Brief article

Post-error slowing: An orienting account

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ABSTRACT

It is generally assumed that slowing after errors is a cognitive control effect reflecting more careful response strategies after errors. However, clinical data are not compatible with this explanation. We therefore consider two alternative explanations, one referring to the possibility of a persisting underlying problem and one on the basis of the low frequency of errors (orienting account). This latter hypothesis argues that infrequent events orient attention away from the task. Support for the orienting account was obtained in two experiments. Using a new experimental procedure, Experiment 1 demonstrated post-error slowing after infrequent errors and post-correct slowing after infrequent correct trials. In Experiment 2, slowing was observed following infrequent irrelevant tones replacing the feedback signals.

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1. Introduction

Cognitive control is responsible for adjusting our information processing network to context demands and goal settings. Empirically, behavioural adaptation effects are taken as a reflection of cognitive control processes. Perhaps one of the most replicable effects is the observation that responses are slower after an error than after a correct trial. Cognitive control theories attribute post-error slowing to adaptive control mechanisms that induce more careful behaviour to reduce the probability of error commission. Conflict monitoring theory (Botvinick, Braver, Barch, Carter, & Cohen, 2001), for instance, explains post-error slowing in terms of a decrease in baseline response activation after errors which is functionally equivalent to increasing the response threshold. As a result, post-error trials are predicted to be slower and more accurate. Conflict monitoring theory adequately simulated the data by Laming (1968) who indeed observed this pattern. Consequently, post-error slowing is now widely accepted as a cognitive control effect, and is used as a marker for cognitive control in clinical studies

(e.g., Bogte, Flamma, van der Meere, & van Engeland, 2007; Kerns et al., 2005; Sergeant & van der Meere, 1988).

Although the combination of post-error slowing and accuracy increase has been reported (Laming, 1968), an overview of the literature suggests that increased accuracy after errors is usually not observed (e.g., Hajcak & Simons, 2008; Hajcak, McDonald, & Simons, 2003; Rabbitt & Rodgers, 1977). Hence, other explanations need to be considered. Gehring, Goss, Coles, Meyer, and Donchin (1993) suggested that post-error slowing could be caused by the persistence of the malfunctioning process that led to an error on the previous trial, leading to a correlation in task efficiency across trials. This account does not only predict post-error slowing, but also a post-error accuracy *decrease*.

In the present paper, we propose that post-error slowing is caused by the relative infrequency of errors which causes attentional capture. This was already hinted at by Burns (1965 in Rabbitt & Phillips (1967), pp. 38): "*Burns himself preferred to suggest that the occurrence of an error was followed by an orienting response which inhibited rather than facilitated subsequent responses*". In line with this, Barcelo, Escera, Corral, and Periáñez (2006) reported slowing after infrequent events (oddballs) and interpreted this in terms of a time-consuming orientation to the oddball and

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a reorientation to the task. We refer to this hypothesis as the orienting account.

The orienting account makes two unique predictions. First, when errors are more frequent than correct trials, correct trials should elicit the orienting response and slowing should be observed after infrequent correct trials. On the basis of a persisting problem and the cognitive control hypothesis, one should always predict post-error slowing irrespective of the relative frequencies of errors and correct responses. Second, if the orienting response causes the slowing after errors, it is also predicted that orienting towards completely irrelevant unexpected signals should slow down subsequent responding.

Both predictions were tested in the following experiments. In Experiment 1 we manipulated the error rates by means of an adaptive program. We predict post-error slowing when errors are infrequent and post-correct slowing when correct trials are infrequent. In Experiment 2, we replace the feedback signal by an irrelevant high or low tone. We predict slowing when an infrequent tone follows the response.

2. Experiment 1

2.1. Method

2.1.1. Participants

Sixteen students (15 female; average age of 18 years and 8 months) of Ghent University participated in turn for course credits.

2.1.2. Procedure

Stimuli were 0.4° by 0.4° colored squares presented centrally on a white background. The brightness of the colors was adjusted in order to keep every participant's performance to a prespecified level (35%, 55% or 75% accuracy). Colors are described according to the HSV color model with three parameters: hue (0–360), saturation (0–100) and value (0–100). The four colors that were used in the practice trials were red (20, 100, 80), yellow (60, 100, 80), green (120, 100, 80) and blue (240, 100, 80). Participants responded to each of the four colors with one of the four buttons on an E-prime response box, with left and right middle and index fingers. Four different color-to-button mapping rules were used, and participants were randomly assigned to one of the mappings.

Each trial begins with a central fixation cross (500 ms) followed by the stimulus which is presented until a response button is pressed. This is immediately followed by a feedback signal (J for correct, F for incorrect, corresponding to the words 'juist' and 'fout' in Dutch). Participants received instructions related to the meaning of the feedback stimuli. The feedback stimuli were presented for 500 ms, followed by a blank screen for 100 ms. The intertrial interval was 600 ms (100 ms blank and 500 ms fixation cross).

In a first practice block, 30 trials were presented without response deadline. In a second block of 100 practice trials, a response deadline of 1000 ms is introduced together with a feedback signal, 'T' for too slow. This is followed by

three blocks of 400 trials with a short break after every 200 trials. The three blocks correspond to the frequency manipulation where every participant runs through the 35%, 55% and 75% accuracy conditions. Two different orders are used (35–55–75 and 75–55–35) and subjects were randomly assigned to one of the orders. In the 75 condition, the initial color value is set to 80, in the 55 condition to 70 and in the 35 to 60. On every trial, we calculate the accuracy of the last 20 trials and adjust the color value accordingly, where color value increases when accuracy was too low and color value decreases when accuracy was too high. With constant hue and saturation levels, adjusting the color value affects the brightness of the stimuli, where lower values make stimuli darker. We adjust the brightness with 1 value point (from 74 to 73 for instance) after every trial. These settings were tested in a small pilot experiment with different subjects.

The data are analyzed with one between-subjects factor (order) and two within-subjects factors. A first within-subject factor is the accuracy condition (35%, 55% or 75% accuracy) and a second is the accuracy of the previous trial (correct or incorrect). Post-error slowing is investigated on correct RTs and is evident from a main effect of the factor previous accuracy, indicating that on average correct RTs depend on the accuracy status of the preceding trial.

2.2. Results and discussion

The data of one participant were excluded from the analyses because of an unusually (>2SD) high proportion of late responses. All trials before the prespecified accuracy percentage was reached were excluded, as well as trials with RTs faster than 100 ms and after the response deadline. In total 26.70% of the trials were deleted. The order in which the conditions were administered did not yield significant effects.

In correct RTs, there was no main effect of accuracy condition (35, 55 or 75), $F(2,26) < 1$, ns, or of accuracy of previous trial, $F(1,13) < 1$, ns. The interaction between accuracy condition and accuracy of the previous trial was significant, $F(2,26) = 22.19$, $p < 0.001$ (see Fig. 1). In the 75 condition, we observed post-error slowing ($M = 25.08$, $SD = 26.16$; $t(14) = 3.71$, $p < 0.001$). Importantly, in the 35 condition, we observed post-correct slowing ($M = -49.78$, $SD = 47.25$; $t(14) = -4.08$, $p < 0.001$). No effect was found in condition 55 ($M = 5.43$, $SD = 39.88$; $t(14) = 0.53$, $p = 0.30$).

In the error proportions, there was an obvious main effect of accuracy condition, $F(2,26) = 386.24$, $p < 0.001$. The adaptation procedure worked excellently in the 75 and the 55 condition with 75.4% and 57.6% accuracy, respectively, but a small deviation was observed in the 35 condition with 40.1% accuracy. There was also an effect of accuracy of the previous trial, $F(2,26) = 144.08$, $p < 0.001$, with more errors after errors than after correct trials. Although the interaction between previous accuracy and accuracy condition, $F(2,26) = 3.95$, $p < 0.05$, indicates differences in the size of the post-error accuracy decrease, it was significant in all conditions (35: $M = 16.76$, $SD = 7.47$, $t(14) = 8.69$, $p < 0.001$; 55: $M = 26.01$, $SD = 12.25$, $t(14) = 8.23$, $p < 0.001$; 75: $M = 22.90$, $SD = 11.79$, $t(14) = 7.52$, $p < 0.001$).
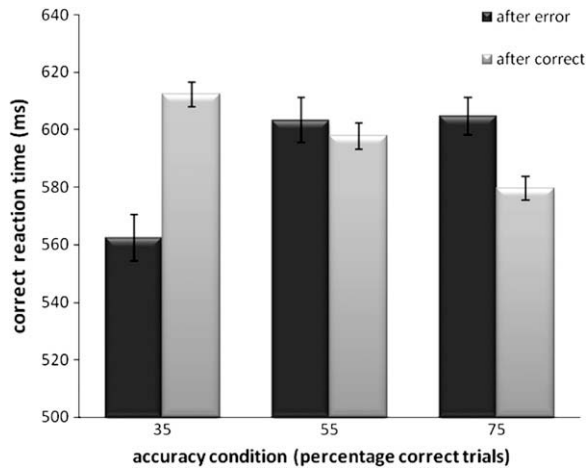
Fig. 1. Correct reaction times for trials following correct trials (previous correct) and trials following incorrect trials (previous incorrect) in the three accuracy conditions (35%, 55% and 75% accuracy). Vertical bars indicate one standard error.

Because performance is affected by the brightness (value) of the colors, we also ran an ANOVA with the same factors on color value as a dependent measure. This analysis revealed that in the three accuracy conditions the brightness on average was lower after errors than after correct trials, $F(1,13) = 711.96$, $p < 0.001$. The lower brightness after errors indicates that it takes more than one trial to adjust performance in the desired direction. Most importantly, the interaction between previous accuracy and accuracy condition in correct RTs cannot be explained in terms of differences in color brightness.

The results indicate that slowing occurred after infrequent events, whether this was an error or a correct trial. This was predicted by the orienting account, and cannot be explained by the cognitive control or the persisting-problem account. Further, there were more errors after an error than after a correct response, independent of error frequency. This effect is most likely caused by the fact that, on average, color value is lower after an error than after a correct trial.

3. Experiment 2

To further investigate the influence of expectancy on slowing, we designed a second experiment where an irrelevant signal substitutes the feedback signal. If post-error slowing is caused by an orienting response, one would also expect slowing after an infrequent irrelevant signal. Indirectly, this was already suggested in Barcelo et al. (2006) where occasionally (26 times in a block of 140 trials) a novel unique sound was presented. The slowing after these novel sounds is in line with our orienting account. Because all novel sounds were only presented once in that study, we wanted to investigate possible slowing after irrelevant sounds where the frequency more closely matched the frequency of errors in typical experiments. Further, our baseline trials also contained auditory stimuli (but frequent ones).
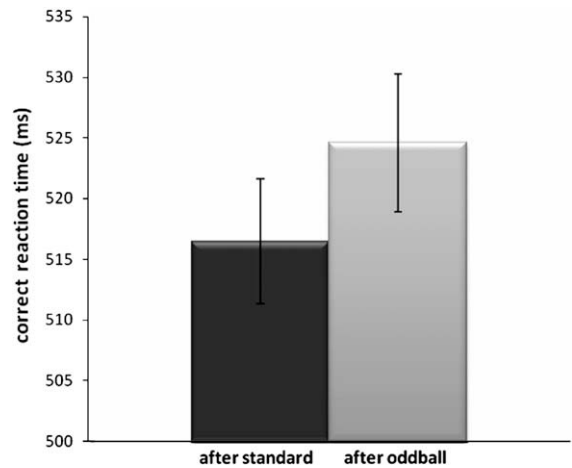

Fig. 2. Correct reaction times for trials following frequent and infrequent irrelevant acoustic stimuli. Vertical bars indicate one standard error.

3.1. Method

3.1.1. Participants
Sixteen undergraduate students (2 females, average age of 19 years) of Ghent University participated for course credits.

3.1.2. Procedure
The procedure was identical to Experiment 1 except that the feedback signal was replaced by a completely irrelevant tone (700 Hz or 1000 Hz). This irrelevant stimulus was unrelated to the performance of the subject. A standard tone was presented in 75% of the trials, while an oddball tone was presented in 25% of the trials or vice versa, counterbalanced over subjects. The four colors were presented with a fixed value of 80.

3.2. Results and discussion

A t-test on correct RTs revealed a significant effect of frequency, $t(15) = -2.41$, p < 0.05 (see Fig. 2). Subjects responded faster after an irrelevant stimulus that was presented in 75% of the trials ($M = 516$ ms; SD = 9.91 ms) compared to one that was presented in only 25% of the trials ($M = 525$ ms; SD = 11.02 ms). A t-test on the proportion errors revealed no effect of the frequency of the irrelevant stimulus, $t(15) < 1$, ns.

As only 8.88% errors are made, the orienting account predicts post-error slowing. There was a significant effect of accuracy of the previous trial on correct RT, $t(15) = 3.26$, $p < 0.01$, but not on the error proportions, $t(15) < 1$, ns. Subjects responded slower after an error trial ($M = 543.12$; SD = 62.87) than after a correct trial ($M = 518.32$; SD = 40.27). Because of the low error rate (in combination with the low oddball frequency), the interaction between post-error slowing and post-oddball slowing could not be measured.

The results demonstrate slowing after infrequent irrelevant acoustic signals in line with the orienting account for post-error slowing. Moreover, the lack of a post-error

accuracy effect in combination with post-error slowing also fits the orienting account.

4. General discussion

In Experiment 1, it was demonstrated that post-error correct RT is modulated by the frequency of errors. Post-error slowing was observed when errors were infrequent, but when errors were frequent, slowing was observed after correct trials. This cannot be explained by mechanisms of adaptive cognitive control or by the persistence of an underlying problem that caused the error. The hypothesis that infrequent events slow down task-relevant processing was further confirmed in Experiment 2 where slowing was observed on trials that followed irrelevant and infrequent acoustic signals.

The orienting account captures clinical data that were previously hard to explain. For instance, there is the dissociation between post-error slowing and two other error-related effects in patients with frontal lobe damage. Gehring and Knight (2000) demonstrated that frontal lobe patients did not show decreased response force on errors and a reduction of error corrections compared to control subjects. However, these patients showed regular post-error slowing. In response, Cohen, Botvinick, and Carter (2000) postulated that there were multiple adaptive control mechanisms, one including frontal cortex (response force effects and error correction) and one bypassing frontal cortex (post-error slowing). In our account, post-error slowing is not considered as an adaptive effect, obviating the need for multiple adaptive mechanisms.

Further support for the orienting account comes from electrophysiological studies that additionally indicate that the account is also applicable in experimental tasks without external feedback. When there is no external feedback, an error leads to internally generated feedback which is probably not all that different from externally presented feedback. In an experiment without external feedback Nieuwenhuis, Ridderinkhof, Blom, Band, and Kok (2001) demonstrated post-error slowing only when participants were aware of the errors, indicating the need of an internally generated feedback signal. Moreover, ERP studies show similar ERP components following error feedback and errors without feedback; in particular, feedback related negativity (FRN) and P3 are observed in the former case, error related negativity (ERN) and error positivity (Pe) in the latter (e.g., Leuthold & Sommer, 1999). In both cases the positive components (P3 and Pe) are more related to post-error slowing than the frontal negativities (FRN and ERN; e.g., Nieuwenhuis et al., 2001), and, interestingly, these positive components are traditionally interpreted as indices of an orienting response (e.g., Friedman, Cycowitz, & Gaeta, 2001). Similarly, Crone, Somsen, Van Beek, and Van Der Molen (2004) demonstrated heart rate deceleration after error feedback, which was also observed by Hajcak, McDonald, and, Simons (2003) on errors in a task without feedback. Interestingly, also this heart rate deceleration is an index of the orienting response (e.g., Hare, 1973). Consequently, electrophysiological and heart rate measurements on tasks with and without feedback indicate an important role for orienting responses towards errors and error feedback.

There is one aspect of the data which deserves further attention, and that is the observation that the size of post-oddball slowing in Experiment 2 is considerably smaller than the size of post-error slowing in Experiment 1 although the relative frequency of errors and oddballs matches. This is most likely caused by differences in relevance (significance) of the signals, a factor known to influence the orienting response (e.g., Bernstein, 1969). This difference boils down to the fact that, in Experiment 2, the oddballs are completely irrelevant, whereas the feedback signals in Experiment 1 are not. Alternatively, this difference in slowing could be explained in terms of the time it takes to process the deviating information. Barcelo et al. (2006) related slowing after unexpected novel events to a task-switch cost. In the present context, a task-irrelevant oddball will not activate task processes related to the 'oddball task' (because no task is required on the oddball), so the RT increase will only reflect the switching process. For feedback stimuli this is different. An unexpected feedback signal that captures attention might also activate task processes in the sense that unexpected feedback carries an important learning signal. In other words, the larger slowing in Experiment 1 could be caused by a larger orienting response as such, but also by additional feedback processing time.

Although the data pattern does not fit typical cognitive control theories, the explanation in terms of feedback processing time could be incorporated in the framework of Holroyd and Coles (2002) and Holroyd, Yeung, Coles, and Cohen (2005). These authors describe error monitoring in terms of adjustments after a deviation from expectancy. Although the original theory only implements various degrees of expectancy for an error, this could be extended to expectations for correct trials and one could argue that post-correct slowing in conditions where errors are the standard in principle fits the essence of the theory. This theory would be able to explain why post-error and post-correct slowing is larger than post-oddball slowing, but more flexibility would be required to explain why post-oddball slowing is observed in the first place.

To conclude, the orienting account for post-error slowing captures electrophysiological and clinical data that were extremely challenging for cognitive control explanations. With at least part of post-error slowing being caused by the low frequency of errors and the orienting response this generates, we suggest that researchers and clinicians are careful in interpreting post-error slowing as a marker for cognitive control.

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