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Time–frequency analysis of the event-related potentials associated with the Stroop test

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ABSTRACT

Multiple executive processes are suggested to be engaged at Stroop test, and time–frequency analysis is acknowledged to improve the informative utility of EEG in cognitive brain research. We aimed to investigate event-related oscillations associated with the Stroop test. EEG data was collected from 23 healthy volunteers while they performed a computer version of Stroop test. Both evoked (phase-locked) and total (phase-locked + non-phase-locked) oscillatory responses in the EEG were analyzed by wavelet transform. Data from the congruent (color–word matching) and incongruent stimuli (color–word non-matching) conditions are compared. In the incongruent condition, N450 wave was more negative and amplitude of the late slow wave was more positive. In the time–frequency plane, the fronto-central total theta amplitude (300–700 ms) was larger in the incongruent condition. The evoked delta (250–600 ms) was larger in the congruent condition particularly over parieto-occipital regions. The larger frontal theta response in the incongruent condition was associated with the detection of interference and inhibition of the response to task-irrelevant features, while the larger evoked delta in the congruent condition was suggestive of the easier decision process owing to congruency between the physical attribute and the verbal meaning of the stimuli. Furthermore, in the incongruent condition, amplitude of the occipital total alpha in the very late phase (700–900 ms) was smaller. This prolonged desynchronization in the alpha band could be reflecting augmentation of attentional filters in visual modality for the next stimulus. These multiple findings on EEG time–frequency plane provide improved description of the overlapping processes in Stroop test.
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1. Introduction

The Stroop test has been widely used in cognition research as a paradigm for investigating the executive control functions, particularly the interference resolution between stimulus dimensions, response inhibition and response selection. The conventional color–word version of the Stroop test requires participants to name or use button press to indicate the ink colors of a series of color names. In this color name series, part of the presented stimuli is incongruent, such as "RED" printed in green font, and part of the stimuli is congruent where color name is printed in the same color as the word meaning (e.g. "RED" printed in red font). The interference between word meaning and ink color (physical attribute) slows down the reaction time (RT) to the incongruent stimuli compared with the congruent stimulus (Stroop, 1935). In comparison with the simple stimulus discrimination tasks like oddball paradigm, additional processes like extra engagement of the attentional set that favors task-relevant information (i.e. color) and inhibition of the overwhelming response alternative related with task-irrelevant information (i.e. verbal meaning) are suggested to be involved during Stroop test performance (Banich et al., 2001; MacDonald et al., 2000). There is debate on whether these processes dealing with the color–word interference are initiated early at stimulus processing or later at the response selection stage (Atkinson et al., 2003). How the color–word interference occurs, its timing and related brain structures have been widely investigated by event-related potential (ERP) studies and functional neuroimaging. The methods in these studies are essentially based on comparing the data collected during processing of incongruent stimuli vs. congruent stimuli.

Neuroimaging studies on the Stroop test reported activations mainly in the anterior cingulate cortex (ACC), the dorsolateral prefrontal cortex, and posterior regions including the superior–parietal cortex and the extrastriate cortex (Banich et al., 2000; Kerns et al., 2004; MacDonald et al., 2000; van Veen and Carter, 2005; Zysset et al., 2001). Banich et al. (2001) interpreted involvement of the dorsolateral prefrontal/parietal cortex circuitry as the source of the control for

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selecting and maintaining the attentional set that is specific for the task-relevant information. Additionally, involvement of the ACC has been associated with evaluation of the interference in response selection and performance monitoring (MacDonald et al., 2000).

Complementary to the information provided by neuroimaging studies about the neuronal structures involved in the Stroop interference, a number of ERP studies have reported information about the timing of sub-processes of the Stroop interference and conflict resolution. P300 is an ERP waveform known to be observed in any task that requires stimulus discrimination and its two main subcomponents (P3a and P3b) are associated with attentional resource allocation and memory update (Polich, 2007). In the ERP studies on Stroop test, no difference was found in P300 latency between the congruent and incongruent stimuli (Atkinson et al., 2003; Duncan-Johnson and Kopell, 1981; Ilan and Polich, 1999; Rosenfeld and Skogsberg, 2006). Longer RTs with lack of a change in P300 latency in the incongruent stimulus trials led to interpretation of the Stroop interference as occurring at the later response selection stage rather than the stimulus evaluation and semantic processing (Duncan-Johnson and Kopell, 1981; Ilan and Polich, 1999; Polich, 2007). Lower amplitude of P300 amplitude in the incongruent stimuli is reported by Ilan and Polich (1999) only when the statistical evaluations are restricted to Pz electrode. Other than this minor finding, it is reported that P300 amplitude did not differ between congruent and incongruent stimulus conditions (Duncan-Johnson and Kopell, 1981; Ilan and Polich, 1999; Rosenfeld and Skogsberg, 2006).

The stronger negative going potential around 400–450 ms in the incongruent condition has been consistently replicated in the Stroop test studies (Badzakova-Trajkov et al., 2009; Donohue et al., 2012; Larson et al., 2009; Liotti et al., 2000; Markela-Lerenc et al., 2004; Rebai et al., 1997; Tillman and Wiens, 2011; West, 2003; West and Alain, 1999; West et al., 2005). This negative wave is widely labeled as N450 in the current literature, though in the earlier studies it was initially labeled as N400 that is known as the ERP marker for detection of semantic incongruity (Kutas and Hillyard, 1980). Liotti et al. interpreted this difference in N450 (larger negativity in the incongruent condition) as the correlate of conflict resolution (Liotti et al., 2000). In that study, the authors reported that the topographic distribution of N450 differed between vocal and manual response conditions, implicating an interaction with the effort for response generation. The generator of the N450 component has been localized in the ACC by several source estimation methods (Badzakova-Trajkov et al., 2009; Hanslmayr et al., 2008; Liotti et al., 2000; West, 2003). The other ERP marker of color–word interference is the larger amplitude of late slow shift (500–800 ms) in the incongruent stimulus condition (Appelbaum et al., 2009; Hanslmayr et al., 2008; Larson et al., 2009; Markela-Lerenc et al., 2004, 2009; West, 2003; West et al., 2005).

N450 and the late positive shift have been widely investigated to describe their functional meanings and to distinguish conflict resolution and response selection processes by comparing the ERP data from several variants of the Stroop test. Considering the estimated source of N450 around ACC, its contribution in response conflict processing and/or stimulus processing in the Stroop test is questioned. West et al. did not find a correlation between the amplitude of N450 and reaction times or accuracy (West et al., 2005). Using the electromyography, Szucs et al. analyzed the ERPs in relation with the latent incorrect responses, and they suggested that N450 was mainly affected by the stimulus conflict (Szucs and Soltész, 2010).

Based on the correlation between amplitude of the late positive shift and reaction times, West et al. suggested that this late component is mostly associated with response selection rather than conflict resolution (West et al., 2005). In several studies, however, the Stroop effect on the late slow potential was reported to peak almost after the response has been made, which suggested that this slow wave might be reflecting post-conflict resolution processes such as re-activation of the semantic information that was initially suppressed (Appelbaum et al., 2009; Liotti et al., 2000). In another study with variable onset asynchrony of color and word dimensions, the authors reported results in favor of both hypotheses about the late slow potential as being correlate of conflict resolution and semantic re-activation (Coderre et al., 2011).

The ERP literature on Stroop test include plenty of ERP modulations due to task or stimuli variations (e.g. stimuli duration, response assignments, response modalities) and lacking a consistent component that remains throughout these task varieties (Appelbaum et al., 2009; Atkinson et al., 2003). We consider that this uncertainty possibly rises from involvement of multiple cognitive processes with variable loads and timing which leads to unsettled interpretation of the ERP parameters.

Time–frequency decomposition of ERPs by wavelet transform helps to distinguish the frequency characteristics or time-scales of multiple processes that are partly or fully overlapping in time (Ademoglu et al., 1998; Basar et al., 1999, 2001; Demiralp and Ademoglu, 2001; Demiralp et al., 1999a, 1999b; Samar et al., 1995). The output of this decomposition includes changes in the oscillatory activity described in various frequency bands. These oscillatory responses are known to represent the temporally overlapping activities of several neural networks that perform in different temporal scales or frequencies during task performance.

Although time–frequency analysis is one of the most adopted approaches for investigating the event-related brain oscillations, we noticed that time–frequency analysis is rarely conducted on the EEG data from this widely used neuropsychological test. In the few studies, the event-related synchronization/desynchronization or event-related spectral perturbation was investigated (Hanslmayr et al., 2008; Kovacevic et al., 2012; Tang et al., 2013) while those analyses were unable to assess phase-locked oscillations. In the study by Hanslmayr et al., frequencies below 4 Hz (i.e. delta band) were not analyzed (Hanslmayr et al., 2008), and in another study, only theta band was investigated (Kovacevic et al., 2012). On the other hand, significant contribution of the phase-locked low frequency oscillations to ERPs like P300 and post-P300 period are well documented (Basar et al., 2000; Bernat et al., 2007; Bernat et al., 2011; Demiralp et al., 2001a, 2001b).

Our previous studies showed that the characterization of the ERPs in the time–frequency plane including both evoked (Ademoglu et al., 1998; Demiralp and Ademoglu, 2001; Demiralp et al., 1999a) and total oscillatory activities (Ergen et al., 2008; Selimbeyoglu et al., 2012) can dissociate sub-processes of a cognitive task more efficiently than complex- looking patterns in the time domain. For instance, the report by Kirmizi-Alsan et al. (2006) nicely dissociated the motor inhibition vs. sustained attention in theta vs delta components of ERPs obtained with Go/NoGo and Continuous Performance Test (CPT). As Stroop test also requires a similar inhibitory control in addition to a set of other sub-processes, we assume that a complete characterization of the time–frequency features of the Stroop-ERPs may help identify those sub-processes in a more efficient manner than the unsettled findings reported in the time domain. Therefore, we analyzed Stroop-ERPs by decomposing them in the time–frequency plane within the wide range of frequencies between 1 and 60 Hz.

2. Methods

2.1. Participants

Twenty-three healthy right-handed, trichromat volunteers (12 males and 11 females) with a mean age of 25.8 ± 5.6 and a mean education of 17.8 ± 3.3 years participated in the study. The study protocol was approved by the local Ethic Committee of Istanbul Faculty of Medicine, Istanbul University, where the data was collected. All participants gave written informed consent in accordance with the Declaration of Helsinki.

2.2. Stimuli

A computer version of the Stroop test was applied, which was carried out by MATLAB program developed using the Psychophysics

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Toolbox (Brainard, 1997; Pelli, 1997). The stimuli were three color names in Turkish presented in upper-case letters as "KIRMIZI" (RED), "MAVİ" (BLUE), "YEŞİL" (GREEN). In the congruent condition, meaning of the word and its color matched (e.g. RED written in red font), and in the incongruent condition, the color of the font was different than the word meaning (e.g. RED written in blue or green font). All stimuli were presented with 4.5 × 4.5 cm letters in the center of a 15 inch computer screen over a gray background with a visual angle of 3°15′ at 80 cm distance. The test consisted of 60 congruent and 60 incongruent stimuli trials in randomized order. Participants were asked to indicate their judgments of the font color by pressing one of the three buttons on the computer mouse as follows: left button for red color, middle button for blue color, right button for green color with their index finger, middle finger and ring finger, respectively. All subjects used their right hand (dominant hand) to operate the mouse. Each stimulus appeared on the screen until the participant responded, and the next stimulus appeared 1.5 s after the response. Participants were told that the task required both speed and accuracy.

2.3. EEG recording

EEG was recorded in an electrically shielded, sound attenuated, and dimly illuminated room, using 30 Ag–AgCl electrodes at Oz, O1, O2, Pz, P3, P4, P7, P8, Cz, C3, C4, T7, T8, Fz, F3, F4, FCz, FC3, FC4, CPz, CP3, CP4, FT7, FT8, F7, F8, TP7, TP8, FP1, FP2 (extended 10–20 system) referenced to linked earlobes. The electro-oculogram (EOG) was recorded bipolarly between the electrodes placed on the external canthus of the right eye and on the nasion to identify the ocular artifacts. EEG was amplified with a band pass of 0.1–70 Hz and sampled at 200 Hz by using a 32 channel digital amplifier (LaMONT Medical Inc., Madison, WI, USA). Impedances were kept below 30 kΩ. The data were epoched between the 500 ms pre-stimulus and 1000 ms post-stimulus time points. Epochs with amplitudes exceeding ±90 μV were automatically discarded. The remaining trials were eyeballed for detecting other artifacts. After epochs with artifacts and/or with incorrect responses were discarded, remaining epochs were grouped as the congruent stimulus trials and incongruent stimulus trials. Baseline correction was performed relative to the mean amplitude in 200 ms pre-stimulus interval.

2.4. ERP analyses

The P100 and N140 peaks in occipital channels, the N100 and P200 peaks in fronto-parietal channels and the N200, P300 and N450 peaks in all channels were identified within the time windows as follows: 70 to 140 ms for P100 and N100; 120 to 250 ms for N140; 140 to 250 ms for P200; 140 to 300 ms for N200; 260 to 450 ms for P300; 350 to 500 ms for N450. The time windows for evaluating ERP peaks were determined by inspecting the grand-averaged waveforms. The late post-P300 period was evaluated through mean amplitudes of 4 consecutive time windows (550–650 ms, 650–750 ms, 750–850 ms, and 850–950 ms).

2.5. Time–frequency analyses

Continuous wavelet transform with complex Morlet basis function was applied. Morlet wavelet with 3 cycles was used for 1–30 Hz and Morlet wavelet with 6 cycles was used for 31–60 Hz range. To represent the oscillatory activity that is phase-locked to stimulus onset (the evoked activity), the wavelet transform was computed on average of the single trials. The total activity that includes both phase-locked and non-phase-locked oscillations was computed by averaging the absolute values of the wavelet transforms of single trials. For each frequency bin, mean amplitude between −400 and −200 ms preceding the stimulus was subtracted from the whole time series for baseline correction. The averages of the transforms of both congruent and incongruent trials were used to define the individual center frequencies and time windows where each of the delta (1–3 Hz), theta (4–7 Hz), alpha (8–14 Hz), beta (15–30 Hz), and gamma oscillations (31–60 Hz) peaked.

2.6. Statistical analysis

A paired *t*-test (two-tailed) was used to compare mean RTs and accuracy between congruent and incongruent conditions.

Separate repeated measures ANOVA designs were used to compare the amplitudes and peak latencies of the ERP peaks (P100, N100, P200, N140, N200, P300, N450), mean amplitudes of the late post-P300 time windows and each time–frequency component (total and evoked activity in each frequency band) between congruent and incongruent conditions. The following 12 channels were included in the statistical analyses: F3, Fz, F4, C3, Cz, C4, P3, Pz, P4, O1, Oz, and O2. For the P100 and N140 waves, only occipital channels were included in the statistics, because these waveforms are specific to occipital region. The ANOVA factors were congruence (CONG [2 levels]: congruent vs. incongruent) and lateral distribution on scalp (LAT [3 levels]: left, midline, right). For the N100 and P200 waves that were observed in fronto-parietal channels, an antero-posterior distribution factor was added (AP [3 levels]: frontal, central, parietal). For the N200, P300 and N450 waves, mean amplitudes in the late post-P300 time windows and all time–frequency parameters, the antero-posterior distribution included all 4 levels (AP [4 levels]: frontal, central, parietal and occipital).

Greenhouse–Geisser correction procedures were applied to the degrees of freedom when the repeated measure factor contained more than two levels, and only the corrected probability values were reported. Bonferonni correction was applied to the statistical results for the mean amplitudes of the five consecutive time windows in 550–950 ms period.

3. Results

3.1. Behavioral results

Mean RT in the incongruent condition was significantly longer than the congruent condition ($p < 0.001$), which were 760.43 ± 182.22 ms in the incongruent trials and 622.14 ± 123.67 ms in the congruent trials. The percentages of the correct responses in the congruent trials (99.13% ± 0.99) were significantly higher than the incongruent trials (94.35% ± 4.49; $p < 0.001$).

3.2. ERP results

After artifact rejection, the numbers of trials were equalized between the two conditions. Mean number of valid trials was 44 ± 8 across all participants. P100, N100, P200, N140, N200, P300 and N450 peaks were observed in both congruent and incongruent conditions. N450 amplitude was more negative (i.e. larger N450 wave) in the incongruent condition compared with the congruent condition (CONG: $F_{(1,22)} = 4.68$, $p < 0.05$). N450 was most negative on frontal electrodes in both the congruent an incongruent conditions (AP factor: $F_{(3,66)} = 6.713$, $p < 0.01$) and the amplitude difference between the two conditions was pronounced on the parietal region observed as CONG × AP interaction ($F_{(3,66)} = 4.02$, $p < 0.05$) (Fig. 1). In the incongruent condition, there was a sustained positive shift within the post-P300 period (550–950 ms) (Fig. 1). In the 550–650 ms time window, the mean amplitude was significantly higher in the incongruent condition ($F_{(1,22)} = 4.49$, $p < 0.05$). Additionally, the CONG × AP interactions in the three consecutive time windows from 550 to 850 ms were significant (550–650 ms: $F_{(3,66)} = 7.65$, $p < 0.01$; 650–750 ms: $F_{(3,66)} = 19.13$, $p < 0.001$; 750–850 ms: $F_{(3,66)} = 10.55$, $p < 0.001$; see also Table 1 and Table 2). These CONG × AP interactions resulted from the larger positive amplitudes over the parietal region in the incongruent condition compared with the congruent condition. No significant difference was found in P100, N100, P200, N140, N200 and P300 between the two conditions.

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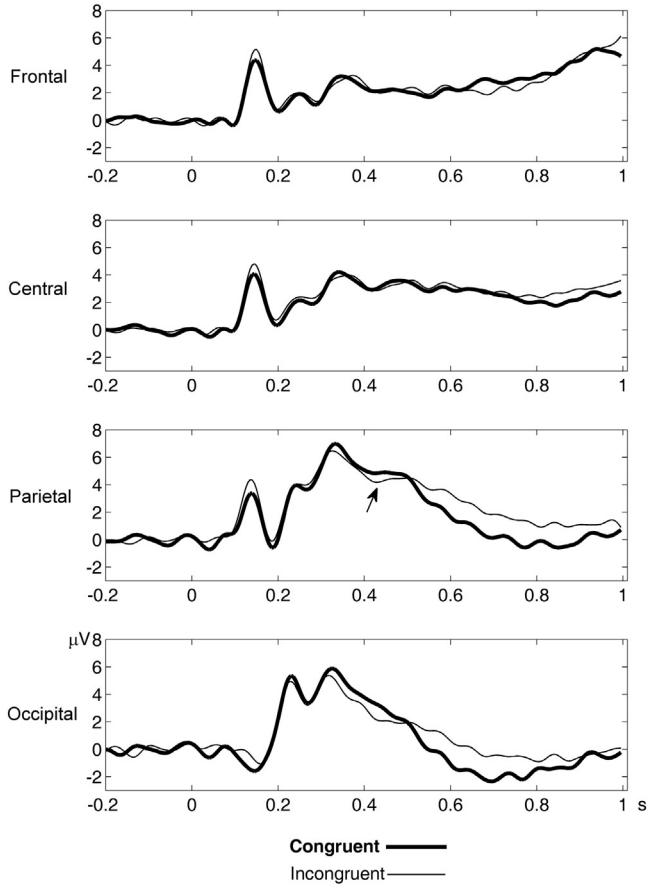

Fig. 1. Grand-average ERP waveforms obtained for the congruent (thick lines) and the incongruent stimuli conditions (thin lines). In order to display the significant congruence × AP effect, the average waveforms of the midline and lateral electrodes for each of the frontal (F3,Fz,F4), central (C3,Cz,C4), parietal (P3,Pz,P4) and occipital (O1,Oz,O2) regions are presented. The arrow points to N450 wave.

3.3. Time–frequency results

The time–frequency regions, which covered the maxima of evoked and total delta, theta, alpha, beta and gamma oscillations among individuals and stimulus conditions were observed as follows: 1–3 Hz at 250–600 ms for evoked and total delta, 4–7 Hz at 100–300 ms for evoked theta, 4–7 Hz at 300–700 ms for total theta, 8–14 Hz at 100–200 ms for evoked alpha, 8–14 Hz at 300–500 ms and at 700–900 ms for total alpha, 15–30 Hz at 100–250 ms for evoked beta, 15–30 Hz at 600–800 ms for total beta, 31–60 Hz at 30–150 ms for evoked gamma, and 31–60 Hz at 30–120 ms for total gamma band activity. Each of these oscillatory components was quantified as the mean amplitude within these time windows for the individual peak frequency of each participant, and tested for the significance of the differences between the congruent and incongruent stimuli conditions.

The evoked delta response was clearly located on parieto-occipital region (AP: $F_{(3,66)} = 3.59$, $p < 0.05$) and its amplitude was significantly larger in the congruent condition ($F_{(1,22)} = 7.51$, $p = 0.012$, Table 3, Table 5, Figs. 2, 4a). In contrast, the total theta amplitude was significantly larger in the incongruent condition ($F_{(1,22)} = 12.94$, $p < 0.01$; see Table 4 and Fig. 3). In both congruent and incongruent conditions, the total theta activity was located in midline frontal region (AP: $F_{(3,66)} = 35.08$, $p < 0.001$, see Fig. 4b), the CONG × AP interaction effect revealed that the incongruent stimuli induced a further increase of the total theta activity over the fronto-central region ($F_{(3,66)} = 3.81$, $p < 0.05$; see Table 4, Figs. 3 and 4b).

Alpha desynchronization (decreasing amplitude in total alpha activity) started by 300 ms in both conditions. In the early window (300–500 ms) alpha was more desynchronized in the congruent condition ($F_{(1,22)} = 4.97$, $p < 0.05$, Figs. 3, 4c). This was followed by a prolonged alpha desynchronization in the late alpha time window (700–900 ms) that was stronger in the incongruent condition ($F_{(1,22)} = 5.0$, $p < 0.05$, Figs. 3, 4c). The late total alpha effect was located in the parieto-occipital area, and this electrode effect is verified by the significant CONG × AP interaction ($F_{(3,66)} = 4.53$, $p < 0.05$).

Evoked alpha amplitude within 100–200 ms time window was higher in the incongruent condition, and this effect was at trend level ($F_{(1,22)} = 3.62$, $p = 0.070$, Table 3, Fig. 4d). No significant difference was found in evoked theta, total delta, and both evoked and total beta and gamma band responses between congruent and incongruent conditions.

4. Discussion

4.1. Behavioral results

Behavioral data replicated the well-known interference effect in the Stroop test by both longer RTs and higher number of errors in the incongruent trials compared with the congruent ones. The mean Stroop effect on RTs (i.e. the difference between the congruent and incongruent RTs) was 138 ms, which was close to findings reported in earlier ERP studies (e.g. 110 ms in Liotti et al., 2000 and 108 ms in Hanslmayr et al., 2008).

4.2. ERP results

The lack of a significant difference in P300 amplitude and latency between the congruent and incongruent conditions in the present study is in accordance with previous studies that investigated P300 in the Stroop test (Duncan-Johnson and Kopell, 1981; Ilan and Polich, 1999). This finding is also mentioned in a comprehensive meta-analysis on the relationship between the RT and P300 latency, which showed that P300 latency becomes insensitive to RT changes when behavioral responses are too slow as in the case of the Stroop test (Verleger, 1997).

In the present study, the N450 negative peak was more negative in the incongruent stimuli, and despite some discrepancies in topography, many ERP studies have reported that post-stimulus 400–500 ms is critical for observing the markers of color–word interference in the Stroop test. N450 effect is reported to be localized over frontal and fronto-central areas for spoken responses (Liotti et al., 2000; Rebai

Table 1
ANOVA results of the N450 peak and mean amplitudes in the late post-P3 time windows.

Factors	d.f.	N450	550–650 ms	650–750 ms	750–850 ms	850–950 ms
Condition	1,22	4.68*	4.49*	–	–	–
AP	3,66	6.71*	19.75**	14.65**	8.24*	8.22**
LAT	2,44	12.59**	24.47**	26.18**	26.76**	29.49**
Condition × AP	3,66	4.03*	7.65*	19.13**	10.55**	–
Condition × LAT	2,44	–	–	–	–	–

Bonferonni corrected results: $p < 0.01$*, $p < 0.001$**.

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Table 2
Average amplitudes from time domain analyses with significant condition effects. The listed averages on each row represent the mean of data from electrodes over 4 antero-posterior levels (Frontal: F3, Fz, F4; Central: C3, Cz, C4; Parietal: P3, Pz, P4; Occipital: O1, Oz, O2).

Condition	Channels	N450 peak amplitude (μV)	Mean amplitude 550–650 ms (μV)	Mean amplitude 650–750 ms (μV)	Mean amplitude 750–850 ms (μV)
Congruent	Frontal	1.33 ± 2.69	1.39 ± 2.79	2.50 ± 3.15	2.39 ± 3.31
	Central	2.19 ± 2.54	4.45 ± 2.95	4.17 ± 3.05	3.55 ± 2.74
	Parietal	3.70 ± 3.11	3.78 ± 2.93	2.37 ± 3.15	1.72 ± 2.94
	Occipital	2.45 ± 3.33	1.56 ± 3.48	0.50 ± 3.66	0.84 ± 3.50
Incongruent	Frontal	0.65 ± 3.11	1.08 ± 2,77	0.96 ± 2.94	1.49 ± 2.83
	Central	1.36 ± 2.45	4.64 ± 2.86	4.21 ± 3.01	3.96 ± 2.69
	Parietal	2.41 ± 2.60	4.75 ± 3.11	3.47 ± 3.07	2.78 ± 2.59
	Occipital	0.65 ± 2.18	2.96 ± 3.41	1.87 ± 3.59	1.66 ± 3.42

et al., 1997) and more dorsally over central or centro-parietal region for manual responses (Appelbaum et al., 2009; Badzakova-Trajkov et al., 2009; Coderre et al., 2011; Liotti et al., 2000; Markela-Lerenc et al., 2004; West, 2003; West and Alain, 1999). Besides, in several studies, the incongruency effect on N450 is evaluated only on frontal or fronto-central electrodes on ERP data from manual response versions of the test (Larson et al., 2009; West et al., 2005). Other than response modality, stimulus duration seems to be another cause of discrepancy in the topographic distribution of the effect on N450 (Appelbaum et al., 2009). In several studies cited above, stimulus duration is 150 ms, 400 ms or 1000 ms or presented until the response. Since the average RTs in the Stroop test are roughly around 600–700 ms, we assume that using very short stimulus presentations like 150 ms, might lead to involvement of very short term visual memory (iconic memory) during the time lag between stimulus offset and behavioral reaction. Stimulus durations like 400 ms might cause deviations in the N450 wave due to intervening off-response. In the present study, we adopted the test design where stimuli were presented until the manual response. We observed that the color–word incongruency related difference in N450 was maximal over the parietal region. Parietal localization of N450 effect was also reported in several studies in which stimuli were presented until the participant made a manual response (Badzakova-Trajkov et al., 2009; Coderre et al., 2011; West, 2003).

The late slow potential over the parietal region was more positive in the incongruent condition that reached significance around 600 ms in the present study. This finding was also a replication of the previously reported results from ERP studies of the Stroop test (Appelbaum et al., 2009; Coderre et al., 2011; Hanslmayr et al., 2008; Larson et al., 2009; Liotti et al., 2000; Markela-Lerenc et al., 2009; West, 2003; West et al., 2005).

There were several condition-independent hemispheric differences in both time domain amplitudes and total activities (Tables 1 and 3). As the subjects responded to both congruent and incongruent stimuli by right-handed movements, these overall lateralization effects might depend on the motor preparatory processes (Hammond and Fox, 2005) or on the processing of the verbal content of the stimuli. Since the present task design does not allow dissociating these lateralization effects into components related with motor preparation/control or verbal processing, we cannot assign a clear functional significance to these overall lateralization effects.

4.3. Results of the time–frequency analysis

4.3.1. Delta band

The evoked delta response was significantly larger in the congruent condition, and this finding is quite novel in the literature on event-related EEG studies of the Stroop test. Larger evoked delta in the congruent condition is somewhat coherent with the earlier studies on oddball experiments (Basar et al., 2000, 2001; Demiralp et al., 2001a, 2001b). The evoked delta response is suggested to be related with stimulus evaluation and decision making (Basar et al., 2001), and the larger delta response in the congruent condition of the present task seems to involve a relatively easier decision process, as a consequence of the facilitation effect due to the congruency between the physical attribute and the verbal meaning of the stimuli. The parieto-occipital distribution of the evoked delta response is also coherent with selective attention circuitry for task-relevant attribute in the Stroop paradigm.

In the 1–3 Hz filtered ERPs, we observed that the weaker evoked delta response in the incongruent condition gave rise to more negative amplitudes within the 350–500 ms (N450 wave period) and more positive amplitudes in the late slow potential period (Fig. 5). Based on the temporal overlapping and the mutual topographic distribution, we infer that the color–word congruency effect on the evoked delta response may have a major contribution to the well replicated ERP findings on N450 and late slow potential. Nevertheless, this remains as a descriptive finding of our study. Partial least square analysis on Stroop test ERP data by West et al. (2005) revealed that N450 and the late sustained positivity in the incongruent condition was associated with a single latent variable that represents a spatiotemporal component. Though in that study, West et al. (2005) did not include frequency domain analyses, it implies that N450 and the late slow potential might have somewhat common neural generators.

The only condition-dependent lateralization effect was obtained in the total delta activity (250–600 ms). Though there was no significant overall lateralization difference, the total delta amplitude in the incongruent condition was significantly higher on the left side in comparison with the symmetric distribution in the congruent condition (Table 3). Total delta activity is a relatively less mentioned time–frequency component. Its significance is reported in schizophrenia (Ergen et al., 2008; Ford et al., 2008) and in long term alcoholism (Andrew and

Table 3
ANOVA results of the mean amplitudes of evoked oscillatory activity.

Factors	d.f.	Delta	Theta	Alpha	Beta	Gamma
Condition	1,22	7.51*	–	3.62	–	–
AP	3,66	3.59*	–	–	–	3.33*
LAT	2,44	–	–	–	–	–
Condition × AP	3,66	–	–	–	–	–
Condition × LAT	2,44	–	–	–	–	–

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

Table 4
ANOVA results of the mean amplitudes of total oscillatory activity.

Factors	d.f.	Delta	Theta	Early alpha	Late alpha	Beta	Gamma
Condition	1,22	–	12.94**	4.97*	5.0*	–	–
AP	3,66	–	35.08***	12.01***	3.06*	–	3.59*
LAT	2,44	7.43**	25.20***	19.34***	5.19*	–	–
Condition × AP	3,66	–	3.81*	–	4.53*	–	–
Condition × LAT	2,44	4.20*	–	–	–	–	–

p < 0.05*, p < 0.01**, p < 0.001***.

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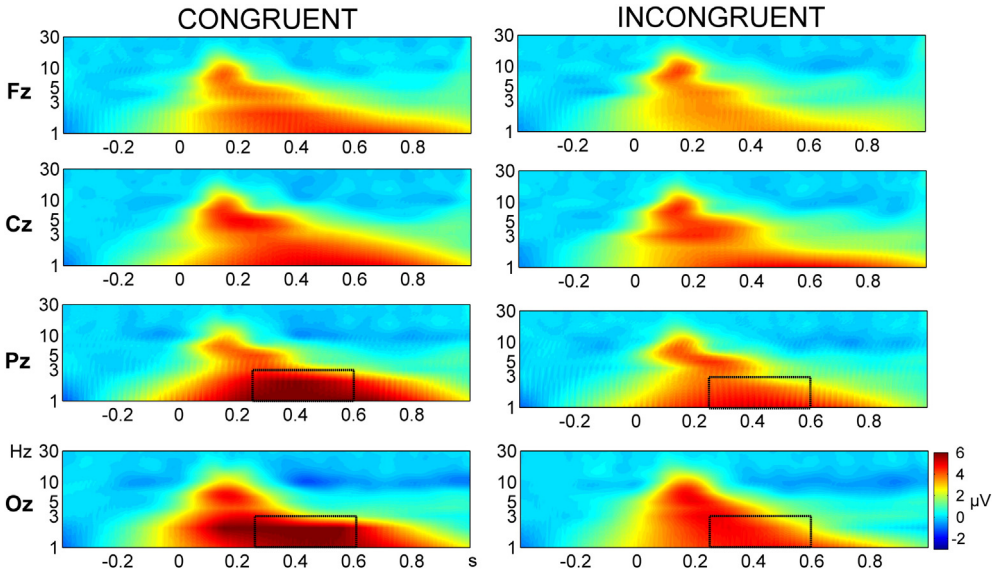

Fig. 2. Grand-average time–frequency plots of evoked delta activity from midline electrodes in response to the congruent and incongruent stimuli. The rectangles indicate maximal differences in the delta activity (1–3 Hz) between the congruent and incongruent conditions. The frequency axis is displayed in logarithmic scale.

Fein, 2010) as a component of P300 wave. Additionally, total delta is reported to be lower especially in the uncertain response condition during a difficult stimulus discrimination task (Selimbeyoglu et al., 2012). In none of these previous reports, a lateralization of the total delta activity is reported. Considering the report of Rushworth et al. (2001), which distinctly localizes the motor attention directed to hand movements to the left parietal cortex, this effect might reflect the need for higher attention allocation to the manual response in the incongruent condition.

4.3.2. Theta band

Event-related oscillations in the theta frequency range (4 to 7 Hz) have been shown to be related to central executive and working memory processes (Klimesch, 1996, 1999; Sarnthein et al., 1998; Sauseng et al., 2005; Tesche and Karhu, 2000). We found that the theta amplitude in the total oscillatory activity was significantly larger in the incongruent condition in 300–700 ms time window primarily over the frontal areas. Three other studies have reported larger theta band response over frontal areas in the incongruent condition. (Hanslmayr et al., 2008; Kovacevic et al., 2012; Tang et al., 2013). In the study by Hanslmayr et al. (2008), increased event-related synchronization in the theta band for the ACC source and a prolonged phase coupling between ACC and left prefrontal cortex in theta band were reported in the incongruent trials of the Stroop test. The event-related total theta amplitude during incongruent trials was suggested be sensitive to conflict detection, and response selection stage (Kovacevic et al., 2012). In support of this argument, Tang et al. (2013) did not obtain greater event-related theta magnitude in the incongruent condition when participants were to look at the Stroop test stimuli with no response and they suggested an association between response inhibition and the theta response.

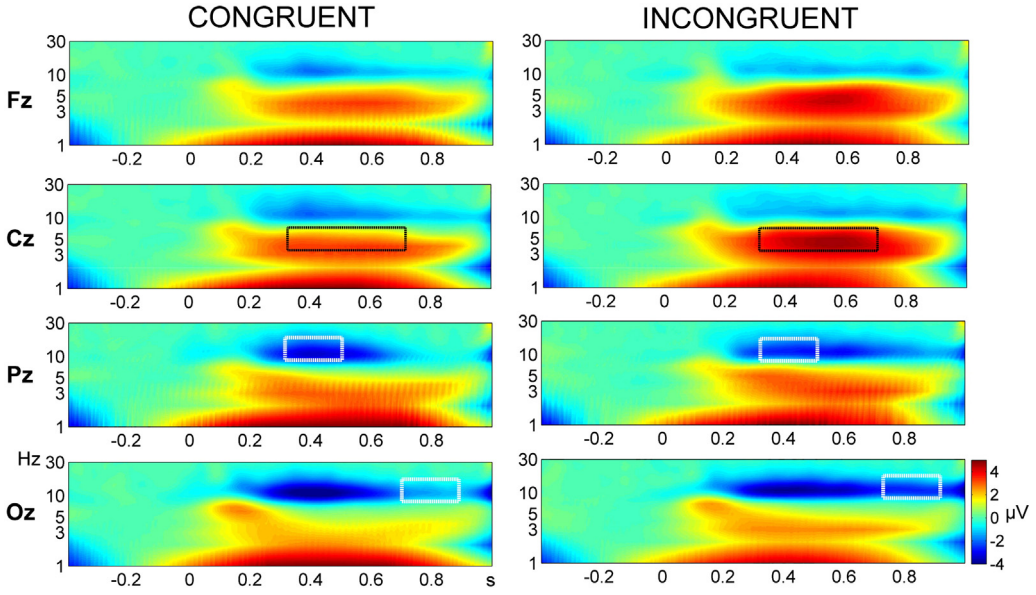

Fig. 3. Grand-average time–frequency plots of total activity from midline electrodes in response to the congruent and incongruent stimuli. Rectangles indicate maximal differences between the congruent and incongruent conditions in the theta band (4–7 Hz) and in the early and late total alpha activities (8–14 Hz). The frequency axis is displayed in logarithmic scale.

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Table 5
Average amplitudes from time–frequency domain analyses with significant condition effects. The listed averages on each row represent the mean of data from electrodes over 4 antero-posterior levels (Frontal: F3, Fz, F4; Central: C3, Cz, C4; Parietal: P3, Pz, P4; Occipital: O1, Oz, O2).

Condition	Channels	Evoked delta mean amplitude 250–600 ms (μV)	Total theta mean amplitude 300–700 ms (μV)	Total alpha mean amplitude 300–500 ms (μV)	Total alpha mean amplitude 700–900 ms (μV)
Congruent	Frontal	3.82 ± 3.09	2.36 ± 1.27	−1.81 ± 2.11	−1.18 ± 2.39
	Central	4.05 ± 3.56	1.89 ± 1.26	−2.23 ± 2.35	−1.49 ± 2.31
	Parietal	5.77 ± 4.61	1.18 ± 1.24	−3.45 ± 3.92	−0.95 ± 1.89
	Occipital	6.55 ± 5.37	0.66 ± 1.21	−4.67 ± 4.50	−1.92 ± 3.75
Incongruent	Frontal	3.32 ± 2.94	3.38 ± 1.43	−1.42 ± 2.30	−1.45 ± 2.73
	Central	3.18 ± 3.38	3.03 ± 1.48	−1.65 ± 2.39	−1.68 ± 2.68
	Parietal	3.84 ± 4.98	2.15 ± 1.10	−3.21 ± 4.15	−2.16 ± 3.26
	Occipital	4.59 ± 4.34	1.00 ± 1.07	−4.44 ± 4.81	−3.09 ± 4.01

Inhibition of the response alternative related with verbal meaning is suggested to be involved during Stroop test performance (Banich et al., 2001; MacDonald et al., 2000). The increase in the total theta amplitude in the incongruent condition appears to reflect some aspects of the conflict in response production stage, and/or inhibition of the response related with semantic information. The fronto-central distribution of

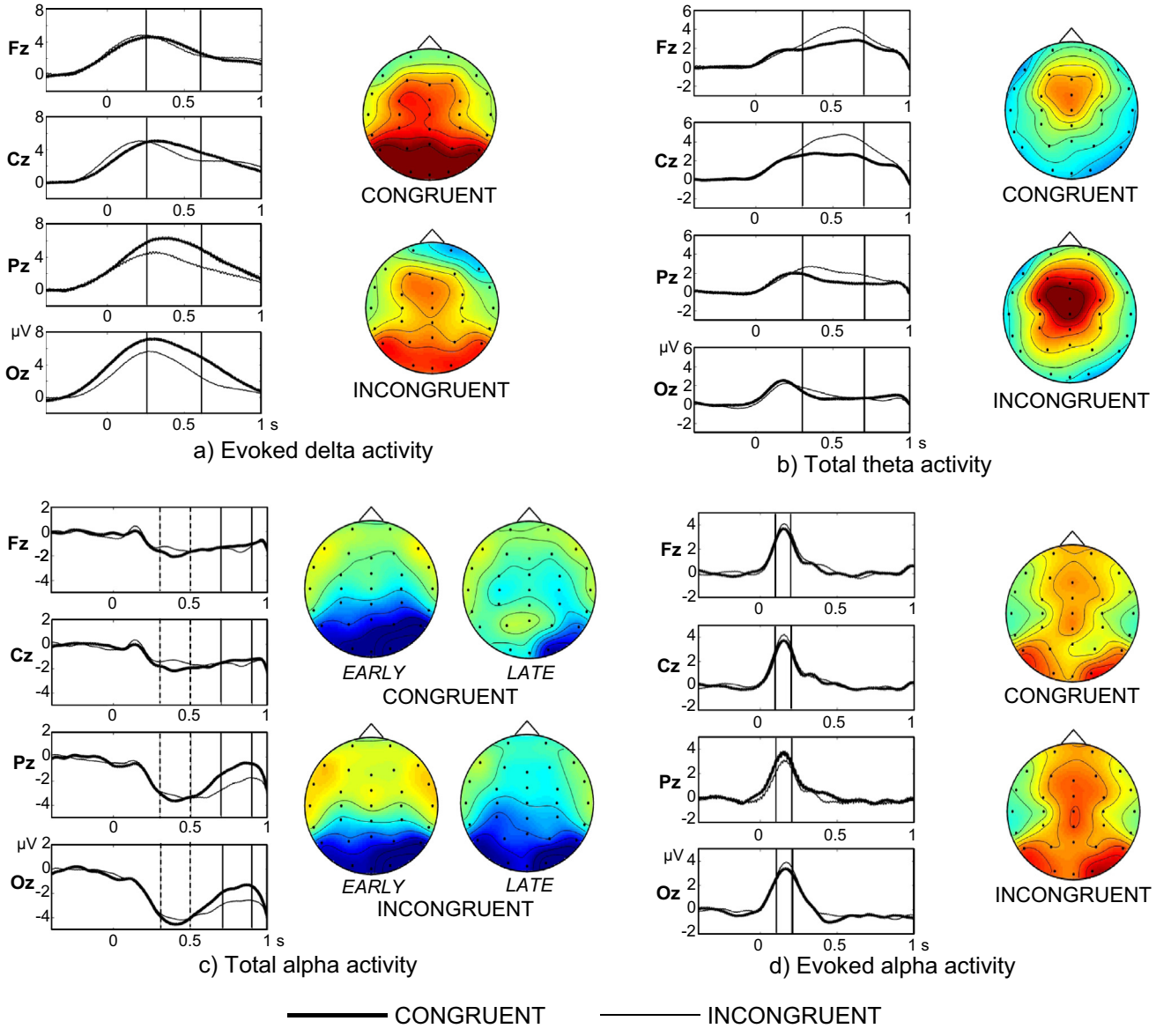

Fig. 4. Grand-average time courses of the evoked delta (a), total theta amplitude (b), total alpha amplitude (c) and evoked alpha amplitudes (d). In each panel, the topographic plots correspond to the mean amplitude of the frequency band within the evaluated time-windows indicated by vertical lines on the time-plots. The upper topography displays the congruent and the lower one displays the incongruent condition. In the total alpha activity panel (c), the topographic plots on the left side correspond to the early time window (300–500 ms) and those on the right side to the late time-window (700–900 ms).

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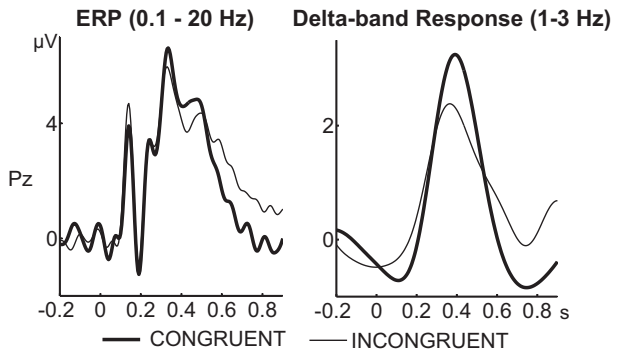

Fig. 5. Grandaverge ERPs obtained from Pz electrode, filtered between 0.1–20 Hz and 1–3 Hz.

the incongruency related total theta activity also displays some similarity to the greater evoked theta activity reported in the NoGo trials compared with Go trials in Go/NoGo and CPT tasks (Harper et al., 2014; Kirmizi-Alsan et al., 2006). Considering the similarity of the topography, common neural structures might be responsible for the theta band response in the Stroop test, Go/NoGo and CPT tasks. On the other hand, we observed the incongruency related larger 4–7 Hz response only in the total activity (i.e. not in the evoked activity). The other authors also reported this incongruency effect in total activity or oscillatory activity that is comparable to total activity (ERS/ERD by Hanslmayr et al., 2008; and event-related spectral perturbation by Tang et al., 2013) that include both phase-locked and induced (non-phase-locked) oscillations. Later onset and non-phase-locked nature of the incongruency related theta response can be attributed to the more demanding nature of the Stroop test for inhibiting the task-irrelevant feature of the stimulus, which interferes with the task-relevant one, in contrast to the easier inhibition of the response to the whole stimulus in tasks like Go/NoGo and CPT. The stronger requirement of top-down control for such feature selection might explain the presence of this effect in the non-phase-locked theta activity, as it is reported in earlier comparative studies (Freunberger et al., 2009) that the non-phase-locked oscillation are produced mainly by top-down mechanisms.

According to several studies, increased theta amplitude with increased task demand is typically observed over fronto-central site having their origin in the ACC (Ishii et al., 1999; Wang et al., 2005). In the two studies that reported larger event-related theta response amplitude in the incongruent trials, ACC has been estimated as the principal generator of this oscillatory response (Hanslmayr et al., 2008; Kovacevic et al., 2012). Based on the error-related intracranial and scalp EEG during Eriksen flanker task and Simon task, several studies (Cohen et al., 2008; Cohen, 2011; Nigbur et al., 2011) supplied further evidence for the role of medial frontal theta in implementation of the cognitive control.

Converging results from functional imaging studies and electrophysiological studies point out that the detection of interference and the initiation of central executive processes like response selection and re-analysis of the task-relevant stimulus features are controlled by ACC during tasks like Stroop test (Banich et al., 2000; Gehring and Fencsik, 2001; Kerns et al., 2004; Liotti et al., 2000; MacLeod and MacDonald, 2000; Markela-Lerenc et al., 2004; van Veen and Carter, 2005). The literature on frontal theta activity and ACC strongly advocates that the 4–7 Hz response described in the present study reflects initiation of the central executive processes to detect interference and to inhibit the response for task-irrelevant features.

4.3.3. Alpha band

In both congruent and incongruent conditions, decrease in total alpha amplitude (alpha desynchronization) began by 300 ms after stimulus onset. In the 300–500 ms window, alpha was significantly more desynchronized in the congruent condition. In the late period (700–900 ms) alpha desynchronization was prolonged in the incongruent condition, while in the congruent condition, the total alpha amplitude almost restored to baseline.

Klimesch (1999) suggested that with increasing task demand in memory tasks, theta synchronizes and alpha desynchronizes. According to this hypothesis, desynchronization in alpha band reflects attentional processes, processing of sensory–semantic information and the difficulty of the task (the more demanding a task, the stronger the amount of event-related alpha desynchronization). In line with this, the prolonged alpha desynchronization in the incongruent condition seems to reflect a longer lasting effort in the processing of the incongruent stimuli compared with the congruent stimuli in which alpha desynchronization was concentrated in the earlier period (300–500 ms).

The alpha band power is reported to be lower in periods following erroneous trials (compared with correct trials) and incongruent trials (compared with neutral trials) in EEG spectrum during inter-trial periods in the Stroop test (Compton et al., 2011). Compton et al. (2011) interpreted this alpha suppression as a higher state of generalized arousal or a result of conflict adaptation. In a recent study, Tang et al. (2013) also reported alpha synchronization effect that is sensitive to conflict adaptation in 200–300 ms as more prominent alpha suppression when the stimulus presentation order is alternated between congruent and incongruent compared with the non-alternating conditions. Although the present task design and analyses do not allow for investigating conflict adaptation, the longer lasting alpha desynchronization in the incongruent trials might also implicate augmentation of attentional filters in visual modality for the next stimulus that is preceded by an incongruent stimulus which requires substantial filtering of the visual input.

Basar et al. (2000, 2001) consider the early evoked alpha response to reflect attention, and Klimesch et al. (2007) interpret the alpha synchronization appearing 100 ms after a visual stimulus to reflect top-down inhibitory control to prevent the interference of task-irrelevant brain areas or processing systems on the sensory input (Klimesch et al., 2007). In the present study, the higher evoked alpha response in 100–200 ms in the incongruent condition suggests that the interference could be starting early at stimulus processing stage. Nevertheless, this difference of the evoked alpha response between the congruent and incongruent conditions was only close to the significance threshold, and this interpretation on evoked alpha response remains tentative.

5. Conclusion

Stroop test performance is suggested to involve at least two subcomponents related to stimulus evaluation and response selection. Evoked delta (250–600 ms) amplitude in favor of the congruent condition and total theta (300–700 ms) amplitude in favor of the incongruent condition suggests that the phase-locked parieto-occipital delta component reflects stimulus evaluation and decision making processes while the non-phase-locked midline frontal theta oscillation results from the initiation of central executive processes like response selection and re-analysis of the task-relevant stimulus features, which are controlled by ACC. EEG signal related with these overlapping processes seem to cancel out in time domain which might explain the lack of a P300 finding in the Stroop test. In addition to the effects on evoked delta and total theta band, long lasting occipital alpha desynchronization in the incongruent condition seems to reflect tuning of neural activity in visual cortex which could facilitate processing of the next stimuli according to task demand.

The evoked (phase-locked) oscillatory responses are expected to have significant contribution to ERPs. The 1–3 Hz filtered display of ERPs advocates that, both N450 and late slow wave findings could have resulted from the modulation of evoked delta response according to congruency of the Stroop test stimuli, which provides a good example

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for the complementary nature of the time domain and time–frequency plane approaches. In the present example, the TF analysis helps to relate two time domain phenomena (differences of N450 and late slow wave between conditions) with a common TF phenomenon (evoked delta difference between conditions).

The remaining three significant results on time–frequency components (theta band and alpha band in two windows) were obtained in total activity, which includes both evoked and induced (non-phase-locked) oscillations. When Tables 3 and 4 are compared, it looks obvious that most of the significant effects are in Table 4 that reports the results of total activity. This contrast in favor of non-phase-locked components suggests that Stroop test performance requires stronger top-down control (Freunberger et al., 2009) compared with easier response inhibition paradigms, where earlier and phase-locked oscillatory components are in the foreground (Kirmizi-Alsan et al., 2006).

Isolation of the processing components by time–frequency transform still offers a progress in elucidation of the neural activity responsible for resolution of the interference between certain dimensions of the stimulus. Hence, in addition to the previously reported results on total theta activity, this study provides clear evidence that evoked delta and total alpha are also sensitive to congruency condition of the Stroop test stimuli. Further studies are needed to test the tentative interpretations in the present study and to explore the interplay between the generators of the oscillatory activities in delta, theta and alpha bands during Stroop test.

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