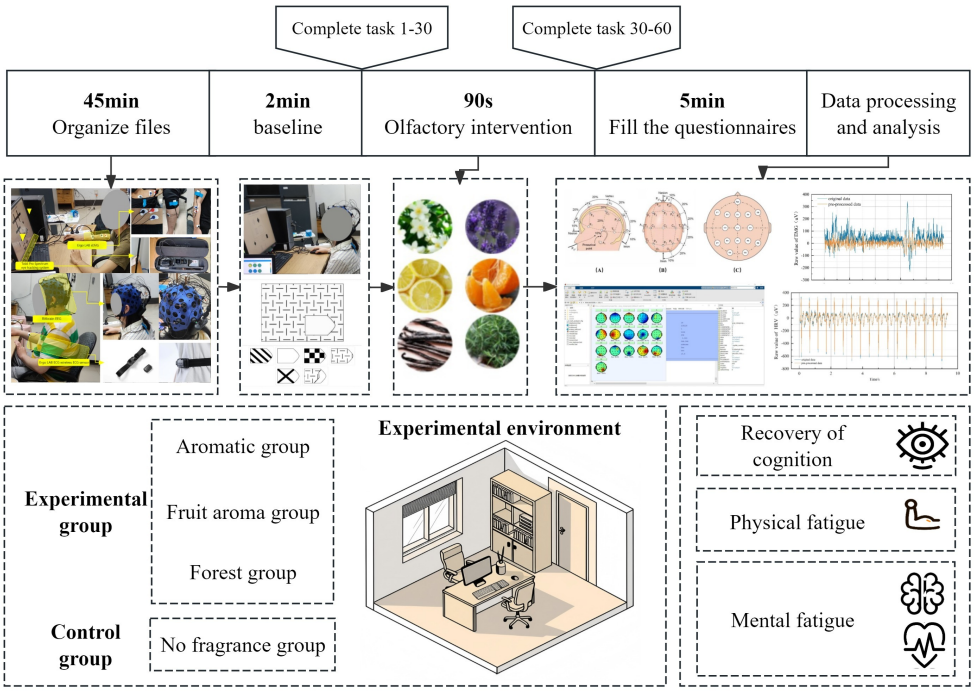


Figure 1. Experiment process.

This study employed three types of olfactory interventions (diffusion of floral, fruity, and forest-scented essential oils at 10% concentration) as experimental groups, alongside an odor-free control group. The dependent variables comprised physiological electrical data and subjective data. Forty participants completed four experimental groups (floral, fruity, forest, control) in Latin square order. Each groups was spaced at least 24 h apart and conducted during the same daytime period to control for circadian rhythms and olfactory adaptation, while preventing olfactory fatigue from multiple scent exposures within a short time frame.

2.4. Experiment Procedures

The experimental procedure comprised seven steps. The experimental process is shown in Figure 1:

(1) Experimental Preparation: The experiment supervisor thoroughly explains the research objectives and operational protocols to participants, ensuring they sign an ethics committee-approved informed consent form with full knowledge of the study. Equipment setup and data collection. Experimenters properly attach physiological monitoring devices to participants while simultaneously recording baseline demographic data.

(2) Fatigue Task: A 45-min simulated office fatigue task involving data classification and organization in an office environment. Participants were required to sort and organize large volumes of data within 45 min. This high-intensity task demanded sustained concentration while ensuring over 95% accuracy in data classification and complete data integrity without omission. Subjective fatigue was assessed using the Multidimensional Fatigue Inventory (MFI; five dimensions: General, Physical, Reduced Activity, Reduced Motivation, and Mental Fatigue, scored 1–5). Participants completed the questionnaire twice: before the fatigue task (T0) and after the task (T1). Paired *t*-tests were conducted using the mean scores for each dimension and the total mean score as indicators. Results showed significant increases in all five dimensions and the total score (all $p < 0.001$), demonstrating that the 45 min task significantly increased multidimensional fatigue within a short period. This supports its validity as an effective fatigue induction paradigm.

(3) Baseline Acquisition: Throughout the experiment, participants must maintain a seated position without engaging in any activity or movement to ensure no active stimuli alter physiological signals. Physiological data will be collected during a 2 min resting period.

(4) Cognitive Task: Subsequently, participants underwent cognitive testing according to the experimental protocol. The entire process involved completing 60 questions selected from the Raven's Progressive Matrices test developed by Raven's Center. Primarily focusing on judgment and reasoning items, participants completed 30 questions.

(5) Olfactory Intervention: Subjects received a 90-s olfactory intervention near their noses. For the intervention group, the experimenter released different scents using a diffuser, while the control group received neutral, odorless distilled water. The specific scent type was not disclosed in the experimental instructions to minimize the expectancy effect.

(6) Cognitive Task: After the intervention, participants will complete the 30-item cognitive test again. Throughout the experiment, if a participant requires extended time to complete the task, no prompts should be given. The actual completion time should be recorded as an assessment metric for cognitive ability.

(7) Upon experiment completion, each participant filled out the SWAT, NASA-TLX, and Brunel Mood Scale.

2.5. Measurements

This study adopted a combination of subjective assessment and electrophysiological methods to evaluate the impact of olfactory stimulation on the alleviation of physiological and psychological fatigue in participants. A total of 8 measurement variables are included (Table 2), with physiological indicators comprising eye movement indicators, electromyography (EMG), electroencephalogram (EEG), electrocardiogram (ECG), and subjective assessment indicators, including the SWAT scale, NASA-TLX scale, and Brunel mood scale questionnaire. Eye movement indicators and task completion time were used to assess cognitive ability, and EMG indicators were used to reflect the physiological fatigue changes of the subjects, while EEG indicators, ECG indicators, and subjective questionnaires were used to reflect the psychological fatigue changes of the subjects.

Table 2. Summary of measurement variables.

Categories	Variables	Analysis Parameters
Cognitive ability assessment	Eye tracking indicators Task completion time	Pupil Diameter
Physiological fatigue assessment	Electromyography (EMG)	Root mean square (RMS), Median frequency (MF)
Psychological fatigue assessment	Electroencephalogram (EEG)	Theta wave, Alpha wave, Beta wave, α/β, θ/β, $(\alpha+\theta)/\beta$, $(\alpha+\theta)/(\alpha+\beta)$, $\theta/(\alpha+\beta)$
	Electrocardiogram (ECG)	Standard deviation of the NN (R-R) intervals (SDNN), Root mean square of successive differences (RMSSD), High frequency (HF), Low frequency (LF), The power ratio in the low frequency and high frequency (LF/HF)
	SWAT scale	Time load, Effort load, Psychological stress Load
	NASA-TLX scale	Mental demand, Physical demand, Temporal demand, Performance, Effort, Frustration
	BRUMS mood scale questionnaire	Assessment of Emotional State by Dimension

2.5.1. Cognitive Recovery Assessment Indicators

Pupil diameter has been widely used as an indicator of cognitive load [45,46]. As cognitive arousal and effort increase, pupil diameter increases [47,48]. Pupil size is primarily used to indicate cognitive load and mental arousal; based on this, this study assesses cognitive recovery [49,50]. In this experiment, the Tobii Pro Spectrum eye tracker was used to record ocular indicators, and the pupil data were processed using linear interpolation and sliding median filtering to remove signals below 2 mm.

This study employs Task Completion Time (TCT) as an objective indicator of cognitive recovery. Task completion time comprehensively reflects working memory capacity and the efficiency of attentional resource allocation [51]. It has been employed in numerous olfactory, soundscape, and cognitive load studies to measure information processing speed and task focus. When cognitive resources are abundant or fatigue is alleviated, individuals typically complete equivalent tasks more rapidly, manifested as reduced task completion time. In the experimental design, the number of tasks, difficulty level, and presentation order remained consistent. Therefore, variations in completion time primarily reflect changes in cognitive efficiency and attention allocation. To control for individual differences, this study employed a within-subjects design, using the "difference before and after intervention (ΔTCT)" metric to compare cognitive recovery effects across different fragrance conditions.

2.5.2. Physiological Fatigue Assessment Indicators

Electromyography (EMG) is a technique that records and analyzes the electrical signals generated during muscle activity. EMG can provide four types of information, including whether the muscle is in use, the relative level of activity, quantitative information on muscle strength, and assessment of muscle fatigue [52,53]. Given the unique advantages of EMG in fatigue assessment, numerous studies have adopted this technology to achieve precise fatigue monitoring [54], and to verify the actual effects of various fatigue-relief measures [55]. EMG signal analysis methods mainly include time-domain analysis, frequency-domain analysis, wavelet transform, time-frequency methods, and higher-order statistics [56]. Amplitude and frequency measurements have been widely used to indicate muscle fatigue during prolonged postures [57]. Several EMG parameters have been introduced and used as indicators of muscle fatigue in previous studies. EMG signals were recorded using the Ergo LAB sEMG wearable surface electromyograph. The original data were rectified, smoothed, and normalized by MVC (Maximum Voluntary Contraction Normalization) to further calculate and analyze the final EMG signals. The Ergo LAB surface electromyography test system was equipped with the corresponding straps and bound to the appropriate positions. In this experiment, the right trapezius muscle group was collected for EMG signals. The median frequency (MF) and normalized amplitude were used to assess muscle fatigue.

2.5.3. Psychological Fatigue Assessment Indicators

Electroencephalogram (EEG) is a non-invasive and cost-effective method that can capture information about cortical neural activity, including cognitive, emotional, mental, and psychological processes [58–61]. Alpha waves are associated with calmness or relaxation [62], beta waves are related to attention and memory [63]. Theta waves are more commonly produced during slow movements and increase when the body is in a floating or trance state, leading to a weakened attention span [64]. Current research has shown that the higher the power and relative strength of α waves, the less arousal and stress are measured [62]. When users focus on work, the activation degree of β waves is greater, and as mental fatigue deepens, the relative power of β rhythm decreases [65]. Lal et al.'s [66] research has shown that in a state of fatigue, the amplitude and relative power of θ rhythm increase. Jiang et al. [67] explored the application of olfactory strategies in relieving driving fatigue and observed that with the extension of driving time, θ wave activity slightly increased. In contrast, α and β wave activities decreased, and the EEG indicators R(α/β), R$\theta/(\alpha+\beta)$, and R$(\alpha+\theta)/(\alpha+\beta)$ continued to increase, and after accepting three types of scent stimulation, the R(α/β) indicator decreased. In this experiment, the θ (Theta) waves, α (Alpha) waves, β (Beta) waves of the EEG signal, as well as their rhythm ratios, α/β, θ/β, $(\alpha+\theta)/\beta$, $(\alpha+\theta)/(\alpha+\beta)$, $\theta/(\alpha+\beta)$ were analyzed.

The autonomic nervous system (ANS) plays an important role in regulating emotions [68], and heart rate variability (HRV) provides an accurate and non-invasive measurement of ANS function [69,70]. HRV is based on normal sinus heartbeats (NNs). SDNN represents the standard deviation of NN intervals, which is an effective indicator of stress levels. Most previous studies have reported a decrease in SDNN under mental fatigue, indicating an increase in mental stress [71,72]. The time-domain measure of the root mean square of successive differences (RMSSD) is an indicator of parasympathetic nerve function. Studies have shown that exposure to mental stress leads to a decrease in RMSSD, while stress relief corresponds to an increase in RMSSD [73,74]. In the frequency-domain analysis parameters of HRV, the high-frequency segment (HF) reflects parasympathetic nerve activity, and the relative power of the low-frequency segment (LF) is related to sympathetic nerve activity [75]. As fatigue increases, LF usually shows a consistent upward trend,

and some studies have reported that HF decreases with increasing time load. In contrast, others have found that HF increases or remains unchanged [76]. The power ratio in the low frequency and high frequency (LF/HF) is usually used to reflect the balance between parasympathetic and sympathetic nerve activities [77]. An increase in LF/HF indicates that the subject's sympathetic nerve is stimulated, and studies have shown that an increase in mental fatigue degree is related to a higher LF/HF ratio [78]. In this study, SDNN and RMSSD were selected as the time domain analysis parameters of HRV signals, and LF, HF, and LF/HF were selected as the frequency domain analysis parameters of HRV signals.

The Subjective Workload Assessment Technique (SWAT) is a subjective rating technique that divides mental load into time load (T), effort load (E), and psychological stress load (S), and evaluates them using three rating levels [79]. The SWAT scale determines the importance of user dimensions through questions, subject completion of questionnaires, and comparison of results by the experimenter. The higher the score, the greater the mental load. The NASA Task Load Index (NASA-TLX) is a technique for measuring subjective mental workload [80], and the overall workload score is derived from the weighted average score of six subscales: mental demand, physical demand, temporal demand, effort, performance, and frustration. It focuses on the demands imposed on the subject and the interaction between the subject and the task. The Brunel Mood Scale (BRUMS) is suitable for assessing the mood of adolescents and adults [81], and this paper used it to evaluate the impact of different scent interventions on users' emotional fluctuations, including tension, anger, vigor, fatigue, confusion and depression [82]. Participants use the standard response time frame, "How do you feel now?" to answer. This scale uses a five-point Likert scale (0 = "Not at all", 1 = "A little", 2 = "Moderate", 3 = "Quite a bit", 4 = "Very strongly") to indicate how angry, energetic, tense, or unhappy they feel.

2.6. Data Collection and Analysis

This study used IBM SPSS Statistics 27 to analyze the experimental data. For physiological (eye movement indicators, EMG indicators, EEG indicators, HRV indicators), psychological, and cognitive recovery ability indicators, the changes before and after olfactory intervention were used as the result variables (the latter value minus the former value). The subjective data are the questionnaire scores after the intervention. The Shapiro–Wilk test was used to evaluate the normal distribution of all measurement variables, and the homogeneity of variance of all variables was tested. For normally distributed data, analysis of variance (ANOVA) was used to compare the differences between different olfactory intervention conditions, while the Kruskal–Wallis test was used for non-normally distributed data. For indicators with statistical significance, post hoc multiple comparisons were performed to analyze the differences between different scents. All data are expressed as mean ± standard deviation (mean ± SD), and the statistical significance threshold for all comparisons is established at $p < 0.05$. The specific results of the variance analysis are presented in Table S1.

3. Results

3.1. The Cognitive Recovery Benefits of Olfactory Intervention for Office Fatigue

The physiological data before and after olfactory intervention were collected to calculate the differences in physiological indexes. The eye-tracking data of participants were analyzed, using pupil diameter as a physiological indicator of cognitive recovery, and the changes in time to complete stress tasks before and after intervention were used to evaluate cognitive performance.

The results showed that there were significant differences in the effects of different fragrance types on the changes in pupil diameter (Figure 2a). Both the floral fragrance

group (A1: 0.17 ± 0.15) and the forest group (A3: 0.14 ± 0.10) showed mild dilation, while the fruit fragrance group (A2: −0.04 ± 0.28) showed a slight contraction. The control group (B: 0.28 ± 0.12) had the largest dilation. Post hoc comparisons revealed that the pupil diameters of the fruit fragrance group ($p < 0.001$) and the forest group ($p = 0.004$) were significantly smaller than those of the control group, while there was a marginal significant difference between the floral fragrance group and the control group ($p = 0.087$). Comparisons among the other groups showed no significant differences.

After each fragrance type intervention, the task completion time was significantly shortened (ΔTCT < 0), but there were significant differences in the improvement extent ($p < 0.001$) (Figure 2b). The fruit fragrance group had the largest reduction in task completion time, significantly better than the floral fragrance group ($p = 0.001$), the forest group ($p = 0.001$), and the control group ($p = 0.040$). There were no significant differences among the floral fragrance group, the forest group, and the control group. Overall, the completion time from shortest to longest was fruit fragrance group < floral fragrance group < control group < forest group.

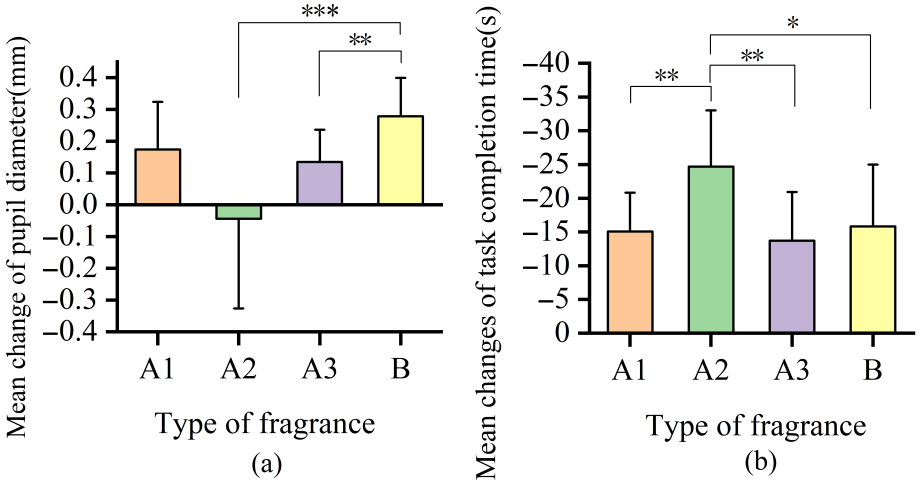


Figure 2. Cognitive responses to olfactory interventions. (**a**) Changes in pupil diameter after the olfactory intervention; (**b**) Change in time to complete the task after the olfactory intervention; (*) $0.01 < p < 0.05$, (**) $0.001 < p < 0.01$, (***) $0.0001 < p < 0.001$; A1—floral type, A2—fruity type, A3—forest type, B—control group.

3.2. The Physiological Recovery Benefits of Olfactory Intervention for Office Fatigue

The electrical signals of the right trapezius muscle group were analyzed, and the details of the changes in the parameters of the time–frequency domain of the EMG signals before and after the intervention in different scent groups are shown in Figure 3. The Kruskal–Wallis analysis results indicated that there were significant differences in the RMS values after the intervention with different fragrances ($p < 0.001$). From the mean difference results, the flower fragrance group had the largest RMS reduction, while the fruit fragrance group and the forest group had smaller reductions, and the control group showed an upward trend. Post-hoc multiple comparisons showed that the RMS of the flower fragrance group was significantly lower than that of the fruit fragrance group ($p = 0.033$) and the control group ($p < 0.001$), and the RMS of the forest group ($p < 0.001$) and the fruit fragrance group ($p = 0.01$) were also significantly lower than that of the control group, while there was no significant difference between the flower fragrance group and the forest group.

The MF values of the aroma group and the fruit fragrance group increased after the intervention, and the increase in MF of the fruit fragrance group was higher (0.90 Hz). The MF indicators of the forest group and the no-fragrance group decreased, and the decrease in the MF indicator of the no-fragrance group was the greatest (−0.61 Hz). There was no

statistically significant difference in the frequency domain indicators MF among the four groups after the intervention.

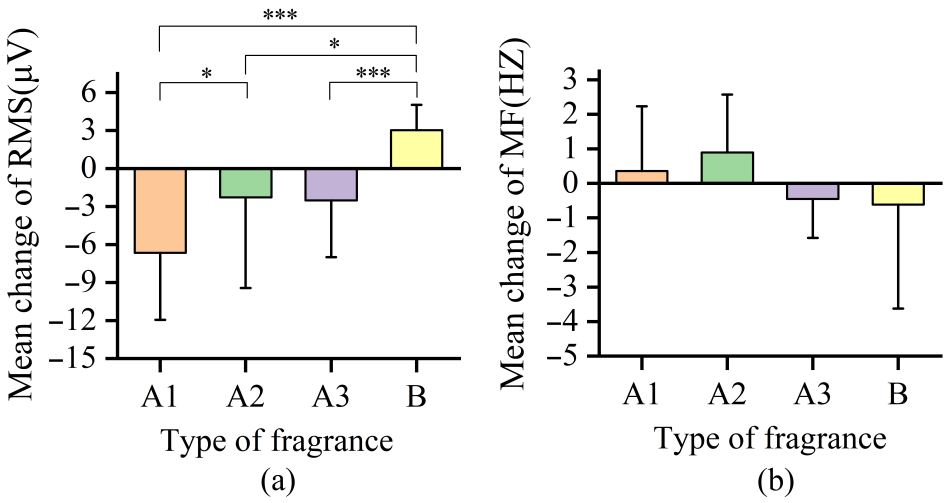


Figure 3. Average Changes in EMG Indicators. (**a**) EMG-RMS. The root mean square (RMS) represents the root mean square value of all amplitudes in a certain period of time; (**b**) EMG-MF. The median frequency (MF) is the median of the firing frequency during muscle contraction; (*) $0.01 < p < 0.05$, (**) $0.001 < p < 0.01$, (***) $0.0001 < p < 0.001$; A1—floral type, A2—fruity type, A3—forest type, B—control group.

3.3. The Psychological Recovery Benefits of Olfactory Intervention for Office Fatigue

3.3.1. EEG Signal Data Results and Analysis

The detailed changes in brain wave band power before and after the intervention for different fragrance groups are shown in Table 3. There are significant differences in the effects of different fragrance interventions on brain wave power, and the change trends in each frequency band are different. In terms of α wave power (Figure 4a), the fruit fragrance group and the control group showed a significant increase, while the flower fragrance group and the forest group showed smaller changes. The post-event comparison results showed that the forest group was significantly lower than the control group ($p = 0.009$), and the difference between the flower fragrance group and the control group was close to being significant ($p = 0.059$). In terms of β wave power (Figure 4b), the power of the fruit fragrance group increased the most, while the flower fragrance group and the forest group showed little change. The difference between the flower fragrance group and the control group was significant ($p = 0.007$), and the comparisons among the other groups did not reach a significant level ($p > 0.05$). θ wave power increased significantly in the fruit fragrance group and the control group (Figure 4c), while the flower fragrance group showed the smallest change. The post-event comparison showed that the flower fragrance group was significantly lower than the control group ($p = 0.007$), and the difference between the forest group and the control group was close to being significant ($p = 0.057$). Aromatherapy intervention has a significant effect on alleviating the increase in the $\theta/(\alpha + \beta)$ ratio; after the fruit fragrance intervention, the α/β, θ/β, $(\alpha + \theta)/\beta$, and $(\alpha + \theta)/(\alpha + \beta)$ all decreased; the forest type promoted the decrease in the α/β ratio. In the control group, the intervention ratios of each rhythm increased before and after, which confirmed that as the fatigue level increased, the intervention ratios of each rhythm also increased.

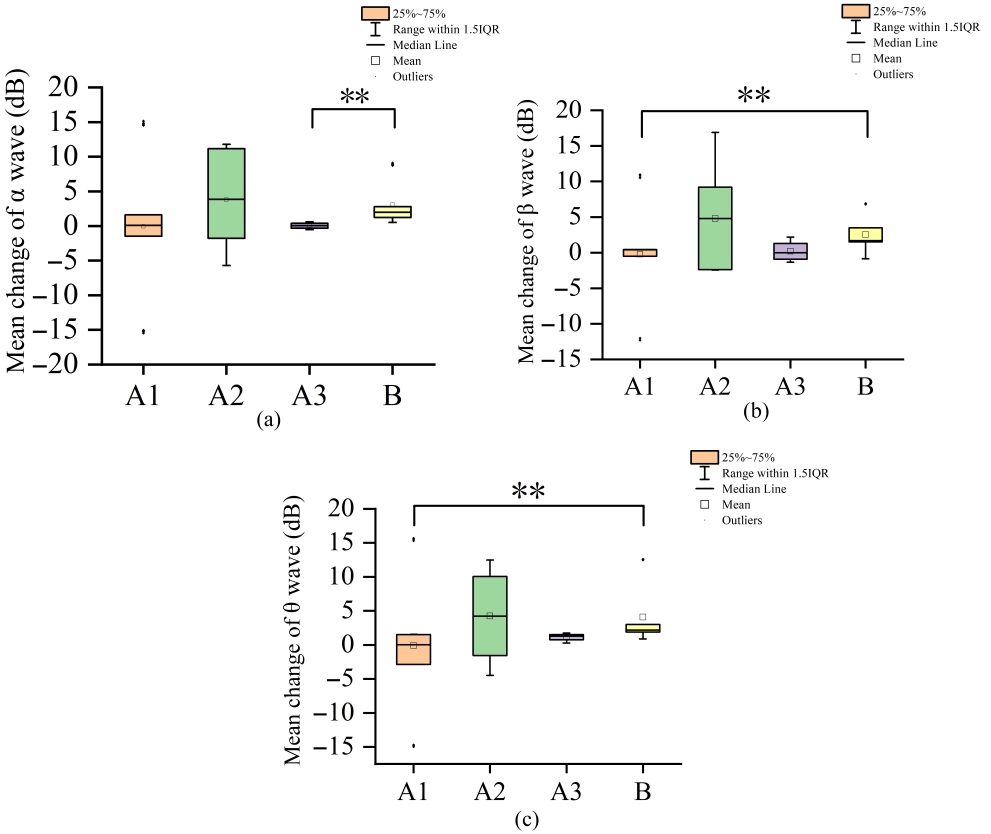


Figure 4. Average Changes in EEG Indicators. (**a**) EEG-α wave; (**b**) EEG-β wave; (**c**) EEG-θ wave; (*) $0.01 < p < 0.05$, (**) $0.001 < p < 0.01$, (***) $0.0001 < p < 0.001$; A1—floral type, A2—fruity type, A3—forest type, B—control group.

Table 3. Changes in the power of brain wave segments and the ratio of brain wave segments under different fragrances.

Power	Variables	Type of Fragrance				*p*
		A1	A2	A3	B	
Total Power	α	-0.04 ± 9.8	3.8 ± 6.68	0.04 ± 0.42	3.09 ± 3.09	0.009 **
	β	-0.23 ± 7.47	4.81 ± 6.73	0.20 ± 1.32	2.53 ± 2.62	0.042 *
	θ	-0.11 ± 9.95	4.25 ± 6.19	1.14 ± 0.54	4.10 ± 4.38	0.006 **
	α/β	0.03 ± 0.18	-0.20 ± 0.30	-0.01 ± 0.08	0.02 ± 0.08	0.307
	θ/β	0.04 ± 0.14	-0.03 ± 0.22	0.06 ± 0.11	0.06 ± 0.12	0.969
	$(\alpha+\theta)/\beta$	0.06 ± 0.23	-0.23 ± 0.48	0.08 ± 0.19	0.08 ± 0.20	0.875
	$(\alpha+\theta)/(\alpha+\beta)$	0.01 ± 0.07	-0.01 ± 0.11	0.03 ± 0.05	0.03 ± 0.05	0.802
	$\theta/(\alpha+\beta)$	0.01 ± 0.10	0.05 ± 0.08	0.03 ± 0.03	0.03 ± 0.03	0.052

(*) $0.01 < p < 0.05$, (**) $0.001 < p < 0.01$.

3.3.2. HRV Signal Data Results and Analysis

The analysis of the changes in time-frequency domain indicators of HRV signals is shown in Figure 5. The Kruskal–Wallis test results showed that the changes in the time–domain features SDNN and RMSSD among the four intervention groups were statistically significant ($p = 0.036$; $p = 0.029$). The multiple comparison was conducted separately for the changes in SDNN and RMSSD. In the fruity intervention group (A2), the change in SDNN was significantly greater than that in the forest group and the control group ($p = 0.021$; $p = 0.014$). As shown in Figure 5a, the increase in SDNN in the three experimental groups was higher than that in the no-scent control group. Compared with the control group, the RMSSD in the floral group and the fruity group increased significantly ($p = 0.005$; $p = 0.021$),

while the RMSSD in the forest group decreased slightly, but the degree of decrease was less than that in the control group (Figure 5b). For the analysis of frequency–domain features, the differences in HF, LF, and LF/HF between the fatigue and recovery stages of the participants were calculated, and box plots for these indicators were drawn for the three olfactory intervention groups and one no-scent control group (Figure 5c–e). An HF difference less than 0 indicates an increase in fatigue, while an LF and LF/HF difference greater than 0 indicate an increase in fatigue. Compared with the control group, the average change in the HF indicator of the three olfactory stimulation groups increased, and the forest group had a better effect on relieving the increase in LF. In contrast, both the fruity and forest groups relieved the increase in LF/HF.

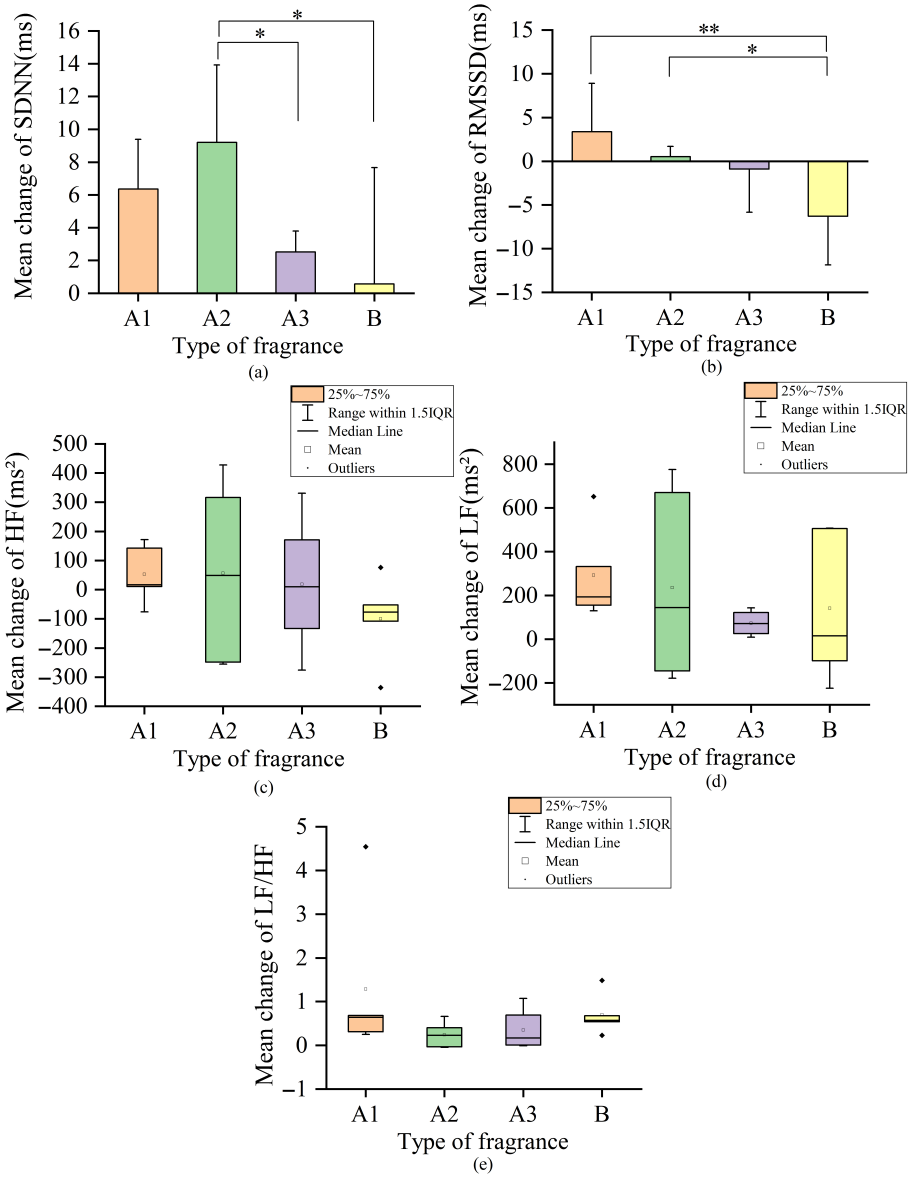


Figure 5. Average changes in HRV indicators. (**a**) HRV-SDNN reflects the total heart rate variability associated with ANS activity; (**b**) HRV-RMSSD measures high-frequency variations in heart rate and represents parasympathetic activity; (**c**) HRV-HF reflects the activity of parasympathetic nerve; (**d**) HRV-LF reflects the activity of sympathetic nerve; (**e**) HRV-LF/HF. The power ratio in the low frequency and high frequency reflects sympathetic activity relative to parasympathetic activity; (*) $0.01< p <0.05$, (**) $0.001 < p < 0.01$, (***) $0.0001 < p < 0.001$.

3.3.3. Subjective Questionnaire Statistical Results and Analysis

The results of the reliability and validity test showed that the reliability (Cronbach's α = 0.708) and content validity (KMO = 0.794, Bartlett = 34.125, p = 0.000) of the SWAT scale, as well as the reliability (Cronbach's α = 0.832) and content validity (KMO = 0.755, Bartlett = 22.555, p = 0.000) of the NASA-TLX scale, were all good. Their Cronbach's α coefficients and KMO values were all greater than 0.7, which means that the data obtained through the SWAT scale and NASA-TLX scale can very truly and reliably reflect the users' cognitive load and work demand situations. The overall reliability (Cronbach's α = 0.952) of the Brunel mood scale was also good. This indicates that the data obtained through the Brunel mood scale can very truly and reliably reflect the users' cognitive load and work demand situations during the office process.

To compare the subjective effects of different scent interventions on psychological indicators, data from the SWAT, NASA-TLX, and Brunel Mood Scales were analyzed (as shown in Figure 6). After conducting normality and homogeneity-of-variance tests, a nonparametric Kruskal–Wallis test was employed. Significant differences were found in the Time load and Psychological stress load dimensions of the SWAT scale across the three olfactory intervention groups and the no-scent control group ($p < 0.001$; $p = 0.046 < 0.05$). Similarly, the Physical demand dimension of the NASA-TLX scale showed significance ($p < 0.001$). In the Brunel Mood Scale, the Vigor dimension showed significant differences among the four interventions ($p < 0.001$), whereas no significant differences were observed in the other subscales.

Figure 6a shows that in the Time load dimension, the floral group had significantly higher scores than the fruity ($p < 0.001$) and forest groups ($p < 0.001$), and the control group also had higher scores than the fruity ($p = 0.028$) and forest groups ($p < 0.001$). The floral group had the highest Time load (2.60 $\pm$ 0.50), while the forest group had the lowest (1.50 $\pm$ 0.51). In the Psychological stress load dimension, the fruity group presented the lowest value (1.5 $\pm$ 0.51), which was significantly lower than the floral ($p = 0.016$), forest ($p = 0.033$), and control groups ($p = 0.018$). These findings indicate that the fruity scent was most effective in reducing psychological stress, while the floral scent had the least impact on psychological load reduction. The forest scent showed a notable effect in alleviating the perception of time pressure.

Figure 6b shows that across the dimensions of the NASA-TLX scale, mental demand was high. In contrast, physical demand was low, suggesting that office workers may require more relief from mental fatigue than physical fatigue. In the Mental demand dimension, the forest group recorded the lowest value (13.20 $\pm$ 3.29), and the floral group reported the highest (15.20 $\pm$ 1.32). However, no significant differences were observed among the four groups. In the Physical demand dimension, the floral group had the lowest value (5.00 $\pm$ 2.18), which was significantly lower than those of the fruity ($p < 0.001$), forest ($p = 0.001$), and control groups ($p < 0.001$).

Figure 6c shows that compared to the control group, the fruity group was most effective in alleviating negative emotions, while the forest group was least effective. In the Vigor dimension, the fruity group achieved significantly higher scores than the floral ($p < 0.001$), forest ($p < 0.001$), and control groups ($p < 0.001$). The result indicates that fruity scent intervention could enhance participants' energy levels and positively impact negative emotions and stress during office work.

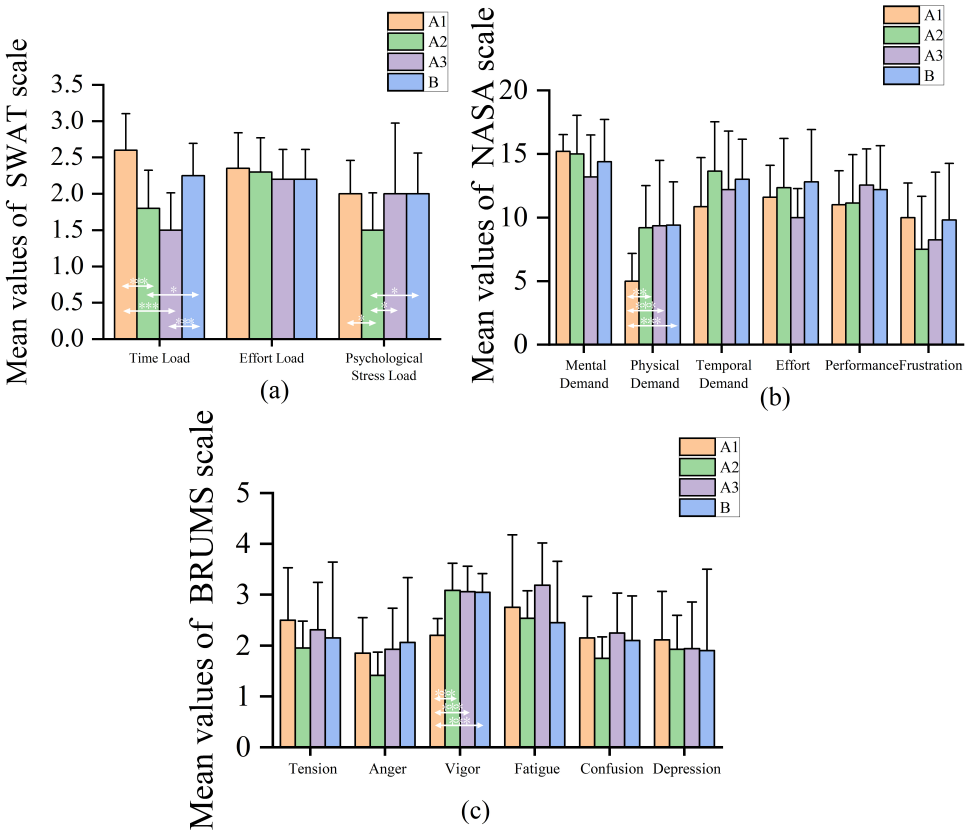


Figure 6. Mean values of sub-dimensions of subjective questionnaire under different fragrance interventions. (**a**) SWAT scale; (**b**) NASA-TLX scale; (**c**) Brunel mood scale; (*) $0.01 < p < 0.05$, (**) $0.001 < p < 0.01$, (***) $0.0001 < p < 0.001$.

3.4. Correlation Analysis

Figure 7 shows that, the correlation matrix revealed a clear pattern of convergence between subjective ratings and physiological indices. The correlation analysis further confirmed that subjective workload and mood states were tightly coupled with the multi-modal physiological responses. Higher ratings of time and effort load, as well as psychological stress and negative mood (fatigue, anger, confusion, and frustration), were generally associated with larger pupil diameter, reduced HRV (lower SDNN, RMSSD, HF), and a higher LF/HF ratio. This pattern reflects a more sympathetic-dominant autonomic state under conditions of perceived overload and stress, indicating that participants who felt more pressured also exhibited objectively heightened physiological arousal. In contrast, higher vigor scores and better perceived performance tended to coincide with more adaptive HRV profiles and β-band activity, suggesting an "alert yet efficient" neural state when participants experienced themselves as energetic and effective.

These subjective and physiological indicators point to a consistent pattern: when olfactory stimulation alleviated perceived workload and negative affect, it simultaneously promoted the transition from sympathetic to parasympathetic control and reduced muscle and eye tension. This consistency supports the use of combined HRV, EEG, EMG, and pupil metrics as sensitive markers for tracking office-related fatigue and recovery. It indicates that even subtle changes in self-reported workload are mirrored by measurable shifts in autonomic and cortical activity.

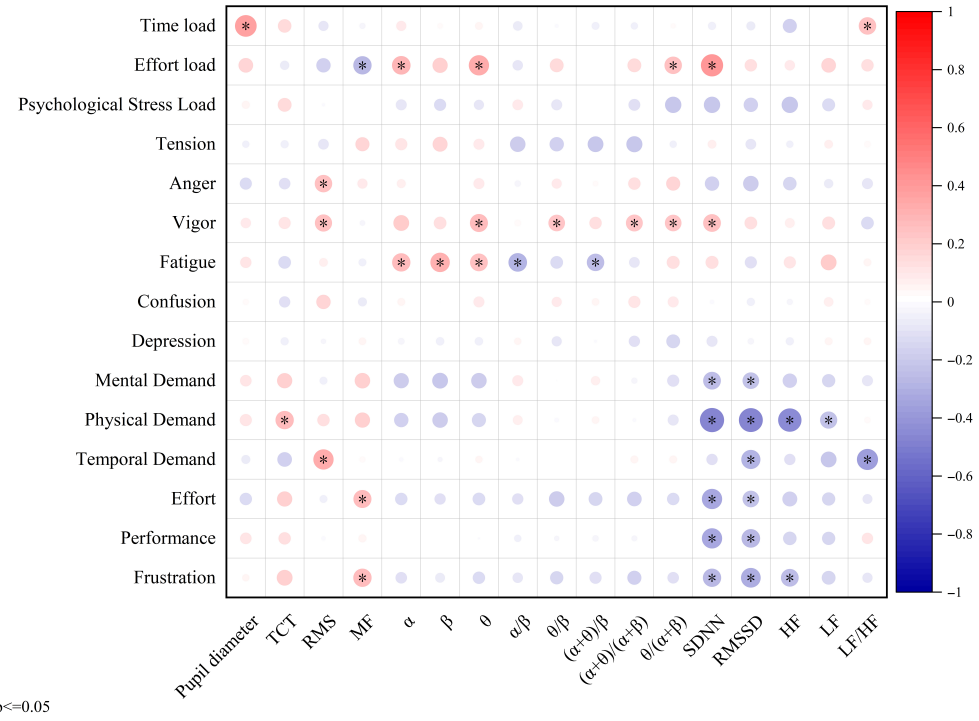


Figure 7. Pearson Correlation Analysis. The size of each circle is proportional to the absolute value of the correlation coefficient, with larger circles indicating stronger correlations and smaller circles indicating weaker correlations.

4. Discussions

Building on the above results, this study demonstrates that specific fragrances can facilitate multimodal recovery from office fatigue, but their effects differ across physiological, psychological, and cognitive dimensions. In the following sections, we first discuss the potential psychophysiological mechanisms underlying these differentiated effects, then relate our findings to previous olfactory and environmental psychology research, and finally outline practical implications for the design of office olfactory environments.

When interpreting the odor-free control condition, it is important to note that participants were still performing the same continuous cognitive task while seated. Thus, the physiological changes observed under "odorless air" mainly reflect time-on-task and fatigue effects rather than a lack of stimulation. Prolonged mental effort and static muscle loading are known to induce gradual reductions in HRV, increases in EMG activity, and pupil dilation, even in the absence of specific olfactory input. In addition, the delivery of filtered air may provide subtle non-olfactory stimulation, such as airflow or temperature cues and task-related expectations, which can modulate autonomic activity. In this study, the odorless condition serves as a reference baseline for fatigue progression, against which the additional restorative effects of floral, fruity, and forest-like fragrances can be evaluated.

4.1. The Impact of Olfactory Stimulation on Cognitive Recovery

This study compared the effects of fruity, floral, and forest olfactory stimuli and a no-scent control group on pupil diameter and task completion speed to explore the impact of olfactory intervention and its types on cognitive recovery.

The impact of olfactory stimulation on cognitive function is primarily achieved through the interaction between the olfactory system and the limbic system. Olfactory information is first transmitted from the olfactory bulb to the amygdala and hippocampus [19], brain regions closely related to emotions, memory and attention. Olfactory stimulation can

quickly activate these areas, thereby affecting cognitive function. Pupil diameter, which is regulated by the autonomic nervous system, has been widely used as an index of cognitive load: more demanding tasks typically elicit larger pupils, reflecting increased resource consumption [45,47,83].

In the floral, forest, and control groups, increases in pupil diameter (commonly interpreted as reflecting greater sympathetic activation), did not translate into equivalent gains in task efficiency (TCT improvement was less pronounced than in the fruity group). Previous reviews indicate that pupil dilation accompanies increased cognitive load and arousal. Yet it remains insensitive to the "valency of arousal": both positive arousal (reducing boredom, enhancing vitality) and negative arousal (stress or mild overload) may lead to pupil enlargement. Consequently, pupil size alone cannot determine whether such arousal is beneficial or detrimental to performance [84]. By contrast, fruity scents produced the largest shortening of TCT without comparable pupil dilation. This pattern is more consistent with a "resource allocation/processing efficiency" mechanism than with simple arousal: positive affective modulation may facilitate more efficient deployment of attentional and executive resources, enabling faster performance without a strong increase in physiological activation, in line with previous work on citrus fragrances [85]. It has been proven that the fruity aroma inhibits the activity of the sympathetic nervous system and induces the activity of the parasympathetic nervous system. To a certain extent, it can promote relaxation in the body and alleviate tension and fatigue. Secondly, it is known that fruity aromas (such as lemon, orange) are usually associated with a sense of pleasure and relaxation [31]. It is worth noting that the control group (without fragrance) showed the greatest degree of pupil dilation but almost no efficiency gain. This is consistent with the finding that "monotonous environments" are prone to causing attentional distraction and an increase in subjective load, which is not helpful for task-related processing [86].

By comprehensively assessing the impact of olfactory intervention on cognitive recovery based on the changes in pupil diameter and task completion time, it can be concluded that all three olfactory interventions have restored cognitive abilities to a certain extent. Among them, fruity olfactory intervention alleviated tension and reduced cognitive load, while floral and forest interventions, compared with the control group, relatively increased arousal, but their effect on cognitive recovery was not as significant as that of fruity intervention.

4.2. The Recovery Benefits of Olfactory Stimulation on Physiological Fatigue

In this study, EMG indicators were used to quantify recovery from physiological fatigue. The root mean square (RMS) reflects EMG amplitude and muscle activation level in the time domain. In contrast, median frequency (MF) characterizes the spectral distribution of EMG power and is commonly used to assess muscle fatigue. Olfactory stimulation affects muscle tension by modulating the autonomic nervous system activity. Existing research on EMG signals in olfactory intervention has mainly focused on emotional responses of facial muscle groups [87]. In office environment studies, EMG signal analysis has been widely used to detect muscle fatigue caused by prolonged sitting and to detect and correct posture. However, there is limited research on the effect of olfactory intervention on alleviating muscle fatigue caused by long-term sitting.

Previous studies have shown that, after long-term computer work, EMG amplitude increases as MF decreases over time [57]. However, some studies also showed that although discomfort across the body increased, there was no significant change in the median frequency or amplitude of the trapezius muscle [88]. The RMS value of the control group increased significantly after the intervention, whereas the RMS values of the three experimental groups decreased significantly. Among them, the decrease in the aromatic group

was the greatest. There was no significant difference in MF among the four groups, and the MF values increased in the floral and fruity groups, indicating that floral and fruity olfactory interventions effectively alleviated muscle fatigue. The MF values decreased in the forest and no-scent groups, but compared with the control group, the forest group partially mitigated the decrease in MF.

Previous studies have proven that floral and fruity essential oils can increase nutrient supply and alleviate muscle fatigue [89,90]. However, there are few comparisons between the effects of different types of olfactory interventions. Although the changes in MF after intervention in the three olfactory stimulations and the control group in this study did not reach a significant level in statistics, combined with the trend of RMS value changes, it can be speculated that compared with the no—scent control group, olfactory intervention has a certain positive effect on alleviating muscle fatigue, among which floral olfactory intervention has significant effect on alleviating physiological fatigue, but the differences between different types of olfactory interventions are not significant. The effect of olfactory intervention on physiological fatigue is influenced by factors such as individual differences, the intensity and duration of stimulation. Therefore, in future research, it is necessary to further explore the specific impact of these factors on the effect of olfactory intervention to optimize the olfactory stimulation plan and improve its restorative effect on physical fatigue.

4.3. The Recovery Benefits of Olfactory Stimulation on Psychological Fatigue

In this study, EEG and ECG indicators and subjective questionnaire results were used as the evaluation basis for psychological fatigue recovery.

Based on the results of physiological and subjective indicators, compared with the control group, the floral fragrance intervention resulted in decreased α, β, and θ wave power, consistent with previous conclusions [30]. The decrease in α wave power did not show a relaxing effect, while the decrease in β and θ wave power indicated reduced stress and anxiety. Moreover, the increase in SDNN and the significant increase in RMSSD after floral fragrance intervention, along with the relative increase in HF, suggest increased vagal tone and parasympathetic nervous system activity. The high ratio of parasympathetic to sympathetic nervous system activity (indicating a relaxed state) leads to decreased heart rate and LF/HF ratio, as well as increased SDNN [91]. This indicates that floral fragrance intervention may reduce psychological fatigue by influencing the autonomic nervous system. Okada and Koji [92] also observed an accelerated recovery of HF, RMSSD, and HR in the lavender aroma environment. Although the floral group in this study had a negative effect on vigor, as indicated by a significantly lower vigor index than that of the fruit, forest, and control groups, it showed significant effects on reducing physical demand.

Compared with the control group, the fruity fragrance intervention resulted in a greater increase in β wave power. The ratios of α/β, θ/β, $(\alpha+\theta)/\beta$, and $(\alpha+\theta)/(\alpha+\beta)$ all decreased after fruity fragrance intervention. The study by Kafaei et al. [93] showed that beta activity increased significantly when individuals were exposed to scents that could enhance arousal. SDNN, RMSSD, and HF significantly increased, while the increase in LF/HF was the smallest. This pattern is consistent with the possibility that fruity aromas reduce sympathetic dominance and enhance parasympathetic activity, which in turn may contribute to alleviating mental stress and fatigue. Combined with the results of the subjective questionnaire, although the fruity fragrance intervention had a lower effect on relieving physical fatigue, it showed a stronger effect on relieving negative emotions, such as psychological tension, frustration, and anger. Furthermore, the fruity group significantly enhanced participants' energy levels and attention during office work. This result is consistent with previous conclusions, Ohata et al. [85] also proved that Japanese citrus

fruits (*Citrus iyo*) and grapefruit (*Citrus junos*) can reduce fatigue, enhance mental vitality, and improve task performance.

Previous studies have shown that wood fragrance can reduce sympathetic nervous system activity and increase parasympathetic nervous system activity, thereby alleviating stress and fatigue [36–38]. In this study, compared with the control group, the forest fragrance intervention had a smaller increase in α, β, and θ wave power. The effects on RMSSD and SDNN were less than those of the floral and fruity fragrance interventions; however, the forest intervention showed a relatively stronger mitigation of the LF/HF ratio, a pattern compatible with increased parasympathetic influence and reduced sympathetic dominance. Such a shift in autonomic balance could help explain the observed reductions in perceived time pressure and psychological tension.

4.4. Suggestions for Olfactory Intervention in Office Scenarios Based on Intervention Effects

Existing experimental studies in office, clinical, and transportation settings also indicate that, under comparable workload conditions, different fragrance families show distinct patterns of effects on cognitive efficiency, emotional recovery, and physiological stress responses (see Table S2). Broadly, citrus and peppermint-type fragrances tend to act as activation-oriented stimuli that help maintain vigilance and limit performance decrements [28,32,67,94]. Floral fragrances are more consistently associated with relaxation, mood improvement, and fatigue relief, and in some cases help maintain work performance after rest [28,95–98]. Forest or wood-derived fragrances mainly induce autonomic down-regulation and perceived restoration [36,98].

These external findings are highly consistent with the multimodal patterns observed in the present study and provide additional support for a task–scent matching strategy. In our data, the floral fragrance condition was most strongly associated with reductions in trapezius EMG and effort-related workload; the fruity fragrance condition primarily facilitated cognitive performance and reduced perceived time pressure; and the forest-like fragrance condition preferentially eased temporal stress and psychological tension. Based on this convergence of evidence, we propose the following design-oriented recommendations.

Floral fragrances can be considered "relaxation-oriented" stimuli that mainly target physical and subjective fatigue. In this experiment, floral fragrance produced the largest decreases in neck–shoulder muscle activity and effort scores, together with improvements in subjective calmness. Similar patterns have been reported in studies in which lavender or jasmine fragrances were administered during work breaks or high-pressure work periods. For example, lavender inhalation during breaks prevented deterioration of computer work performance compared with jasmine and a no-odor control condition [95]. Randomized controlled trials further show that lavender aromatherapy can significantly reduce fatigue and anxiety in intensive-care nurses and cardiac patients [28,96], while office workers receiving lavender or jasmine aromatherapy exhibit improved mood and increased alpha activity in EEG, especially under lavender exposure [97]. Taken together, these findings support the use of floral fragrances in office zones characterized by prolonged sitting and postural load (e.g., document processing, data entry), and especially during short recovery periods after intensive work, where the main goal is to relax the musculoskeletal system and stabilize mood.

Fruity (citrus) and peppermint-type fragrances can be considered "activation-oriented" stimuli that primarily support tasks with high mental demand and strong time pressure. In the present study, fruity fragrance led to the clearest improvements in task completion time, reduced pupil diameter, and lower mental demand and frustration scores, indicating more efficient information processing under equivalent workload. These results align with experimental and building-environment studies showing that sweet orange essential

oil during mental work breaks can enhance heart-rate variability, reduce blood pressure elevation, and relieve emotional stress, thereby promoting recovery without compromising cognitive performance [32]. Laboratory work on multiple aromas has also shown that citrus-ginger and other stimulating scents can suppress heart-rate increases and modulate HRV during demanding arithmetic tasks [98]. In driving-fatigue paradigms, peppermint and grapefruit fragrances significantly reduce subjective sleepiness and EEG-based fatigue indices compared with a control condition, with grapefruit showing the strongest immediate effect and peppermint contributing to sustained alertness [67]. In addition, continuous low-level diffusion of an essential oil blend in office workers has been found to speed up computer task completion and favorably adjust HRV parameters [94]. These converging results suggest that fruity and peppermint-type fragrances are particularly suitable for office settings with high cognitive load and strong time pressure, such as intensive data analysis, complex problem-solving, or deadlines, where maintaining alertness and processing speed are critical.

Forest fragrances can be positioned as "restorative-oriented" stimuli that help moderate temporal stress and support long-duration tasks with moderate cognitive demand. Although the forest-like fragrance in our study produced comparatively modest changes in objective performance indices, it significantly reduced perceived time pressure and led participants to report feeling less rushed. This subjective pattern mirrors laboratory studies in which wood and forest-derived odors, such as Hinoki cypress leaf oil, decreased prefrontal oxy-Hb concentration, enhanced parasympathetic activity, and increased subjective comfort during short seated exposure [36]. In work-like cognitive tasks, cedarwood and related aromas have also been associated with attenuated heart-rate responses and modulated HRV, suggesting a buffering effect on autonomic arousal [98]. Combined with evidence from biophilic indoor environments, these findings support the use of forest-like fragrances in spaces where the aim is to reduce background stress and temporal pressure—such as reading rooms, monitoring stations, or long but moderately demanding administrative workstations—rather than to maximize speed or intense focus.

On this basis, a simple task–scent matching framework can be formulated. Floral fragrances are recommended when physical and subjective fatigue (e.g., neck–shoulder strain, high effort ratings) is the primary concern; fruity and peppermint-type fragrances are recommended when cognitive fatigue and time pressure (e.g., increased task completion time, high mental demand, and frustration) are prominent. Forest fragrances are recommended when long-term psychological stress and perceived temporal load need to be moderated. These recommendations translate the laboratory evidence into actionable guidance for office olfactory design and can be further refined in future field studies.

Beyond this qualitative framework, the present laboratory paradigm also provides initial quantitative parameters that can guide implementation in real office environments. Our experimental protocol consisted of 45 min of continuous computer work followed by a 90-s fragrance exposure, which effectively induced measurable fatigue and allowed recovery effects to be detected. In practice, olfactory stimulation is better organized as short "micro-breaks" rather than continuous background scenting. For typical knowledge work involving sustained screen use, we recommend brief exposure windows of approximately 1.5–2 min after about 40–60 min of intensive work. To limit olfactory adaptation and avoid overexposure, the number of such exposures may be constrained to roughly 2–4 fragrance episodes per half-day for a given workstation. Fragrance intensity should be kept at a moderate level—clearly noticeable but not intrusive.

These guidelines should be regarded as preliminary design parameters derived from controlled laboratory evidence rather than as prescriptive standards. Individual differences in olfactory sensitivity, preferences, and possible allergies must be taken into account.

Where feasible, occupants should be allowed to opt in or out of specific interventions, or to select from a small validated set of fragrances within each category. Future field studies in real office buildings are needed to test and refine these quantitative parameters under longer-term, ecologically valid conditions, and to integrate olfactory design with other environmental interventions such as lighting, acoustics, and biophilic elements.

4.5. Limitations and Prospects

This study offers objective insights into olfactory intervention's impact on office workers' physiological, psychological, and cognitive recovery. However, several limitations point the way for future research.

Firstly, all participants were younger than 30 years. This homogeneous age range helped reduce variability related to age-dependent changes in olfactory function, autonomic reactivity, and subjective fatigue, but it also limits the generalizability of the present findings. Older adults often exhibit altered olfactory perception and different patterns of autonomic and fatigue responses, and the effectiveness of olfactory interventions may therefore differ across age groups. Future studies should deliberately recruit participants from a broader age range and perform age-stratified or age-by-condition analyses to examine whether the observed effects extend beyond young office workers. Secondly, the study didn't analyze the specific components of olfactory stimuli. Future work should explore how these components affect physiological, psychological, and cognitive regulation. Thirdly, the study used only olfactory assessment of essential oil scents. Future research might consider the combined impact of multi-sensory interventions and interactions between senses.

In the future, with the further understanding of olfactory intervention mechanism, and innovation in technology, office olfactory environments could become smarter and more personalized. Smart olfactory systems could automatically adjust scents and concentrations based on employees' real-time status to maximize intervention effectiveness. Moreover, integrating virtual and augmented reality with olfactory intervention could create immersive work settings that offer employees more holistic and personalized support. This multi-sensory office environment could boost work efficiency and significantly enhance employees' physical and mental well-being, steering future office scenarios towards greater human-centeredness and efficiency.

5. Conclusions

This study used a standardized office-fatigue paradigm and multimodal measurements to demonstrate that olfactory stimulation can support recovery across cognitive, physiological and psychological domains, and that the profiles of benefit differ by fragrance type. Floral scents mainly promoted physiological recovery by reducing trapezius activation and effort-related workload; fruity scents improved cognitive performance and vigor while attenuating negative mood; forest-like scents reduced perceived time pressure during sustained work.

Conceptually, these findings extend previous olfactory research by showing that the impact of fragrances on office fatigue cannot be captured by single outcomes such as relaxation or pleasantness alone. Instead, the proposed tri-dimensional perspective—cognitive efficiency, physiological strain and psychological stress—reveals differentiated recovery profiles for different scent types. The robust correlations between subjective ratings and physiological indicators further support the convergent validity of this multi-modal framework and underscore the importance of integrating behavioral and neurophysiological evidence when evaluating workplace interventions.

From an applied standpoint, the findings suggest a matching strategy for office olfactory design: floral scents for postural and effort-related fatigue, fruity scents for tasks with

high mental demand and tight deadlines, and forest-like scents for prolonged but moderate workloads where mitigating temporal stress is desirable. Such targeted use of fragrances may contribute to healthier and more productive knowledge-intensive workplaces.

The study is limited by its acute laboratory setting, a relatively homogeneous sample of young adults and a restricted set of fragrance types and intensities. Future work should examine more diverse worker groups and office layouts, longer exposure periods, individual differences in olfactory sensitivity and preference, and the combined effects of olfactory, visual and acoustic interventions. Within these boundaries, the present study provides an empirical foundation and an initial matching framework for using fragrances as a nuanced tool to manage office fatigue.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings16010003/s1, Table S1: Statistical Results of Indicators; Table S2: Task–scent matching and preliminary implementation parameters for olfactory interventions.

Author Contributions: Conceptualization, C.Z.; methodology, C.Z., J.K.; validation, C.Z. and J.K.; formal analysis, M.F.; investigation, F.Y.; resources, M.F. and C.Z.; data curation, M.F., F.Y. and J.K.; writing—original draft preparation, M.F., C.Z., F.Y.; writing—review and editing, M.F., C.Z., F.Y. and J.K.; project administration, C.Z.; funding acquisition, C.Z. All authors have read and agreed to the published version of the manuscript.

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

Data Availability Statement: Data will be made available on request. Due to the privacy and ethical restrictions in the laboratory, our data can be obtained by contacting the corresponding author.

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