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The grasping side of post-error slowing

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A B S T R A C T

A common finding across many speeded reaction time (RT) tasks is that people tend to respond more slowly after making an error. This phenomenon, known as post-error slowing (PES), has been traditionally hypothesized to reflect a strategic increase in response caution, aimed at preventing the occurrence of new errors. However, this interpretation of PES has been challenged on multiple fronts. Firstly, recent investigations have suggested that errors may produce a decrement in performance accuracy and that PES might occur because error processing has a detrimental effect on subsequent information processing. Secondly, previous research has been criticized because of the limited ecological validity of speeded RT tasks. In the present study, we investigated error-reactivity in the context of goal-directed actions, in order to examine the extent to which PES effects impact on realistic and complex movements. Specifically, we investigated the effect of errors on the reach to grasp movement (Experiment 1). In addition to RTs, we performed a kinematical analysis in order to explore the underlying reorganization of the movements after an error. The results of the present study showed that error reactivity strategically influences the grasping component of the action, whereas the reaching component appears to be impermeable to PES. The resistance of the reaching component to PES was confirmed in a second 'only reaching' experiment (Experiment 2). These finding supports the hypothesis that error reactivity is a flexible process whose effects on behavior also depend on the motor components involved in the action.

1. Introduction

Error commission is associated with several physiological and behavioral changes. In first instance, heart rate deceleration (Danev & Winter, 1971), pupil dilation (Critchley, Tang, Glaser, Butterworth, & Dolan, 2005) and a larger skin conductance response (O'Connell et al., 2007) following an error have been observed. In second instance, behavioral studies have shown that after making an erroneous decision people tend to slow down on the next decision. This empirical regularity is known as post-error slowing (PES; Jentzsch & Leuthold, 2006) and it has been observed in a variety of tasks, including Stroop (Gehring & Fencsik, 2001), forced-choice and go/no-go (Jones, Cho, Nystrom, Cohen, & Braver, 2002), Simon (Fan, Flombaum, McCandliss, Thomas, & Posner, 2003), and categorization (Jentzsch & Dudschig, 2009) tasks.

To explain PES two theoretical accounts have been put forward, namely *functional* and *non-functional* (Houtman & Notebaert, 2013). Functional accounts, such as the conflict monitoring (Botvinick, Braver, Barch, Carter, & Cohen, 2001), the inhibition (Marco-Pallarés, Camara, Münte, & Rodríguez-Fornells, 2008; Ridderinkhof, 2002), and the reinforcement learning (Holroyd & Coles, 2002) theories propose that PES is the product of a compensatory control mechanism serving the purpose of improving subsequent performance. PES is thus interpreted as the result of a more cautious response strategy aimed at producing a *post-error improvement of accuracy* (PIA). However, PES might not necessarily be the expression of an adaptive mechanism. In this perspective, *non-functional accounts* explain PES in terms of reduced cognitive processing after errors (Notebaert et al., 2009). Notebaert et al. (2009) suggested that PES reflects an orienting response to an unexpected event. Since errors are usually rare, they represent unexpected, motivationally salient events that automatically capture attention and thus distract the participant from the task, producing both PES and a decrease in post-error accuracy. According to this theory, it is not the error *per se* that causes the slowing, but rather the attentional orientation toward that event.

Despite the majority of studies on error reactivity have found PES, empirical evidence concerning post-error accuracy is mixed, sometimes supporting the functional accounts (e.g., Neubert, Mars, Buch, Olivier, & Rushworth, 2010), sometimes supporting the non-functional accounts (e.g., Gehring & Fencsik, 2001). In their review, Danielmeier and Ullsperger (2011) point out that there is evidence for both functional

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and non-functional accounts of error reactivity and that these accounts are not necessarily mutually exclusive. Indeed, the functional and non-functional aspects of error reactivity may follow different time courses. Recent investigations indicate that PES tends to decay over time (Danielmeier & Ullsperger, 2011; Jentzsch & Dudschig, 2009). In particular, short inter-trial intervals (ITIs) (< 500 ms) are usually associated with a larger PES and a post-error decrease in accuracy. Instead, long ITIs (> 1000 ms) tend to elicit a post error increase in accuracy and a decrease of PES. A possible explanation for these findings is that at short ITIs, the non-functional aspects of error reactivity are predominant, and thus, attentional reorientation may be the main responsible for PES. Instead, at longer ITIs, strategic influences become more effective since more time is available to adjust behavior after error detection, and PES may be mainly determined by strategic change in speed-accuracy tradeoff (Dutilh et al., 2012b; White, Ratcliff, Vasey, & McKoon, 2010). In support of this suggestion, Dutilh et al. (2012b), using drift diffusion model analysis, found that with ITIs longer than 1000 ms, PES can be attributed almost entirely to a strategic increase in response caution.

Generally, with just a few exceptions (see Anguera, Seidler, & Gehring, 2009; Krigolson & Holroyd, 2006; Vocat, Pourtois, & Vuilleumier, 2011), error reactivity has been investigated by means of speeded reaction time (RT) tasks and most studies have measured only arbitrary button-press responses (Gehring, Liu, Orr, & Carp, 2011). However, as pointed out by Gehring et al. (2011), most daily life movements have a slower time course than speeded RT response, and more realistic and ecologically valid tasks may afford a better opportunity to investigate error-reactivity. Moreover, since the functional meaning of PES is yet unclear, it might be useful to explore error-reactivity by using richer measures than RT, which limit the investigation to pre-movement processes. For instance, the consequences of self-generated errors on the kinematics of goal directed actions has yet to be investigated. Here, we fill this gap by testing PES theories looking at the kinematics underlying the organization of the reach-to-grasp movement, one of the most common goal-directed actions performed in daily life.

Reach-to-grasp behavior has been described as the act of coordinated reaching and grasping (Castiello, 2005; Grafton, 2010; Jeannerod, 1981). The reaching component concerns the transport of the hand toward the target, whereas the grasping component consists in a progressive opening of the hand, followed by a gradual closure of the grip until it matches the object's size. This characterization of prehension dates back to Jeannerod's seminal studies, in which he proposed the *visuomotor channel hypothesis* (Jeannerod, 1981). This hypothesis suggests that the visuomotor mechanisms involved in reaching and grasping are independent, even if temporally coupled. More recently, the visuomotor channel hypothesis has been challenged by a number of studies, showing that the control mechanisms underlying reaching and grasping can be affected by the same spatial and intrinsic properties of the target (e.g., Gentilucci et al., 1991; Jakobson & Goodale, 1991).

Reach-to-grasp behavior is not only constrained by spatial and intrinsic properties of the stimulus (*direct effects*), but also by preceding motor events (*sequential effects*), a phenomenon termed *hysteresis* (Kelso, Buchanan, & Murata, 1994). Hysteresis has been supported by several studies showing its effects on a variety of reaching and grasping parameters. For example, Jax and Rosenbaum (2007) demonstrated that participants, after avoiding an obstacle in order to reach for a target, tended to use a similar trajectory in the following trial, even when the obstacle was no longer present (*hand path priming*). Dixon and Glover (2009) found a potent tendency to perseverate in grip aperture during the latter portion of a movement to grasp a disc. Similarly, Kent, Wilson, Plumb, Williams and Mon-Williams (2009) found that reach-to-grasp movements are susceptible to movement history effects, both in adults and in children. Recent studies have suggested that the hysteresis effect arises due to priming of action plan elements in the motor system (Dixon, McAnsh, & Read, 2012; Glover & Dixon, 2013).

A point worth noting is that until now research on hysteresis has focused the investigation on sequential effects arising from sequences of correct movements. In daily life, however, carrying out a task does not always run smoothly and people can fail to perform a reach-to-grasp movement, which begs the question - how and to what extent the failure to grasp an object influences the following movement?

With this in mind, the overarching aim of the present study is to investigate the consequences of self-generated errors in the context of goal directed actions. To do this we investigate error reactivity effects on both the preparation and the execution of reach-to-grasp movements. Movement preparation includes the relevant sensory and perceptual processes preceding movement initiation (Haith, Pakpoor, & Krakauer, 2016). Traditionally, it is assessed through measurement of RT (Wong, Haith, & Krakauer, 2015). Instead, movement execution is customarily assessed via kinematical analysis and allows investigating the added benefit of monitoring and occasionally adjusting motor programs in flight (Erlhagen & Schöner, 2002). A further aim of the present study is to verify whether error-reactivity has a different impact on the grasping and reaching components or whether it produces an unspecific slowing of the whole movement execution.

2. Experiment 1

In Experiment 1, participants were asked to reach out and grasp a steel ball, without knocking the wooden support over. In order to correctly accomplish this task, participants had to carefully transport the hand near the target and accurately close the fingers upon the steel ball.

In addition to RTs, we also examined the kinematics of the reach-to-grasp movement in terms of both temporal and amplitude measures. And, in order to emphasize the strategic planning that may occur in natural settings after an error, which may differ from the responses elicited by the speeded RT tasks, we used relatively long inter-trial intervals (ITIs).

We hypothesize that if error reactivity processes extend to movement execution, we should find evidence of post-error adjustments also at kinematical level. Functional and non-functional accounts offer the opportunity to put forward different predictions with respect to post-error accuracy as investigated here. If errors lead to a more cautious movement execution, then we should find a post-error improvement of accuracy. Conversely, if error processing has a detrimental effect on subsequent information processing, then we expect a decrease in post-error accuracy.

2.1. Methods and materials

2.1.1. Participants

As there were no previous studies investigating error reactivity in the context of goal directed actions upon which to refer for an a priori power analysis, we selected a target sample size of 15 subjects (8 females, 7 males) with a mean age 26 (SD = 3.5 yrs), which would give 82.1% power to detect a large effect (f = 0.4) at an α level of $p = .05$ (GPOWER 3.1; Erdfelder, Faul, & Buchner, 1996). All participants were right-handed, had normal or corrected-to-normal vision and were naive as to the purpose of the experiment. All subjects gave informed consent to participate in the study. The experimental procedure was approved by the Institutional Review Board at the University of Padua and was in accordance with the declaration of Helsinki. The participation was voluntary.

2.1.2. Apparatus

The experimental setup is represented in Fig. 1A. Participants were tested individually in a well-lit room, and were seated on a height adjustable chair so that the thorax pressed gently against the front edge of the table (90×90 cm) and the feet were supported. Head movements were restricted by the use of a head-chin-rest in order to maintain a constant viewing distance from the target. The target object consisted of