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"Emotional measurement methods that combine physiology, behavior, and psychology"

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1. Introduction

The fragrance industry is increasingly concerned about the impact of fragrance on emotions, particularly in terms of scientifically measuring emotions. Currently, some studies have attempted to evaluate the emotional changes caused by odors by utilizing physiological measurement methods such as electroencephalography (EEG) [1-4], heart rate variability [5], blood pressure [5, 6], galvanic skin response [7], and salivary cortisol [8, 9]. Among these modalities, EEG offers a direct measure of brain activity and millisecond-scale temporal resolution unmatched by other physiological measures [10], enabling precise capture of the rapid cortical dynamics underlying odor-evoked emotional processing.

By directly measuring neuronal oscillations, EEG allows frequency-domain analyses—such as α (8-12 Hz) and β (13-30 Hz) band power—that correlate robustly with valence and arousal induced by fragrances. Previous studies have shown that a decrease in β activity, along with an increase in α activity and the α/β ratio, is associated with reduced stress and enhanced relaxation induced by fragrances such as jasmine, lavender, and citrus [2, 8, 11-13]. The imbalance in cortical activity between the left and right frontal lobes is commonly linked to motivational tendencies, with relatively greater right-than-left frontal activation reflecting withdrawal motivation, whereas the reverse—relatively greater left-than-right frontal activation—reflects approach motivation [14]. Because α power is inversely related to regional cortical activation [15], frontal α asymmetry (right vs. left α power) has been widely employed to index affective valence in the hedonic evaluation of fragrances, reflecting the degree of positive (approach) versus negative (withdrawal) emotional responses [16, 17]. Meanwhile, β activity have been found to be associated with an active state of mind, thus the α/β ratio asymmetry is also commonly used to measure emotional valence [18, 19].

In addition to spectral power analyses, EEG functional connectivity (FC) provides a complementary, network-level approach to measuring emotional valence by quantifying interactions between brain regions across frequency bands [20, 21]. Metrics such as coherence and weighted phase-lag index (wPLI) capture frequency-specific coupling, revealing how affective stimuli modulate large-scale brain networks. Specifically, early studies found that positive valence enhances frontal α-band coherence, whereas negative valence increases γ-band coherence [20]. As for the wPLI, which measures consistent phase leads/lags mitigating volume-conduction artifacts [22, 23], previous studies revealed that pleasant odors could enhance frontal β-band wPLI [24].

Although scholars have attempted various methods for measuring emotions, there is still a need to verify and further explore how to scientifically measure emotions by comprehensively combining physiological and psychological methods. Furthermore, to date, only few studies have applied EEG FC to quantify odor-induced emotional responses, leaving a notable gap in olfactory affect assessment. Therefore, the aim of the present study is to investigate which EEG metrics (including EEG spectral power and functional connectivity) are suitable for assessing changes in pleasantness induced by olfactory stimuli.

2. Materials and Methods

2.1. Participants

A total of thirty-three participants within the age range of 23-55 completed the study. Ethical approval for this study was obtained from the Shanghai Clinical Research Ethics Committee, adhering to the principles of the Helsinki Declaration. Informed consent was obtained from all participants, and they were compensated appropriately upon the completion of the experiment.

2.2. Procedure

Two fragrances, sweet orange, and mint, were chosen for this study. Each participant will undergo two visits, with each visit involving the testing of a single fragrance. Following the initial visit, participants will review the informed consent form in conjunction with the research staff. Subsequently, participants will engage in behavioral tasks (Go/No-go Association Task, GNAT), EEG data collection, and questionnaire completion (Self-Assessment Manikin, SAM) under the supervision of the research team. They will then undergo EEG data collection while being exposed to fragrance samples, followed by a repeat of questionnaire assessments and behavioral tasks. The initial visit will last between 40-60 minutes, with a mandatory minimum interval of 24 hours before the second visit. The detailed information about the GNAT and SAM scale have been reported in our recent work. The discriminant index d in the GNAT was utilized as the analytical parameter.

2.3. EEG PSD-based Emotion Measurement

Calculate the power spectral density of θ (4-8 Hz), α (8-12 Hz), β (13-30 Hz) and γ (30-45 Hz) waves. The valence algorithms in the current study could be divided into two major categories: α PSD asymmetry and α/β PSD ratio asymmetry. The α PSD asymmetry between corresponding left and right frontal electrodes (i.e., AF4-AF3, F4-F3, and F8-F7), as well as the overall frontal α PSD difference between the left and right hemispheres (i.e., (AF4+F4+F8) – (AF3+F3+F7)), were analyzed.

As for the arousal, two major categories of algorithms were used: β PSD and β/α PSD ratio. Parietal (P8 and P7 electrodes) β PSD, β/α PSD ratio of each corresponding frontal electrodes pairs (i.e., AF4 & AF3, F4 & F3, and F8 & F7), as well as the overall frontal β/α PSD ratio (i.e., AF4+F4+F8+AF3+F3+F7) were used to assess the emotional arousal.

2.4. EEG Functional Connectivity

To examine the effects of fragrance and fragrance-induced emotion on EEG functional connectivity, we obtained magnitude squared coherence (MSC) and weighted phase lag index (wPLI) between different EEG channels in each frequency band (θ, α, β and γ bands in this study). MSC represents the degree of mutual interference and frequency-dependent correlation between two brainwave signals, and the wPLI is a measure of phase synchronization between them.

2.4.1. Magnitude Squared Coherence

The MSC between two specific brain regions could be calculated as shown in equation (1):

$$MSC = \frac{\left|P_{xy}(f)^2\right|}{P_{xx}(f) * P_{yy}(f)} \tag{1}$$

in which f represents the frequency range of interest, Pxy refers to corss power spectral density (CPSD) between signals of two brain regions, and Pxx and Pyy refers to PSD of signals from two distinct brain regions.

2.4.2. Weighted Phase Lag Index

The wPLI between two specific brain regions could be calculated as shown in equation (2):

$$wPLI = \frac{\left|E\left[\left|\Im\{S_{xy}(f)\}\right| * sign\left(\Im\{S_{xy}(f)\}\right)\right]\right|}{E\left[\left|\Im\{S_{xy}(f)\}\right|\right]} \tag{2}$$

in which Sxy represents cross-spectrum of two signals at frequency f, $\Im$ means the imaginary part of spectrum, E means the expectation over time or trials. The wPLI ranges from 0 to 1, where higher values suggest stronger functional connectivity at a given frequency.

2.5. Statistical Analysis

Repeated measures ANOVAs and paired sample t-tests were employed for data that followed a normal distribution and EEG data, whereas Wilcoxon tests were utilized for data that did not adhere to a normal distribution.

3. Results

3.1. SAM Scale and Behavioral Tasks

The results of SAM scale and behavioral tasks have been reported in detail in our previous work. In brief, the sweet orange fragrance induced a significant increase in subjective emotional valence lasting for 8 min (*ps* < 0.001), an immediate significant increase in emotional arousal (*p* = 0.044), a marginally significant increase in d-values of the GNAT (*p* = 0.071). On the other hand, the mint fragrance invoked continuous significant increase in both subjective valence and arousal, but didn't affect performance of the GNAT. Table 1 presents SAM scale, and behavioral paradigm data of all participants both before and after exposure to the fragrances.

TABLE 1. SAM scale scores and performance of behavioral tasks before and after fragrance stimulation.

Fragrance	Indicators	T0	T1	T2	T3	T4
Orange	Pleasant	6.06±1.27	6.82±1.57	7.24±1.06	7.48±1.23	7.39±1.37

	d	-0.66±1.37	/	/	/	0.21±0.88
	Arousal	3.64±1.43	4.30±1.88	4.15±1.72	3.82±1.79	3.82±2.05
	Pleasant	6.06±1.27	6.67±1.45	6.91±1.16	7.27±1.44	7.33±1.29
Mint	d	-0.19±2.11	/	/	/	0.49±2.11
	Arousal	3.42±1.30	4.30±1.94	4.30±1.88	4.61±2.42	4.82±2.48

* T0 – T4 represents different time points of each visit, corresponding respectively to: before smelling, the initial 2 minutes of smelling, 2–4 minutes, 4–6 minutes, and 6–8 minutes.

3.2. EEG PSD of Different Frequency Bands

Paired sample t-tests demonstrated that after exposure to sweet orange fragrance, α PSD at AF4 (p = 0.015) and F4 (p = 0.037) electrodes, β PSD at F4 (p = 0.035) and θ PSD at AF4 (p = 0.029) were significantly higher than pre-stimulation baseline.

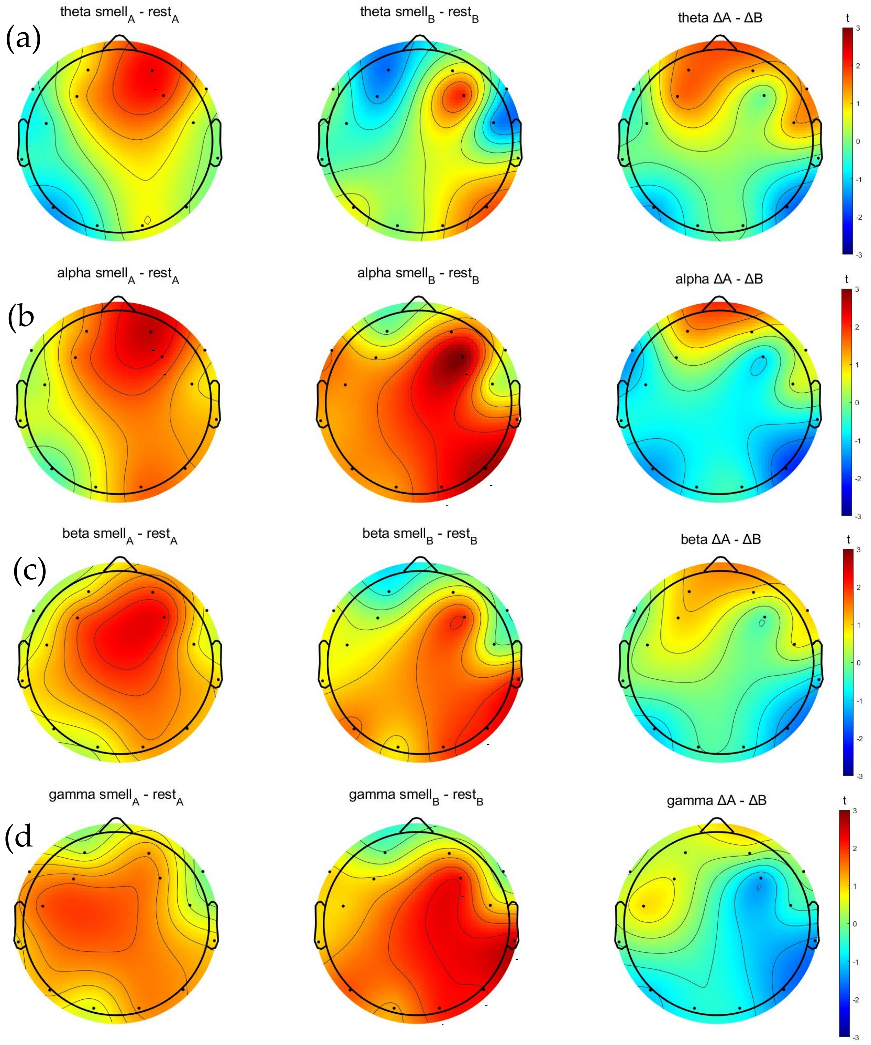

Figure 1. The t-values of paired sample t-tests on θ (a), α (b), β (c) and γ (d) waves. The left and middle columns depict the fragrance-induced PSD changes (post – pre), and the right column represents the differences of fragrance-induced change of PSD

between two fragrances (A - B). Product A symbolize the sweet orange fragrance, while B symbolize the mint fragrance. Asterisks indicate electrodes with significant differences.

As for the mint fragrance, exposure led to significantly increased α PSD at P8 (p = 0.011), O2 (p = 0.040) and F4 (p = 0.006) electrodes, increased β PSD at P8 (p = 0.041) and T8 (p = 0.047) and γ PSD at O2 (p = 0.045), P8 (p = 0.033), T8 (p = 0.017) and F4 (p = 0.040). However, no significant differences were found in EEG PSD changes when comparing the effects of the two fragrances (ps > 0.05). All these results of EEG PSD changes induced by two fragrances are depicted in Figure 1.

3.3. EEG-based Emotional Valence

In our recent work, EEG-based valence was defined as the overall right-left frontal α asymmetry. A repeated measures ANOVA found a significant main effect of fragrance stimulation (F (1,27) = 6.09, p = 0.020, η_p^2 = 0.18) on this valence index: fragrances significantly raised emotional valence. The post hoc analysis demonstrated that participants experienced a noteworthy increase in valence when exposed to the sweet orange fragrance in comparison to their baseline state. Conversely, there was no significant alteration in valence when exposed to the mint fragrance.

To identify which frontal asymmetry indicators are more reliable in emotion recognition, we also analyzed α PSD asymmetry and α/β PSD ratio asymmetry across pairs of frontal electrodes. A repeated measures ANOVA indicated a significant interaction effect between fragrance type and experimental time stages (F (1,27) = 9.59, p = 0.005, η_p^2 = 0.26), the post-hoc analysis found that smelling of sweet orange fragrance led to a marginally significant increase in α asymmetry between F8 and F7 electrodes, whereas the mint scent did not. The smelling of mint fragrance resulted in a significant increase in α asymmetry between AF4-AF3 and F4-F3 electrode-pairs. However, no significant difference was detected in valence changes caused by different scent stimuli.

With respect to the α/β PSD ratio asymmetry, no related indicator was affected by the olfactory stimulation, and there were no significant differences in indicator changes caused by different scent stimuli (ps > 0.05). Table 2 presents the EEG-based emotional valence indicators which significantly changed followed by olfactory stimuli.

TABLE 2. EEG-based emotional valence before and after fragrance stimulation.

Fragrance	Indicators	Pre	Post	*p*
Orange	α(F4+F8+AF4)-α(AF3+F3+F7)	2.61±2.96	3.68±2.44	0.017*
	αAF4-αAF3	0.44±0.94	0.81±1.21	0.200
	αF4-αF3	1.21±1.42	1.48±1.53	0.261
	αF8-αF7	0.96±1.48	1.39±1.04	0.062*
Mint	α(F4+F8+AF4)-α(AF3+F3+F7)	2.34±3.66	3.36±3.36	0.126
	αAF4-αAF3	0.37±1.01	1.01±1.27	0.006*
	αF4-αF3	0.77±2.60	1.61±2.03	0.051*
	αF8-αF7	1.20±1.28	0.75±1.48	0.120

3.4. EEG-based Emotional Arousal

In our recent work, EEG-based arousal was defined as the overall frontal β/α PSD ratio. This arousal index of participants marginally significantly decreased when exposed to the sweet orange fragrance compared to the baseline (pre: 0.97±2.94, post: -0.30±3.37, $p = 0.092$). There was no significant change in the arousal index when participants were exposed to the mint fragrance (pre: -2.08±9.00, post: -0.39±3.12, $p = 0.295$) and no significant difference between the two fragrances ($p = 0.093$).

Parietal β PSD and β/α PSD ratio of each corresponding frontal electrodes pairs were further analyzed. Only the β PSD of the P8 electrode increased during the 8 minutes of smelling the mint scent compared to the baseline (pre: -3.18±4.24, post: -1.66±2.75, $p = 0.041$); other arousal indicators were not affected by the olfactory stimulation, and there were no significant differences in indicator changes caused by different scent stimuli (*ps* > 0.05).

3.5. EEG Functional Connectivity Measures

3.5.1. Magnitude Squared Coherence

Paired sample t tests found that the MSC of α band between AF3 & F4 (t (27) = 4.21, *p_corrected* = 0.023, Cohen's d = 1.62) and AF3 & FC6 (t (27) = 3.69, *p_corrected* = 0.046, Cohen's d = 1.42) significantly increased when inhaling the sweet orange fragrance, as illustrated in Figure 2(a). However, inhalation of mint fragrance failed to induce any significant changes in MSC of four frequency bands (*ps_corrected* > 0.05). No significant differences were observed in MSC changes across the different olfactory stimuli. For the other three frequency bands (θ, β and γ bands), neither olfactory stimulus elicited significant changes in MSC (*ps_corrected* > 0.05).

3.5.2. Weighted Phase Lag Index

As it is shown in Figure 2(b), a significant reduction in β-band wPLI between AF3 & F3 was observed during the 8-minute inhalation of mint fragrance (t (27) = -4.19, *p_corrected* = 0.025, Cohen's d = 1.61), while sweet orange fragrance inhalation did not elicit any significant change compared to baseline (*ps_corrected* > 0.05). No significant differences were observed in wPLI changes across the different olfactory stimuli. For the other three frequency bands (θ, α and γ bands), neither olfactory stimulus elicited significant changes in wPLI (*ps_corrected* > 0.05).

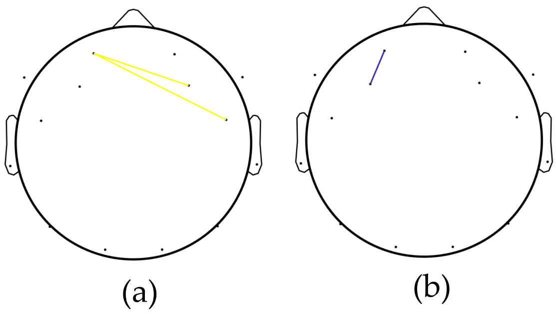

Figure 2. Electrode pairs showing significant changes in α MSC after orange fragrance exposure (a) and β wPLI after mint fragrance exposure (b). Yellow and blue lines indicate statistically significant increases and decreases in functional connectivity, respectively.

3.6. Relationships Between Different Measurements

The results of Spearman correlation analysis showed that the change in valence estimated from F8-F7 α asymmetry was positively correlated with the alteration in d-value of GNAT triggered by fragrance ($r = 0.38$, $p = 0.027$), and the change in arousal estimated from β PSD of P8 showed a marginally significant positive correlation with subjective emotional arousal change assessed by SAM scale ($r = 0.25$, $p = 0.068$).

Regarding the EEG FC, the change in MSC of α band between AF3 & F4 showed a marginally significant positive correlation with subjective emotional valence change ($r = 0.25$, $p = 0.059$), while the alternation in β-band wPLI between AF3 & F3 and subjective arousal were positively correlated at a marginal level of significance ($r = 0.25$, $p = 0.060$).

Apart from that, no significant correlations were found among the remaining EEG, behavioral, and questionnaire data (*ps* > 0.05).

4. Discussion

The present study aimed to identify the valid and reliable EEG indicators of the emotional valence evoked by olfactory stimulation. Overall, the findings demonstrate that different fragrances modulate distinct patterns of neural activity in the whole brain regions, particularly in the α and β frequency bands. These results underscore the potential utility of these EEG features as objective markers of olfactory-induced emotional states.

4.1. EEG PSD and PSD ratio

Among the indicators based on EEG PSD, frontal α asymmetry emerged as particularly sensitive to olfactory-induced emotional valence changes.

Inhalation of sweet orange fragrance, associated with pleasant emotional valence (proved by the SAM scale and GNAT), was found to significantly enhance θ, α, and β power in the right frontal cortex, and increase α asymmetry specifically in the ventral prefrontal cortex. These findings align with the frontal alpha asymmetry model, where greater left-hemisphere activity (indicated by increased α PSD on the right relative to the left) is associated with approach-related positive affect [14]. Also, previous research examining the emotional effects of cosmetic fragrances has similarly reported that fragrances that could elicit pleasant emotions had been shown to enhance frontal α asymmetry [1, 25]. The positive correlation between Ventral frontal α asymmetry and d-values in the GNAT further substantiate the pivotal role of α asymmetry in the recognition of emotional valence. Previous studies had shown that the GNAT could be utilized as a measure of the automatic associations formed between odors and emotion, i.e., implicit affective responses to fragrance [26, 27]. Thus, this correlational finding underscores the emotional relevance of ventral frontal α asymmetry, suggesting that greater asymmetry in this region may reflect enhanced pleasant responses to olfactory stimuli.

In contrast, mint fragrance, potentially associated with both more arousing and pleasant effects (proved by the SAM scale), induced a broader increase in α, β, and γ PSD across the entire right hemisphere, along with elevated α asymmetry in the dorsal prefrontal cortex. Food-related odors were found to elicit stronger activations of the limbic system and reward areas (such as orbitofrontal cortex and insula) compared to odors not related to food [24, 31, 32]. These regional differences in α asymmetry modulation between orange and mint scent (ventral versus dorsal frontal cortex) may reflect distinct affective and neural responses to food-related versus non-food-related odors.

Regarding the α/β PSD ratio asymmetry, we did not find any significant change induced by fragrance stimulation. The relative stability of α/β PSD ratio asymmetry may be attributed to the concurrent increase in α and β-band PSD in the right frontal cortex. β oscillations are associated with increased attentional resources (heightened in emotionally arousing states), odor identification and odor memory encoding [33, 34]. Therefore, the α/β PSD ratio asymmetry might be affected by both emotional pleasant and arousal, and more suitable for studies focusing on stimuli with similar arousal levels but marked differences in emotional valence [18, 19].

4.2. EEG Functional Connectivity

Among the indicators based on EEG FC, the frontal interhemispheric α-band MSC was particularly sensitive to olfactory-evoked valence changes, highlighting its potential utility in affective scent evaluation.

Frontal interhemispheric α MSC was found to increase following sweet orange inhalation and showed a significant positive correlation with subjective emotional valence. These findings are consistent with previous research suggesting that enhanced coherence between left and right frontal regions in the α band may support the integration of affective information across hemispheres, possibly facilitating a more balanced or harmonious emotional state [35,36]. Furthermore, intra-left frontal β-band wPLI was reduced during mint stimulation but was positively correlated with arousal, suggesting that decreased phase-lagged connectivity within the left frontal cortex might reflect a loosening of regulatory control, reduced anxiety or increased emotional reactivity [5, 24].

Importantly, PSD and FC measures capture complementary aspects of neural processing: α PSD asymmetry reflects localized emotional activation, while MSC inform on the network-level integration or dissociation of affective information [37]. Future research and practical applications should aim to incorporate these complementary EEG indices in an integrated framework for emotion assessment.

4.3. Limitations

Despite these promising results, several limitations should be acknowledged. Given the relatively small sample size in this study, the results should be interpreted with caution and require further validation in larger samples. Additionally, only two types of fragrance stimuli were tested, which limits the scope of emotional valence and arousal that can be explored. Extending this work to include a wider range of olfactory cues—including unpleasant or neutral, and food-related or non-food-related scents —would enhance our understanding of the full spectrum of affective olfactory processing.

5. Conclusion

In conclusion, the current study highlights that α asymmetry (especially in ventral frontal areas) and frontal interhemispheric α MSC are the most informative EEG indicators for tracking emotional valence responses to olfactory input. These findings contribute to the growing body of research on EEG-based emotion recognition, offer valuable insight for assessing consumer affect in the fragrance industry and point toward potential applications in fragrance product design process.

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