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Neural signatures of adaptive post-error adjustments in visual search

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ABSTRACT

Errors in speeded choice tasks can lead to post-error adjustments both on the behavioral and on the neural level. There is an ongoing debate whether such adjustments result from adaptive processes that serve to optimize performance or whether they reflect interference from error monitoring or attentional orientation. The present study aimed at identifying adaptive adjustments in a two-stage visual search task, in which participants had to select and subsequently identify a target stimulus presented to the left or right visual hemifield. Target selection and identification can be measured by two distinct event-related potentials, the N2pc and the SPCN. Using a decoder analysis based on multivariate pattern analysis, we were able to isolate the processing stages related to error sources and post-error adjustments. Whereas errors were linked to deviations in the N2pc and the SPCN, only for the N2pc we identified a post-error adjustment, which exhibits key features of source-specific adaptivity. While errors were associated with an increased N2pc, post-error adjustments consisted in an N2pc decrease. We interpret this as an adaptive adjustment of target selection to prevent errors due to disproportionate processing of the task-irrelevant target location. Our study thus provides evidence for adaptive post-error adjustments in visual search.

Introduction

Human behavior is fallible. Even in the simplest cognitive tasks, errors can occur due to attentional lapses (Weissman et al., 2006), speeding, or failures of cognitive control (Steinhauser et al., 2012). In recent years, errors like these have been investigated to elucidate how the human brain can detect and learn from these errors. Although this research has identified an error monitoring system in the medial frontal cortex that rapidly detects and evaluates errors (Ridderinkhof et al., 2004), the cognitive and behavioral consequences of error monitoring are still unclear (Danielmeier and Ullsperger, 2011). Some studies demonstrated that errors lead to adaptive adjustments that aim to prevent further errors (e.g., Dutilh et al., 2011; Maier et al., 2011), whereas others suggested that errors primarily elicit non-adaptive adjustments that impair performance even further (e.g., Notebaert et al., 2009; Van der Borght et al., 2014). In the present study, we applied a visual search task that allows for distinguishing between two stages of selective attention – target selection and target identification. By measuring event-related potentials (ERPs) associated with each stage, we aimed to identify the specific processes at which errors and post-error adjustments occur, and to describe whether and how adjustments are related to the source of the error.

Post-error adjustments are thought to be adaptive if they serve to improve performance by preventing further errors (Ridderinkhof et al., 2004). Generally speaking, *any* adjustment that prevents further errors can be considered adaptive, and there are indeed studies that find evidence for adaptive post-error adjustments that improve performance independently of the source of the error (e.g., by compensating error-induced detriments through a general increase of cautiousness; (Purcell and Kiani, 2016)). However, most studies on adaptivity report adjustments that specifically seek to counteract the source of the error (Dutilh et al., 2012; Jentzsch and Leuthold, 2006; King et al., 2010; Maier et al., 2011; Steinhauser and Kiesel, 2011; Danielmeier et al., 2011). Such *source-specific adaptation* requires that the type of adjustment is directly linked to the error source and attempts to counteract the deviations in cognitive processes that lead to the error in the first place.

A well-known example for source-specific adaptation is the variation in the response criterion. Errors in speeded choice tasks are often preceded by decreased response times (pre-error speeding) but followed by increased response times (post-error slowing, PES). Whereas pre-error speeding has been attributed to a low response criterion favoring speed over accuracy (Jentzsch and Leuthold, 2006; Brewer and Smith, 1989; Danielmeier et al., 2011), post-error slowing has been ascribed to a response criterion shift towards a more cautious response strategy in order to reduce this error source (Dutilh et al., 2012; Botvinick et al., 2001). Further examples are post-error adjustments of selective attention. Studies considering hemodynamic corre-

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lates of brain activity found that post-error trials were associated with decreased activity in brain regions linked to task-irrelevant stimulus features, if these regions had shown increased activity on the error trial and thus had formed a potential error source (King et al., 2010; Danielmeier et al., 2011). Moreover, it was shown that when different error types could occur within the same task, then post-error adjustments varied depending on the error type. Maier, Yeung, and Steinhauser (Maier et al., 2011) used a variant of the Eriksen flanker task (Eriksen and Eriksen, 1974) in which errors could occur because participants erroneously responded to the flanking distractors or because of speeding alone. Whereas both error types elicited post-error slowing, only erroneous responses to the distractor led to reduced distractor processing on the subsequent trial, which was interpreted as an adaptive adjustment to counteract the error source. Steinhauser and Kiesel (2011) distinguished between errors caused by the participant (internally-caused) and errors caused by presumed technical failures (externally-caused). Whereas internally-caused errors led to post-error slowing, externally-caused errors were followed by a decrease of selective attention presumably reflecting an adaptive disengagement from the task that served to save resources in the face of uncontrollable action outcomes.

Whereas these studies demonstrated source-specific adaptive post-error adjustments, other studies provided evidence for non-adaptive adjustments, that is, post-error adjustments that do not prevent further errors but even further impair performance. An alternative explanation for post-error performance decrements is the idea of a resource-consuming response monitoring process that interferes with subsequent processing (Jentzsch and Dudschig, 2009; Dudschig and Jentzsch, 2009). Furthermore, Notebaert and colleagues (Houtman and Notebaert, 2013; Notebaert et al., 2009) proposed that errors, like any infrequent event, elicit an orienting response. Both ideas could explain why errors are followed not only by post-error slowing but often also by a decrease of post-error accuracy. Specific evidence for an orienting response was provided by Notebaert et al. (2009) showing that post-error slowing turns into post-correct speeding when correct responses become less frequent than errors, and by Van der Borght et al. (2014), who report reduced attentional selectivity following errors in a flanker task.

Adaptive and non-adaptive adjustments have frequently been viewed as two alternative accounts. However, recent studies provided evidence that both types of adjustments can co-occur. Purcell and Kiani (2016) combined intracranial recordings in primates with model-based analysis of post-error slowing to show that errors are followed by a non-adaptive reduction of the sensitivity of stimulus processing and an adaptive increase of the response criterion. They argued that the adaptive criterion increase serves to compensate for the reduced sensitivity (in a source-*un*specific way). Steinhauser, Ernst, and Ibald (in press) analyzed behavioral data in a dual-task paradigm to demonstrate that the same error can elicit adaptive and non-adaptive adjustments. Whereas non-adaptive adjustments were task-unspecific and decayed within a second, adaptive adjustments spanned several trials and affected only the same task in which the error had occurred.

Our brief review of research on post-error adjustments shows that valid conclusions about the nature of post-error adjustments may in many cases require that the exact processes that cause errors are taken into account. This is even more important given that it can be impossible to distinguish non-adaptive from adaptive adjustments if both types manifest in a similar way, such as response slowing. In the present study, we investigated the relationship between error sources and post-error adjustments by combining a conflict task with a visual search paradigm. Visual search tasks typically require participants to indicate whether a target stimulus is present among a set of distractors, with target and distractors differing in one or more feature dimensions (e.g., color, shape). Selective attention in such a task follows a succession of distinct stages (Eimer, 2014a; Eimer, 2014b; Ghorashi et al., 2010). After information about task-relevant features is accumulated, visual attention is allocated towards the target (*target selection*). If the task requires to subsequently classify the target, a further stage is involved in which relevant target features are processed in working memory (*target identification*). Although there is behavioral and neural evidence for the distinctness of these stages, they do not necessarily proceed in a strictly serial manner and partial overlapping in time is likely (Eimer, 2014a; Wolfe, 2007). Such a two-stage visual search task has two crucial advantages for our purpose: First, errors as well as post-error adjustments can emerge on either of these stages. This allows us to investigate whether post-error adjustments occur on the same stage that caused the error, i.e., whether error source and adjustment are directly linked. Second, the stage at which errors and post-error adjustments occur can easily be identified using ERPs because each stage is associated with a characteristic ERP component that we describe in the following.

A neural correlate of target selection in visual search is the N2pc, a negativity emerging about 200 to 250 ms after stimulus onset on posterior electrodes contralateral to the hemifield at which the target is presented. Whereas it is generally believed that the N2pc represents the allocation of attention towards the target, it is up to debate whether it reflects the suppression of distractors (Luck and Hillyard, 1994) or the enhancement of the target (Mazza et al., 2009b). In visual search tasks that involve target classification, a later sustained posterior contralateral negativity (SPCN) is thought to represent the target identification stage (Eimer, 2014a; Mazza et al., 2007). Depending on the paradigm and the duration of the presented stimulus, it can be found in a time period of 300 ms to 800 ms post-stimulus. As this component is sensitive to working memory load (Jolicœur et al., 2008), it is argued that in fact the SPCN represents the storage of selective features of the target items (Woodman and Vogel, 2008).

By considering these components in a paradigm that has previously been used to investigate ERP correlates of visual search (Mazza et al., 2009b; Mazza et al., 2007), we aimed to identify the exact time course of the employment of post-error adjustments as well as their relationship to the error source. In the paradigm at hand, participants viewed displays with twenty items (one red target and 19 green distractors) each being a diamond with a missing corner on the left or right side, respectively (Fig. 1). The red target was presented in the left or right hemifield. The participants' task was to indicate whether the missing corner of the target was on the left or right side. Because participants first had to select the target and then analyze the target features, this task involves two stages of selective attention, target selection and target identification, which, on the neural level, are represented by the N2pc and the SPCN (Eimer, 2014a; Mazza et al., 2007). Another important feature of this paradigm is that the required response category (left/right) can be compatible or incompatible to the target location (left/right hemifield), thus leading to two conditions of stimulus-response compatibility (Simon and Rudell, 1967). As error sources and adjustments might differ across these conditions, we conducted all analyses separately for compatible and incompatible trials.

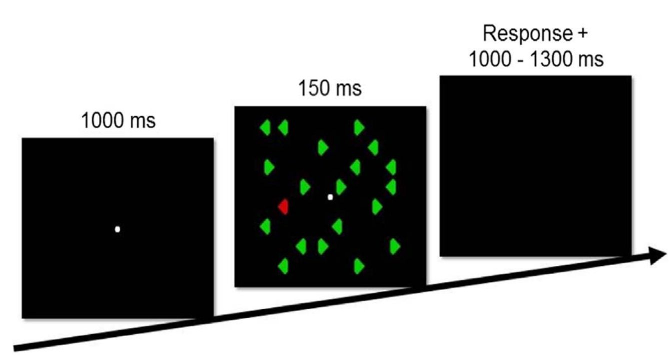

Fig. 1. Visual search paradigm that was used in the present study, adapted from Mazza et al. (2009b). The depicted trial is SR incompatible (target diamond on the *left* hemifield but clipped-off corner on the *right* side).