NeuroImage 56 (2011) 2339–2347

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/ynimg

Error-related brain activity and adjustments of selective attention following errors☆

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ARTICLE INFO

Article history:
Received 28 February 2011
Revised 28 March 2011
Accepted 31 March 2011
Available online 12 April 2011

Keywords:
Performance monitoring
Error processing
Behavioral adjustments
Selective attention
Error-related negativity
Event-related potentials

ABSTRACT

The present study investigated adjustments of selective attention following errors and their relation to the error-related negativity (Ne/ERN), a correlate of errors in event-related potentials. We hypothesized that, if post-error adjustments reflect an adaptive mechanism that should prevent the occurrence of further errors, then adjustments of attentional selectivity should be observed only following errors due to insufficient selective attention. To test this, a four-choice flanker task was used in which errors due to insufficient selective attention (flanker errors) and other errors (nonflanker errors) could be distinguished. We found strong adjustments of selective attention following flanker errors but not following nonflanker errors. Moreover, the Ne/ERN amplitude was correlated with adjustments of selective attention on a trial-by-trial basis. The results provide support for the notion that the Ne/ERN is a correlate of adaptive adjustments following errors.

Introduction

Efficient task performance requires an internal performance monitoring system, which detects errors and initiates behavioral adjustments in order to optimize performance. Evidence for such a system comes from studies investigating the error negativity or error-related negativity (Ne/ERN), a negative deflection in the event-related potential (ERP) following errors (Falkenstein et al., 1990; Gehring et al., 1993), which is presumably generated in the anterior cingulate cortex (ACC, Carter et al., 1998; Dehaene et al., 1994; Ullsperger and von Cramon, 2001; van Veen and Carter, 2002). Several theories have been proposed that assume the Ne/ERN to be related to behavioral adjustments that should prevent the occurrence of further errors (Botvinick et al., 2001; Holroyd and Coles, 2002). Evidence for this notion comes from studies showing that Ne/ERN amplitudes are correlated with the amount of post-error slowing, which refers to the typically obtained response time increase following errors (e.g., Debener et al., 2005; Gehring et al., 1993; Holroyd et al., 2005).

The present study aimed to investigate whether errors in a selective attention task lead to adaptive adjustments of attentional selectivity, and whether these adjustments are also related to the Ne/ERN. To achieve this, we considered performance in the flanker task, which is a standard paradigm to investigate visual selective attention (Eriksen and Eriksen, 1974; Miller, 1991). The task requires participants to classify a target stimulus while ignoring simultaneously presented flanker stimuli that are associated with the same (congruent) or a different (incongruent) response than the target. The so-called congruency effect refers to the impaired performance for incongruent relative to congruent stimuli. Because the congruency effect indicates the influence of the irrelevant flanker stimulus, it can serve as an index of attentional selectivity. Computational models of the flanker task assume that the congruency effect reflects the efficiency by which selective attention enhances target processing and simultaneously suppresses flanker processing (Hübner et al., 2010; Servan-Schreiber et al., 1998). These models further imply that a large portion of errors on incongruent trials occur because selective attention fails and the flanker stimulus is processed more strongly than the target stimulus. Because these errors can be prevented by increasing the efficiency of selective attention, we hypothesize that detecting an error implies that attentional selectivity is adjusted on the subsequent trial in order to prevent further errors.

Indeed, post-error adjustments of selective attention are directly predicted by a major theory on performance monitoring. Conflict monitoring theory (Botvinick et al., 2001; Yeung et al., 2004) assumes that adjustments of selective attention are initiated whenever response conflict is detected in a flanker task. In this way, the theory can account for so-called conflict adaptation effects, that is, the increase of attentional selectivity following trials on which the

☆ This research was supported by grants from the Deutsche Forschungsgemeinschaft (DFG: STE 1708/1-1) and the Young Scholar Fund of the University of Konstanz to the third author. We are grateful to Marleen Vogt for assistance in conducting the experiment.
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doi:10.1016/j.neuroimage.2011.03.083

stimulus induced high response conflict (Botvinick et al., 2001). This theory further assumes that the Ne/ERN reflects response conflict following errors, which emerges because an upcoming error correction elicits conflict with the still-activated error response. Accordingly, if response conflict implies that selective attention is adjusted and errors produce response conflict, then errors should also lead to adjustments of selective attention.

In accordance with this prediction, adjustments of selective attention following errors have been found in studies using the Simon task, another conflict paradigm in which stimulus position serves as task-irrelevant distractor feature (Burle et al., 2002; King et al., 2010; Ridderinkhof et al., 2002). In contrast, other paradigms, like the flanker task, have not shown this effect consistently (e.g., Ullsperger and von Cramon, 2006; see, Ridderinkhof et al., 2002 for an exception). Thus, it is unclear whether adjustments of selective attention following errors are a general phenomenon.

The goal of the present study was to clarify this issue by considering a possible explanation for the difficulty to find adjustments of selective attention following errors in the flanker task. We propose that adjustments of selective attention are difficult to observe because they occur only on a proportion of error trials. If adjustments of selective attention serve to prevent errors due to insufficient attentional selectivity, they should be initiated only following errors of this type. In contrast, errors resulting from other sources (like premature responding or motor failure) should not lead to adjustments of selective attention. If this assumption turned out to be valid, it would have two implications: On the one hand, it would imply that performance monitoring involves an evaluation of the error source. On the other hand, it would imply that adjustments of selective attention following errors are difficult to detect because errors due to insufficient attention cannot be isolated in conventional conflict paradigms.

To test this assumption, it is necessary to empirically isolate errors due to insufficient attentional selectivity. This can be achieved by using a modified flanker task that we recently used to investigate the relation between the Ne/ERN and error detection (Maier et al., 2008). By using four response alternatives, two types of errors could be distinguished (see, Fig. 1): When target and flankers required different responses (i.e., incongruent stimuli), errors could occur either because the response associated with the flankers was produced (i.e., a flanker error) or because a response not associated with any element on the display was produced (i.e., a nonflanker error). These error types should differ with respect to the underlying error source. Basically, errors in the flanker task result because of speed pressure or unspecific noise (Ratcliff and Rouder, 1998), or because of insufficient attentional selectivity resulting, e.g., from random fluctuations or from maladaptation (Eichele et al., 2010, 2008). Crucially, whereas flanker errors and nonflanker errors can both be due to speed pressure or unspecific noise, only flanker errors can be due to insufficient selective attention. Accordingly, errors due to insufficient attentional selectivity should be more frequent among flanker errors than among nonflanker errors.

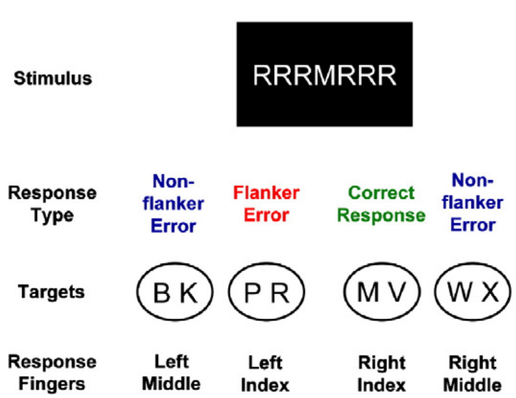

Fig. 1. Stimulus response mappings and classification of responses in the four-choice flanker task. Each of the four response fingers (fourth line) were associated with two target letters (third line). Given a specific stimulus, each response was classified as either a correct response, a flanker error, or a nonflanker error (second line). In the present example, the stimulus consists of the target letter 'M' and the flanker letters 'R' (first line). Given this stimulus, a response with the right index finger would be classified as a correct response, a response with the left index finger would be classified as a flanker error, and a response with the remaining fingers would be classified as a nonflanker error.

The validity of this assumption can be tested by considering the relative frequency of flanker errors in the modified flanker task. If all errors in this task were due to speed pressure or unspecific noise, the relative frequency of flanker errors should be 33%, because only one of the three possible incorrect responses corresponds to a flanker error. This results because, due to the four response alternatives, unspecific noise should elicit each of the three incorrect responses with an equal probability. However, if there were additional errors due to insufficient selective attention, these errors should mainly be flanker errors. Accordingly, a relative frequency of flanker errors exceeding 33% would provide evidence that a portion of flanker errors is due to insufficient selective attention. Consistent with this prediction, we found relative frequencies of flanker errors that robustly exceeded 33% in our earlier study (Experiment 1: 43.4%, Experiment 2: 53.6%; Maier et al., 2008). Moreover, the analysis of error-related brain activity in these experiments showed that Ne/ERN amplitudes were increased for flanker errors relative to nonflanker errors (Maier et al., 2008), which suggests that the two error types are processed differentially by the performance monitoring system.

These findings suggest that the modified flanker task by Maier et al. (2008) is well-suited for isolating errors due to insufficient selective attention. In the following, we report an experiment in which we used this task to investigate whether adjustments of selective attention are only initiated when an error occurs due to insufficient selective attention, and whether these adjustments are related to the amplitude of the Ne/ERN. We hypothesized that attentional selectivity is increased on trials following flanker errors as compared to trials following nonflanker errors. This would imply that the performance monitoring system initiates adaptive behavioral adjustments after evaluating the source of an error. Moreover, it might explain the failure to find evidence of adjustments of selective attention following errors in those studies in which errors due to insufficient attentional selectivity could not be isolated. In a second step, we examined whether stronger adjustments of selective attention are obtained following trials with large Ne/ERN amplitudes than following trials with small Ne/ERN amplitudes. To analyze this, we applied a linear integration method to determine single-trial amplitudes for the Ne/ERN (Parra et al., 2002, 2005). Finding such a relationship would imply that the Ne/ERN is indeed related to adaptive behavioral adjustments.

Materials and methods

Participants

20 participants (17 female) between 19 and 45 years of age (mean 23.2) with normal or corrected-to-normal vision participated in the study. They were recruited at the University of Konstanz and received 5 Euro per hour. The study was conducted in accordance with institutional guidelines and informed consent was acquired from all participants.

Apparatus

Stimuli were presented on a 19-inch color monitor, and a PC controlled stimulus presentation and response registration.