Analyses of Stroop EEG using Event Related Potentials and Time-Frequency Decomposition

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***Abstract*—An event-related potential (ERP) measures the brain response that is the direct result of a specific sensory, cognitive, or motor event. In this paper we apply time-frequency analysis to the ERPs to investigate the sub-cognitive processes of the Stroop test. EEG data from 50 healthy participants are collected while performing the Stroop test. The test comprised of congruent and incongruent trials. Response time, response accuracy, and peak amplitudes and latencies are compared between congruent and incongruent trials. It is found that participants took significantly longer time to respond to incongruent trials than the congruent trials. It is also observed that the peak amplitudes in multiple ERPs are significantly higher in the congruent trials than incongruent trials. The time-frequency results revealed that brain oscillations in both congruent and incongruent trials increased in the higher beta range (18-30 Hz). We conclude that brain responses to stimulus are strongly correlated with higher beta band (18-30 Hz).**

I. Introduction

The Stroop test is a neuropsychological test that assesses the ability to inhibit cognitive interference. It is extensively used for both experimental and clinical purposes. This interference effect is considered to be strongly associated with the executive control functions and particularly response conflict phenomenon [1]. The interference effect associated with the difference of the color name to the color in the Stroop test is investigated via time series and frequency domain analysis [2]. Event related potentials (ERP) are widely studied to investigate the color-word interference related timing occurrences and brain structure.

P300 (P3) a widely known ERP which is observed in response to the presented stimulus in any task. The sub-components of this ERP known as P3a and P3b are related to the attention and memory of the participants [3]. The P300 responses in the congruent and incongruent trials of Stroop test have revealed no differences in the latencies. This indicates that longer response time to the incongruent trials is because of the interpretation of the interference effect of the color and the word [3].

The Stroop stimuli cover many cognitive control functions, such as response conflict resolution, attention control and stress coping [4]. Because of the variant features in the stimulus structure, many ERP modulations in Stroop test are studied [5]. But these studies are lacking in the ERP component consistency evaluation that remain throughout these task varieties. The involvement of multiple cognitive processes are considered the primary reason of this uncertainty [3]. Because these processes require variable loads and have different timings; it is not possible to develop a meaningful interpretation of ERP parameters based on only time series analysis.

On the other hand, the time-frequency domain analysis helps to investigate the data from multiple processes in frequency or time-scale that overlap partly or fully in time-domain [6]. Besides, the non-stationary nature of the EEG signal is a strong motivation for the time-frequency domain analysis of the EEG signals. Time-frequency decomposition of the task based EEG represents the temporally overlapping oscillatory responses of several neural processes during the task performance.

Although, many studies in the literature performed time-frequency analysis of the event-related brain responses but few are conducted using the Stroop test data [3] [7]. Event related synchronization or desynchronization of the Stroop test is investigated using time-frequency analysis but this analysis was limited to non-phase locked activities and was unable to assess phase-locked activity [7]. Studies have shown that ERP investigation in time-frequency domain can efficiently distinguish the sub-processes of cognitive task than in time-domain [8].

Hence, we hypothesize that time-frequency decomposition of the event related brain responses that are associated with Stroop test will help to identify the associated sub-processes. Therefore, in this paper we aim to apply time-frequency domain analysis to the ERP associated with Stroop test. The methods that are adopted during the analysis are reported in the section II. The EEG data of the Stroop test is cleaned from the artifacts and ERPs are computed. The ERPs are decomposed into time-frequency domain using complex morelet wavelet (cmw) convolution method and analyses were performed. After that we report and discuss the results in section III. Finally, we conclude the study in section IV, followed by acknowledgment and references.

II. Methods

A. Participants

A total of 50 healthy participants (18 female) with mean age of 24.76 ± 4.97 years participated in this study. The students were recruited from different faculties at Universiti Tunku Abdul Rahman, Malaysia and participated voluntarily.

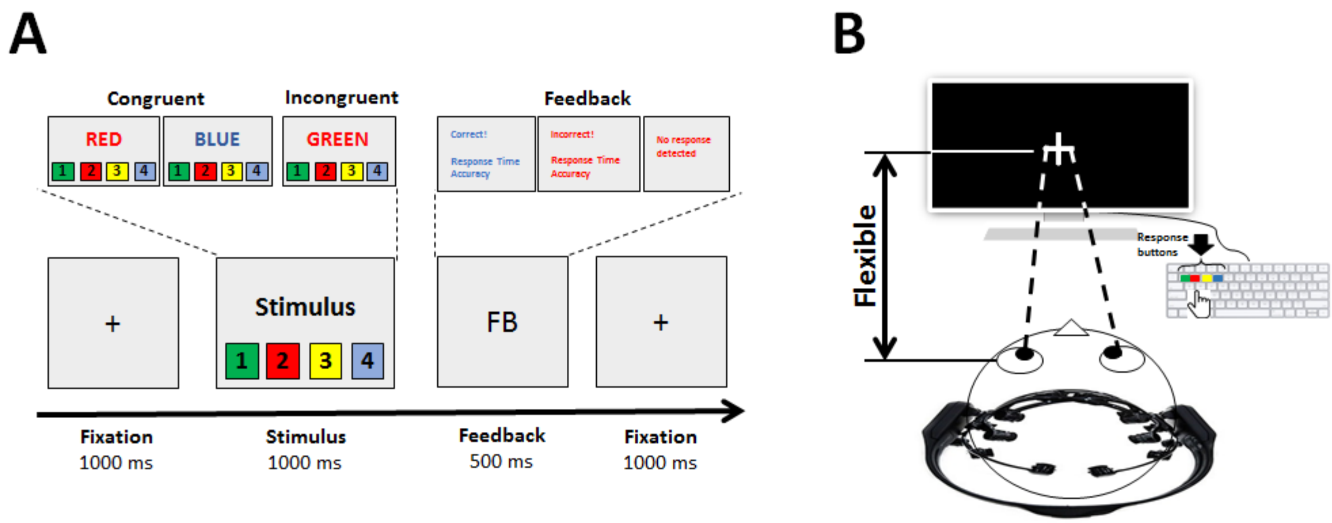

Fig. 1: (A) structure of the stroop test and (B) participant seating and EEG recordings

Before performing the experiment, they were briefed about the procedures involved and signed the consent form. The study was approved by the ethics committee of the university under the reference number U/SERC/90/2018. All the experimental procedures were performed according to the Declaration of Helsinki.

B. Stroop task and EEG recordings

The computer version of Stroop color and word test was performed by each participant. The test was designed using E-Prime, a psychology software tool for behavioral assessment. The test comprised of congruent (word-color matching) and incongruent (word-color not matching) conditions that were presented in pseudo-random order. A total of 128 stimuli are presented to each participant. The first eight stimuli were neutral trials used for practice, which were removed from the analyses. Each trial had a maximum duration of 2500 ms that included 1000 ms fixation time, 1000 ms stimulus presentation time and 500 ms feedback time. The structure of the Stroop test is shown in Figure 1. The participants entered their responses using computer keyboard. Response time and response accuracy were automatically saved in the E-Prime tool.

The EEG signal was recorded using Emotiv Epoc+ device that consists of 14 active and 2 reference EEG sensors placed on the scalp according to the 10-20 international system of electrodes placement. The active sensors are placed on the AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8 and AF4 locations. The sampling rate of the EEG device is 128 samples per sec. Continuous EEG data are recorded while the participants were performing the Stroop test.

C. Data pre-processing

The EEG data recorded during the Stroop test was pre-processed using the EEGLAB [9] and custom written MATLAB scripts. Continuous EEG signal was segmented into 1500 ms long epoch where 0 ms corresponds to the stimulus onset. The data were visually inspected and bad trials were removed. After that independent component analysis (ICA) using informax method [10] implemented in EEGLAB is applied to decompose the signal into independent components (ICs). The ICs that correspond to muscle and eye artifacts were identified using an automated method called ADJUST [11]. The EEG signal is reconstructed removing these ICs.

The data from the frontal channels AF3, F7, F3, F4, F8 and AF4 were combined to create a dataset for the frontal lobe. Similarly, data from P7 and P8 were combined to create parietal lobe data and O1 and O2 were combined to create occipital lobe data.

D. ERP analysis

The time-domain signal across all trials in congruent and incongruent conditions were averaged to create congruent and incongruent ERP signal. Then, N100 and P100 ERP peaks in the time window of 70-120 ms after stimulus onset were identified. Similarly, P300a, P300b and late P300 waves were identified in 180-300 ms, 350-550 ms and 650-750 ms respectively. All ERP waves were identified separately for frontal, parietal and occipital lobe.

E. Time-frequency analysis

The non-stationary nature of the EEG signal is the key motivation for the time-frequency (TF) decomposition of the signal. In TF decomposition, the power spectrum of the signal is computed over short time windows, which are considered roughly stationary [12]. There are several methods which can be used for TF decomposition e.g. Fourier transform, complex wavelet convolution and Hilbert transform. Due to the optimal temporal and spectral precision trade off [6], we used complex Morlet wavelet (cmw) as defined by equation 1, to perform TF decomposition. We used 40 logarithmically

TABLE I: THE MAIN EFFECT OF CONGRUENCY CONDITION AND THE INTERACTION EFFECT OF CONGRUENCY AND LOBE CONDITIONS FOR THE PEAK AMPLITUDES IN DIFFERENT ERP COMPONENTS

ERP component	Main effect of congruency	Interaction effect of congruency and lobe
N100	$F(1, 147) = 7.22, \quad p = 0.008, \quad \eta^2 = 0.047$	$F(2, 147) = 0.019, \quad p = 0.981, \quad \eta^2 = 0.000$
P100	$F(1, 147) = 19.003, \quad p < 0.001, \quad \eta^2 = 0.114$	$F(2, 147) = 0.015, \quad p = 0.98, \quad \eta^2 = 0.000$
P300a	$F(1, 147) = 32.169, \quad p < 0.001, \quad \eta^2 = 0.18$	$F(2, 147) = 0.133, \quad p = 0.875, \quad \eta^2 = 0.002$
P300b	$F(1, 147) = 41.305, \quad p < 0.001, \quad \eta^2 = 0.219$	$F(2, 147) = 0.364, \quad p = 0.695, \quad \eta^2 = 0.005$
Late P300	$F(1, 147) = 25.59, \quad p < 0.000, \quad \eta^2 = 0.138$	$F(2, 147) = 0.388, \quad p = 0.679, \quad \eta^2 = 0.005$

spaced frequency bins between 1-30 Hz for this convolution. The number of wavelet cycles varied from 3-8 cycles in 40 log space intervals. The time-frequency decomposition was performed on each trial separately and then averaged across the trials. The stimulus preceding time from -100 to 0 ms in each trial was used for baseline correction.

$$cmw = e^{i2\pi ft}e^{-t^2/2\sigma^2} \tag{1}$$

where t represents the time, f represents the frequency and σ stands for the full-width at half maximum (FWHM). FWHM is defined using equation 2.

$$FWHM = n/2\pi f \tag{2}$$

where n represents the number of wavelet cycles and varies between 3 and 8 in 40 log spaced intervals.

F. Statistical analysis

To statistically compare the mean response time and response accuracy between congruent and incongruent trials, a paired sample t-test with alpha value of 0.05 is used.

A 2(CONG: congruent vs incongruent) × 3(LOBE: frontal vs parietal vs occipital) repeated measures ANOVA design was used to compare the peak amplitudes and latencies in the ERP peaks (N100, P100, P300a, P300b and late P300) between congruent and incongruent trials crossing for the lobes (frontal, parietal and occipital). The with-in subject factors were congruency (CONG) and between subject factors were lobes (LOBE). All the statistical analysis were carried out at a significance level of $p < 0.05$.

III. RESULTS AND DISCUSSION

A. Behavioral results

Mean response time and response accuracy for the congruent and incongruent trials are shown in Figure 2. The statistical analysis revealed that mean response time in the incongruent trials (580.09 ± 90.27 ms) was significantly longer than congruent trials (552.79 ± 90.01 ms) ($p < 0.001$). However, the mean response accuracy for incongruent trials (95.92 ± 4.2%) was not significantly different from the congruent trials (96.05 ± 4.45%) ($p > 0.05$).

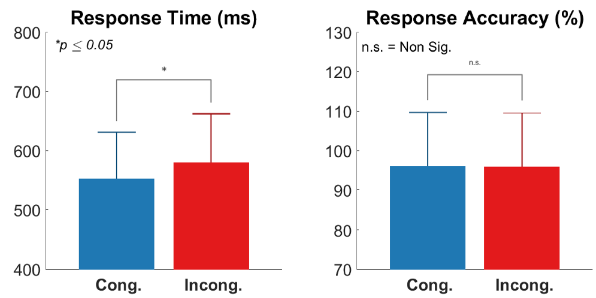

Fig. 2: Behavioral results. Response time (ms) and response accuracy (%). The error bars represents the standard errors.

B. ERP results

The ERPs for congruent and incongruent trials were plotted in three equal time intervals from the stimulus onset (0-300 ms, 300-600 ms and 600-900 ms) as shown in Figure 3. From the visual inspection it is observed that the voltage amplitude values are comparatively lower in the incongruent trials as compared to the congruent trials in each lobe. However, in the occipital lobe the voltages are nearly equal in the middle time window (i.e. 300-600 ms). This indicates that participants were able to integrate the information from the visual cortex nearly equally in congruent and incongruent trials. The interference effect was more obvious at the early stages of the stimulus onset. As the participants of the study were healthy students this could be one of the reasons that at a later stage (i.e. 300-600 ms) of stimulus onset, they were able to integrate the information from the visual cortex that reduced the interference effect.

Peak amplitudes and peak latencies were observed for N100, P100, P300a, P300b and late P300 waves. The peak amplitudes for the congruent trials were significantly different from the incongruent trials. The ANOVA test revealed a significant main effect of the congruency in all ERP peak amplitudes. However, the interaction effect of congruency and lobe was not significant. The ANOVA results of the peak amplitudes for all of the ERP components are summarized in Table I.

The ANOVA results for the peak latencies revealed no significant main effect of the congruency (congruent vs incongruent) nor interaction effect of congruency and lobe in all ERPs (all $p > 0.05$) except P300a wave where a marginally significant difference is observed between congruent and incongruent trials (i.e. marginally significant main effect of

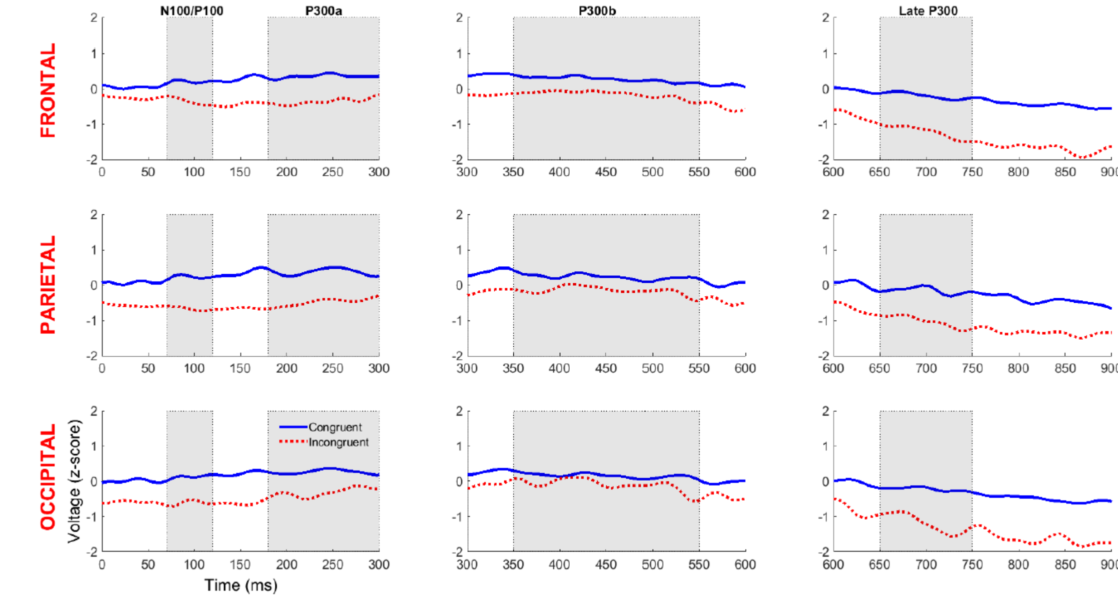

Fig. 3: ERP results for congruent and incongruent trials in frontal, parietal and occipital lobes. The grey patches represents the time windows for different ERPs (N100/P100: 70-120 ms, P300a: 180-300 ms, P300b: 350-450 ms, late P300: 650-750 ms)

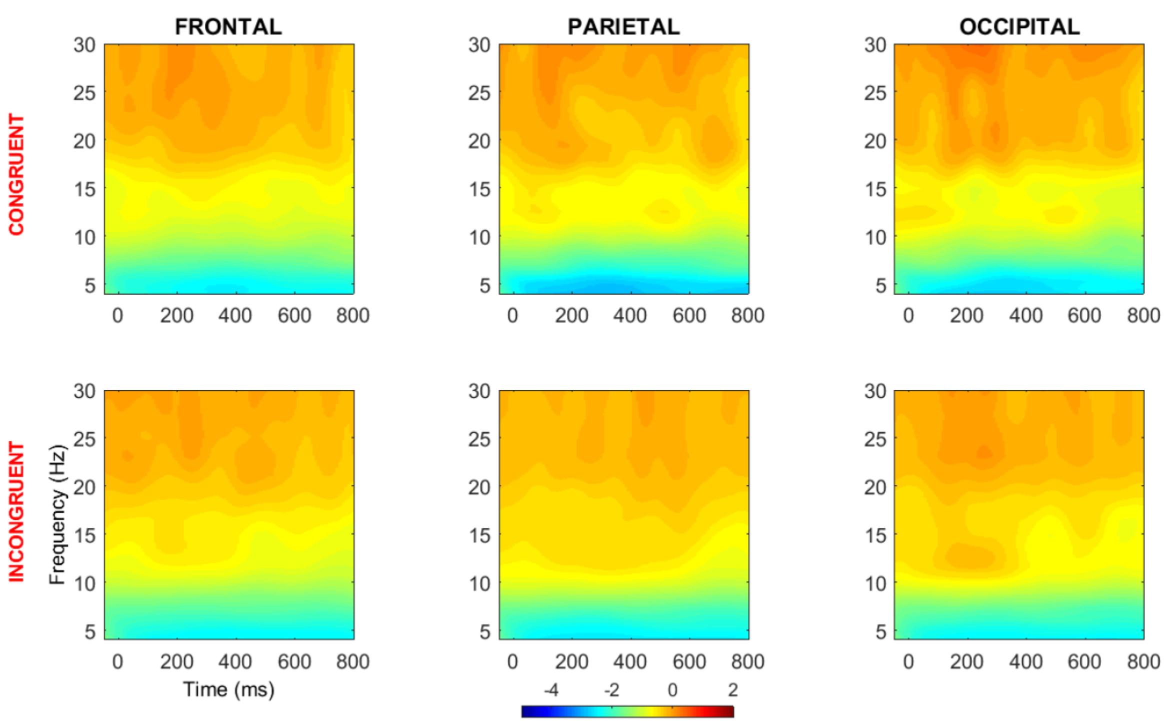

Fig. 4: Time-frequency results in frontal, parietal and occipital brain lobes and separated for congruent and incongruent trials

congruency) P300a ($F(1,147) = 3.062, p = 0.08, \eta^2 = 0.02$).

C. *Time-frequency results*

The time-frequency results are shown in Figure 4 for frontal, parietal and occipital lobes, and congruent and incongruent trials. This simultaneous investigation provides information regarding brain responses about the executive processes associated with Stroop interference effect [13]. The visual inspection of time-frequency results provides a simultaneous investigation of the ERPs in time and frequency domain which is not possible in the ERP analysis alone. As a general observation it can be seen that in both congruent and incongruent trials the evoked activities were associated with high beta band (around 18-30 Hz) as shown by increased power in this frequency range in all time-frequency plots in Figure 4. The early P3 wave (i.e. P300a) in the occipital lobe was associated with higher beta activity in the congruent condition while in the incongruent condition it was associated with lower beta (around 12-15 Hz) (see the congruent and incongruent plots in the occipital lobe). These results suggest that evoked activities by congruent and incongruent conditions greatly increase the beta band activations in the brain.

IV. Conclusion

In the current study we analyzed the evoked responses of the brain activities in the healthy participants when they performed Stroop test. We applied time-series and time-frequency domain analysis to investigate the temporally overlapped brain responses to multiple cognitive functions. The time series analysis revealed that the peak amplitudes of different ERP peaks were significantly different between congruent and incongruent trials. However, the peak latencies were not different among the two conditions. The time-frequency results show that brain response to the presented stimulus was strongly associated with beta band activity in the EEG signal. We conclude that longer response times in the incongruent trials led to the interpretation of the Stroop interference. This interference effect caused the later response selection stages rather than the stimulus evaluation. One important finding of the study is that participant were able to integrate the information from the visual cortex equally in congruent and incongruent trials at later stage of stimulus onset as shown by the ERPs in the occipital lobe (middle time window i.e. P300b).

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