

Exploring Cortex Connectivity Signal in Sensory Response to Odors

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Abstract—Recent neuroscience studies using fMRI have shown specific cortex activities are associated with scent stimuli. This has shed light on the use of EEG for investigating the neuronal processes and effects of olfactory sensory. While there were a few EEG studies using ERP or spectral power analysis, the results are often not converging or lack of generality. This study attempts to explore a potentially more generalized approach by looking into the connectivity patterns in the brain during olfactory sensing. Human olfactory system collects odorants and transduces them into neural signals which are transmitted to the olfactory bulb that connects to the orbitofrontal cortex for further processing. We study connectivity of cortex signal through the coherence analysis on scalp EEG data. We propose a novel protocol for robust olfactory stimulus identification and synchronization experiment. We adopt Magnitude Squared Coherence Estimation for coherence analysis and derived a coherence index (CI) to infer the collaborative effect derived from a region of interest, e.g., left side and right side of scalp. From the 14 subjects' EEG data, we observe the lateralization effect of olfactory processes in the human brain. The results suggest a stronger collaborative effect in the left hemisphere compare to the right side when pleasant stimuli are delivered.

I. INTRODUCTION

Human beings are able to memorize thousands of distinct odors that could trigger memories taking people all the way back to their childhood. The reason lies in that olfactory is the only sense directly connected to the brain's limbic system which houses emotions and memories, making smell our *most emotional* sense. Discovering the impact of ambient scent on enhancing consumer behavior has prompt the rapid growth of scent-marketing industry. To date, the research and development of scent product relies heavily on *Sensory Panels* – experts trained in performing standard evaluations on scent and flavor attributes using sensory terminologies and rating scales, to produce a unambiguous perception of what regular consumers may experience. However, training and hiring sensory experts are time consuming and costly. Their evaluation may be subject to biases due to inter observer variation. Furthermore, the lengthy process may induce fatigue for human experts. Recent advance in EEG based perception analysis has make it possible to develop cost-effective, consistent and potentially more objective assessment toolkit via understanding the olfactory responses in the human cortex.

Various features derived from EEG signals have been proposed in odor perception and some particular features performs highly discriminative for odor preferences recognition. Study has shown that Event-Related Potentials (ERP) could effectively reflect of the smelling process [1], [2], though the accuracy is not high due to noises [3]. It is reported that theta power band becomes more active when subjects were exposed to fragrances [4]; however in another study, an decrease of theta and alpha bands were observed while subjects smelling essential oil [5]. Moreover, a recent study demonstrates that the beta band possesses highest distinguish power in odor pleasantness recognition task [6].

Though studies have tried to capture the oscillatory nature of olfactory perception by means of EEG analysis. There is a missing picture about the connectivity analysis reflecting the comprehensive timely cortex response to the scent stimuli. In this study we study the connectivity of cortex activities through the coherence analysis on scalp EEG data. We propose an algorithm for connectivity analysis on cortex olfactory preference. A protocol for scent preference study is designed to collect accurately labeled EEG data. We then perform the statistical analysis to observe the timely connectivity response to olfactory stimuli. The following sessions describe in detail of the methodology and experiment result.

II. METHOD

A. Data acquisition protocol

We first develop a novel data acquisition protocol, aiming to acquire reliable labeled EEG data from human subjects perceiving various odor stimuli with preference such as like vs dislike, or pleasant vs unpleasant. Figure 1 describes the workflow of proposed protocol. Prior try out sessions are conducted in advance to label a group of scent stimuli based on each subjects preference to form a set of scent stimuli which marked with subject specified preference. In the experiment setup, two sensing modalities – breathing sensor and EEG electrodes, are employed to measure the respiration and cortex signals. We then develop a software system to controls data collection flow, where signals are triggered via a synchronized mechanism, making sure the stimuli are delivered in keeping with the subject's breathing cycle and in the mean while

tagging the EEG data. The EEG data was collected during each session which contains a number of trials. Each trial is tagged with starting time, ending time and the type of the stimuli delivered (pleasant, neutral and unpleasant). At the end of session EEG data was saved in the EEG database for further study.

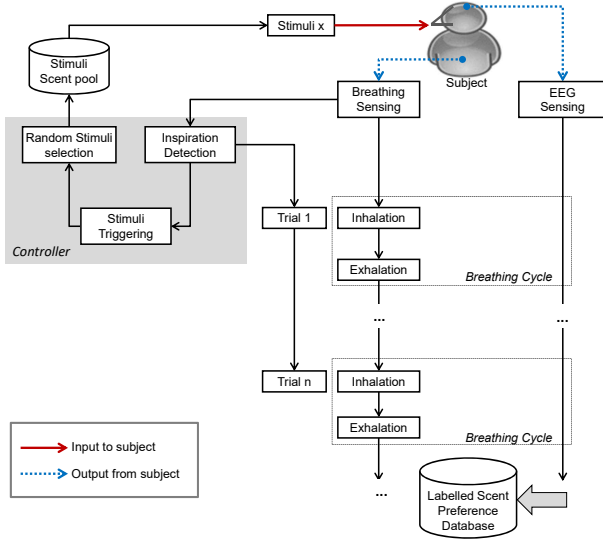


Fig. 1. Respiration Synchronization for EEG Data Tagging

The protocol allows scent stimuli perception being synchronized with the subject's breathing pattern. In this way the operator is able to actively control the experimental flow, ensuring a high quality data acquisition.

B. Neural Connectivity Study through Coherence Analysis

Studies have shown that there exists a lateralization effect for emotional processes in the human brain. A relative left hemispheric activation in the frontal zones is associated with positive emotions and a relative right hemispheric activation in the frontal zones is associated with negative emotions [7]. In this work, we study the brain response to scent preference through coherence analysis, to measure signal consistency between pairs of EEG channels at frequencies that are phase-consistent over many trials [8]. Among various coherence analysis techniques, the Magnitude Squared Coherence Estimation (MSCE) is a function of frequency that gives a real value to indicate how well the data acquired in i^{th} channel corresponds to that from j^{th} channel, computed at each frequency separately [9].

The MSCE value $MC_{ij}(f) \in [0, 1]$ is defined by a function of Power Spectrum Density (PSD) $P_{ii}(f)$ (of i^{th} channel) and $P_{jj}(f)$ (of j^{th} channel), given in Equation (1).

$$MC_{ij}(f) = \frac{|P_{ij}(f)|}{\sqrt{P_{ii}(f) \times P_{jj}(f)}} \quad (1)$$

where f is the frequency, $P_{ii}(f), P_{jj}(f), MC_{ij}(f)$ denote the f^{th} samples of $\mathbf{P}_{ii}, \mathbf{P}_{jj}, \mathbf{MC}_{ij}$ respectively. The PSD of i^{th} or j^{th}

channel and the cross PSD in equation 1 are estimated as following:

$$\mathbf{P}_{ii} = |\mathbf{z}_i \mathbf{z}_i^*|,$$

$$\mathbf{P}_{jj} = |\mathbf{z}_j \mathbf{z}_j^*|,$$

$$\mathbf{P}_{ij} = |\mathbf{z}_i \mathbf{z}_j^*|$$

The \mathbf{z}_i denotes the Discrete Fourier Transform (DFT) of windowed \mathbf{x}_i whereby $\mathbf{z}_i \in \mathbb{C}^{N \times 1}$. The DFT transforms \mathbf{x}_i from the time domain to the frequency domain. The $\mathbf{z}_i, \mathbf{z}_j$ are given by

$$z_i(f) = \sum_{n=0}^{N-1} x_i(n) \times e^{-\frac{2J\pi f n}{N}}, \quad (2)$$

$$z_j(f) = \sum_{n=0}^{N-1} x_j(n) \times e^{-\frac{2J\pi f n}{N}}, \quad (3)$$

where J is the imaginary unit, $f = [0, 1, \dots, N-1] \times \left(\frac{f_s}{2 \times N}\right)$ and f_s is the sampling frequency of the system.

The coherence among the EEG electrodes in the left and right side of the hemisphere are used to indicate the collaborative efforts in that hemisphere. To study the lateralization effect, 12 out of 40 channels, located on left and right side of the scalp respectively, are used for the coherence analysis, as shown in Figure 2. We compute coherence index ($0 \leq CI \leq 1$)

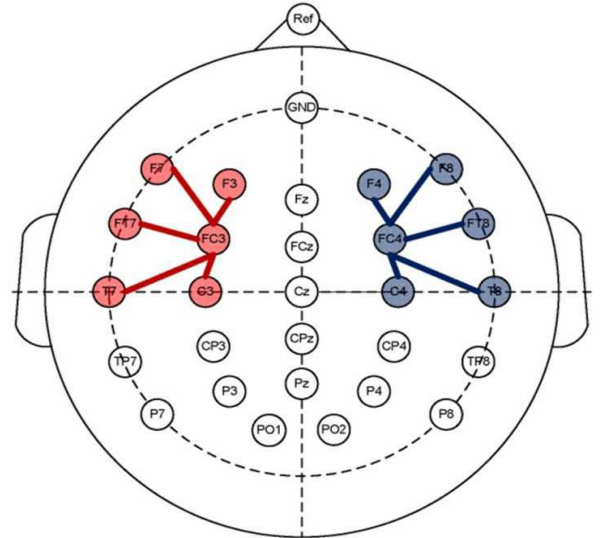


Fig. 2. Channel Selection for Coherence Study

for each session by realize the channel information for equation (1) as follows:

- for left hemisphere:

$$\begin{cases} i = FC3 \\ j = F3, F7, FT7, C3, T7 \end{cases} \quad (4)$$

- for right hemisphere:

$$\begin{cases} i = FC4 \\ j = F4, F8, FT8, C4, T8 \end{cases} \quad (5)$$

Comparisons between the 6 corresponding left-right hemisphere channel pairs were performed over the trials, i.e.,

$$\left\{ \begin{array}{ll} \{(FC3, F3), & (FC4, F4)\}, \\ \{(FC3, F7), & (FC4, F8)\}, \\ \{(FC3, FT7), & (FC4, FT8)\}, \\ \{(FC3, C3), & (FC4, C4)\}, \\ \{(FC3, T3), & (FC4, T8)\} \end{array} \right\} \quad (6)$$

Pairwise comparison is conducted, the winner of a particular comparison was chosen as that with the most number of winning trials. For example, the winner is $(FC3, F3)$ if there are more trials for which $MC_{(FC3, F3)} > MC_{(FC4, F4)}$. The coherence index $0 \leq CI \leq 1$ was then calculated as the average number of winners in the size of hemisphere.

C. Subject-dependent baseline

The coherence among channels can be subjective due to the fact that each individual may have their distinct cortex connectivity characteristics. In this study, a subject-dependent baseline was adopted. For N number of sessions, the subject-dependent baseline θ was calculated as in (7):

$$\zeta = \frac{\sum_{n=1}^N CI^{(n)}}{N} \quad (7)$$

where $CI^{(n)}$ is the coherence index for the n^{th} session. The hemisphere with $CI \geq \zeta$ was regarded as the more collaborated one during a session.

III. EXPERIMENT AND RESULT

A. Experiment set up

Written consent forms are pre-acquired from all participants. Ethical approval for the experiment is obtained from Institute Review Board of National University of Singapore. There are 14 healthy subjects participated in the experiment, each contributes two sessions of data collection. EEG data is recorded at 250 Hz sampling rate from 40 electrodes placed at the standard 10-20 positions on the scalp, in a setting of pleasant, unpleasant and neutral odor stimuli presentations. Several different scent samples are presented to the subjects prior to the data collection. User preference is considered in the experiment by providing and letting the subjects choose the most pleasant and most unpleasant odor, which form pleasant vs. unpleasant odor stimuli pair for the two sessions to be conducted. In this way, the pair of stimuli odor used in model training can be different from what is used in model evaluation or testing. Therefore, our approach could capture the EEG patterns reflecting scent preferences that are common across different odors.

Each session of experiment contains 60 trials. In each complete trial, the stimuli type is pseudo-randomly assigned by the computer and prompted to the operator; the class of stimuli and the onset / end of the perception is marked in the recording of EEG data. At the end of each session, EEG data with a equal number of pleasant, unpleasant and neutral trials are collected.

B. Comparison of subjects' breathing pattern between pleasant and unpleasant stimuli

To understand whether the type of scent stimuli, e.g., pleasant or unpleasant would influence the subject's breathing pattern, we compared the 14 subjects breath duration \mathbf{D}_P vs \mathbf{D}_U , for

$$\mathbf{D}_{stimuli} = \frac{\sum_{i=1}^n (\mathbf{T}_{inhale}^{i2} - \mathbf{T}_{inhale}^{i1})}{n} \quad (8)$$

where n is the number of trials for $stimuli$, including \mathbf{P} and \mathbf{U} , \mathbf{T}_{inhale}^{i2} and \mathbf{T}_{inhale}^{i1} are the onset of respiration at first and second breathing cycles of the i trial respectively.

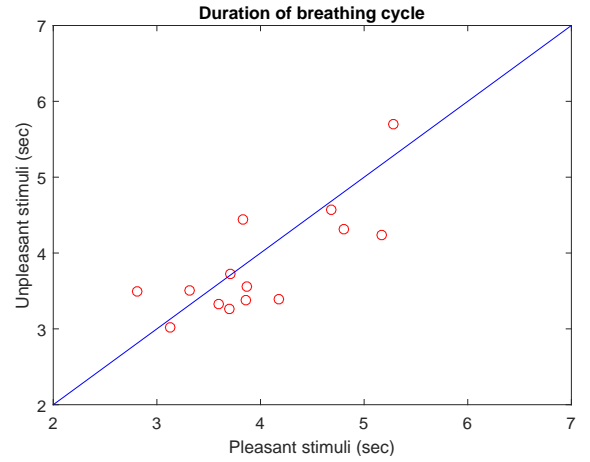


Fig. 3. Comparing breathing duration between pleasant and unpleasant stimuli

Figure 3 shows the scatter plot comparing 14 subjects' average breath duration \mathbf{D}_P and \mathbf{D}_U for pleasant and unpleasant stimuli respectively. It is observed that breathing pattern are highly consistent between different types of stimuli. The same conclusion can be drawn from a T-test conducted to compare the breath duration of pleasant and unpleasant trials. The p-value of 0.607 implies no difference found between the two groups.

C. Coherence Analysis for Lateralization Effect

We use MSCE-based coherence index (CI) to analyze the correlation among multiple channels. The CI is calculated among two groups of 6 channels located on left and right hemisphere respectively as shown in Figure 2. After taking into consideration of subject dependent baseline, the accumulated CI values among the EEG electrodes are used to indicate more collaborative efforts in the left hemisphere as compare to right hemisphere. A 2 seconds window with 0.25 second shifting is used to scan along the [-2 4] seconds duration, with 0 second pointing to the start of the first breath-in onset upon the stimuli delivered. 25 windows are obtained within the total 6 seconds duration. For each window, the CI value is calculated based on averaging the 14 subjects' CI values.

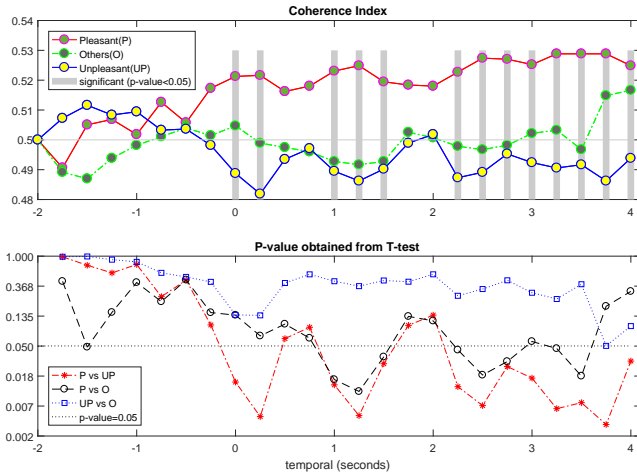


Fig. 4. Correlation Index of Different Scent Stimuli (all subjects)

Three curves are obtained indicating the temporal response to pleasant, unpleasant and other unspecified stimuli respectively. Figure 4 shows the result of CI values along the [-2 4] second period. For pleasant stimuli, we observe an increasing collaborative efforts at left size and for unpleasant and other stimuli, a slightly more coherence in the right side.

We conduct statistics analysis using two sample t-test. The changes between 2 groups are significant if $p\text{-value} < 0.05$. Bottom plot of figure 4 shows the p-values obtained by comparing pleasant vs unpleasant vs other stimuli respectively. Along the temporal axis, we observe the increase of difference between pleasant and unpleasant stimuli significantly. We mark the top plot along the temporal axis when $p < 0.05$ for CI differences comparing pleasant vs unpleasant.

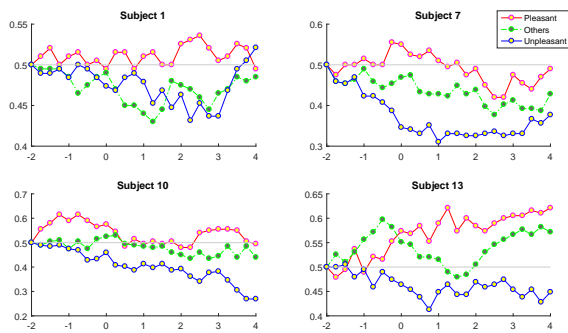


Fig. 5. Correlation Index for Single Subjects

We also show several subject's individual temporal CI trends in figure 5. Temporal lateralization effect responding to pleasant and unpleasant stimuli in these individuals are clearly observed.

IV. DISCUSSION

EEG-based approach offers great potential in developing objective and cost-effective tool for understanding ordinary consumer's preference in odor perception. However, approaches deployed upon ERP analysis are highly sensitive to noise and has limited application other than in research laboratory settings. On the other hand, studies based on spectrum band power analysis reported contradictory results [4], [5]. There is a missing picture about the connectivity analysis reflecting the comprehensive timely cortex response to the scent stimuli.

In this work we study connectivity of cortex activities through the coherence analysis on scalp EEG data. We propose an algorithm for connectivity analysis on cortex olfactory preference. We report our novel protocol for robust olfactory stimulus identification and synchronization experiment. From the experiment we observe the lateralization effect for olfactory processes in the human brain. There are stronger collaborative effect in the left side of brain compare the right side when pleasant stimuli are delivered. With 14 subjects data, we conclude the difference observed between pleasant and unpleasant stimuli is statistically significant.

The main contributions of this work are two fold: firstly we proposed a novel approach devising a portable and robust EEG-based olfactory preference prediction and olfactory stimulus identification system, secondly, we proposed algorithm for coherence analysis to understand temporal lateralization effects of olfactory response to scent stimuli.

In the future work, we attempt to develop a scent preference prediction system by combining coherence study with spectrum based analysis.

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