

Neural Markers for Immediate Performance Accuracy in a Stroop Color-word Matching Task: an Event-related Potentials Analysis

Guofa Shou*, *IEEE Member*, Lei Ding *IEEE Member*

Abstract—The present study examined the neural markers measured in event-related potentials (ERPs) for immediate performance accuracy during a cognitive task with less conflict, i.e., a Stroop color-word matching task, in which participants were required to judge the congruency of two feature dimensions of a stimulus. In an effort to make ERP components more specific to distinct underlying neural substrates, recorded EEG signals were firstly dissolved into multiple independent components (ICs) using independent component analysis (ICA). Thereafter, individual ICs with prominent sensory- or cognitive-related ERP components were selected to separately reconstruct scalp EEG signals at representative channels, from which ERP waveforms were built, respectively. Statistical comparisons on amplitudes of stimulus-locked ERP components, i.e., prefrontal P2 and N2, parietal P3, bilateral occipital P1 and N1, revealed significant reduced P3 amplitude in error trials than in correct trials. In addition, significant evident ERN was also observed in error trials but not in correct trials. Considering the temporal locus of semantic conflict in the present task, we concluded that reduced P3 amplitude in error trials reflect impaired resolving process of semantic conflict, which further lead to a performance error in the Stroop color-word matching task.

I. INTRODUCTION

To err is human. A person's behavior should be conducted in a goal-directed manner that requires a dynamic and collaborative operation of multiple neurocognitive functions, to successfully accomplish a task in daily life, e.g., sending an email without forgetting attachment. In the regard of elucidating neural underpinnings of behaviors, as a central goal of cognitive neuroscience, studies of behavioral errors have been proven informative and thus numerous studies have been conducted to explore neural correlates of different aspects of errors, such as generation, detection, or post-error adaptation [1-5]. For example, error-related negativity (ERN) in event-related potentials (ERPs) that reflects spontaneous detection of errors has been discovered as immediately following errors [1].

In another aspect, neural antecedents of errors are of particular interests since any detectable neural patterns preceding errors can be used to foreshadow immediate performance accuracy and, therefore, timely prevent

catastrophic consequences. In this regard, some neural antecedents measured in ERPs [4, 6, 7] and in oscillatory activities [5] have been reported in different tasks. Among them, cognitive conflict paradigms, such as Stroop tasks [7], Flanker tasks [8], or go/nogo tasks [3-5], which involve response conflict and/or response inhibition, have been widely employed to induce significant numbers of errors. Neural markers reflecting the failure of inhibiting error responses, induced by irrelevant feature dimensions of stimuli, have been elucidated in details [2-5, 7, 8]. However, neural antecedents of errors in cognitive tasks with less or no response conflict have not been sufficiently studied.

The aim of the present study was thus to examine electroencephalography (EEG) neural precursors of immediate errors during a specific cognitive task with less conflict, i.e., the Stroop color-word matching task [6, 9]. Compared to the classic Stroop tasks responding to either color or word, the Stroop color-word matching task responds to the congruency of both feature dimensions (i.e., word meaning and ink color), and thus does not involve response conflict. Moreover, the involved stimulus-related semantic conflict between two processing pathways (color and word) for incongruent stimuli will occur before the generation of a motor response, since both responses (i.e., congruent or incongruent) require the intersection of these two processing pathways. After disentangling scalp EEG signals into different components by independent component analysis (ICA) and selecting dominant ICs with evident ERP components, we statistically examined post-stimulus (but pre-response) ERP components linked to sensory and cognitive functions, i.e., bilateral occipital P1 and N1, prefrontal P2 and N2, parietal P3, calculated from back-projected EEG signals of individual selected ICs at representative channels.

II. MATERIALS AND METHODS

A. Participants

Twenty-six normal participants (age 20-36, three females, all right-handed) were enrolled in the study after signing informed consents. All participants have reported normal or corrected-to-normal visions. The study was approved by the Institutional Review Board at the University of Oklahoma. Data from 8 participants was excluded due to few errors (error rate less than 2.5% in one or more stimulus conditions) or performance at the chance level (only one participant). None excessive EEG artifacts were shown in remaining participants and thus total 18 participants (one female) were included in the following analysis.

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Guofa Shou is with the School of Electrical and Computer Engineering, University of Oklahoma, Norman, OK 73072 USA (phone: 405-496-8661; fax: 405-325-7066; e-mail: guofashou@gmail.com).

Lei Ding is with the School of Electrical and Computer Engineering, the Center of Biomedical Engineering, University of Oklahoma, Norman, OK 73019, and the Laureate Institute of Brain Research, Tulsa, OK USA (e-mail: leiding@ou.edu).

B. Task and Stimuli

The participants were presented with 720 stimuli separated into two sessions (i.e., each comprised three blocks of 120 stimuli with a self-paced rest period of 30 s between two consecutive blocks), with an impedance check of the sensor net for about 10 minutes between them. The Stroop color-word matching task was illustrated in Fig. 1. Four English words “WHITE”, “RED”, “BLUE” and “GREEN” (each word displayed 180 times), printed into one of these four colors on a black background, were employed as stimuli, which constituted either congruent stimulus (word meaning and color matched) or incongruent stimulus (word meaning and color not matched). Stimuli were presented in a pseudorandomized order on a 21-inch computer screen, each last 80 ms and followed by a black screen of 1400 ms when participants were required to press a button using either index (incongruent) or middle finger (congruent) of the right hand as accurate and fast as possible. A timing feedback (“Hurry up”) was given for 600 ms after the 1400 ms response window if response time (RT) exceeded 600 ms. Every trial lasted 4000 ms on average with a ± 1500 -ms jitter. In addition, 60 null-stimulus trials were interspersed across the task with 10 trials per block. Prior to the test session, participants performed a short practice session of 48 trials to familiarize the task.

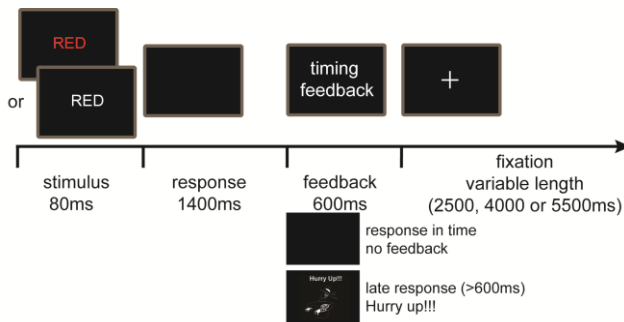


Figure 1. Schematic representation of the Stroop color-word matching task.

C. EEG acquisition and preprocessing

EEG signals were referenced to the channel on the vertex and were recorded using a 128-channel Net Amps 300 amplifier (Electrical Geodesics, Inc., OR, USA) at the sample frequency of 250 Hz. Data were offline filtered with a band-pass filter of 0.5-30Hz, and re-referenced to an arithmetically derived common average. The *FASTER* [10] and *EEGLAB* [11] toolboxes were used to remove EEG artifacts via a fully automated statistical thresholding method with the threshold Z -score > 3 for each metric used on functions for bad channels interpolation, bad epochs removal (continuous EEG were segmented into epochs of 3800 ms with 1500 ms before stimulus onset), artifactual independent components (ICs) subtraction, and bad channels interpolation on epochs. Remaining EEG epochs corresponding to trials with RTs exceeding three standard deviations of averaged RT in the same stimulus and response condition were further removed. Then, the number of correct trials (much more than the number of error trials) was matched to the number of error trials by finding a correct trial with the closest RT for every

error one in the same stimulus condition to remove the compound of RT on ERPs. Finally, it resulted in 72 (± 28) EEG epochs each for correct and error responses from each of 18 participants for the following analysis.

D. Group-wise Independent Component Analysis

To obtain dissociable EEG signatures linked to distinct neural substrates from scalp EEG signals, especially for these ones that are related to prominent sensory and/or cognitive functions, a group-wise ICA method was applied [12]. Specifically, RT-matched EEG epochs from all participants were temporally concatenated for the infomax ICA process in *EEGLAB* [11]. After the dimension reduction using principle component analysis, 32 ICs were calculated; from which ICs that have prominent ERP components linked to visual sensory perception and cognitive processes were selected for further investigations.

E. ERP analysis

Based on ICs' spatial and temporal patterns, the dominant IC that reflected specific ERP components was selected to build scalp EEG signal specific to this IC, and ERP waveforms were calculated on representative channels. For example, an IC with fronto-central topography and evident stimulus-locked N2 and response-locked ERN, was selected to build scalp EEGs, from which the ERP waveform for N2 and ERN components was calculated at channel FCz. In total, four ICs were selected to separately build ERP waveforms at O1, O2, Pz and FCz, which were baseline corrected using mean signals at a 100-ms window (-100~0ms before stimulus onset for stimulus-locked waveforms or -150~50 ms before response onset for response-locked waveforms) [13]. Thereafter, stimulus-locked P1, N1, and P3 were identified and their amplitudes were measured as the mean values between 120 and 160 ms, 180 and 220 ms, and 360 and 400 ms post-stimulus at O1, O2 and Pz, respectively. At FCz, stimulus-locked P2 and N2 and response-locked ERN were identified and their amplitudes were measured as the mean values between 170 and 210 ms, 280 and 320 ms post-stimulus, and 80 and 120 ms post-response, respectively. These latencies were selected based on grand-averaged stimulus- or response-locked ERP waveforms (Fig. 3). Moreover, N2 amplitude calculated as a relative value to the preceding P2 was also performed as the difference between amplitudes of N2 and P2 [13], and it was labeled as N2P2 to distinguish it from original N2 amplitudes. Finally, the amplitudes of these ERP components were statistically compared using paired t tests between error and correct responses.

III. RESULTS

A. Behavioral Data

On average, participants made errors on 73 (± 29) trials, plus 13 (± 13) nonresponse trials. RTs were significant slower on correct compared to error trials (618 ms vs. 599 ms, $t_{(17)} = 2.4$, $p < 0.05$). And RTs in incongruent trials were significant larger relative to congruent trials (630 ms vs. 606 ms, $t_{(17)} = 3.47$, $p < 0.005$), which replicated the previous findings [6, 9].

B. ICs with Prominent ERP Components

Fig. 2 displays the spatial and spectral patterns of four selected ICs with prominent ERP components: frontal IC, parietal IC, right occipital IC and left occipital IC, named according to their local maximum or minimum areas in spatial topographies. The topographies of these ICs are well explained by a single dipolar source [14] within the prefrontal, parietal, right and left occipital cortices, suggesting the validity of the present calculation of ICs. Moreover, the local maximum or minimum were located around the corresponding channels of FCz, Pz, O2 and O1, which are often selected to examine the ERP components of P2, N2, ERN, P3, P1 and N1 [1-3, 15-17]. The spectral patterns of these ICs also indicate the consistence with underlying neural sources reflected in these ICs, e.g., visible alpha peaks in all ICs and evident theta peak in the prefrontal IC. Taken all these evidences together (with the following ERP waveforms, Fig. 3), these ICs can be confidently linked to the medial prefrontal cortex, posterior parietal cortex, right and left primary visual cortices, which are supposed to be the locations of the neural sources for N2 [16], P2 [17] and ERN [1], P3[15], and right and left P1 and N1 [18].

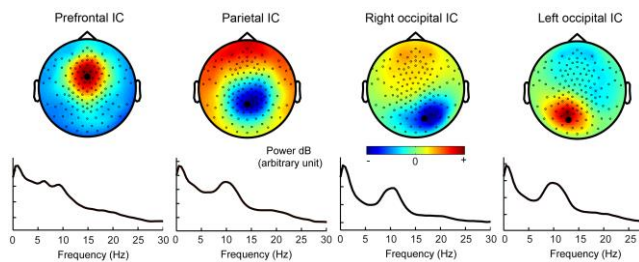


Figure 2. Spatial and spectral patterns of four ICs with prominent ERP components. The large black dots (from left to right) denote the channels

C. ERPs

The grand averaged ERP waveforms at FCz, Pz, O1 and O2 calculated from the dominant IC were illustrated in Fig. 3. At FCz, the response-locked waveform was also calculated for the post-response ERN. It is observed that the studied ERP components are evidently revealed in EEGs calculated from one of four selected ICs at different channels, such as the N2 and ERN at FCz from the prefrontal IC, and the P3 at Pz from the parietal IC.

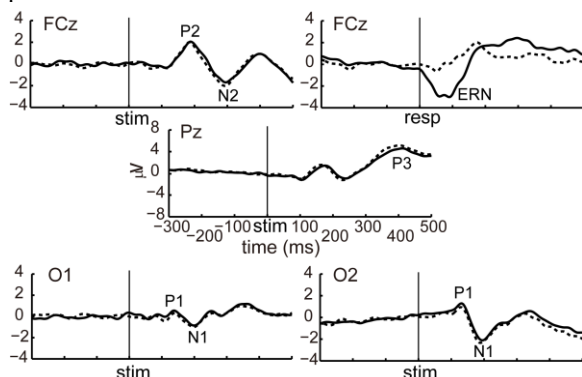


Figure 3. Grand averaged stimulus- and response-locked ERP waveforms at FCz, Pz, O1 and O2 for error (solid) and correct (dashed lines).

The amplitudes of different ERP components were summarized in Fig. 4. For the early visual perception components (left and right P1 and N1) at bilateral primary visual cortex, no significant differences were observed, although reduced N1 amplitude was similarly detected in error than correct trials as that in [2]. For the early cognitive process related components at the prefrontal cortex (P2, N2 (or N2P2)), the differences between correct and error trials still didn't reach the significant level. For the late cognitive component at the posterior parietal cortex (P3), significantly reduced amplitudes were detected in error than correct trials ($t_{(17)}=3.64, p<0.005$). In addition, the post-response ERN was significantly revealed in error trials ($t_{(17)}=5.55, p<0.0001$).

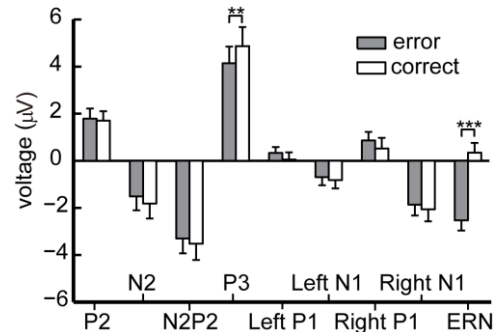


Figure 4. Summary of the amplitudes of multiple ERP components for error and correct trials. ** $p<0.005$, and *** $p<0.0001$. The bars denote the standard error of the mean.

IV. DISCUSSION AND CONCLUSION

In the present study, EEG neural markers in post-stimulus (but pre-response) ERPs for immediate performance accuracy were examined in a cognitive task with less conflict, i.e., the Stroop color-word matching task. To make identified ERP components more specific to underlying neurocognitive processes, scalp ERP waveforms were calculated from back projections of individual dominant ICs, which account for individual sensory- or cognitive-related ERP components, at representative channels.

The ICA method revealed four ICs that dominantly corresponded to post-stimulus bilateral occipital P1 and N1, posterior parietal P3, and anterior prefrontal N2, as well as post-response ERN components, respectively, in terms of their spatial (scalp maps, Fig. 2), spectral (spectral powers, Fig. 2), and temporal (ERP waveforms, Fig. 3) patterns [1-3, 15-17]. Though selected ICs have contributions on EEG signals over multiple channels (Fig. 2), their local maximum or minimum areas are surrounding selected channels. Therefore, the present calculation of ERP components can reduce as many contributions from other neural processes as possible due to the volume conduction, and largely improve specificity of each ERP component to its underlying neural processes.

In all post-stimulus ERP components, error responses were only characterized by a significantly reduced magnitude in P3 (Fig. 4). The P3, in particular the posterior P3, has been linked to the selective attention and information processing [15]. In literature, reduced P3 amplitude has been identified in go/nogo task, reflecting the failure of response inhibition [3,

19]. In the examination of semantic conflict during the Stroop color-word matching task [6], reduced P3 amplitude was observed in incongruent trials other than congruent trials. Considering that the P3 amplitude is negatively correlated with the difficulty of the task [20], Zurrón et al [6] interpreted the P3 pattern as a result of the greater difficulty induced by the semantic conflict from incongruent stimuli, and concluded that the temporal locus of semantic conflict might occur in a window around P3 component. In the present study, since same numbers of RT-matched congruent and incongruent trials were used in error and correct response groups, the observed P3 pattern should not be attributed to the group-level task difficulty (i.e., more incongruent trials in error group than in correct group). However, if following the same consideration that reduced P3 amplitude in error trials reflects greater difficulty in these trials, the greater difficulty might be caused by the deficient information processing capability to resolve semantic conflict in error trials, which is also supported by a recent interpretation of P3 that the P3 reflects the process mediating between the perceptual analysis of the stimulus and the initiation of response process [21]. On the contrary, no significant difference was revealed in the early visual perceptual P1 and N1 that are modulated by sustained attention [2, 18], suggesting that errors might not be caused by impaired attention-induced visual perception. Moreover, different from reduced N2 amplitude in nogo errors [3, 16], no significant difference in N2 amplitude was observed in the present study, which might due to the absence of response conflict/inhibition in the present task.

In the post-response ERPs, an evident ERN was observed in error trials, which replicated neural process of detecting errors in literature [1]. It is also noted that the ERN and the P2/N2 are calculated from the same IC, suggesting that these ERP components might have same locations of underlying neural source within the medial prefrontal cortex.

In conclusion, the present study investigated EEG neural markers for immediate performance accuracy in a cognitive task with less conflict. Via comparing amplitudes of multiple sensory- and cognitive- related ERP components calculated from ICs, reduced amplitude of the parietal P3 component was revealed in error trials than correct trials. The findings demonstrated that errors mainly happen due to impaired resolving of semantic conflict in the Stroop color-word matching task rather than response conflict in the classic Stroop task.

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