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Research report

Attentional resources modulate error processing-related brain electrical activity: Evidence from a dual-task design

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A R T I C L E I N F O

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A B S T R A C T

Attention plays an important role in the processing of error, but only a few studies have explored the relationship between them. The current study used a dual-task paradigm, combining the classic flanker task with a working memory load task, to explore how changes in the amount of attentional resources modulate error negativity (Ne) and error positivity (Pe). The results showed that the reduction of attentional resources overall caused a decrease in Pe amplitude, especially in the late stage of Pe, which had a significant diminution in amplitude. However, changes in the amount of attentional resources did not cause significant changes in the Ne amplitude. These results suggest that the early stage of error processing in the Ne time window is less affected by attention, but the Pe stage is regulated by attentional resources, especially in the late Pe stage.

1. Introduction

By detecting and correcting errors, the cognitive control system works to improve behavioral performance and to adapt to the surroundings. Errors are an important source of information for the individual to regulate cognitive processes. Research interest in the underlying mechanism by which people detect their errors has increased in recent years. Previous studies involving event-related brain potentials (ERPs) have revealed a negative deflection component, which has been labeled error negativity (Ne) (Falkenstein et al., 1990, 1991) or error-related negativity (ERN) (Gehring et al., 1993), peaking approximately 50–100 ms after an erroneous response. Another component correlated to error processing called error positivity (Pe), occurring after Ne, peaks approximately 200–400 ms after the response (Falkenstein et al., 1991, 2000; Overbeek et al., 2005).

Some researchers considered the Ne component to be induced by the simultaneous activation of the correct and erroneous response representations, and proposed that Ne reflects conflict processing in the conflict monitoring system (Carter et al., 1998). Other researchers presumed that Ne was elicited when the actual reaction (erroneous reaction) mismatched with the intended response, reflecting the error detecting mechanism (Bernstein et al., 1995; Falkenstein et al., 1991). Pe reflects the salience or awareness of the errors (Endrass et al., 2012; Falkenstein et al., 1995, 2000; Nieuwenhuis et al., 2001) and is associated with behavioral adjustments following errors (Kaiser et al., 1997; Leuthold and Sommer, 1999; Nieuwenhuis et al., 2001).

The anterior cingulate cortex (ACC) is thought to be the most likely neural generator of Ne (Carter et al., 1998; Dehaene et al., 1994; Luu et al., 2000; Ullsperger and von Cramon, 2001; Van Veen and Carter, 2002) and Pe (Herrmann et al., 2004; Van Veen and Carter, 2002). This region is related in important ways to attentional control (Corbetta et al., 1991; Mesulam, 1999; Shen et al., 2014) and contributes to performance monitoring and behavioral adjustments in the control of cognitive processes (Carter et al., 1998; Davies et al., 2001; Kiehl et al., 2000; Yeung et al., 2004).

On the one hand, the attention control system engages in functions such as behavioral monitoring and adjustment, especially when conflicts or errors are presented in the tasks (Kaiser et al., 1997). On the other hand, error processing, as one central aspect of performance monitoring (Grützmann et al., 2014), involves mobilization of cognitive control to improve performance (Gehring et al., 1993; Xiao et al., 2015). It seems that the attention control system and error processing mechanism are closely connected. Yeung et al. (2004) have developed a computational model

Abbreviations: ACC, anterior cingulate cortex; CRN, correct-response negativity; EEG, electroencephalogram; EMG, electromyogram; EOG, electrooculogram; ERN, error-related negativity; ERP, event-related potential; HA, high-attention; LA, low-attention; Ne, error negativity; ICA, independent component analysis; PDP, process dissociation procedure; Pe, error positivity.

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to elucidate Ne and error processing in terms of the conflict monitoring theory. They have also claimed that attention plays an important role in error processing. Hence, research on the effects of attentional resources on error processing plays a vital role in uncovering the mechanisms of behavioral monitoring and adjustment.

Some studies have involved the influences of attentional resources on error processing, although they did not aim to study this effect. Pailing and Segalowitz (2004) utilized the dual-task design to test how response uncertainty affects error-related brain activity and found that the ERN/CRN (correct-response negativity) amplitudes were lower in dual-task condition than in the single task condition. In addition, to examine how errors are processed in a state of mental fatigue (Boksem et al., 2006; Kato et al., 2009; Xiao et al., 2015), researchers usually asked participants to finish the first task to achieve the fatigue state, and then proceed to finish the main task for measurement of error-related brain potentials. The results showed that mental fatigue affected error processing by reducing the attentional resources dedicated to main tasks, causing a decrease of Ne amplitudes. In addition, alcohol does harm to control processing (Bartholow et al., 2012; Ridderinkhof et al., 2002). Researchers (Bartholow et al., 2012) have used the process dissociation procedure (PDP[1]; Jacoby, 1991; Payne, 2001; Payne et al., 2005) to estimate the control processing level in both non-alcohol and alcohol groups and analyzed the relations between control level and Ne. The results showed that the non-alcohol groups exhibited more negative Ne amplitudes, which were positively correlated with control estimates, while the subjects in alcohol group showed less negative amplitudes, which had no correlation with control estimates.

In some other conditions, participants would allocate more attention to the task and thus facilitate error processing. For instance, Yeung et al. (2004) found that the more emphasis the task placed on response accuracy, the larger the Ne that was evoked. Additionally, some studies instructed participants to rate the accuracy of their responses to test how error awareness affects error processing; with this method, Grützmann et al. (2014) revealed that Ne and CRN in the rating condition were more negative than those in the no-rating condition. Scholars claimed that when accuracy was emphasized or explicitly rated, participants paid more attention to their responses and thus produced larger error-related potentials. Luu et al. (2000) also suggested that increases in Ne were associated with a higher degree of activity in the centromedial frontal cortex, as a consequence of significant increases in attentional self-monitoring. However, research conducted by Moser et al. (2005) showed that Ne was not affected by attentional resources. The relationship between attentional resources and Ne is still disputed.

Although the relationship between Ne and attentional resources has been studied extensively, only a few studies have examined how attentional resources modulate Pe. Grützmann et al. (2014) suggested that the higher the attention level of the task, the greater the magnitude of Pe induced by the error responses. Moser et al. (2005) obtained a consistent result that the amplitude of Pe decreased when the task stimulus processing received less attention. However, the results of a mental fatigue study showed that changes in the attentional resources allocated to task did not lead to changes in the amplitude of Pe (Xiao et al., 2015).

[1] In this task, a photo of either a Black or White face preceded a photo of a gun or tool. Participants needed to ignore the faces and press one key for gun and another for tool (Payne, 2001). In congruent trials (e.g., tool followed White face), the race bias (automatic process) facilitated response (control process) and lead to less errors, while in incongruent trials (e.g., tool followed Black face) participants made more errors given the race bias. By utilizing the equation of "$C = P$ (correct|congruent) $- P$ (stereotypic error|incongruent)", researchers calculated the control level for each participant.

The analyses above indicate that attention is closely connected with error processing. However, these studies did not aim to explore the effects of attentional resources on error processing, but focused on the influences of mental fatigue (Boksem et al., 2006; Kato et al., 2009; Xiao et al., 2015), alcohol use (Bartholow et al., 2012) or error awareness (Grützmann et al., 2014; Nieuwenhuis et al., 2001; Yeung et al., 2004) on error processing. In these studies, apart from attentional resources, there were also other factors acting on error processing; for example, in the research on mental fatigue, except fatigue, there also existed discrepancies on the extent of sleepiness and mental clarity between fatigue and control groups (Xiao et al., 2015). It is necessary to design an experiment to elucidate how attentional resources act on the error processing more clearly, which was the aim of our experiment.

The current study adopted a dual-task design, with the flanker task as the primary task and the working memory load task as the secondary task. In each trial, participants finished a flanker task during the memory maintaining stage of the memory task. In addition, by manipulating the number of items to be remembered, we obtained a high-attention condition (HA condition) and a low-attention condition (LA condition). We recorded and compared error-evoked brain activity in the HA and LA conditions.

As mentioned above, there were two studies adopting the dual-task design, but both of them compared the single task condition with the dual task condition (Pailing and Segalowitz, 2004; Grützmann et al., 2014). In addition to differences in attentional resources, the dual task condition contained a task switch process more than the single task condition, which would affect error processing undoubtedly (Grützmann et al., 2014). Thus, to remove the interference of task switching, both the HA and LA conditions in the current study were dual task conditions. The spatial working memory load task was used as the memory load task; this task provides 16 possible positions to remember in a 4×4 grid. In the high- and low-attentional-resource conditions, participants needed to remember one and three positions, respectively.

According to the attention resource allocation theory (Kahneman, 1973), one's attention capacity is limited. The more attention the participants allocate to the memory task, the less would be left for the flanker task. Thus, participants would have more attentional resources to process error in the low-load condition than in the high-load condition. Referring to the results of past studies of mental fatigue (Boksem et al., 2006; Kato et al., 2009; Xiao et al., 2015), error evaluation (Grützmann et al., 2014; Yeung et al., 2004), and alcohol use (Bartholow et al., 2012), we predicted that as the memory load increased, the attentional level on the flanker task would decrease; that the behavioral reaction would be slower; and that both the Ne amplitudes and Pe amplitudes would diminish.

2. Results

2.1. Behavioral results

Table 1 presents the behavioral data. No systematic difference was found in error rates or reaction times for flanker tasks between the LA and the HA conditions; error rates, $t\,(13) = 1.594$, $p = 0.135$; reaction times, $t\,(13) = -1.304$, $p = 0.215$. The correct rates of the memory load task were different between the LA and the HA conditions, $t\,(13) = 2.353$, $p < 0.05$, indicating that the load task operation is effective in this experiment.

2.2. ERP results

Fig. 2 depicts the difference waveforms for Ne and Pe in two conditions and the grand average waves before subtracting at the