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Post-error slowing is influenced by cognitive control demand[☆]

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ABSTRACT

Post-error slowing (PES) has been shown to reflect a control failure due to automatic attentional capture by the error. Here we aimed to assess whether PES also involves an increase in cognitive control. Using a cued-task-switching paradigm (Experiment 1) and a Stroop task (Experiment 2), the demand for top down control was manipulated. In Experiment 1, one group received dimension cues indicating the relevant stimulus dimension (e.g., "number") without specifying the response-category-to-key mapping, hence requiring considerable top down control. Another group was shown mapping cues providing information regarding both the relevant task identity and its category-to-key mapping (e.g., "one three"), requiring less top down control, and the last group received both types of cues, intermixed. In Experiment 2, one group performed a pure incongruent Stroop condition (name ink color of incongruent color names, high control demand), and another group received a pure neutral Stroop condition (name color patches, low control demand). In Experiment 2a, participants received the two conditions, intermixed. A larger PES was observed with dimension cues as compared with mapping cues, and with incongruent Stroop stimuli as compared to neutral stimuli, but not when the conditions were intermixed. These findings reveal that PES is influenced by the control demands that characterize the given block-wide experimental context and show that proactive cognitive control is involved in PES.

1. Introduction

Interestingly, after committing an error, normal individuals tend to slow down their performance on the next trial. This phenomenon is called "post-error slowing" (PES; Laming, 1979; Rabbitt, 1966; Smith & Brewer, 1995; see Danielmeier & Ullsperger, 2011, for a review) and is in the focus of behavioral studies on error monitoring and processing.

PES was first described by Rabbitt (1966) as reflecting either disruption of regularity or precaution. To date, there is still an ongoing debate regarding the mechanism underlying this phenomenon. Some theories view transient control failure as the cause for both the occurrence of an error and the slowing observed afterward. For example, Cheyne, Carriere, Solman, and Smilek (2011) have recently suggested that transient failures of sustained attention impair task performance. The error, in turn, being a significant outcome causes an additional failure in sustained attention that is being reflected in subsequent response slowing. Another theory (Notebaert et al., 2009) that interprets PES as a result of an attentional lapse is the orienting account. This theory views PES as an outcome of an involuntary attentional shifting towards a rare event (error). Such attention reorientation results in slowing. In support, the authors showed PES in a typical condition with infrequent errors, but also showed response slowing that came after correct but infrequent trials. In a similar vein, rare erroneous responses and rare correct responses led to an increase in P3 amplitude (Núñez-Castellar, Kühn, Fias, & Notebaert, 2010), an event-related brain potential (ERP) component associated with involuntary attentional capture by novel events (P3a) and limited-capacity memory updating (P3b, see Polich, 2007, for a review). Moreover, in Núñez-Castellar et al.'s (2010) study, PES size was positively correlated with P3 amplitude, but not with two other ERP components: error-related negativity and feedback-related negativity, which arguably reflects error detection and evaluation of negative feedback regarding outcomes, respectively (Falkenstein, Hoormann, Christ, & Hohnsbein, 2000; Hajcak, Moser, Holroyd, & Simons, 2006). Although some studies did find a positive correlation between PES and the amplitude of error-related negativity (e.g.: Debener et al., 2005), this evidence has been inconsistent (see, Van Veen & Carter, 2006, for a review). In sum, Núñez-Castellar et al.'s neurophysiological findings support the idea that PES is not associated with error monitoring but rather with attentional processing of unexpected novel events. This conclusion was further supported by a functional MRI study demonstrating that both error and novelty processing were associated with brain activity in common cortical and subcortical regions (Wessel, Danielmeier, Morton, & Ullsperger, 2012).

The aforementioned theories seem to share the assumption concerning automatic/involuntary attention orientation as the main

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cause. Supportive findings for the notion that automatic processing underlies PES show that shortening the response-to-stimulus interval led to PES increase (Danielmeier & Ullsperger, 2011; Dudschig & Jentzsch, 2009). These results may be interpreted as showing that PES does not depend on capacity-limited adjustments that require sufficient time to take place, but is rather triggered automatically by the error and is thus shown to be larger with short intertrial intervals when the error signal is still strong and had not yet decayed. Nonetheless, these results are inconclusive since one could argue, for example, that the detection of the error occupies the central processing bottleneck (Pashler & Johnston, 1989). This in turn leads to a postponement in subsequent response selection that must wait for the bottleneck to be freed (e.g., Houtman & Notebaert, 2013; Jentzsch & Dudschig, 2009).

The fact that PES may be influenced by involuntary attention orientation does not rule out the possibility that, in addition, it also reflects controlled processing. Specifically, cognitive control can be conceptualized as involving both reactive and proactive components (according to Dual Mechanisms of Control framework, DMC; Braver, 2012; Braver, Gray, & Burgess, 2007). Reactive control operates in response to an imperative event (such as an error) immediately after its occurrence. In contrast, proactive control is engaged in advance, based on goal-relevant information maintained active over a period of time. It has recently been proposed that these modes can interact (Ridderinkhof, Forstmann, Wylie, Burle, & van den Wildenberg, 2010) such that anticipatory top-down control can proactively amplify reactive online control, contingent to performance difficulty, in order to prevent further errors. Accordingly, reactive control manages the recruitment of cognitive control which depends on error detection. On the other hand, proactive control mechanisms adjust control involvement in a proactive manner and may thus serve to amplify post-error control adjustments. Below we detail the putative involvement of both reactive and proactive control in the PES phenomenon.

An account that stresses the role of increased reactive control in post-error processing is the conflict monitoring theory (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Yeung, Botvinick, & Cohen, 2004). This theory holds that slower post-error performance reflects reactive implementation of cognitive control, elicited by the detection of conflict. Specifically, error trials entail response conflict between co-activated representations of the correct and erroneous responses. A system responsible for detecting conflicts in information processing then leads to a relatively more conservative and controlled behavior on subsequent trials.

There is also evidence suggesting that proactive control is also involved in PES. The evidence comes from studies showing that wide context-level manipulations of control involvement or demand influence PES size. For example, PES was shown to increase when accuracy was emphasized over speed and when punishment followed errors (Jentzsch & Leuthold, 2006; Riesel, Weinberg, Endrass, Kathmann, & Hajcak, 2012; Ullsperger & Szymanowski, 2004). Additionally, PES was abolished with time on task (Boksem, Meijman, & Lorist, 2006; Lorist, Boksem, & Ridderinkhof, 2005), following sleep deprivation (Murphy, Richard, Masaki, & Segalowitz, 2006) and when participants believed that their errors were caused by an external source and not by themselves (Steinhauser & Kiesel, 2011), conditions believed to compromise cognitive control. Moreover, incentive given after the fatigue induction led to PES reappearance (Boksem et al., 2006), presumably showing a recovery of control resources.

Individual difference studies also suggest that PES is influenced by cognitive control. Specifically, PES is large among individuals who are relatively more accurate (Steinborn, Flehmig, Bratzke, & Schröter, 2012), have higher academic achievements (Hirsh & Inzlicht, 2010), have higher cardiorespiratory fitness (Themanson & Hillman, 2006) and are more physically active (Themanson, Hillman, & Curtin, 2006). Nonetheless, these individual and group-difference studies are not completely conclusive since PES was not correlated with working memory capacity (Unsworth, Redick, Spillers, & Brewer, 2012) and was shown to be numerically larger among old adults than among young adults despite the known deterioration in executive functioning in aging (e.g., Band & Kok, 2000; Smith & Brewer, 1995).

Further support for the increased control position comes from studies showing greater reduction in compatibility-related interference (indicating better resolution of interference) on trials following errors compared to those following correct responses (De Bruijn, Miedl, & Bekkering, 2011; King, Korb, von Cramon, & Ullsperger, 2010). However, post-error reduction of interference was not found consistently across experiments (Bombeke, Schouppe, Duthoo, & Notebaert, 2013; Carp & Compton, 2009), and even if reliable, this effect was found to act independently from PES effect (e.g., Bombeke et al., 2013).

Most relevant in the present context are the few studies which *manipulated control demands*. One study (Hogan, Vargha-Khadem, Kirkham, & Baldeweg, 2005) reported larger PES and a corresponding decrease in self-corrected errors for incompatible stimuli during a four-choice response task, than for compatible stimuli in a two-choice response task. Another study manipulated cognitive demands in a flanker task by reversing stimulus–response mappings between blocks. This study found enhanced PES and reduced post-error accuracy in the more demanding switch blocks (Schroder, Moran, Infantolino, & Moser, 2013). This evidence further shows that PES increases with increased task complexity.

Unfortunately, many of the findings which presumably indicate controlled processing in PES are equally well explained by the involuntary attention account. According to the increased control position, more demanding conditions, incentives, higher ability, and conditions in which control is not compromised are associated with increased control in general, resulting in more robust behavioral adjustments following errors. According to the reduced control position, when the task is complex, it requires more control resources than when it is less complex. Errors, as unexpected events, grab the necessary resources needed to execute the required task, resulting in poorer performance. An analogous point can be made with respect to incentives, individual differences, and conditions involving compromised control such as mental fatigue.

To conclude, while there is strong support for the involvement of low-level attention-grabbing processes in PES, clear cut evidence that PES also reflects top-down controlled processing is still lacking.

Thus, the aim of the present experiments was to test the influence of control demands manipulated globally and locally on post-error processing. This was done by examining the influence of variables known to involve strategic top-down control. In Experiment 1, we used a cued task switching paradigm (see Kiesel et al., 2010; Meiran, 2010; Monsell, 2003; Vandierendonck, Liefooghe, & Verbruggen, 2010, for a review) in which participants are required to constantly switch between a number of simple tasks, with or without task-repetition. Experiment 2 employed the Stroop task (Stroop, 1935; see MacLeod, 1991, for a review).

The task switching paradigm was chosen based on theoretical and methodological considerations despite the fact that it is not commonly used in PES research (but see e.g., Gupta, Kar, & Srinivasan, 2009; Jentzsch & Leuthold, 2006; Nee, Kastner, & Brown, 2011; Themanson et al., 2006). Specifically, since we were interested in the involvement of control processes, we needed a paradigm in which the degree of control demand can be easily manipulated. Indeed, Notebaert and colleagues (Núñez-Castellar et al., 2010) had noted that errors made in a paradigm with stimuli affording only one response such as those used in their studies (oddball task in Notebaert et al., 2009; four-choice color-discrimination task in Núñez-Castellar et al., 2010), are qualitatively different from errors made in the tasks typically employed in PES studies in which the stimuli afford several (sometimes competing) responses, such as the Stroop task and the flanker task (Eriksen & Eriksen, 1974).

Our manipulation of cognitive control demand was based on Mayr and Kliegl (2000) who employed in one of their experiments a cued task switching paradigm in which the tasks changed randomly and