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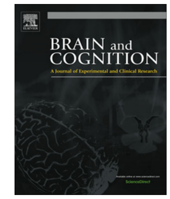

What happens when children encounter an error?

Silvan F.A. Smulders [a,*], Eric Soetens [b], Maurits W. van der Molen [a]

[a] Department of Psychology, University of Amsterdam, Amsterdam 1018 XA, The Netherlands
[b] Department of Psychology and Educational Sciences, Vrije Universiteit Brussels, Brussels B-1050, Belgium

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ABSTRACT

The current study presents the results of two experiments designed to assess developmental change in post-error slowing (PES) across an age range extending from 5 to 25 years. Both experiments employed two-choice tasks and manipulated response-to-stimulus intervals (RSIs). The results showed that PES decreased with advancing age; a disproportional developmental trend was observed in experiment 2 while the age-related change in PES in experiment 1 was similar to the developmental decrease in basic response speed. In both experiments, age and RSI effects on PES did not interact. This pattern of results was interpreted to suggest that PES at long RSIs is due to increased caution and at short RSIs to a combination of increased caution and the time it takes to orient toward the error. The developmental change in PES at longer RSIs was interpreted to suggest that as children grow older they are becoming more effective in setting appropriate response thresholds.

1. Introduction

The ability to adjust performance to a dynamically changing environment is a hallmark of intelligent behavior. A key aspect of this ability refers to error detection and remedial action to prevent further errors. Typically, responses following an error are slower and usually more accurate. This pattern has been observed in humans (Laming, 1979; Rabbitt & Rodgers, 1977), monkeys (Jedema et al., 2011) and rodents (Narayanan, Cavanagh, Frank, & Laubach, 2013). Post-error slowing (PES) attracted various interpretations but the notion of 'increased response caution' is probably most prominent (Dutilh et al., 2012). This interpretation is readily integrated with various models of cognitive control (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001).

The seminal work on error processing (e.g., Laming, 1968; Rabbitt, 1966, 1968; Rabbitt & Vyas, 1970; Welford, 1980) suggested that errors are not random events but, typically, represent attempts to assess optimal performance limits in response to the instruction to perform as quickly and accurately as possible. Participants do not know how fast they can respond until they commit an error and then they have to slow down in order to prevent further errors. The tracking of performance may result in trial-by-trial speeding toward an error and a post-error response that is typically slower than the average correct response. Rabbitt and Rodgers (1977) considered several interpretations of PES. One is that response monitoring, i.e., the evaluation of whether the response matched the intended one, takes longer following an error and may interfere with processing on the post-error trial. A related interpretation suggested that participants, knowing that they committed an error, try to correct it by making the intended response. Accordingly, PES would be due to interference between error correction and responding to the signal on the post-error trial. A third interpretation assumed that participants are distracted following an error, which negatively affects their speed of responding on the post-error trial. It should be noted, however, that these interpretations related to data obtained using very short response-to-stimulus intervals (RSIs). Hence, Laming (1979) indicated that these interpretations may not apply for RSIs longer than half a second or so. For longer RSIs a fourth interpretation would be more appropriate. That is, PES under those conditions is due to a re-adjustment of response boundaries, i.e., the criteria that must be satisfied before a response is executed. Laming (1979) demonstrated that his data were consistent with the response caution interpretation and this has been confirmed by a recent application of diffusion modeling to PES data derived from a lexical decision task (Dutilh et al., 2012).

The primary aim of the current study is to examine developmental change in PES. To attain this goal, we will briefly review developmental or child studies of error processing with an eye on age-related change in PES. At this point, it should be noted that most studies examining error processing in children focus on its

* Corresponding author at: The Hague University of Applied Sciences, The Netherlands.

E-mail addresses: silvan.f.a.smulders@gmail.com, S.F.A.Smulders@hhs.nl (S.F.A. Smulders).

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neural concomitants. The developmental or child studies relevant to PES build upon a large body of research employing electrocortical indices of error processing (Overbeek, Nieuwenhuis, & Ridderinkhof, 2005). The adult electrocortical studies revealed that error detection is associated with a negative brain potential, coined 'error negativity', Ne (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1995) or ERN (Gehring, Goss, Coles, Meyer, & Donchin, 1993), followed by a positive brain potential, 'error positivity' (Pe), that has been associated with error awareness (Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001). Brain imaging revealed that the ERN is generated within the posterior medial prefrontal cortex (e.g., Ridderinkhof, van den Wildenberg, Segalowitz, & Carter, 2004). Collectively, these findings have been interpreted to suggest that the ERN and Pe are manifestations of an error detection system that is linked to lateral regions of prefrontal cortex implicated in the implementation of strategic performance adjustments, which may result in trading off speed for accuracy in order to prevent future errors (see review in Ullsperger, Danielmeier, & Jocham, 2014).

The cognitive neuroscience studies of performance monitoring and adjustment provide the context for a rapidly growing literature on developmental change in ERN and PES (for reviews Ferdinand & Kray, 2014; Tamnes, Walhovd, Torstveit, Sells, & Fjell, 2013). The ERN research, included in Table 1, revealed a developmental increase in ERN during childhood into adolescence while PES showed little change with advancing age. It should be noted, however, that the majority of these studies focused on individual differences rather than developmental change. The developmental increase in the ERN has been interpreted to reflect the maturation of brain mechanisms implicated in error-monitoring (i.e., the dorsal medial prefrontal cortex). The observation that PES was relatively age invariant suggested the idea that, initially, the mechanisms involved in error monitoring and performance adjustments are disconnected to become intertwined only later in development (cf. Lyons & Zelazo, 2011).

A handful of performance studies, included in Table 1, are most relevant for the current purpose and, thus, will be reviewed here in somewhat greater detail. Fairweather (1978) was first in examining developmental change in PES. In contrast to the bulk of developmental ERN studies, typically employing conflict tasks, his participants performed on a series of standard choice reaction tasks. For the two-choice task, he observed a substantial decrease in PES with advancing age, from about 600 ms in 5-year olds to around 225 ms in 12-year olds. His findings led Fairweather (1978) to conclude that the basic mechanisms involved in error-monitoring and performance adjustment are in place in young children. He interpreted the developmental decrease in PES to suggest that with advancing age the implementation of remedial action becomes more efficient.

The most detailed study of developmental change in PES was done by Brewer and Smith (1989). These authors examined error detection and performance monitoring in separate experiments using four-choice reaction tasks. In the first experiment, participants were asked to signal their errors by depressing a detection button when they felt they committed one. Error detection rate was seen to increase rapidly from 38.5% in five-year olds to 91.1% in 11-year olds while error rates were similar across age groups. These findings indicate that children do detect their errors although the youngest children are grossly inaccurate in doing so. The results of the second experiment showed response speeding toward errors and PES in the adult participants. This pattern was present also in young children, albeit less clear. The data seem to indicate that the performance tracking mechanism is present already from a very young age. But Brewer and Smith (1989) noted also important differences between age groups. Young children continued fast responding following an error more frequently relative to older age groups. Furthermore, sequences of correct RTs were not close to average but much slower. Finally, young children made multiple errors in succession more frequently than other age groups. Collectively, these data suggest inaccurate error detection and inefficient performance adjustments in young children.

Three other developmental studies examining PES used conflict rather than standard choice RT tasks. Jones, Rothbart, and Posner (2003) reported a developmental increase in PES examining 3- to 4-years olds performing on a go-nogo task. They interpreted this trend to suggest a developmental increase in cognitive control. It should be noted, however, that this conclusion is based on a limited number of trials (20 go vs. 20 nogo trials) and exceptionally high error rates (78%). Moreover, the age range under investigation was restricted to only one year. Schachar et al. (2004) examined PES across a more extended age range, 7–16 years, using a stop-signal task. They obtained a positive correlation between advancing age and response slowing following a failed inhibit. In contrast, van de Laar, van den Wildenberg, van Boxtel, and van der Molen (2011), using a similar stop-signal task, observed that response slowing following failed inhibits was age-invariant. Finally, Gupta, Kar, and Srinivasan (2009) employed a task-switching paradigm including error feedback. They observed that PES decreased across an age range between 6 and 11 years and interpreted this pattern in terms of orienting toward the error signal (see Rabbitt & Rodgers, 1977). The remaining performance studies of PES in children did not have a developmental focus. Two studies showed that PES was present in children aged between 8 and 11 years (O'Connell et al., 2004; Ornstein et al., 2009) but one study failed to observe PES in children aged between 7 and 16 years (Yordanova et al., 2011). All in all, the performance studies investigating PES in children yielded a heterogeneous pattern of results.

The current, admittedly cursory, review of studies examining PES in children indicates that, given the paucity of developmental data, little definitive can be said about age-related change in PES. Both developmental decrease and invariance have been observed and a few studies reported even an increase in PES. The latter observation, an age-related increase in PES, would be compatible with developmental neuroscience studies examining error monitoring. These studies revealed a developmental increase in the ERN, an electrocortical manifestation of error detection or response conflict (for reviews Crone, 2014; Ferdinand & Kray, 2014; Tamnes et al., 2013). The developmental increase in ERN amplitude has been associated with the functional maturation of anterior cingulate cortex (ACC), a region of the medial frontal cortex that has been suggested to serve as an anatomical hub where performance-monitoring information is integrated to inform the highly interconnected networks subserving subsequent action selection (e.g., Luna, Marek, Larsen, Tervo-Clemmens, & Chahal, 2015). Within this framework, one would be led to predict a developmental increase in PES. On the hypothesis that the brain mechanisms implicated in error monitoring are not yet fully developed in young children most of their errors should go unnoticed and, thus, they lack the information needed for performance adjustments. Consequently, the speed of responding following an (unnoticed) error should not differ from the speed of responding following a correct response.

In view of the heterogeneous pattern of age-related change in PES, the primary goal of the present study was to perform a systematic assessment of developmental change in PES from childhood into adulthood. A standard two-choice RT task was used to generate PES patterns. We employed a standard choice RT task rather than a conflict task that is most prominent in the developmental literature on error processing. This was done for, primarily, two reasons. First, standard choice tasks generated stable PES patterns in adults (e.g., Laming, 1979). Secondly, the heterogeneous pattern that emerged