


Mind Your Errors: Evidence for a Neural Mechanism Linking Growth Mind-Set to Adaptive Posterror Adjustments

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Abstract

How well people bounce back from mistakes depends on their beliefs about learning and intelligence. For individuals with a growth mind-set, who believe intelligence develops through effort, mistakes are seen as opportunities to learn and improve. For individuals with a fixed mind-set, who believe intelligence is a stable characteristic, mistakes indicate lack of ability. We examined performance-monitoring event-related potentials (ERPs) to probe the neural mechanisms underlying these different reactions to mistakes. Findings revealed that a growth mind-set was associated with enhancement of the error positivity component (Pe), which reflects awareness of and allocation of attention to mistakes. More growth-minded individuals also showed superior accuracy after mistakes compared with individuals endorsing a more fixed mind-set. It is critical to note that Pe amplitude mediated the relationship between mind-set and posterror accuracy. These results suggest that neural mechanisms indexing on-line awareness of and attention to mistakes are intimately involved in growth-minded individuals' ability to rebound from mistakes.

Keywords

individual differences, electrophysiology, cognitive processes

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Whether you think you can or think you can't—you are right. (popularly attributed to Henry Ford)

Decades of research by Dweck and her colleagues indicate that academic and occupational success depend not only on cognitive ability, but also on beliefs about learning and intelligence (e.g., Dweck, 2006). Dweck's model of implicit theories of intelligence (TOIs) distinguishes people who believe intelligence is unchangeable (i.e., those who have a *fixed mind-set*) from people who believe intelligence is malleable and can be developed through learning (i.e., those who have a *growth mind-set*). It is critical to note that these mind-sets are associated with different reactions to failure. Fixed-minded individuals view failure as evidence of their own immutable lack of ability and disengage from tasks when they err; growth-minded individuals view failure as potentially instructive feedback and are more likely to learn from their mistakes (Dweck, 1999; Utman, 1997).

Despite years of work examining the self-report and behavioral correlates of these different mind-sets, little is known about the neural mechanisms that underlie them—only one study has examined the neural underpinnings of mind-set. In

that study, Mangels, Butterfield, Lamb, Good, and Dweck (2006) measured event-related potentials (ERPs)—electrical brain signals elicited by external or internal events—in college students endorsing a fixed or growth mind-set while they performed a difficult general knowledge test. They found that compared with fixed-minded individuals, growth-minded individuals allocated more attentional resources to corrective information following error feedback and were more likely to correct their mistakes on a surprise retest.

Although Mangels et al. (2006) found differences between individuals with fixed versus growth mind-sets in neural and behavioral responses to corrective information, they demonstrated these effects on a task in which performance accuracy was ambiguous. Participants became aware of their mistakes only when they were signaled by external feedback. This task was also quite difficult (success rates were kept at ~40%), which may have exaggerated differences between the groups

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because of the preponderance of failure. Moreover, the difficulty level of their task is not representative of the sorts of tasks typically encountered in daily life. Thus, their findings do not speak to how mind-set affects on-line and immediate reactions to internally generated errors in simpler, more ecologically valid tasks.

In the study reported here, we aimed to extend the findings of Mangels et al. (2006) by examining *response-locked* ERPs that tap into internal performance-monitoring processes elicited by response execution in a speeded reaction time (RT) task. Specifically, we examined the error-related negativity (ERN) and the error positivity (Pe), two widely studied ERPs elicited during error processing that relate to adaptive behavioral adjustments following mistakes. We therefore directly assessed the relationship between mind-set and the monitoring of one's own performance and immediate self-initiated reactions to mistakes.

The ERN is a fronto-centrally maximal negative ERP elicited approximately 50 ms after an erroneous response (Gehring, Goss, Coles, Meyer, & Donchin, 1993). Evidence from source-localization studies indicates that the anterior cingulate cortex (ACC), a brain region involved in monitoring behavior and signaling the need for increased cognitive control, is the most likely generator of the ERN (Carter et al., 1998; Dehaene, Posner, & Tucker, 1994). The Pe is a centro-parietally maximal positive ERP occurring between 100 and 600 ms after an erroneous response (Ridderinkhof, Ramautar, & Wijnen, 2009). Research suggests that the Pe also originates in the ACC (van Veen & Carter, 2002). Current conceptualizations suggest that the ERN and the Pe are dissociable neural signals involved in error processing, with the former reflecting conflict between the correct and the erroneous response and the latter reflecting awareness of and attention allocation to errors (Hughes & Yeung, 2011; Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001; Steinhauser & Yeung, 2010). Consistent with the role of these ERPs in on-line error monitoring, larger ERN and Pe amplitudes are associated with adaptive behavioral adjustments, such as slower and more accurate responses following mistakes (Compton et al., 2008; Frank, D'Lauro, & Curran, 2007; Hajcak, McDonald, & Simons, 2003; Themanson, Pontifex, Hillman, & McAuley, 2011).

In the study reported here, we explored relationships between mind-set, the ERN and Pe, and behavioral adjustments following mistakes—posterror slowing and accuracy—in a simple two-choice RT task. Given the links between the growth mind-set and adaptive reactions to mistakes, we predicted that a growth mind-set would be associated with larger ERN and Pe amplitudes and greater posterror adjustments than a fixed mind-set would. We further examined whether these on-line measures of performance monitoring mediated the relationship between mind-set and posterror behavioral adjustments.

Method

Twenty-five native-English-speaking undergraduates (20 female, 5 male; mean age = 20.25 years) participated for course

credit. A letter version of the Eriksen flanker task (Eriksen & Eriksen, 1974) was administered. Participants were instructed to click a mouse button to correctly identify the center letter (target) of a five-letter string in which the target was either congruent (e.g., "MMMMM") or incongruent (e.g., "NNMNN") with the flanker letters. Flanking letters were presented 35 ms prior to target-letter onset, and all five letters remained on the screen for a subsequent 100 ms (total trial time was 135 ms). A fixation cross was presented during the intertrial interval, which varied between 1,200 and 1,700 ms.

The experimental session consisted of 480 trials grouped into six blocks of 80 trials each, during which accuracy and speed were equally emphasized. To elicit a sufficient number of errors for ERP analysis, we differed the letters making up the strings by block (e.g., "M" and "N" in Block 1 and "E" and "F" in Block 2), and mouse button-letter assignments were reversed at the midpoint of each block (e.g., left mouse-button click for "M" through 40 trials of Block 1, then right mouse-button click for "M" for the last 40 trials of Block 1).

Following the flanker task, participants completed a TOI scale that asked respondents to rate the extent to which they agreed with four fixed-mind-set statements on a 6-point Likert-type scale (1 = *strongly disagree*, 6 = *strongly agree*). These statements (e.g., "You have a certain amount of intelligence and you really cannot do much to change it") were drawn from previous studies measuring TOI (e.g., Hong, Chiu, Dweck, Lin, & Wan, 1999). TOI items were reverse-scored so that higher scores indicated more endorsement of a growth mind-set, and lower scores indicated more of a fixed mind-set.

Continuous electroencephalographic activity was recorded using the ActiveTwo system (BioSemi, Amsterdam, The Netherlands). Recordings were taken from 64 Ag-AgCl electrodes embedded in a stretch Lycra cap. In addition, two electrodes were placed on the left and right mastoids. Electrooculogram activity generated by eye movements and blinks was recorded at FP1 and three additional electrodes placed inferior to the left pupil and on the left and right outer canthi. During data acquisition, the Common Mode Sense active electrode and Driven Right Leg passive electrode formed the ground. All signals were digitized at 512 Hz using BioSemi's ActiView software.

Off-line analyses were performed using BrainVision Analyzer (Brain Products, Gilching, Germany). Scalp-electrode recordings were re-referenced to the mean of the mastoids and band-pass filtered with cutoffs of 0.1 and 30 Hz (12 dB/octave roll-off). Ocular artifacts were corrected using the method developed by Gratton, Coles, and Donchin (1983). Response-locked data were segmented into individual epochs beginning 200 ms before response execution and continuing for 800 ms following the response. Physiological artifacts were detected using a computer-based algorithm, and trials in which the following criteria were met were rejected: a voltage step exceeding 50 μ V between contiguous sampling points, a voltage difference of more than 200 μ V within a trial, and a maximum

voltage difference less than 0.5 μV within a trial. Trials were also removed from subsequent analyses if the RT was less than 200 ms or more than 800 ms.

To quantify response-locked ERPs, we subtracted a baseline equal to the average activity in the 150- to 50-ms pre-response window from each data point subsequent to the response. The ERN and the corresponding ERP amplitude on correct trials were defined as the average voltage occurring in the 0- to 100-ms postresponse time window across five fronto-central recording sites (Fz, FC1, FCz, FC2, Cz) where the ERN was maximal (see Fig. S1 in the Supplemental Material available online). On the basis of previous research suggesting the presence of an early and a late Pe (Ullsperger & von Cramon, 2006; van Veen & Carter, 2002), we defined the Pe and the corresponding ERP amplitude on correct trials as the average voltage occurring in two successive postresponse time windows (150–350 ms and 350–550 ms) across five centroparietal recording sites (Cz, CP1, CPz, CP2, Pz) where the Pe was maximal (see Fig. S1).

Results

Overview of data analyses

Repeated measures analyses of variance (ANOVAs) were first conducted on behavioral and ERP measures without regard to individual differences in TOIs in order to establish baseline experimental effects. ANOVAs conducted on behavioral measures and the ERN included one 2-level factor: accuracy (error vs. correct response). The Pe was analyzed using a 2 (accuracy: error vs. correct response) \times 2 (time window: 150–350 ms vs. 350–550 ms) ANOVA. Subsequently, TOI scores were entered into ANOVAs as covariates to assess the main and interactive effects of mind-set on behavioral and ERP measures. When significant effects of TOI score were detected, we conducted follow-up correlational analyses to aid in the interpretation of results.

Behavioral data

On average, participants were correct on 91.23% ($SD = 6\%$) of trials. Overall accuracy was not correlated with TOI ($r = .06, p > .79$). Participants were also faster on error trials ($M = 386.13$ ms, $SD = 49.14$ ms) compared with correct trials ($M = 449.30$ ms, $SD = 43.99$ ms), $F(1, 24) = 151.50, p < .001, \eta_p^2 = .86$. When TOI was entered into the ANOVA as a covariate, there were no significant effects ($F_s < 1.78, p_s > .19, \eta_p^2_s < .08$).

In terms of posterror adjustments, correct responses were slower on trials immediately following errors ($M = 496.34$ ms, $SD = 61.47$ ms) relative to trials immediately following correct responses ($M = 445.34$ ms, $SD = 45.78$ ms), $F(1, 24) = 32.89, p < .001, \eta_p^2 = .58$. When TOI was entered into the ANOVA as a covariate, there were no significant effects ($F_s < 1.15, p_s > .29, \eta_p^2_s < .05$). Although, overall, participants were slower on trials immediately following errors, they were

equally accurate on trials immediately following errors ($M = 90.70\%$, $SD = 8.31\%$) and correct responses ($M = 91.38\%$, $SD = 6.20\%$), $F(1, 24) < 1, \eta_p^2 < .01$. When entered into the ANOVA as a covariate, however, TOI scores interacted with postresponse accuracy, $F(1, 23) = 5.22, p < .05, \eta_p^2 = .19$. Correlational analysis showed that as TOI scores increased, indicating a growth mind-set, so did accuracy on trials immediately following errors relative to accuracy on trials immediately following correct responses (i.e., posterror accuracy – post-correct-response accuracy; $r = .43, p < .05$).

ERPs

As expected, the ANOVA confirmed greater ERP negativity on error trials ($M = -3.43$ μV , $SD = 4.76$ μV) relative to correct trials ($M = -0.23$ μV , $SD = 4.20$ μV), $F(1, 24) = 24.05, p < .001, \eta_p^2 = .50$, in the 0- to 100-ms postresponse time window. This result is consistent with the presence of an ERN. There were no significant effects involving TOI ($F_s < 1.24, p_s > .27, \eta_p^2_s < .06$).

The ANOVA conducted on Pe amplitude confirmed that errors elicited larger positivity ($M = 4.40$ μV , $SD = 5.56$ μV) than did correct responses ($M = -5.43$ μV , $SD = 3.62$ μV), $F(1, 24) = 91.24, p < .001, \eta_p^2 = .79$; these results are consistent with the presence of a Pe. There was also a significant effect of time window, $F(1, 24) = 84.89, p < .001, \eta_p^2 = .78$. These two main effects were qualified by a significant interaction between accuracy and time window, $F(1, 24) = 7.52, p < .05, \eta_p^2 = .24$, suggesting that the difference between error and correct postresponse positivity was larger in the early time window (M difference = 10.76 μV) than in the late time window (M difference = 8.88 μV). When entered as a covariate, TOI showed a significant interaction with accuracy, $F(1, 23) = 8.64, p < .01, \eta_p^2 = .27$. Correlational analysis demonstrated that as TOI scores increased so did positivity on error trials relative to correct trials averaged across both time windows (i.e., error activity – correct-response activity; $r = .52, p < .01$; Fig. 1; see also Table S1 in the Supplemental Material).

Mediation analysis

In addition to significant associations between TOI scores and Pe (averaged across early and late time windows) and between TOI scores and posterror accuracy, Pe was also positively correlated with posterror accuracy (see Fig. 2). That is, larger Pe amplitude on error trials (relative to correct trials) was associated with greater accuracy after errors (versus correct responses). Therefore, the preconditions for establishing mediation (Shrout & Bolger, 2002) were met. To test for mediation, we implemented Preacher and Hayes's (2008) bootstrapping procedure. As Figure 2 illustrates, controlling for Pe amplitude significantly attenuated the relationship between TOI scores and posterror accuracy. The 95% confidence intervals derived from the bootstrapping test did not include zero (.01–.04), and thus indicated significant mediation.

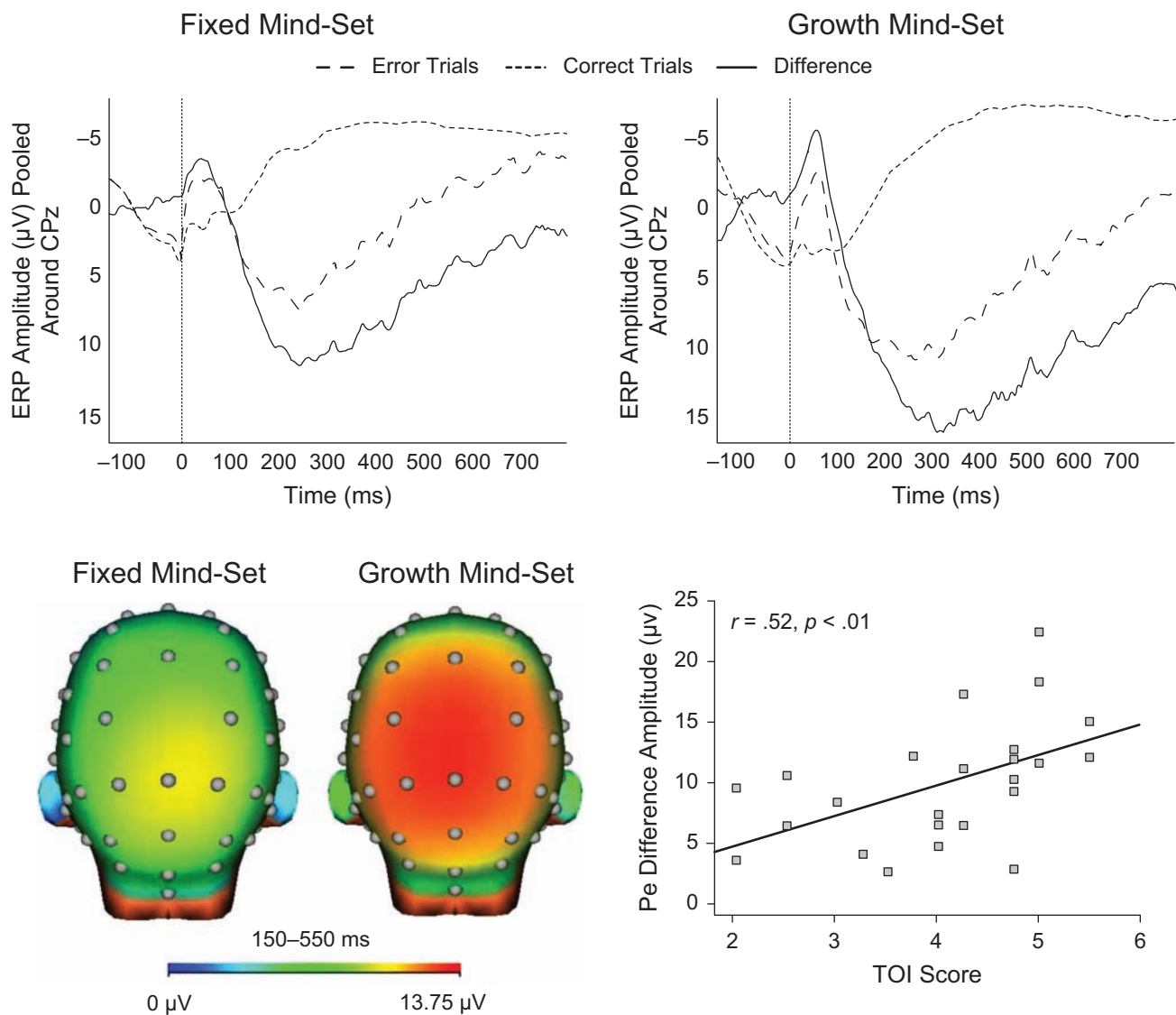


Fig. 1. Relationship between the error positivity component (Pe) of the event-related potential (ERP) and theory of intelligence (TOI). The top row shows grand-average response-locked ERP waveforms pooled from the CPz electrode and four adjacent recording sites, separately for individuals with a fixed mind-set (left) and individuals with a growth mind-set (right). Waveforms for trials on which responses were correct and trials on which responses were incorrect, as well as the difference between these waveforms, are shown. Time point 0 is response execution (highlighted by the vertical line). The fixed mind-set group (TOI scores from 1 to 3) and the growth mind-set group (TOI scores from 4 to 6) were formed on the basis of a median split for illustrative purposes only. The voltage maps in the bottom panel show the Pe difference amplitude from 150 to 550 ms (average ERP amplitude on error trials – average ERP amplitude on correct trials) in each of these groups. The scatter plot (with best-fitting regression line) in the bottom right panel illustrates the relation between Pe difference amplitude (pooled from electrode CPz and four adjacent recording sites) and TOI score.

Discussion

The findings reported here are consistent with previous results demonstrating that growth mind-sets are associated with adaptive responses to mistakes (Dweck, 1999, 2006). We extended these previous findings by identifying an on-line neural mechanism underlying this association. Specifically, a growth mind-set was associated with enhanced Pe amplitude—a brain signal reflecting conscious attention allocation to mistakes—and improved subsequent performance. That the Pe mediated

the relationship between mind-set and posterror performance further underscores its significance in linking mind-set to rebounding from mistakes.

Enhanced Pe and posterror performance in growth-minded individuals is consistent with previous results showing that a growth mind-set was associated with enhanced attention to corrective feedback following errors and subsequent error correction (Mangels et al., 2006). Our findings substantively extend this prior work by showing that a growth mind-set is associated with heightened awareness of and attention to

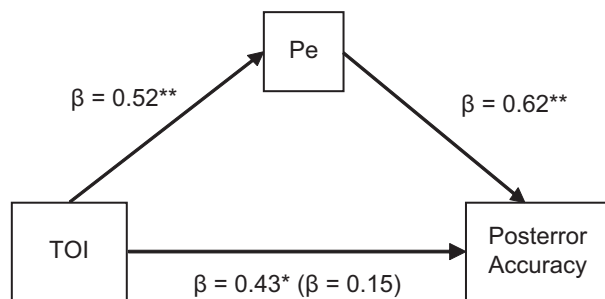


Fig. 2. Mediation model showing the effect of theory of intelligence (TOI) on posterror accuracy as mediated by the error positivity component (Pe) of the event-related potential. The value in parentheses indicates the relationship between TOI and posterror accuracy after controlling for Pe amplitude. Statistical significance is indicated by asterisks (* $p < .05$; ** $p < .01$).

errors as early as 200 ms following error commission. Whereas Mangels and her colleagues measured neural responses to a very difficult task in which accuracy was ambiguous prior to the presentation of external feedback, we found effects of mind-set on the monitoring of one's own internally generated errors and immediate self-generated adjustments following mistakes in a simple two-choice RT task. We have therefore shown that growth-minded individuals are characterized by superior functionality of a very basic self-monitoring and control system. The finding that mind-set was associated with Pe and not ERN suggests that a growth mind-set is specifically associated with enhanced ACC-mediated error processing (Steinhauser & Yeung, 2010). Together with past findings, the current results suggest that one reason why a growth mind-set leads to an increased likelihood of learning from mistakes is enhanced on-line error awareness. Future studies could manipulate mind-set directly (e.g., Hong et al., 1999) to isolate the causal role of growth mind-sets in boosting error awareness and posterror performance.

Overall, the current findings shed new light on the neural underpinnings of growth mind-sets and their links to adaptive responses to mistakes and have important implications for academic and occupational performance. One implication is that Pe amplitude and posterror adjustments measured in a simple RT task could serve as indicators of the effectiveness of programs that train individuals to be more growth minded. Such programs have been found to improve academic performance (Aronson, Fried, & Good, 2002; Blackwell, Trzesniewski, & Dweck, 2007). Implementing the procedure described here could be an efficient way to provide objective evidence of the success of programs that have the potential to produce more highly motivated students and workers.

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

Supplemental Material

Additional supporting information may be found at <http://pss.sagepub.com/content/by/supplemental-data>

Note

1. Controlling for trait anxiety (Spielberger, 1983) and achievement motivation (Elliot & McGregor, 2001) did not affect this relationship (partial $r = .57$, $p < .01$).

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