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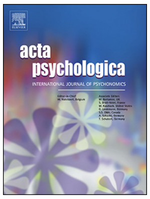

Response time distribution parameters show posterror behavioral adjustment in mental arithmetic[☆]

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ABSTRACT

After making an error, we usually slow down before our next response. This phenomenon is known as the posterror slowing (PES) effect. It has been interpreted to be an indicator of posterror behavioral adjustments and, therefore, has been linked to cognitive control. However, contradictory findings regarding PES and posterror accuracy cast doubt on such a relation. To determine whether behavior is adjusted after making an error, we investigated other features of behavior, such as the distribution of response times (RT) in a mental arithmetic task . Participants performed an arithmetic task with (Experiments 1 and 2) and without (Experiment 1) an accuracy-tracking procedure. On both tasks, participants responded more slowly and less accurately after errors. However, the RT distribution was more symmetrical on posterror trials compared to postcorrect trials, suggesting that a change in processing mode occurred after making an error, thus linking cognitive control to error monitoring, even in cases when accuracy decreased after errors. These findings expand our understanding on how posterror behavior is adjusted in mental arithmetic, and we propose that the measures of the RT distribution can be further used in other domains of error-monitoring research.

1. Introduction

An important feature of the human cognitive system is its ability to flexibly adjust behavior in the context of goal-directed actions and environmental demands. This ability is usually termed executive or cognitive control (Carter & Krug, 2011; Petersen & Posner, 2012). A context in which this capability is evident and one that serves as a useful platform for studying cognitive control is *error detection* (Botvinick, Braver, Barch, Carter, & Cohen, 2001). One of the best known behavioral findings following the commission of an error is the posterror slowing (PES) effect (Laming, 1979; Rabbitt, 1966). The PES effect is commonly measured by subtracting the response times (RT) of postcorrect trials from the RT of posterror trials.

Although PES is commonly used as a direct measure of control (e.g., Hajcak, McDonald, & Simons, 2003; Rigoni, Wilquin, Brass, & Burle, 2013), the relation between cognitive control and posterror behavioral adjustment is far from being fully understood. Most investigators interpret the magnitude of slowing (in RT) that follows an incorrect response to be a positive indicator of control, meaning that more PES represents increased cognitive control (Kerns et al., 2005). This positive relation is supported by studies that show a diminished PES effect in clinical populations compared to control populations (Bogte, Flamma, van der Meere, & van Engeland, 2007; Kerns et al., 2005; Schachar et al., 2004; Shiels & Hawk Jr., 2010). However, there is also some support for interpreting PES to be a negative indicator of control, for example, the increased PES seen in young children (Fairweather, 1978; Gupta, Kar, & Srinivasan, 2009) and the elderly (Band & Kok, 2000; Falkenstein, Hoormann, Christ, & Hohnsbein, 2000; P. Rabbitt, 1979; Smith & Brewer, 1995).[1]

The contradictory pattern of results regarding PES is even more prominent when looking at posterror accuracy. Some studies show that participants respond more slowly but more accurately after making an error (Chiu & Deldin, 2007; Desmet et al., 2012; Fischer, Danielmeier, Villringer, Klein, & Ullsperger, 2016; Saunders & Jentzsch, 2012) and that a positive correlation exists between PES and the increase in accuracy after errors (Fischer et al., 2016). This pattern of results supports the cognitive control account for PES, which means that after an error is made, readjustment of cognitive control takes place (Botvinick et al.,

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[1] Although the mentioned studies did not test this directly, the increase in PES might have been caused by a general slowing, which caused PES to increase.

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2001; Jentzsch & Dudschig, 2009; Ridderinkhof, van den Wildenberg, Wijnen, & Burle, 2004). In contrast, there are a considerable number of studies that challenge this view by showing that performance is *less* accurate after the commission of an error (Castellar, Kühn, Fias, & Notebaert, 2010; Danielmeier & Ullsperger, 2011; Hajcak et al., 2003; Notebaert et al., 2009) and that no correlation exists between PES and accuracy change after errors (Carp & Compton, 2009; Danielmeier & Ullsperger, 2011). As an explanation for this pattern of results, the orienting account for PES (Notebaert et al., 2009) proposes that PES is not related to a control mechanism, but rather to a shift in attention created by an unusual event (i.e., the error).

However, accuracy is not the only standard by which behavioral adjustment can be measured. For example, Dutilh, Vandekerckhove, and colleagues (2012) have used the drift diffusion model decomposition to test the different explanations for the PES. Their results showed a clear representation for the inconsistency regarding posterror accuracy; for example, within the experiment, accuracy increased after errors on some of the experimental conditions and decreased or was unchanged on others. Yet, by implementing a more advanced analysis on RT and accuracy, the authors were able to show that – almost exclusively – the increase in response caution accounted for PES. The authors concluded that their results confirm the traditional explanation for PES. A recent implementation of the drift diffusion model to posterror behavior of humans and monkeys (Purcell & Kiani, 2016) supports the usefulness of the RT decomposition, but it also reveals a more complex picture. Namely, a combination of stimulus-independent increased caution, a stimulus-dependent decrease in perceptual sensitivity, and a task-specific increase in selective attention (Ullsperger & Danielmeier, 2016).

Another useful way to tap into cognitive processes beyond the standard RT measures can be achieved by an analysis of RT distribution. The ex-Gaussian distribution analysis is performed by fitting a theoretical distribution to the empirical RT data. The theoretical ex-Gaussian distribution is believed to provide a good fit to empirical RT by assuming that the RT is the sum of a normally distributed variable and an exponentially distributed variable (Balota & Yap, 2011; Ratcliff, 1979). The resulting theoretical distribution is a convolution of the Gaussian and the exponential distribution. The parameters of the fitted function can be analyzed to reveal how experimental conditions affect the specific feature of the RT distribution. Specifically, the three parameters of the ex-Gaussian are those of the two component distributions: μ and σ represent the mean and the standard deviation of the Gaussian component, respectively, whereas the τ parameter represents the mean and standard deviation of the exponential component. Therefore, the mean of the ex-Gaussian equals $\mu + \tau$, and its variance equals $\sigma^2 + \tau^2$ (Ratcliff, 1979).

It has been suggested that the perceptual and motor processes are reflected in the Gaussian component, whereas the reaction times from the decision component are reflected in the exponential component (Hohle, 1965). Converging evidence supports this initial assumption in a broader view of relating the higher order processes to the exponential parameter and lower order processes to the Gaussian parameters (Balota & Spieler, 1999; Gordon & Carson, 1990; Kieffaber et al., 2006; Madden et al., 1999; Moutsopoulou & Waszak, 2012; Possamaï, 1991; Rotello & Zeng, 2008; Schmiedek, Oberauer, Wilhelm, Süß, & Wittmann, 2007; Spieler, Balota, & Faust, 1996; Steinhauser & Hübner, 2009; however, see Matzke & Wagenmakers, 2009 for opposing view). In regard to PES explanations, effects that are limited to the Gaussian component would fit the orienting account for PES, whereas differences in the exponential component would fit the cognitive control account for PES.

2. Experiment 1

To test the hypothesized mapping mentioned above, in Experiment 1, we reanalyzed an existing dataset that included two different tasks in terms of the degree of control that the participant has and in which the effects of error processing on ex-Gaussian measures could be tested.

Accordingly, Experiment 1 addressed two questions. The main question was whether the use of different variance indices, such as distribution parameters, can capture and reflect posterror behavioral adjustment. Assuming that behavior is adjusted after the commission of an error, we expected that the exponential component of the ex-Gaussian distribution would be different on posterror and postcorrect trials. The second question was related to the generalizability of such measures across task contexts. Specifically, we tested whether the degree of control that the task conditions elicit have an impact on the posterror behavioral adjustment.

2.1. Method

2.1.1. Participants

Forty-eight students (38 females, average age of 23 years; standard deviation of 1.1 years) from Ben-Gurion University of the Negev participated in the experiment in return for course credit. Half of the participants participated in the tracking task and the other half in the nontracking task.

2.1.2. Material

A 17″ LCD computer monitor was used to present visual stimuli. Participants were seated about 60 cm from the screen. Responses were recorded with a standard keyboard that was placed on a desk in front of the participant; all participants responded with the middle and index finger of each hand. The experiment was programmed with *E*-prime 2.0 software (Schneider, Eschman, & Zuccolotto, 2002).

2.1.3. Stimuli

Visual stimuli were white characters presented on a black background. For each trial, we presented the participants with a division problem (e.g., $\frac{4}{2}$) that varied in the range of numbers based on the difficulty of the trial (see Procedure). The possible answers for the presented problems were: 2, 3, 4, or 5. We used two odd and two even answer types to keep the ratio between odd and even stimuli as balanced as possible.

2.1.4. Design

It is difficult to obtain numerous posterror trials because, in most cognitive tasks, the number of errors made by participants is usually low. Nevertheless, there are few methods in which the number of errors in the task can be controlled. One way is to incorporate an accuracy-tracking paradigm. Here, we adapted the accuracy-tracking paradigm used by Notebaert et al. (2009). The original task used by Notebaert et al. (2009) was a four-choice color-discrimination task that was considered easy. Because we wanted to prevent a possible floor effect, the task was modified to a similar four-choice decision task, but the decision had to be made based on an arithmetic calculation (e.g., Desmet et al., 2012).

One of the advantages of the tracking procedure in error monitoring research is that it provides an efficient way to control for accuracy. However, there is also a cost: This procedure introduces a unique setting in which behavioral adjustments following an incorrect response might be less required. Quite simply, the tracking procedure makes the necessary changes to task difficulty to maintain accuracy at a certain level (i.e., after an error is made, the task gets easier), and any additional adaptation from the participant seems to be redundant. However, some posterror control processes are executed even when they are not required (Lavro & Berger, 2015). To show that the effects tested are not limited to errors committed in the tracking procedure, we ran a nontracking design in addition to the tracking procedure.

To test whether the effects tested on posterror trials compared to postcorrect trials were limited to the accuracy-tracking task, we asked a second group of participants to perform the task without the accuracy-