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FACULTEIT PSYCHOLOGIE EN
PEDAGOGISCHE WETENSCHAPPEN

Error Monitoring:
Support for an Orienting Account

Femke Houtman

Promotor: Prof. Dr. Wim Notebaert

Proefschrift ingediend tot het behalen van de academische graad
van Doctor in de Psychologie

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Opgedragen aan Annelies Capiau

1985 – 2007

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Femke,

10 april 2013

CHAPTER 1
INTRODUCTION

“*A man of genius makes no mistakes.*
His errors are volitional and are the portals of discovery.”

Ullysses (1922), James Joyce (1882-1941)

ERROR MONITORING

Making errors is part of life. Mostly, it's not the error itself but the way you react to it that is important. By investigating what went wrong instead of ruminating about being wrong, you can in fact learn something from your error. By doing this you make your human error truly a portal of discovery. In industry there are many examples of human errors that turned out to be very beneficial for the company's growth. Like for example the legend of Ivory soap. Proctor and Gamble wanted to come to the soap market with a new white soap in the late 1800's. When one of their employee's one day went to lunch he forgot to switch off the soap mixing machine. By the time he got back the soap turned out to be extra frothy because of the extra air that got into it. At that point they could have thrown the mixture away and start over from scratch. However, they decided to use the mixture and to sell the bars of soap. From then on their floating soap was sold all over the world. It's a legend though, as research in 2004 revealed that in fact the floating soap was an invention of one of the chemists at Proctor and Gamble. Nonetheless, it is still a good illustration of how the reaction after making an error is far more important than making the error itself.

Table 1. Quotes about erring of ancient philosophers.

Venia dignus error est humanus
Titus Livius (59 BC - AD 17)

Humanum fuit errare, diabolicum est per animositatem in errore manere
Aurelius Augustinus Hipponensis (354 – 430)

Errare humanum est, perseverare
autem diabolicum, et tertium non datur
Lucius Annaeus Seneca (often known simply as Seneca; ca. 4 BC – AD 65)

Cuiusvis errare:insipientis nullius nisi, in errore perseverare
Marcus Tullius Cicero (106 BC - 43 BC)

Making errors is such an important part of being a human that it is not surprising that ancient philosophers have written about it. A few of their quotes are presented in Table 1. Remarkably, they do not focus on the act of making an error. The central message all of these great thinkers have is that making errors is not really a problem; however, it becomes a problem when you persist in it.

In the late-60s error monitoring research in experimental psychology kicked off with the hallmark studies of Rabbitt and Laming (Rabbitt, 1966; Laming, 1968). Both researchers investigated human error monitoring on the behavioural level. These researchers were also more interested in behaviour after making an error than in the error itself. They reported that people are capable of correcting most of their errors on the spot. On top of that, the phenomenon of post-error slowing was described. Apparently, correct responses are slower when they follow an error compared to when they follow another correct reaction. In the work presented in the following chapters, errors are typically incorrect key presses in computer tasks. Mostly, a modified version of the Eriksen Flanker task is used (Eriksen & Eriksen, 1974). As can been seen in Figure 2, participants are presented with a target that is surrounded by two stimuli on each side. These surrounding stimuli are called flankers. The task of the participants is to categorise the target according to the side the arrow is pointing. When the target arrow points to the left, participants have to press the left button and vice versa. Mostly, in half of the trials the target and the flankers are the same stimuli. In that case we call the trial a compatible trial because all the information that is presented on the screen is compatible with the correct answer. In half of the trials the flankers are pointing in the opposite direction of the target. This type of trial is referred to as incompatible trials, as most information on the screen is incompatible with the correct response. Errors are made when the wrong button is pressed.

In this dissertation we will broaden the knowledge about the immediate reaction, both behavioural and neuronal, people have after committing an error. A new account, named the orienting account will be described and hypotheses made by this account will be investigated. In this introduction some theoretical background of error monitoring and used methods will be described shortly. Chapter 2 is set up as a second introduction chapter where the orienting account will be proposed.

BEHAVIOURAL ADJUSTMENTS FOLLOWING ERRORS

POST-ERROR SLOWING

Probably, the most reported behavioural adjustment after making an error is the observation that people tend to slow down on the subsequent trial. This effect is better known as post-error slowing (PES) and is the core effect studied in this dissertation. Back in 1966 Rabbitt was the first researcher to report this remarkable finding. His results are presented in Figure 1; correct reaction times are slower following an error than the mean correct reaction times. He interpreted this slowing as a precaution for not erring on the next exercise. PES has been shown to be stable when participants are retested over periods ranging from 20 minutes, a couple of weeks (Segalowitz et al., 2010), even when PES is measured several months after the first test (Danielmeier & Ullsperger, 2011).

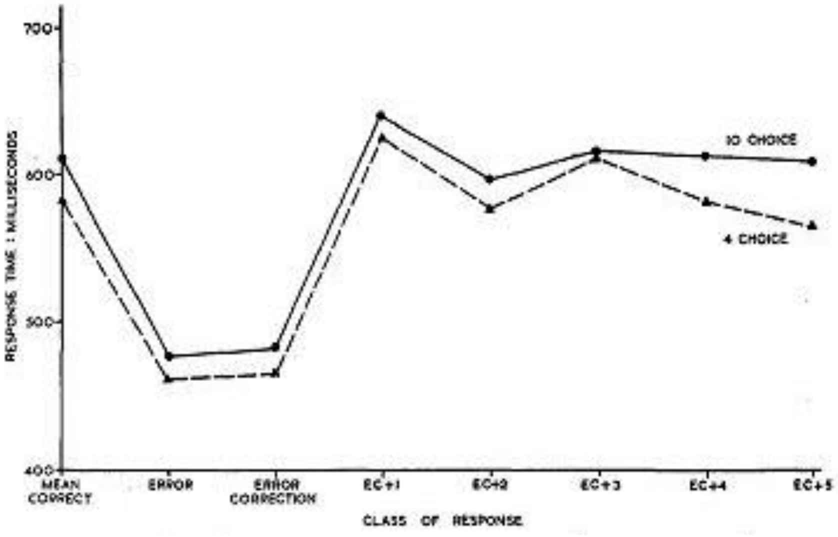

Figure 1. Response times of correct response, errors, error corrections and correct responses following errors in both a 10 choice and a 4 choice task. Post-error slowing is shown by the slower reaction times at EC + N responses than the mean correct responses. From Rabbitt (1966).

POST-ERROR ACCURACY

Apart from reaction times, also accuracy is measured after making an error and compared to after responding correctly. Although, the post-error slowing effect is reported very consequently, this is not the case for post-error accuracy changes. The three possible outcomes have been reported in several articles. That is post-error accuracy improvement (e.g. Laming, 1968; Marco-Pallares, Camara, Münte, & Rodriguez-Fornells, 2008; Maier, Yeung, & Steinhauser, 2011). In this case, fewer errors are made after an error compared to after a correct response. It could be assumed that PES results in improved performance. However, in other studies relatively more errors are made after errors than after correct responses (e.g. Rabbitt & Rodgers, 1977; Cheyne, Carriere, & Smilek, 2009; Steinborn, Flehmig, Bratzke, & Schröter, 2012). Here, you could assume that the process that leads to slower reaction times also leads to less correct behaviour, in other words, that PES is caused by processes that interfere with performance. Finally, also no difference between post-error and post-correct accuracy (e.g. Hajcak, McDonald, & Simons, 2003; King et al., 2010) have been reported.

POST-ERROR REDUCTION OF INTERFERENCE

Ridderinkhof (2002) added to the two previous post-error behavioural adjustments the finding that effects of interference are reduced after errors. He presented participants with a Simon task (Simon, 1969). This is a conflict inducing task because the stimuli are presented for example on the left or the right sides of the screen and the required responses also have this horizontal dimension. An example of this task is presented in Figure 2. In this version of the Simon task you have to press the right button when a star is presented and press the left button when a circle is presented. Therefore, a star presented on the right side on the screen is a compatible stimulus, whereas a circle presented on the right side of the screen is an incompatible stimulus.

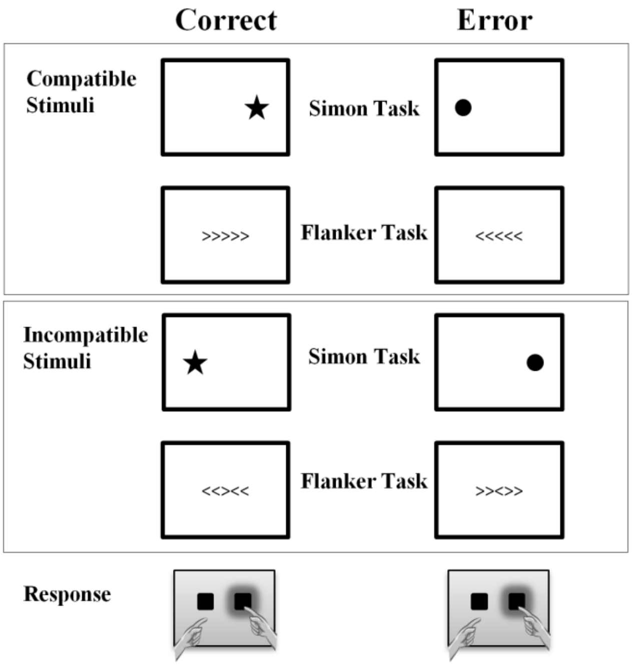

Figure 2. Illustration of two typical congruency tasks. A Simon task (Simon, 1969) and an Eriksen Flanker task (Eriksen & Eriksen, 1974). Examples of compatible and incompatible stimulus presentations are provided both with a correct response and an incorrect response.

An incompatible stimulus mostly results in slower and more error-prone behaviour, and is better known as the compatibility or the congruency effect. Ridderinkhof reported that this congruency effect is smaller when you just made an error than after a correct response. An example of this effect is presented in Figure 3. This was explained by the fact that an error evokes a heightened cognitive control which results in a smaller influence of the incongruent stimulus. Several studies indicate that PES and PERI are independent (although Carp and Compton, 2009 found a correlation) and are produced by different neuronal networks (De Bruijn, Hulstijn, Verkes, Ruigt, & Sabbe, 2004; Ridderinkhof, 2002; King, Korb, von Cramon, & Ullsperger, 2010).

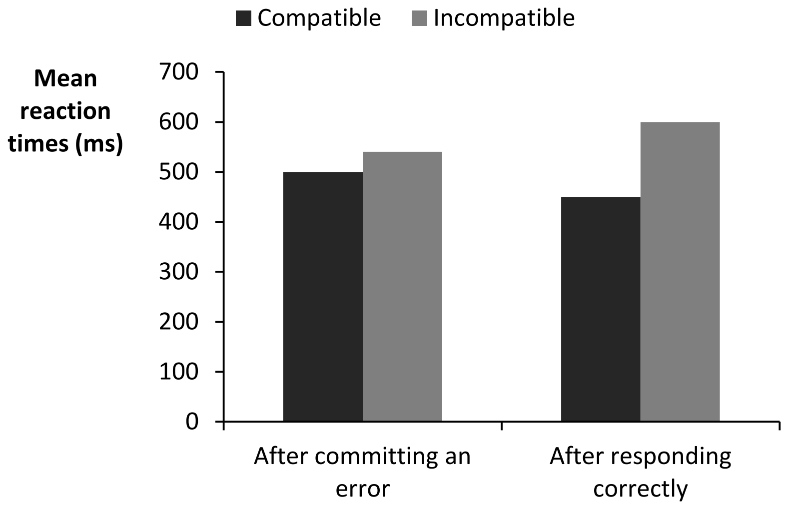

Figure 3. Bar chart that shows a smaller compatibility effect after committing an error compared to after responding correctly. This effect is better known as “post-error reduction of interference. The presented data are only for illustrating purpose.

THEORIES OF ERROR MONITORING

Where functional theories hold that error processing and post-error adjustments aim to improve performance on the following trial(s), non-functional theories explain PES in terms of reduced cognitive processing after errors. In the following I present the most prominent theories in both categories briefly, as they are discussed in detail in **Chapter 2**.

FUNCTIONAL THEORIES

Functional theories describe slowing as a strategy to reduce the likelihood of subsequent errors. The conflict monitoring theory, formulated by Botvinick and colleagues (2001) and updated in 2004 (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, Cohen, & Carter, 2004), is one of the most influential and investigated theories about performance monitoring. This model has two major components, the conflict monitor, located in the dorsal Anterior Cingulate Cortex (dACC) and a system for applying cognitive control, presumably located in the PreFrontal Cortex (PFC). The ACC is divided into a dorsal “cognitive” division and a ventral “affective” division (Bush, Luu, & Posner, 2000). The dACC monitors the degree of conflict and sends a signal to the PFC to call for cognitive control. Within this framework, errors tend to elicit high levels of conflict because both the executed erroneous response and the not executed correct response are active. Conflict detection increases cognitive control by increasing the response threshold resulting in slower and more accurate performance. In this theory, post-error slowing is framed in a more cautious response style in order to perform better on the next trial. The CMT was originally tested in a connectionist model (Botvinick et al., 2001). Indeed, they found larger response conflict on error trials than on correct trials.

Later, this model has been refined by Yeung, Botvinick, and Cohen (2004). The model for the Eriksen flanker task (Eriksen & Eriksen, 1974) is presented in Figure 4. A different version of the Flanker task than the one presented in Figure 2 is used. Instead of arrows the letters H and S are used. In this case participants have to categorise the letters by pressing for example the left button when the target is H and the right button when the target is S. The model consists of three layers of units. In the input layer the possible stimulus presentations are represented by six position-specific letter units. Both the H and the S can be presented centrally or on the left or on the right side of the computer screen. The response layer has a unit for each response, namely the left response and the right response. The third layer is an attentional layer with three units, one for every possible location in the stimulus (left, right and central).

Information is sent through the model by bi-directional excitatory weights between the layers, represented by the black lines in the model. The lines with an arrow represent the conflict monitoring feedback loop which is presumably located in the PFC. When conflict is detected in the response layer this information is sent to the dACC, which is the conflict monitor. This conflict monitor will call for cognitive control by the PFC. Cognitive control will be applied by biasing input from the attention layer. The attention layer will increase the attention directed to the target, which is presented centrally on the screen. By doing this, the corresponding response will be activated. Response conflict is measured by computing a multiplication of the response unit activations. When both responses have high activation, their product will also be large and as a consequence response conflict will be large. When one of both response units crosses an arbitrary response threshold, the corresponding response will be produced.

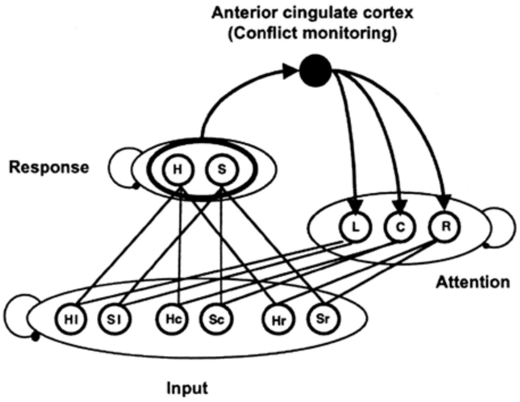

Figure 4. The letters H and S designate the stimulus input, which can occur on the left (l/L), in the center (c/C) or on the right (r/R) side of the computer screen. The black lines indicate bidirectional excitatory weights between input, attention and response layers. The arrows represent the conflict monitoring feedback loop. Figure adapted from Yeung, Botvinick and Cohen, 2004.

Evidence for this theory has been provided by functional magnetic resonance imaging (fMRI) studies. For example the hypothesis that post-error adjustments are triggered by signals from the PFC has been supported by showing a correlation between pMFC activity and PES (Garavan, Ross, Murphy, Roche, & Stein, 2002; Chevrier & Schachar, 2010). This correlation is, however, not consistently found (Gehring & Fencsik, 2001). Danielmeier and Ullsperger (2011) suggested in their review on post-error adjustments that the mixed findings regarding this correlation could be explained by an indirect relation between PES and the performance monitoring system. In fMRI studies presented in the next paragraph about the inhibition account it is shown that PES is linked to the performance monitoring system via a decrease in activity in the motor system (King, Korb, von Cramon, & Ullsperger, 2010; Danielmeier, Eichele, Forstmann, Tittgemeyer, & Ullsperger, 2011).

The inhibition account (Ridderinkhof, 2002; Marco-Pallares et al., 2008) has much in common with the conflict monitoring theory. It states that after error commission, selective suppression or inhibition of response activation occurs. PES correlates with an increase in beta band power which is associated with motor inhibition processes (Marco-Pallares et al., 2008; Kühn et al., 2004; Swann et al., 2009). Evidence for this account can be found in fMRI studies (King et al., 2010; Danielmeier et al., 2011) that investigated the relation between posterior medial frontal cortex activity and post-error behavior. In these studies a relationship between post-error slowing and decreased motor activation was observed. King et al. presented their participants with a modified Simon task (see Figure 2 for an illustration of a basic Simon task). Female and male faces were presented on the left or on the right side of the screen. The task was to classify the gender by pressing the left or the right button. In half of the trials the stimulus presentation side was incompatible with the correct response button. By using faces as stimuli, the researchers could measure changes in the Fusiform Face Area (FFA) (Kanwisher et al., 1997). This area is known to be active exclusively when faces are being processed. King and colleagues found that after making an error, more attention was given to the faces. This was seen by increased activity of the FFA. At the same time the sensorimotor cortex was suppressed. These changes in FFA en SMC covaried with individual measures of PES and PERI. Importantly, although PES correlated with decreased SMC activity, errors were not followed by improved accuracy. The setup of the study by Danielmeier and colleagues was similar. Again, a modified Simon task was used in which coloured dots had to be classified. These dots were moving to the right or moving to the left side of the screen. Activity in areas that encode colours was increased on post-error trials, whereas activity in motion-encoding areas was decreased. They also found a decrease in motor system activity that correlated with PES.

A third theory that cannot be left out from this brief overview is the reinforcement learning theory (Holroyd & Coles, 2002). This theory integrates findings on reward processing and reinforcement learning. Studies on reward processing in primates show a phasic increase or decrease in activity of the dopamine system when events are better or worse (respectively) than expected (Schultz, 2000, 2002). In most cases, errors are events that are worse than expected. These dopaminergic reinforcement signals are used for selecting and reinforcing the motor controllers to perform the ongoing task optimally.

NON-FUNCTIONAL THEORIES

In recent years, the traditional functional theories for post-error slowing were challenged. For instance, it was demonstrated that patients with severe mediofrontal lesions, including ACC, showed PES (Stemmer, Segalowitz, Witzke, & Schönle, 2004). Moreover, functional theories predict that accuracy would increase after errors, an observation that has often not been observed (e.g. Rabbitt & Rodgers, 1977; Cheyne et al., 2009; Steinborn et al., 2012). These and other data (see **Chapter 2**) gave rise to so-called non-functional accounts that explain PES in terms non-strategic mechanisms.

The bottleneck error-monitoring theory (Jentzsch & Dudschig, 2009; Dudschig & Jentzsch, 2009) is based on the principle of a bottleneck. Imagine being at a festival with 3000 people that only has one exit. What happens when all of a sudden some trees that are on the festival site start to burn? Everyone will try to escape by using that one exit. This will cause a severe bottleneck at the exit. When translating that to error monitoring, the central information processor in our brain is the single exit on the festival site. The error monitoring processes that take place when making an error also have to be processed by that same capacity-limited information processor. Together with error monitoring processes, the next task also has to be processed. This bottleneck leads to slower and less accurate performance when a task immediately follows an error. However, when there is enough time between the error and the following trial, compensatory mechanisms, like post-error slowing, can be implemented to prevent subsequent mistakes.

A similar explanation is postulated in the bidirectional model for attention lapses (Cheyne, Carriere, Solman, & Smilek, 2011) where errors caused by lapses in attention can on their turn induce dips in attention. A third non-functional account explains PES in terms of persistent malfunctioning (Gehring, Goss, Coles, Meyer, & Donchin, 1993; Gehring & Knight, 2000), where it is argued that the error is caused by a lapse of attention which lingers on to the following trial.

In this dissertation, the orienting account will be described. In most reaction time tasks in experimental psychology, the number of errors is very small. From the learning psychology literature we know that surprising events tend to evoke an orienting response. This is a short lived disturbance of cognitive processes accompanied by several reactions in the autonomic nervous system (ANS) like for example heart rate deceleration, skin conductance changes and pupil dilation. The orienting account states that post-error slowing is a reaction to the infrequent nature errors have in most experimental studies. Evidence for this account is provided in the following chapters.

ORIENTING RESPONSE

Because the term "orienting response" (OR) is used numerously in the following chapters, I will provide some background about this innate reflex that has been studied by numerous researchers up till now. The orienting response, also known as the "orienting reflex", was first described by Ivan Sechenov (1863) in his book *Reflexes of the brain*. Later on, Ivan Pavlov (1927) referred to it as the "what is it" reflex (p. 12) "*It is this reflex which brings about the immediate response in man and animals to the slightest changes in the world around them, so that they immediately orientate their appropriate receptor organ in accordance with the perceptible quality in the agent bringing about the change, making full investigation of it.*" Sokolov (1963) further investigated this reflex and found that the OR is accompanied by increased skin conductance and heart rate deceleration. He also described the phenomenon of habituation. After several incidences of the same stimulus the OR becomes smaller and eventually disappears, this process is called habituation. When the stimulus changes however, dishabituation takes place. A renewed OR is evoked by this 'new' stimulus. Hajcak, McDonald and Simons (2003) reported error-related modulations in the ANS. Errors were accompanied by larger skin conduction and greater heart rate deceleration.

THE ERP TECHNIQUE

The elektro-encephalogram (EEG) is a technique that has a very high temporal resolution; however, the information regarding the anatomical origin of the electrical signal is less exact. In contrast, other neuro-imaging techniques like Positron Emission Tomography (PET) and fMRI have better spatial resolution but poor temporal resolution. When EEG is measured during an experimental task involving specific events (for example stimuli or responses) we can examine epochs of the EEG that reflect neural processes uniquely associated with those events. An event-related potential (ERP) is simply a voltage relative to a specific time-locked event. It is a time-varying scalp field that results from the summation of electromagnetic activity generated by neuronal populations in different parts of the brain (Otten & Rugg, 2005). Psychologically, ERPs represent neural manifestations of specific information-processing activities associated with stimulus or response events (Bartholow & Amodio, 2009).

In an ERP experiment the EEG is recorded from 32, 64, 128 or more electrodes that are mounted in an elastic cap that has electrode positioned over the entire scalp surface. From the amplifiers, the raw signals are digitized onto a computer and recorded (Hillyard & Kutas, 1983). Afterwards a signal averaging procedure is performed to extract the ERPs time-locked to specific stimulus or response.

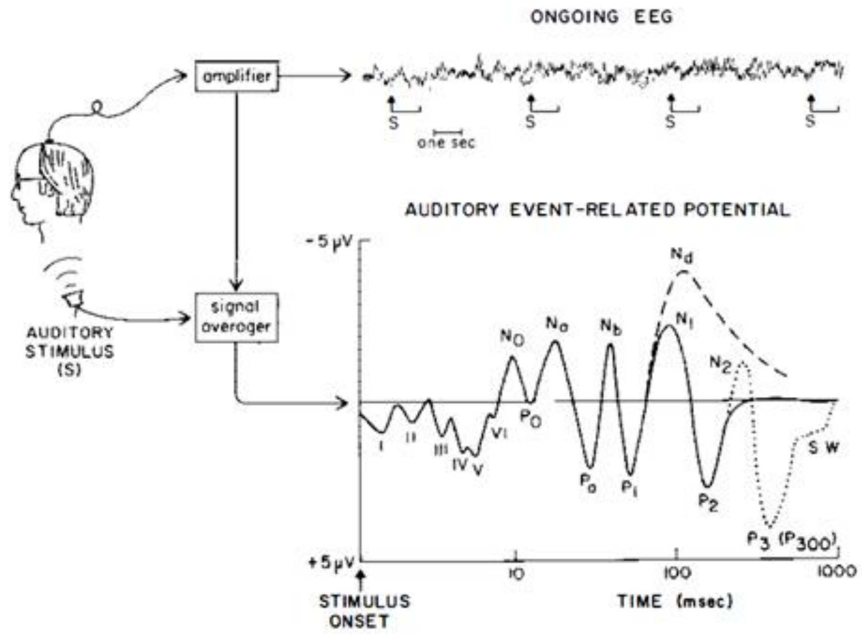

Figure 5. Idealized picture of obtaining an ERP waveform based on the presentation of an auditory stimulus (S). The P3 for example is the positive deflection occurring 300ms after stimulus presentation. The figure is taken from Hillyard and Kutas, 1983.

In Figure 5, an example of segments extracted of the EEG can be observed. Each segment shows the activity locked to the onset of an auditory stimulus (S). The averaged ERP waveform is the averaged signal of all the segments. The resulting averaged ERP waveforms consist of a sequence of positive (P) and negative (N) voltage deflections. These deflections are called peaks, waves, or components. In Figure 5, some of the peaks are labelled P1, N1, P2, N2, and P3. The number in the component name usually refers to the timing in the wave form. The P3 for example is a positive peak occurring 300 ms after stimulus presentation. Depending on the experimental variables of the tasks, researchers make functional interpretations of the ERP components.

ERROR-RELATED ERP COMPONENTS

The Error-Related Negativity (ERN/NE)

The first deflection observed locked to the erroneous response is a negative voltage deflection in the event-related brain potential peaking between 0 en 100ms after the erroneous response (see Figure 6) and thought to be generated by the ACC (Dehaene, Posner, & Tucker, 1994; Dikman & Allen, 2000; Ghering, Himle, & Nisenson, 2000), usually referred to as the error-related negativity (ERN; Gehring, Coles, Meyer, & Donchin, 1990) or the error negativity (N_E; Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991). The ERN pops up very fast after making an error and occurs even before participants are aware that a mistake has been made (Nieuwenhuis et al., 2001). This component seems to be apparent on correct responses as well (Falkenstein et al., 2000; Vidal, Hasbroucq, Grapperon, & Bonnet, 2000). Both the ERN and the correct- related negativity (CRN) have a similar scalp topography and time-course. The amplitude of the CRN is, however, generally smaller than the ERN. A source-localisation study has demonstrated that the ERN and CRN share a common generator in the rostral cingulate zone (Roger, Benar, Vidal, Hasbroucq, & Burle, 2010). The functional significance of the CRN is still unclear. Several proposals have been reported like for example the uncertainty of a correct response (Coles et al., 2001; Pailing et al., 2002) or a coactivation of correct and incorrect responses (Luu, Collins, & Tucker, 2000; Scheffers et al., 1996; Vidal et al., 2000).

The ERN/N_E was originally described as a mismatch signal when the representation of the desired response did not match with the representation of the actual response. Therefore, the amplitude should be directly related to the degree of mismatch between the correct and erroneous response. This hypothesis was confirmed by several ERP studies (Bernstein et al., 1995; Falkenstein et al., 1995; Scheffers et al., 1996). The ERN is also integrated in the earlier described reinforcement learning theory (Holroyd & Coles, 2002). The reinforcement learning theory states that the ERN is modulated by the impact of the dopamine signals on the ACC. Therefore, small ERNs are associated with phasic increases in dopamine activity. In other words, small ERNs are apparent when ongoing events are better than expected. Also the opposite is predicted by the reinforcement learning theory, large ERNs appear when ongoing events are worse than expected. In the conflict monitoring theory (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, Cohen, & Carter, 2004) the ERN reflects the activation of the conflict-monitoring system following error commission.

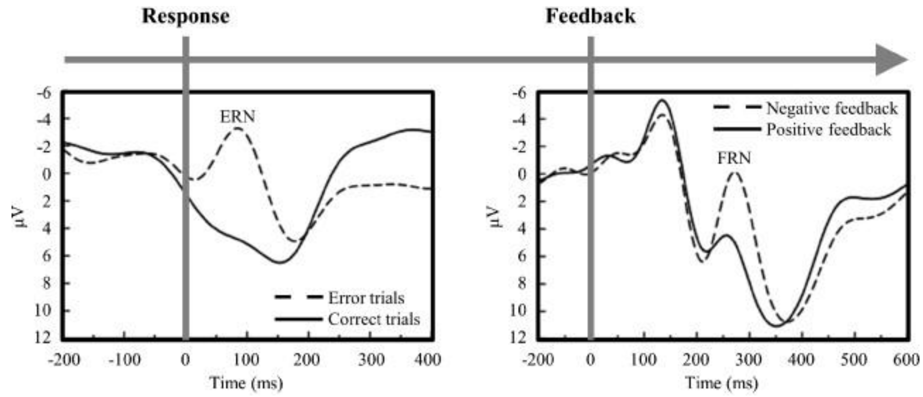

Figure 6. On the left the response-locked ERN is presented. On the right the feedback stimulus-locked FRN is shown. This figure is taken from Walsh and Anderson, 2012.

The Error-Related Positivity (P_E)

The error positivity (Pe) is a positive slow wave maximal at centro-patietal sites that peaks approximately 200-400 ms after the onset of the erroneous response. In Figure 7 grand-average ERP waveforms that are response-locked are presented. Two-hundred milliseconds after making an error a slow wave positive potential develops, whereas this is not the case after a correct response. Although the PE follows the ERN, they are not always modulated in the same manner. While the ERN can be measured after unaware errors, the PE is modulated by error awareness. Perceived errors are accompanied by a more pronounced PE than unperceived errors (Nieuwenhuis et al., 2001; Endrass, Franke, & Kathmann, 2005). This dissociation between the ERN and the PE is further supported by a source-localisation study of Herrmann, Römmler, Ehlis, Heidrich, and Fallgatter

(2004). They reported that the source of the ERN was located in medial prefrontal areas, whereas the PE originated more rostral within the ACC.

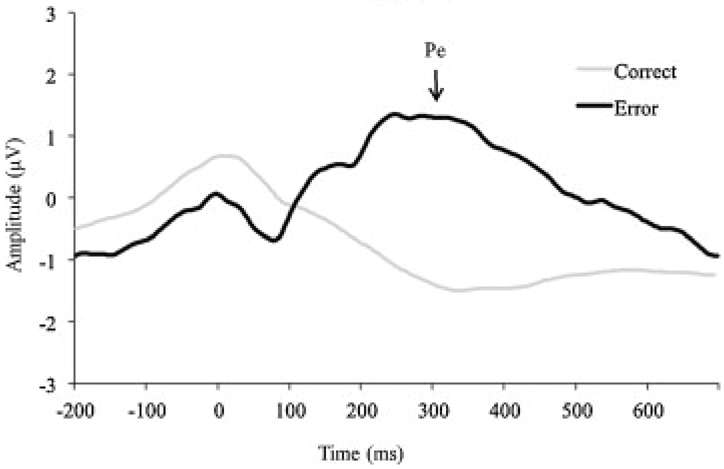

Figure 7. Response-locked ERP waveform representing the PE. The figure is adapted from Larson, Clayson and Baldwin, 2012.

Remarkably, the Pe and the P3 component seem to have much in common in terms of morphology and scalp topography (Davies, Segalowitz, Dywan, & Pailing, 2001; Falkenstein et al., 1999; Hajcak, McDonald, & Simons, 2003; O'Connell et al., 2007). The P3 is a positive stimulus-locked slow wave appearing between 200 and 400 ms after the onset of a surprising event (Yeung, Holroyd, & Cohen, 2005). The P3 has generally been associated with the processing of unexpected events (Sutton, Braren, Zubin, & John, 1965; for a review, see Nieuwenhuis, Aston-Jones, & Cohen, 2005). Later on, the P3 has been subdivided into two subcomponents, namely the P3a and the P3b. Whereas the P3a is more sensitive to the novelty of events (Friedman, Cycowicz, & Gaeta, 2001) the P3b is ought to be sensitive to the amount of attentional resources allocated to a stimulus (Polich, 2007). In a study of Ridderinkhof, Ramautar, and Wijnen (2009) the relation between P_E and P3 was investigated. The amplitude of the P_E in a Simon task covaried with the effect of a manipulation known to influence stimulus saliency as reflected in the P3. Davies, Segalowitz, Dywan, and Pailing (2001) also reported a correlation between the size of the stimulus-locked P3 and the response-locked P_E in a Flanker task. It seems that the P_E is a P3-like reaction to the motivational and salient nature most errors have.

THE PRESENT DISSERTATION

This dissertation started with the observation that traditional accounts for error-monitoring were challenged by a growing body of empirical data. We developed the hypothesis that post-error slowing might in fact not be a strategic adaptation, but rather a by-product of paying attention to the error. Around the same time, other labs developed other non-functional accounts for PES (see above). The similarities and differences will be discussed in the general discussion.

In **chapter 2** the orienting account is presented. The orienting account explains slowing after committing an error as an orienting response due to the infrequent nature of most errors. In order to manipulate the amount of errors participants make, we developed an adaptive paradigm that adjusted the discriminability of the target according to the recent performance in a four choice colour discrimination task. This was done by calculating on each trial the mean accuracy of the previous 20 trials. When this number was larger than the pre-set value of, for example, 55% then the stimulus would be slightly darker on the next trial. By doing this, we created 3 within-subjects conditions where we aimed respectively at 35%, 75% and 55% accuracy. In a second experiment an irrelevant stimulus was presented on 25% or 75% of the trials. This was done to verify the prediction of the orienting account that the frequency of an event influences the behaviour afterwards. In **chapter 3** these experiments were expanded by two experiments. Because in chapter 2 immediate feedback was given, it could that the results found were reactions to the infrequent visual presentation of the feedback, instead of infrequent error-specific reactions. Another reason to set up this experiment was to replicate the results in a different range of accuracies. This time we aimed at 50%, 70% and 90% accurate trials in the three conditions. One group saw immediate feedback, whereas another group saw feedback after every fiftieth trial. The third reason to do this experiment was to discard the continuous use of the adaptive algorithm. This would allow us to measure post-error accuracies in each condition. In chapter 3, each condition started with a block of trials during which the adaptive algorithm defined the darkness at which that particular participant performed at the predefined level of accuracy. In **chapter 4** the same rationale was used in an ERP study. However, this time we completely removed the adaptive paradigm and used a difficult and an easy version of a modified flanker task.

The difference in difficulty was created by using a 4:2 stimulus:response mapping and a 8:2 stimulus:response mapping of a speeded flanker task. No immediate feedback was given, which enabled us to investigate error-response specific potentials, namely the ERN and the PE. At the same time, we could correlate behavioural adjustments with these error-related potentials. In **chapter 5** a new paradigm is presented to investigate behavioural processes that occur immediately after committing an error without relying on post-error accuracies. A modified flanker task was used in order to have enough errors to analyse. The response on the flanker task was immediately followed by a rapid visual presentation (RSVP) of single digits. In this RSVP one letter was presented in 95% of the trials. Participants were asked to type the letter they just saw, or to indicate that they had not seen a letter. This experiment was done both with immediate feedback on the flanker task and without immediate feedback. In a third experiment we aimed to investigate the impact on target detection in the RSVP when this started with an irrelevant red or green stimulus which was presented frequently or infrequently. In **chapter 6** we investigated how the presentation of feedback signals might modulate post-error behavioural adjustments by manipulating feedback frequency and magnitude experimentally in an arrow flanker task with different reinforcement contexts. Participants were either rewarded for correct trials, or punished for error trials. Moreover, both the reward and the punishment groups were further divided in a high and low reward/punishment condition, resulting in four between-subjects conditions. In each of these conditions, occasional infrequent feedback was presented.

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CHAPTER 2

POST-ERROR SLOWING: AN ORIENTING ACCOUNT[1]

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] Notebaert, W., Houtman, F., Opstal, F. V., Gevers, W., Fias, W., & Verguts, T. (2009). Post-error slowing: an orienting account. *Cognition*, *111*(2), 275-279.

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 of 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, Cohen, MacDonald III, Johnson, Stenger, Aizenstein, & Carter, 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, MacDonald & Simons, 2003; Rabbitt & Rogers, 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, Escero, Corral and

Perianez (2006) reported slowing after infrequent events (oddballs) and interpreted this in terms of a time-consuming orientation to the oddball and 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.

EXPERIMENT 1

METHOD

Participants

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

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 (100ms blank and 500ms 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 condition. 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.

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, $F(2, 26) = 22.19$, $p < .001$ (see Figure 1). In the 75 condition we observed post-error slowing ($M = 25.08$, $SD = 26.16$; $t(14) = 3.71$, $p < .001$). Importantly, in the 35 condition, we observed post-correct slowing ($M = -49.78$, $SD = 47.25$; $t(14) = -4.08$, $p < .001$). No effect was found in condition 55 ($M = 5.43$, $SD = 39.88$; $t(14) = 0.53$, $p = .30$).

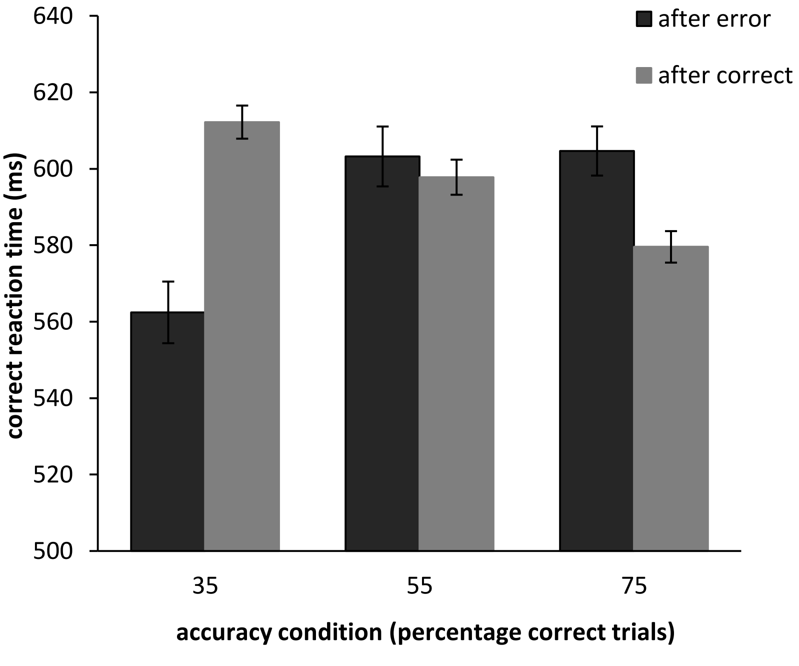

Figure 1. Correct reaction times for trials following correct trials (previous correct) and trials following incorrect trials (previous incorrect) in the three accuracy conditions (35%, 55% and 75% accuracy). Vertical bars indicate one standard error.

In the error proportions, there was an obvious main effect of accuracy condition, $F(2, 26) = 386.24$, $p < .001$. 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, $F(2, 26) = 144.08$, $p < .001$, with more errors after errors than after correct trials. Although the interaction between previous accuracy and accuracy condition, $F(2, 26) = 3.95$, $p < .05$, indicates differences in the size of the post-error accuracy decrease, it was significant in all conditions (35: $M = 16.76$, $SD = 7.47$, $t(14) = 8.69$, $p < .001$; 55: $M = 26.01$, $SD = 12.25$, $t(14) = 8.23$, $p < .001$; 75: $M = 22.90$, $SD = 11.79$, $t(14) = 7.52$, $p < .001$).

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 analyses revealed that in the three accuracy conditions the brightness on average was lower after errors than after correct trials, $F(1, 13) = 711.96$, $p < .001$. 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.

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).

METHOD

Participants

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

Procedure

The procedure was identical to Experiment 1 except that the feedback signal was replaced by a completely irrelevant tone (700 Hz or 1000Hz). 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.

RESULTS AND DISCUSSION

A t-test on correct RTs revealed a significant effect of frequency, $t(15) = -2.41$, $p < .05$ (see Figure 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, $t(15) = 3.26$, $p < .01$, 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.

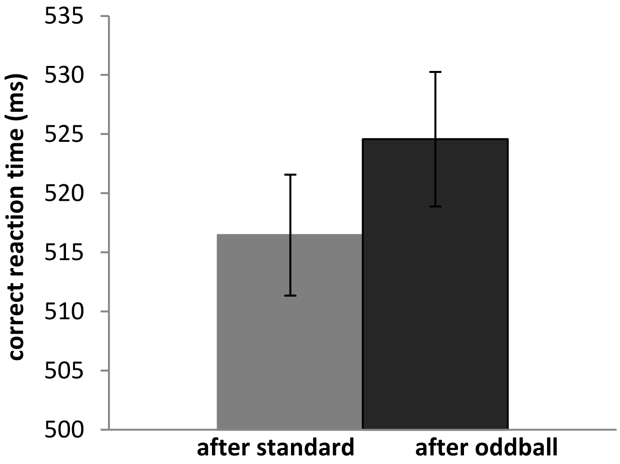

Figure 2. Correct reaction times for trials following frequent and infrequent irrelevant acoustic stimuli. Vertical bars indicate one standard error.

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.

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, & 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, Cycowicz, & 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 et al. (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 that 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 match. 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; Holroyd, Yeung, Coles, & 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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CHAPTER 3
ORIENTING TO ERRORS WITH AND WITHOUT IMMEDIATE FEEDBACK[2]

A slow-down in reaction time (RT) after committing an error is a well-known effect. Recently, Notebaert and colleagues (Notebaert et al., 2009; Nunez Castellar et al., 2010) suggested that post-error slowing is a reaction to the infrequent nature of errors. After infrequent errors, post-error slowing was observed but after infrequent correct trials, post-correct slowing was observed. These data were obtained in a paradigm with trial-by-trial feedback. In this study we tested whether post-error slowing was similar with and without immediate feedback. We manipulated the overall accuracy parametrically per condition (50%, 70% and 90% accuracy) and predicted an increase in post-error slowing as the accuracy increased. This linear effect was observed with and without immediate feedback. The data are interpreted in terms of an orienting response towards unexpected events.

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INTRODUCTION

In everyday life's ever-changing environment it is necessary to adapt our behaviour. This demanding task requires monitoring of internal and external feedback signals indicating suboptimal behaviour. Among these signals, the ones indicating erroneous responses should be considered as highly relevant. When performing an impossible action on your computer for instance, you will hear an annoying beep indicating an erroneous key-press. In other cases, there is no such external feedback and you have to rely on internal monitoring processes. For example, even without a computer sound you sometimes feel you hit the wrong key. In this paper, we focus on internal action monitoring and investigate whether behavioural changes after internally detected errors are comparable to externally motivated behavioural changes.

Behavioural adjustment after error detection is a well-described phenomenon. Usually reaction times (RTs) after incorrect responses are longer than after correct responses. This slow-down in performance was initially explained as a behavioural adjustment in order to prevent further errors. The conflict monitoring theory by Botvinick, Braver, Barch, Carter, and Cohen (2001) further specified that an erroneous trial is detected by the anterior cingulate cortex (ACC) which increases cognitive control, in this particular case, by increasing the response threshold. These cognitive explanations predict post-error slowing in combination with increased accuracy after an error. Although this pattern has been observed on some occasions (e.g., Laming, 1968), post-error slowing has also been observed in combination with post-error accuracy *decrease* (e.g., Fiehler, Ullsperger, & von Cramon, 2005).

A recent account explains post-error slowing as an orienting response towards surprising events (Notebaert et al., 2009). This attention shift away from the task results in a RT increase and possibly an error rate increase. Notebaert et al. demonstrated this in a four-choice colour discrimination task. When, like in most RT experiments, correct responses outnumbered erroneous responses, post-error slowing was observed. However, when the majority of the trials were incorrect, post-correct slowing was observed, indicating that slowing occurs after infrequent events irrespective of the accuracy. Notebaert et al. also demonstrated slower RTs following infrequent irrelevant signals (see also Barcelo, Escera, Corral, & Perianez, 2006). The influence of expectancies was further supported by the results of a recent event-related potential (ERP) study where it was also demonstrated that the feedback-related P3, a component likely associated with attentional orienting, predicted the slowing on the following trial (Núñez Castellar, Kuhn, Fias, & Notebaert, 2010). Crucially, in both experiments (Notebaert et al., 2009; Núñez Castellar et al., 2010) feedback was provided after every response. Consequently, it was impossible to determine whether slowing after infrequent events was triggered by the unexpected action outcome or by the unexpected feedback signal.

Post-error slowing has also been observed in studies without immediate feedback (e.g., Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001; Allain, Burle, Hasbroucq, & Vidal, 2009). In studies where no immediate trial-by-trial feedback is delivered, the orienting account perhaps loses some face validity. Feedback signals are usually designed to minimize the chance that a participant or operator of a machine would miss it. Therefore it is not surprising that these, usually infrequent, events capture one’s attention and delay subsequent stimulus processing. When there is no feedback and a participant or operator has to rely on internal monitoring, the signal that should capture one’s attention is an internal mismatch signal. Although this is perhaps less salient than external feedback signals, this internal feedback signal provides us with the same important information. Consequently, the orienting account would predict similar slowing after internally detected errors. If the orienting account would be limited to explaining data patterns with immediate feedback, this would seriously limit the impact of this theoretical account.

Because there are reasons to assume that external feedback signals differ from internal feedback signals in saliency and hence attention-capturing properties, we investigated post-error slowing with and without immediate feedback. One group received feedback after every response, whereas the other group only received feedback after every fiftieth trial. In order to evaluate the orienting response to internally and externally detected errors, we created three accuracy conditions: 50% accurate, 70% accurate and 90% accurate. Based on the orienting account, we predicted an increase in post-error slowing as errors decrease. The main question is whether we can also observe this pattern in conditions without external feedback.

In order to obtain these accuracies we used the same adaptive programme as used in Notebaert et al. (2009) and Núñez Castellar et al. (2010). This programme keeps track of the performance and adjusts the stimulus discriminability when performance is too high or too low. Different from previous studies using this adaptive procedure, we only adjusted the stimulus discriminability in the beginning of the experiment. This allowed us to measure post-error accuracy changes, as the constant adjustment in previous studies made post-error accuracy measurements difficult to interpret. Contrary to the conflict monitoring theory, the orienting account does not predict a post-error accuracy increase. On the contrary, the account predicts a higher error rate after unexpected errors than after correct trials. When attention is drawn away from the task by an error, the obligatory shifting back to the task could result in more errors on top of a RT increase.

METHOD

PARTICIPANTS

Thirty-two students (21 females, average age of 20 years and 6 months) of Ghent University participated based on their written informed consent with approval of the local ethical committee and according to the Declaration of Helsinki. They all received course credits.

APPARATUS AND STIMULI

Participants had to react to the colour of a centrally presented square. These squares, with a size of 0.4° by 0.4°, were presented on a white background. Colours are described according to the HSV colour model with three parameters: hue (0°-360°), saturation (0%-100%) and value or brightness (0%-100%). The four colours that were used in the practice trials were yellow (60°, 100%, 90%), blue (240°, 100%, 90%), red (20°, 100%, 90%) and green (120°, 100%, 90%). Participants responded to each of the colours with one of the four buttons on a Cedrus response box, with left and right index and middle fingers. Four different colour-to-button mapping rules were used. Each participant was randomly assigned to one of them. The participants were tested on a Pentium IV personal computer with a 17-inch colour monitor running Tscope (Stevens, Lammertyn, Verbruggen, & Vandierendonck, 2006).

DESIGN

Participants were asked to respond as fast and accurately as possible to the colour of the square. There were two within-subject factors and two between-subject factors. The first within-subject factor was the accuracy of the previous trial (correct or incorrect) and the second one was the accuracy condition (50, 70 or 90% accuracy). The first between-subject factor was the order of the accuracy conditions (50%-70%-90% or 90%-70%-50%) and the second between-subject factor indicated whether the participant received feedback after every trial (feedback condition) or only after every fiftieth trial (from now on called the no-feedback condition).

PROCEDURE

Half of the participants were randomly assigned to the feedback condition, the other half to the no-feedback condition. Participants entered a quiet room and sat in front of a computer and a response box. Instructions appeared on the screen and were supported orally by the experimenter. There were two practice blocks and three experimental blocks. The practice blocks were the same in both the feedback and no-feedback condition. The first practice block consisted of 30 trials without a response deadline. Each trial began with a central fixation cross (500 ms) followed by a stimulus which was presented until a button on the response box was pressed. Immediately after pressing the button the feedback signal appeared on the screen (J for correct, F for incorrect, corresponding to the words ‘juist’ and ‘fout’ in Dutch). This feedback signal was presented for 500 ms, followed by a blank screen for 100 ms, resulting in a total intertrial interval of 600 ms. In the second practice block, 100 trials were presented with a response deadline of 1000 ms. A feedback signal was presented (T, for too slow, ‘te traag’ in Dutch) when the participant did not respond during that interval.

This block was followed by three experimental blocks of 500 trials (200 adaptation trials and 300 experimental trials) each with a short break after every 125 trials. The three blocks corresponded to the frequency manipulation. Only the experimental trials of each block were analyzed. Every participant ran through the 50%, 70% and 90% accuracy conditions. Participants were randomly assigned to one of the two orders of the frequency manipulation. The initial colour brightness was set at 70%, in the 50% condition, at 80%, in the 70% condition and at 90%, in the 90%

condition. Participants in the feedback condition got the same kind of trials as in the second block of the practice trials. In the no-feedback condition new instructions were presented on the screen. Instead of feedback a blank screen was presented for 600 ms. After every fiftieth trial the participants received feedback as follows: “xx% correct trials”.

In the first 200 trials of each block an adaptive program was used in order to know the brightness that was needed to get a specified amount of correct trials in each block (50, 70, or 90%). The adaptive program calculated on every trial the accuracy of the past 20 trials. The brightness of the colours changed when the accuracy deviated from the specified level. For example in the 50% accuracy condition, when more than 10 errors were made in the previous 20 trials the brightness increased. This made the task easier. But when fewer than 10 errors were made the brightness decreased. After those 200 adaptation trials, the brightness stayed the same and was calculated as the average of the brightness of the last 100 trials. After that, 300 experimental trials were presented. The only difference with the adaptation trials was that the stimuli had a fixed brightness.

RESULTS

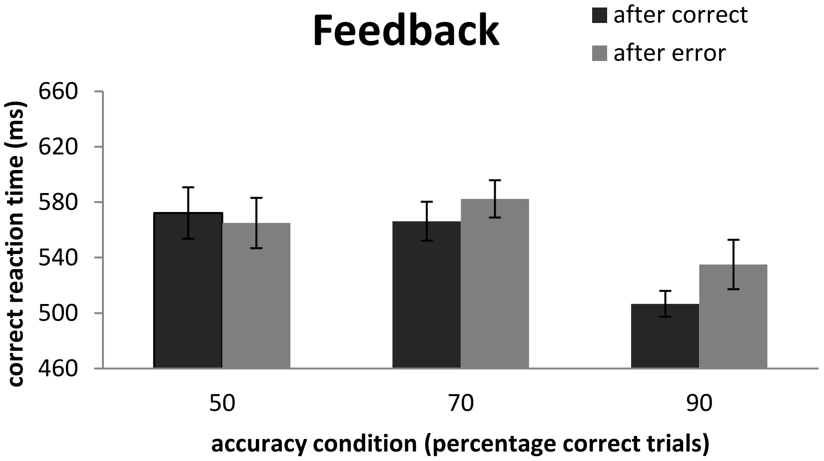
All trials in the practice blocks and the adaptation blocks were excluded from the analysis. Also the trials with RTs faster than 200 ms and RTs exceeding the response deadline and the immediately following trials were excluded. In total 10.60% of the experimental trials were deleted. Both for correct RTs and error proportions a 3 (accuracy conditions) by 2 (accuracy on the previous trial) by 2 (feedback group or no-feedback group) by 2 (order of the accuracy conditions) repeated measures ANOVA was conducted. The order in which the conditions were administered did not yield significant effects; therefore we removed this factor from the presented results. The adaptation procedure worked well in the 90% condition with 92.3% accuracy, but a small deviation was observed in the 50% condition and the 70% condition with 56.5% and 83.8% accuracy.

REACTION TIMES

In correct RTs, there was a main effect of accuracy condition (50%, 70% or 90%), $F(2,56) = 10.96$, $p < 0.001$. Reaction times were fastest in the 90% accuracy condition ($M = 547.73$, $SD = 8.88$) and there was almost no difference between the 50% and the 70% accuracy condition (50: *M* = 587.01, *SD* = 12.34; 70: *M* = 587.63, *SD* = 9.19). This effect did not interact with the feedback condition (*F*(2, 56) < 1, *ns*).

There was a main effect of feedback, *F*(1, 28) = 5.05, $p < 0.05$, as RTs were faster when immediate feedback was provided (feedback: *M* = 554.57, *SD* = 12.32; no-feedback: *M* = 593.72, *SD* = 12.32).

There was an overall post-error slowing effect, *F*(1,28) = 8.20, $p < 0.01$, which interacted with accuracy condition, *F*(2,56) = 5.44, $p < 0.01$. In the 90% accuracy condition we observed post-error slowing (*M* = 30.24, *SD* = 51.23; *t*(31) = 3.34, $p < 0.05$), as well as in the 70% accuracy condition (*M* = 13.43, *SD* = 34.46; *t*(31) = 2.21, $p < 0.05$). No effect was found in the 50% accuracy condition (*M* = -1.90, *SD* = 33.61; *t*(31) < 1, *ns*). Most importantly, post-error slowing did not interact with feedback condition (*F*(1, 28) < 1, ns), and also the three-way interaction was not significant (*F*(2, 56) < 1, ns) (see Figure 1).



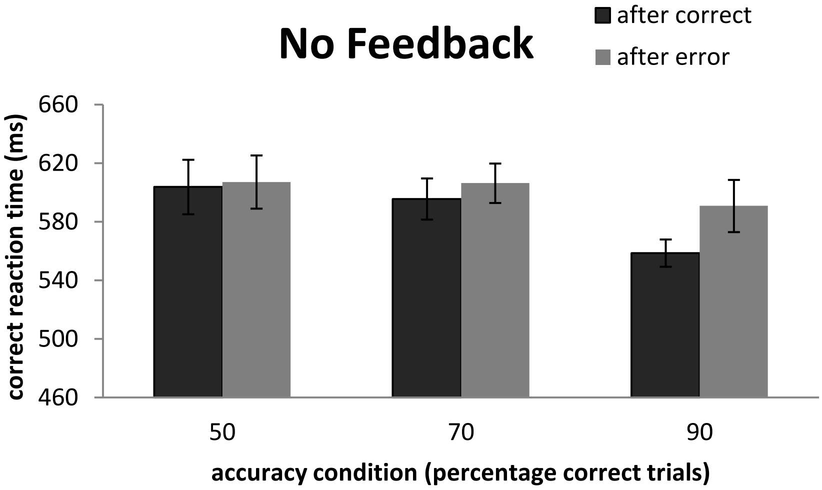


Figure 1. Correct reaction times for trials following correct trials (after correct) and trials following incorrect trials (after error) in the three accuracy conditions (50%, 70% and 90% accuracy). Upper graph: results for the group that received immediate feedback. Lower graph: results for the group that did not receive immediate feedback. Vertical bars indicate two standard errors.

To specifically test increased slowing as a function of accuracy, we tested the linear increase in slowing as accuracy increased. For every participant the post-error slowing effect was calculated per condition and a regression coefficient was calculated. Because we predicted that the regression coefficients would be larger than zero we used a one tailed t-test to test this (see Lorch & Myers, 1990). As predicted, the regression coefficients were larger than zero (M = 80.35, SD = 149.01, $t(31) = 3.05$, $p < 0.01$). A two sample t-test showed that the regression coefficients of both groups (feedback condition and no-feedback condition) did not differ from one another ($t(30) < 1$, ns).

ERROR PROPORTIONS

There was an obvious main effect of accuracy condition, $F(2, 56) = 104.94$, $p < 0.001$. This effect did not interact with the feedback condition ($F(2, 56) = 1.61$, p = 0.21) and there was no main effect of feedback for the error proportions, $F(1, 28) < 1$, *ns*.

Most interesting, there was post-error accuracy *decrease*, $F(2, 28) = 21.22$, $p < 0.001$, with a higher error proportion after errors ($M = 24.6\%$, $SD = 1.1$) than after correct trials ($M = 20.4\%$, $SD = 1.0$) . No interaction with the feedback condition was observed ($F(1, 28) < 1$, *ns*).The interaction between accuracy on the previous trial and accuracy condition, $F(2, 56) = 9.910$, $p < 0.001$, indicates differences in the size of the post-error accuracy decrease. In the 50% accuracy condition post-error accuracy decrease was significant while in the 70% condition this effect was marginally significant and not significant in 90% condition (50%: $M = 8.87$, $SD = 8.12$, $t(31) = 6.18$, $p < 0.001$; 70%: $M = 2.60$, $SD = 8.05$, $t(31) = 1.83$, $p = 0.078$; 90%: $M = 1.04$, $SD = 7.53$, $t(31) = 0.78$, $p = 0.44$). There was no interaction with the feedback condition ($F(2, 56) = 1.513$, $p = 0.223$), as is shown in Figure 2. In order to gain insight in the unpredicted interaction between post-error accuracy changes and accuracy condition we performed an extra analysis. We suspected that the accuracy decrease after errors was affected by the overall error proportions, in the sense that one can expect more double errors in the 50% accuracy condition than in the 70% or 90% accuracy condition. We therefore analysed the error proportion of trials *preceding* an error in the three different conditions and observed that the error proportions of trials preceding an error differed for the three accuracy conditions, $F(2, 56) = 10.62$, $p < 0.001$. The accuracy difference preceding an error or a correct trial was significant in the 50% accuracy condition while this effect was marginally significant in the 70% condition and not significant in 90% condition. This post-hoc analysis clearly indicated that post-error accuracy differences over accuracy conditions are not related to post-error adjustments as exactly the same pattern was observed before the actual error. This suggests that the post-error accuracy decrease differences over accuracy conditions reflect the overall probabilities of error commission.

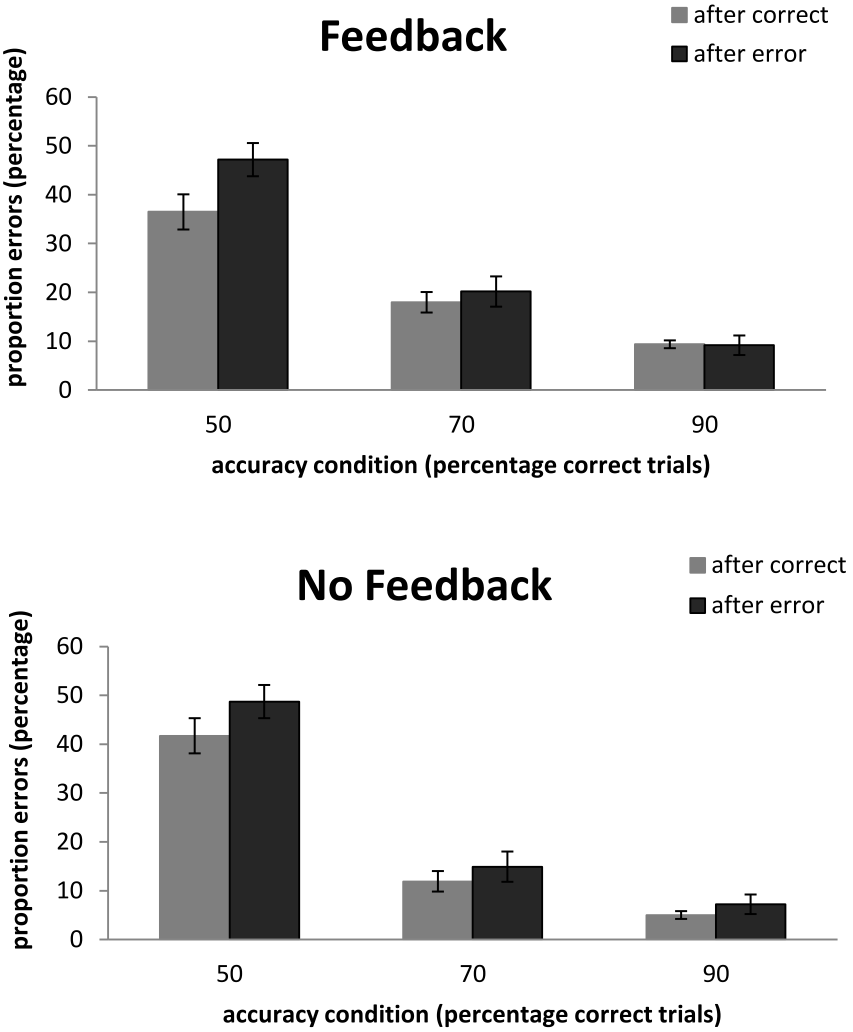


Figure 2. Proportion errors following correct trials (after correct) and following incorrect trials (after error) in the three accuracy conditions (50%, 70% and 90% accuracy). Upper graph: results for the group that received immediate feedback. Lower graph: results for the group that did not receive immediate feedback. Vertical bars indicate two standard errors.

DISCUSSION

The present study aimed to further investigate the orienting account (Notebaert et al., 2009; Núñez Castellar et al., 2010). More precisely, we wanted to examine the effect of external feedback on post-error performance. This was done by testing a group that received external feedback and a group that had to rely on internal monitoring. Additionally, we manipulated error frequency parametrically in order to test predictions made by the orienting account.

As predicted by the orienting account, the size of the post-error slowing depends on the error frequency, replicating previous studies (Notebaert et al., 2009; Núñez Castellar et al., 2010). When only few errors are made, the orienting response is large because infrequent errors elicit a large surprise effect. In that case, attention is distracted from the task and RTs to the following stimulus are delayed. When errors become more frequent, they become less surprising or unexpected and they receive less attention resulting in better performance on the following trial. The linear increase in post-error slowing from 50% over 70% to 90% nicely demonstrates the effect of error frequency and surprise.

Most importantly, this linear increase was essentially the same in the condition without immediate feedback. This suggests, at least within the framework of the orienting account, that orienting to internally detected errors and externally indicated errors is similar. One possible interpretation for this finding is that the orienting response is triggered by the internal error signal, even in the condition with feedback. This interpretation can be supported by the findings of a recent study showing that if, occasionally, false error feedback is delivered, post-error slowing is present only after incorrect responses but not after correct responses (de Bruijn, Mars, & Hulstijn, 2004). Likewise, in a recent study where errors were inserted during type writing, it was found that although participants in general accepted the authorship for inserted errors, post-error slowing was found only following actual committed errors but not after inserted errors (Logan & Crump, 2010). These studies suggest that internal error detection is more important than feedback. On the other hand, we have already described slowing after completely irrelevant but infrequent feedback signals and after infrequent correct feedback (Notebaert et al., 2009). Consequently, it appears that slowing can occur following internal and external infrequent signals. However, it is important to keep in mind that feedback was manipulated between subjects. It should be investigated whether these conclusions remain the same when feedback is manipulated within subjects.

Interestingly, ERP studies have described two components locked to either the onset of error responses or to the onset of error feedback: the error positivity (Pe) and the P3, respectively. Recent findings suggest that the Pe can be considered as a P3-like component associated with the motivational significance of an error (Overbeek, Nieuwenhuis, & Ridderinkhof, 2005; Ridderinkhof, Ramautar, & Wijnen, 2009). Given that the P3 component has been consistently linked to the allocation of attention, we think that both components, Pe and P3, reflect attentional capture by errors as infrequent events. In fact, several studies have found a close relationship between the slowing following an error and the amplitude of the Pe (e.g., Nieuwenhuis et al., 2001; Hajcak, McDonald, & Simons, 2003). Similarly, a recent ERP study has shown that when feedback is presented after every response, the P3 amplitude is correlated with the slowing in the subsequent trial (Núñez Castellar et al., 2010). In the near future we will further investigate this idea by examining the neural correlates of the slowing when feedback is delivered versus when it is not, and test experimentally whether we can find evidence for the uniformity of the Pe and the P3 components in relation to the slowing.

Recent fMRI studies (King, Korb, von Cramon, & Ullsperger, 2010; Danielmeier, Eichele, Forstmann, Tittgemeyer, & Ullsperger, 2011) that investigated the relation between posterior medial frontal cortex activity and post-error behaviour observed a relationship between post-error slowing and decreased motor activation. Although this could be interpreted in terms of a motor inhibition account (Danielmeier et al.), it is also possible that the distraction on the basis of the infrequent error results in decreased motor activation. Considered this way, both post-error slowing and decreased motor activation could be the result of the orienting. Another goal of this study was to investigate possible changes in accuracy after errors. In the 50% accuracy condition a significantly higher chance of committing an error after an error compared to after a correct response was found. This post-error accuracy decrease was not observed in the 70% and the 90% condition. An additional analysis, however, indicated that this interaction was also observed prior to the error. This indicates that this interaction was caused by the overall likelihood of double errors which is much higher in the 50% condition. Importantly, while this analysis indicates that comparing the accuracy effects over conditions should be avoided, the overall pattern suggests that there is absolutely no support for an accuracy increase after errors. These findings are in line with several studies that also failed to find a post-error accuracy increase (Hajcak et al., 2003).

The increase in post-error slowing with increasing accuracy was explicitly predicted by the orienting account but also the model of Holroyd and Coles (2002; Holroyd, Yeung, Coles, & Cohen, 2005) can capture these data. In conditions where errors are infrequent, the learning signal derived from infrequent errors will be larger and slowing could be larger. However, when post-error slowing is the result from learning processes one would expect reduced error rates after errors, which is not observed. On the other hand, we would like to argue that with longer intertrial intervals, the orienting response is indeed the first step in a learning processes aimed at improving performance. Jentzsch and Dudschig (2009) for instance, demonstrated that with short intervals slowing was accompanied with accuracy decrease which was not observed with longer intervals. In order to investigate a possible integration of the orienting account and Holroyd and Coles' model, more empirical work is necessary.

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CHAPTER 4

THE P_E AS AN INDEX OF INTERNAL ORIENTING TO ERRORS[3]

Understanding the link between neural correlates of error commission and behavioural adjustments afterwards is central for understanding error monitoring. In previous studies, we demonstrated that post-error slowing (PES) was modulated by participants' error frequency with more PES when errors were less frequent (Houtman, Nùñez-Castellar, & Notebaert, 2012). We observed PES when errors were unexpected and we even observed post-correct slowing when correct responses were unexpected (Notebaert et al, 2009). In an EEG study, we replicated this finding and showed that the P3 followed this pattern, but the ERN and the FRN did not, which was interpreted in terms of orienting towards unexpected errors (Nùñez-Castellar, Kühn, Fias, & Notebaert, 2010). In this study we investigated the influence of error frequency after errors without immediate feedback both on brain and behaviour. Error frequency was manipulated by creating an easy and a difficult version of a flanker task. Surprisingly, we did not find a difference in PES between both conditions. The P_E *and the ERN, however, were larger in the easy condition where errors were more infrequent, but only the* P_E *effect was specifically related to the error rate difference between both conditions. Additionally, across participants, PES correlated with the amplitude of the* P_E *in the difficult condition. The results are interpreted in favour of the orienting account for PES and in terms of a functional similarity between the P3 when feedback is presented and the* P_E *when no performance feedback is presented.*

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[3] Houtman, F., Van der Borght, L., & Notebaert, W. The P_E as an index of internal orienting to errors.

INTRODUCTION

In order to behave adaptively to the requirements of the environment it is necessary to monitor external and internal signals that point out the need for adjustment. In this study, we investigate the relation between neural correlates of such signals and the behavioural consequences of the actual adjustment. In a previous study, we demonstrated that feedback-related P3 activity correlated with subsequent post-error slowing (PES) (Nùñez-Castellar, Kühn, Fias, & Notebaert, 2010). In this study, no feedback is presented and we investigate the relationship between neural correlates of internal error detection and subsequent reaction times.

Although many signals indicate that performance is suboptimal and cognitive adjustments are required, the detection of an error is probably the most important signal. According to many, PES (slower RTs after errors than after correct trials) is the prototypical result of cognitive adaptation after errors. In the conflict monitoring theory (CMT) (Botvinick, Braver, Barch, Carter, & Cohen, 2001), an error is detected as co-activation of two or more responses and leads to increased cognitive control. Increasing cognitive control is done by heightening the response threshold. Similarly, the inhibition account (Ridderinkhof, 2002; Marco-Pallares, Camara, & Münte, 2008), suggests that error commission leads to selective suppression or inhibition of motor processes.

In scalp-recorded EEG, response-locked error-related activity is usual found as two subsequent waves. First there is a negative voltage deflection in the event-related brain potential peaking between 0 en 100ms after the erroneous response and thought to be generated by the anterior cingulate cortex (ACC) (Dehaene, Posner, & Tucker, 1994; Dikman & Allen, 2000; Gehring, Himle, & Nisenson, 2000) usually referred to as the error-related negativity (ERN; Gehring, Coles, Meyer, & Donchin, 1990) or the error negativity (N_E; Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991). This is followed by a slow positive wave with maximum amplitude between 200 and 400 ms and a more diffuse scalp distribution (Falkenstein, et al., 1991), which is referred to as the P_E. The ERN/N_E was originally described as a mismatch signal when the representation of the desired response did not match with the representation of the actual response. Whereas the P_E was attributed to additional processes like for example error recognition (Falkenstein et al, 1991; Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001). For the remainder of the paper we will use the term ERN to refer to the ERN/ N_E.

The P_E has been related to the P3, a positive stimulus-locked slow wave appearing between 200 and 400 ms after stimulus onset (Yeung, Holroyd, & Cohen, 2005). The P3 has generally been associated with the processing of unexpected events (Sutton, Braren, Zubin, & John, 1965; for a review, see Nieuwenhuis, Aston-Jones, & Cohen, 2005). Later on, the P3 has been subdivided into two subcomponents, namely the P3a and the P3b. Whereas the P3a is more sensitive to the novelty of events (Friedman, Cycowicz, & Gaeta, 2001) the P3b is ought to be sensitive to the amount of attentional resources allocated to a stimulus (Polich, 2007). In a study of Ridderinkhof, Ramautar, and Wijnen (2009) the relation between and P3 was investigated. The amplitude of the P_E in a Simon task covaried with the effect of a manipulation known to influence stimulus saliency as reflected in the P3. Davies, Segalowitz, Dywan, and Pailing (2001) also reported a correlation between the size of the stimulus-locked P3 and the response-locked P_E in a Flanker task. It seems that the P_E is a P3-like reaction to the motivational and salient nature most errors have.

In the present paper, we are especially interested in the relation between these brain components and behaviour. Nùñez-Castellar and colleagues (2010) reported that the amplitude of the feedback-locked P3 correlated with the size of the post-error and the post-correct slowing, unlike the amplitudes of the ERN and the FRN (i.e. a feedback-locked ERN-like brain wave). In the condition with 75% correct trials, PES was observed and the amplitude of the P3 was larger after error feedback than after correct feedback. In the condition with 35% correct trials the reverse was found: post-correct slowing was observed and P3 amplitude was higher for unexpected correct trials. These results are explained with the orienting account that explains PES in terms of the orienting to unexpected events (Notebaert et al., 2009; Houtman, Nùñez-Castellar, & Notebaert, 2012).

In experiments without immediate feedback, the results are less clear. Some studies report an association between the amplitude of the ERN and PES (Hewig, Coles, Trippe, Hecht, & Miltner, 2011; Compton et al., 2008, Debener et al., 2005), whereas other studies fail to find this (Endrass, Reuter, & Kathmann, 2007; Gehring & Fencsik, 2001; Hajcak, McDonald,

& Simons, 2003). Furthermore, the ERN has also been reported in the absence or reduction of PES (Mathalon, Faustman, & Ford, 2002; Nieuwenhuis et al., 2001; Wiersema, van der Meere, & Roeyers, 2005). The P_E on the other hand, seems to be more related to behavioural measures associated with error monitoring. In a study where unperceived errors are not followed by PES (Nieuwenhuis et al., 2001) also no P_E is found. In one study PES correlates positively with P_E amplitudes (Hajcak et al., 2003), whereas it does not correlate with the number of errors that are made.

In this experiment we further investigated the relation between neural correlates of internal error detection (without feedback) and behavioural adjustments. Recently, we demonstrated that also without feedback, error frequency determines the size of PES (Houtman et al., 2012). Therefore, we applied a similar logic as Nùñez-Castellar et al. and manipulated task difficulty in order to influence error frequency. Moreover, we predicted higher PES in the easy condition than the difficult condition. Given the presumed relation between P_E and P3, we predict an increased P_E in the easy condition that should directly be related to the error-rate difference between both conditions. Because we can also expect considerable across-participant variability in error rates within conditions, we will also correlate individual accuracy rates, PES indices, ERN and P_E.

METHOD

PARTICIPANTS

Sixteen participants participated in the experiment. Every participant gave written informed consent. The study was approved by the ethical committee of the Faculty of Psychology and Educational Sciences of Ghent University. They all had normal or corrected to normal vision and were neurologically and psychiatrically healthy. Participants were paid 15€ per hour.

PROCEDURE

The participants were seated in a comfortable armchair in a light-dimmed and sound-attenuated room. They were tested on a Pentium IV personal computer with a 17-inch monitor running Tscope (Steven, Lammertyn, Verbruggen & Vandierendonck, 2006). Participants had to press two buttons on a Cedrus response box to give a manual response with the left and right index fingers. The classical flanker task was modified in order to create two conditions that differed in difficulty. There were four blocks in the experiment, two easy blocks and two difficult blocks. Half of the participants started with an easy block, followed by a difficult, an easy and again a difficult block. In the other half of the group this order was reversed. The response mapping was randomly picked in each block, with the restriction that that particular response mapping was not used in an earlier block for that particular participant. In the easy condition the stimulus-response mapping was 2:1, whereas in the difficult condition the stimulus-response mapping was 4:1. In each of the blocks 512 trials were presented. Each block started with the presentation of the response mapping. After every 128th trial there was a break. During the self-paced break feedback about the past 128 trials was presented in the form of the percentage correct responses and the percentage too slow responses. As a reminder the response mapping of the current block was shown again.

In the easy condition there were four possible stimuli, namely: {, }, [and]. The curly brackets were mapped on one response button and the blocked brackets on the other response button. In each trial one target stimulus flanked by four, two on each side, stimuli were presented. Fifty percent of the trials were congruent trials; in this case all 5 presented stimuli were the same. And 50% of the trials were incongruent trials; in that case the target and the flanker stimuli were different. There was one restriction; flanking stimuli were always stimuli that needed another response. This means that there were only response-incongruent trials and no stimulus-incongruent trials. For example, when participants had to respond to curly brackets by pressing the right button and to blocked brackets by pressing the left button, an incongruent trial could look like this {{]{{ but never like this {{}{{. In the difficult condition there were 8 possible stimuli, namely {, }, [,], (,), | and ¦. Four stimuli were mapped on the left response button and four on the right response button. Again there were no stimulus-incongruent stimuli, but only incongruent stimuli at response level.

The stimulus was presented centrally on a blank screen for 145 ms or until a response button was pressed. Participants had a maximum response time of 800 ms. After the response was given or when the response deadline was reached there was an inter trial interval of 1100 ms. During the inter trial interval the screen was blank.

ELECTROPHYSIOLOGICAL RECORDINGS

EEG data were recorded using the BioSemi ActiveTwo system (Biosemi, Amsterdam, Netherlands). With active scalp electrodes 64 channels of EEG data (10–20 system positions) were recorded at a rate of 1024 Hz per channel (filters: DC to 268 Hz, 3 dB/octave). The vertical electrooculogram (VEOG) was recorded by means of a single electrode placed just below the left eye. The horizontal electrooculogram (HEOG) was measured with two electrodes positioned on the two outer canthi. Off-line, the data were referenced to the right mastoid.

DATA ANALYSIS

ERPs

The ERP analyses were done in Matlab (www.mathworks.com) with the academic freeware toolboxes EEGLAB (http://sccn.ucsd.edu/eeglab) and ERPLAB (http://erpinfo.org/erplab). The continuous EEG signal was filtered off-line with a high-pass filter of 0.16 Hz and down-sampled to 256 Hz. Independent component analysis (ICA) was conducted to identify and remove stereotypical eye blink components.

The EEG was segmented into condition-related epochs time-locked to the response, starting from 300 ms before until 1400 ms after the response. Then, averages for error and correct responses were derived separately. The resulting ERPs were baseline-corrected using the 300 ms pre-stimulus window. In line with previous investigations (e.g., Olvet & Hajcak, 2009), the ERN was measured as the mean amplitude in a time-window between 0 and 50 ms after the incorrect response at electrode FCz. For the CRN, we calculated the amplitude in the same time-window following on correct responses. For the P_E analysis the mean amplitudes in the time-window of 200ms to 400ms after errors and correct responses at electrode Pz were calculated separately.

RESULTS

BEHAVIOURAL DATA

Manipulation check

In order to verify that the manipulation lead to different levels of difficulty measured in error rates a paired-sample t-test was done on the error rates in the easy condition and in the difficult condition. Participants made more errors (*M* = 29%) in the difficult condition than in the easy condition (*M* = 20%), *t*(15) = 5.227, *p* < .001. Overall, reaction times were faster in the easy condition (*M* = 453 ms, *SD* = 11) than in the difficult condition (*M* = 500 ms, *SD* = 15), *F*(1, 15) = 52.749, *p* < .001. Erroneous responses (*M* = 469 ms, *SD* = 14) were faster than correct responses (*M* = 483 ms, *SD* = 12), *F*(1, 15) = 11.273, *p* < .01. There was no interaction effect of condition and accuracy, *F* < 1. This means that the errors in both conditions were comparable, at least in terms of response speed.

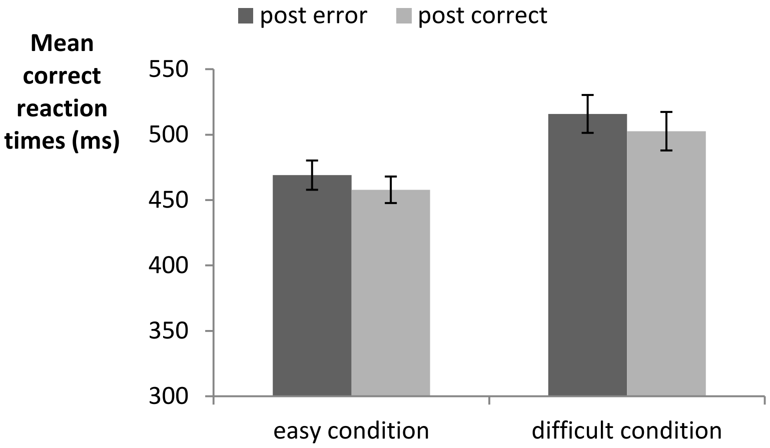

Figure 1. Post-error and post-correct reaction times. Generally, responses are slower in the difficult condition than in the easy condition. The post-error slowing effect, however, is the same in both conditions.

Post-error adjustments.

In order to test for post-error slowing, both error rates and correct reaction times were analysed with rm ANOVAs. The within-subject factors were condition and previous accuracy. In the correct reaction times an overall effect of PES was found, $F(1, 15) = 9.934$, $p < .01$. Responses after making an error were slower ($M = 492$ ms, $SD = 12$) than after a correct response ($M = 480$ ms, $SD = 12$). Contrary to our expectations (see Figure 1), there was no modulation of the PES effect by the difficulty manipulation, $F < 1$. As was already shown in the previous analysis, correct reaction times were faster in the easy condition ($M = 463$ ms, $SD = 10$) than in the difficult condition ($M = 509$ ms, $SD = 14$), $F(1, 15) = 41.747$, $p < .001$. In the error rates analysis no effect of the accuracy of the previous trial or an interaction effect was found, respectively $F(1, 15) = 1.445$, $p = .248$ and $F < 1$. As expected, error rates in the easy condition were lower than in the difficult condition, $F(1, 15) = 25.712$, $\mathrm{p} < .001$.

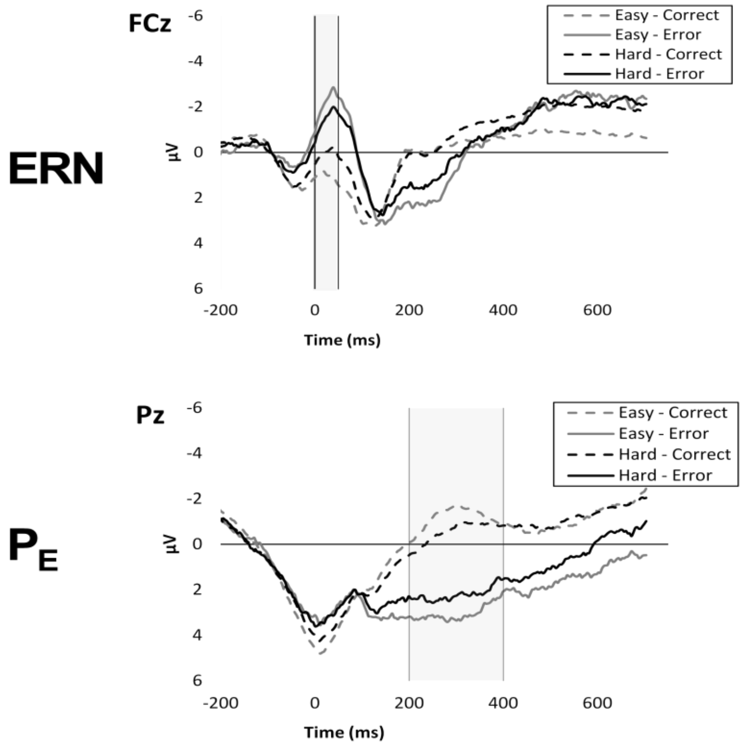

Figure 2. Grand average ERP waveforms at FCz (top figure) and Pz (bottom figure) as a function of accuracy of the response and difficulty condition. Both the ERN and the P_E are larger in the easy condition compared to in the difficult condition

ERPS

P_E

The mean amplitudes at Pz between 200ms and 400ms after response per condition and per accuracy were subjected to an rm ANOVA. There was no main effect of condition, $F < 1$. The significant effect of the accuracy, $F(1, 15) = 35.324$, $p < .001$, shows the P_E because the mean amplitude after an error was more positive ($M = 3.198$, $SD = 0.7$) than after a correct response ($M = -0.159$, $SD = 0.8$). Most importantly, there was an interaction effect of condition and accuracy, $F(1, 15) = 7.289$, $p < .02$. As can be seen on Figure 2, the P_E was larger in the easy condition (error related: $M = 3.578$, $SD = 0.7$ vs. correct related: $M = -0.485$, $SD = 0.8$) than in the difficult condition (error related: $M = 2.818$, $SD = 0.8$ vs. correct related: $M = 0.166$, $SD = 0.8$). In order to verify whether the difference between the easy P_E and the difficult P_E was linked to the difference in error rates, we performed a correlation analysis between participants' difference in error rates between conditions and participants' difference in P_E between conditions. This correlation revealed that the difference in P_E was indeed tied to differences in error rates, $r(16) = -.608$, $p = .013$, see Figure 3.

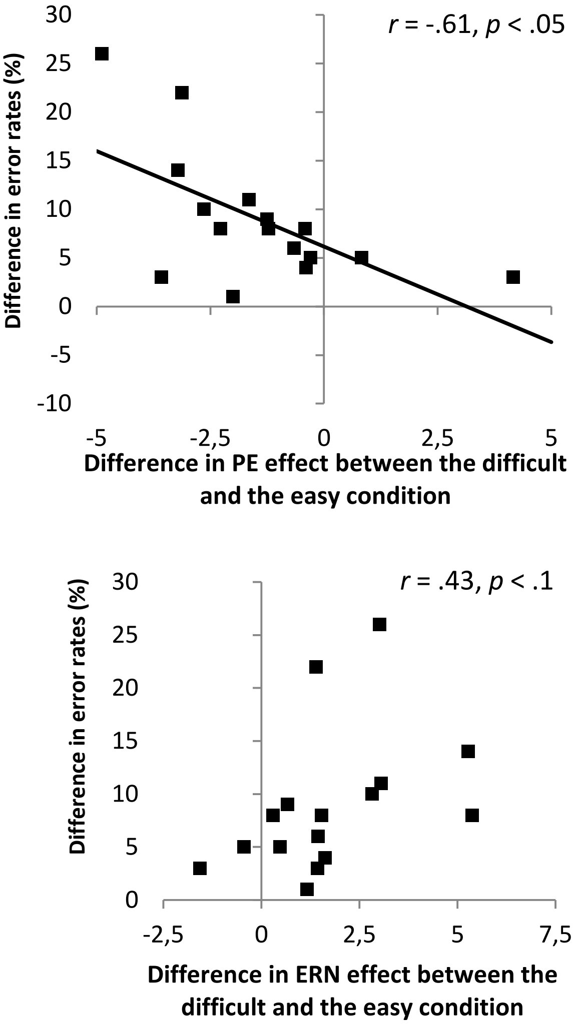

Figure 3. Scatter plots of the differences in error rates between both conditions and the differences in P_E (on the left) and the differences in ERN effect (on the right).

ERN

A 2 (condition: easy, difficult) by 2 (accuracy: correct, error) rm ANOVA revealed a main effect of accuracy, *F*(1, 15) = 32.739, *p* < .001. The mean amplitudes were more negative for errors (*M* = -1.786, *SD* = 0.6) than for correct responses (*M* = 0.658, *SD* = 0.6). There was also a significant interaction between the condition and the accuracy of the response, *F*(1, 15) = 13.913, *p* < .01. The difference between the ERN and the CRN was much larger in the easy condition (ERN: *M* = -2.155, *SD* = 0.5 vs. CRN: *M* = 1.151, *SD* = 0.7) than in the difficult condition (ERN: *M* = -1.417, *SD* = 0.6 vs. CRN: *M* = 0.164, *SD* = 0.5), as can be seen on Figure 4. There was no main effect of condition, *F* < 1. In order to verify whether this difference was associated with the difference in terms of error rates we correlated participants' difference score in terms of error rates and difference score in terms of ERN effect (ERN-CRN). The scatter plot is presented in Figure 3. This analysis revealed a marginally significant correlation, *r*(16) = .427, *p* = .099, not allowing strong conclusions.

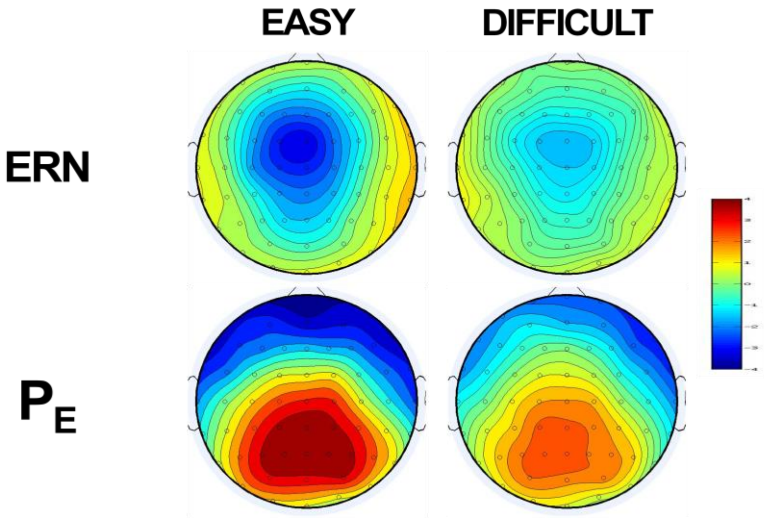

Figure 4. Voltage scalp maps show activation evoked by making an error as the difference between making an error minus responding correctly at different time intervals after response. A larger ERN is shown 0-50 ms after response in the easy condition than in the difficult condition. The same was found for the P_E in the 200-400 ms interval.

The data show that while the ERN and the P_E are influenced by our difficulty manipulation, PES is not. However, only for the P_E, we have support for the claim that P_E differences are really linked to differences in error frequencies. Finally, we tested whether error frequency *within each condition* has an effect on PES and neural indices of error monitoring. Again, we calculated the ERN by subtracting the mean amplitudes on correct trials from the mean amplitudes on error trials. The same procedure was done to calculate the P_E. Importantly, within conditions, PES was influenced by error frequency, see Figure 5. In the difficult condition a negative correlation between PES and the mean error rates was found, $r(16) = -.546$, $p = .029$. In the easy condition there was a marginal correlation, $r(16) = -.469$, $p = .067$. As predicted by the orienting account, the more errors that participants make, the smaller their PES becomes.

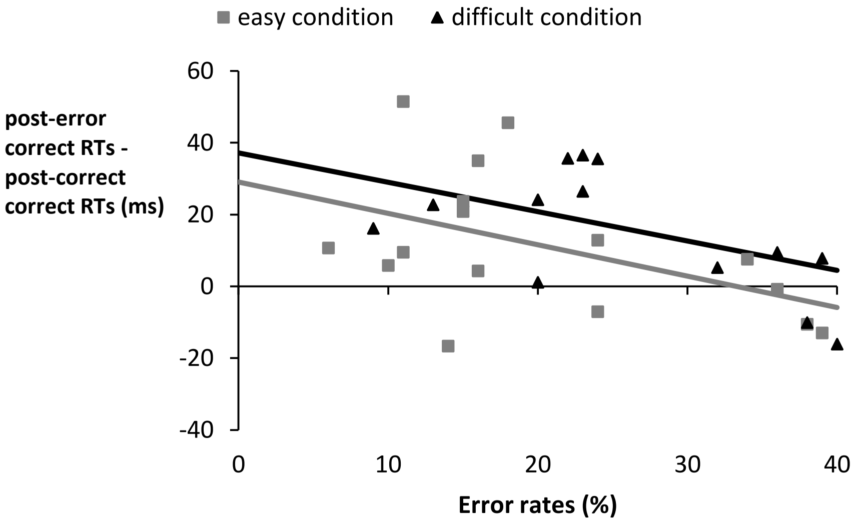

Figure 5. The scatter plot of mean error rates and the difference between correct RTs after correct response and after errors (PES) both for the easy and for the difficult condition. Making more errors goes together with a smaller PES effect, in both conditions.

Mean error rate within conditions also influenced the size of the ERN effect. The size of the ERN in the hard condition correlated positively with the percentage errors in that condition, $r(16) = .754$, $p < .01$. This means that the more errors that were made, the smaller the ERN effect became. In the easy condition there was a marginal significant correlation, $r(16) = .458$, $p = .074$.

The mean error rates in the easy condition correlated negatively with P_E, $r(16) = -.585$, $p = .017$. In other words, participants with higher error rates had a lower P_E. The same negative correlation was found in the difficult condition, $r(16) = -.863$, $p < .001$.

Most interestingly, PES correlated with the P_E, at least in the hard condition, $r(16) = .571$, $p = .021$. Participants that show a large P_E also have increased PES, as can be seen in Figure 6. In the easy condition PES did not correlate with the P_E, $r(16) = .138$, $p = .610$. PES did not correlate with the ERN, not in the easy condition, $r(16) = -.386$, $p = .140$, nor in the hard condition, $r(16) = -.253$, $p = .345$.

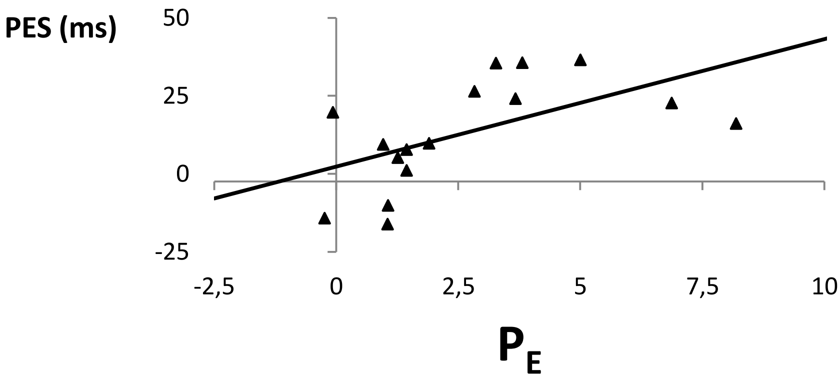

Figure 6. PES correlates only in the difficult condition with the amplitudes of the P_E.

DISCUSSION

In this ERP-study, task difficulty was manipulated in order to investigate post-error behavioural adjustments and neural correlates of error processing. The difficulty manipulation was established by creating a condition with a 2:1 stimulus response mapping and a more difficult condition with a 4:1 stimulus response mapping. More errors were made in the difficult condition than in the easy condition, although this effect was not large (on average 9% more errors in difficult condition).

Unexpectedly, PES did not depend on error frequency, at least not on group level. The orienting account would predict that overall PES is smaller in the difficult condition than in the easy condition because there is a significant difference in error frequency between both conditions (21% in the easy condition vs. 30% in the difficult condition). It is possible that the difference of 9% errors between both conditions was not sufficiently large to impact PES on a group level. In previous studies where we also manipulated error frequency we consistently observed an effect on PES. In conditions where errors outnumbered correct response, post-correct slowing was found (Notebaert et al., 2009, Nùñez-Castellar et al., 2010, 2011). In a study where error frequency was manipulated in three conditions (50%, 30% and 10% errors) PES was largest in the 10% error conditions, smaller in the 30% condition and no PES effect was found in the 50% errors condition. Although the effect of the error frequency manipulation on PES was absent on group level, we did find an effect on the individual level. The correlation analyses showed that, in both conditions, participants with the highest error rate also showed the smallest PES. The same effect was reported in an article by an independent research group (Steinborn, Flehmig, Bratzke, & Schröter, 2012). Although there was a rather small range in accuracy rates (94% to 99%), also in that study high accuracy rates resulted in large PES.

The difficulty manipulation did have an impact on the error-related ERP measures. Both the ERN and the P_E were more pronounced in the easy condition than in the difficult condition. Interestingly, only the P_E effect was directly related to the differences in error rates between both conditions. Within conditions, both neural indices were related to participants' error rates, but only P_E and PES correlated.

Our results therefore add to the cumulative evidence that the P3 and the P_E are neural correlates with very comparable functionalities. Both ERP measures covary with the saliency of an event. In the study of Nùñez-Castellar et al. the P3 was largest after the least frequent feedback in a particular condition. Similarly, in our study the P_E was largest in the condition with less error rates and largest for participants with the smallest error rate. Falkenstein, Hoormann, Christ, and Hohnsbein (2000) already suggested that the P_E might reflect the subjective significance of an error. Or as Falkenstein et al. (pp. 104) stated: *“For subjects who commit errors often, an error has probably less subjective and emotional significance than for subjects who commit errors only rarely, which is reflected in a small amplitude of the P_E”.* They found that the P_E was larger in a subgroup performing better (6% errors) than in the other subgroup (20% errors), there was however no difference in the amplitude of the ERN in both subgroups. This study was done with only 5 participants in each subgroup. By replicating this finding with a larger group and a within-subjects manipulation we provide further evidence that the P_E is a neural correlate of the significance of an error. Studies arguing that the P_E reflects the awareness of an error (Nieuwenhuis et al., 2001) do not contradict our finding. The more significant an error is to you, the more aware you probably are that you made that error. It is important to remark that the relationship between P_E and PES was only observed in the difficult condition. One of the reasons could be that PES is calculated more reliably when more errors occur, this is also suggested by that fact that the correlation between error rates and PES was significant in the difficult condition, and only marginally significant in the easy condition. Alternatively, one could argue that the restricted accuracy range in the easy condition makes it more difficult to find any reliable correlations within this condition.

The relation between error frequency, ERN and PES is less straightforward. Although the ERN was larger in the condition with fewer errors, the difference scores between both conditions of these two measures were not directly correlated. On the other hand, within the difficult condition there was a correlation between error frequency and ERN. However, there was no correlation between ERN and PES. Consequently, it seems that also the ERN is linked to overall performance statistics but not directly to error frequency, and clearly not to PES. An explanation for our results is provided by the reinforcement theory of Holroyd and Coles (2002). Within this framework, the ERN is a reinforcement learning signal. Based on this theory one could argue that in the difficult condition the expectations about performance are lower and therefore the ERN is smaller. Note that the ERN is in fact the difference between the ERN and the CRN, and our study nicely demonstrates that when more errors are made, the ERN decreases while the CRN increases, resulting in a smaller (difference) ERN. This pattern of results can also be interpreted in terms of the ERN as an index of cognitive conflict (Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004; Cavanagh, Cohen, & Allen, 2009). In the easy condition correct trials presumably evoke less conflict because of the simple mapping rule resulting in fast RTs, low error rates and a small CRN. Errors in this condition, however, evoke more response conflict, and therefore an increased ERN effect, because there is more chance that both responses were simultaneously activated. Nùñez-Castellar et al. also observed a modulation of the ERN when manipulating error frequency: only in the condition with more correct trials than errors, the ERN was observed, in the condition with more errors than correct trials, there was no ERN. In this study, the difficult condition was very difficult (in order to have a condition with more errors than correct trials). It is likely that in this condition, the response conflict was as large on correct trials as on incorrect trials, yielding no difference between the CRN and the ERN. However, just as in our study, there was no direct link between the ERN and PES.

This is consistent with a study of Nieuwenhuis et al. where no difference in ERN between aware and unaware errors was observed, whereas there was a difference in PES and P_E. This finding indicates that ERN does not depend on error awareness and presumably reflects the detection of response conflict or other indications of internal processing. Similar findings were reported in the study of Hajcak et al. (2003) where skin conductance (SCR) correlated with the P_E and PES but not with the ERN. The increased SCR is one of the autonomic responses (others are pupil dilation and heart rate deceleration) known to occur during an orienting response.

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CHAPTER 5
BLINDED BY AN ERROR[4]

Errors are typically followed by a series of behavioural changes. Although most of these changes are well understood, accuracy changes following errors are not. A new paradigm is presented where participants performed a flanker task followed by a rapid serial visual presentation (RSVP) of numbers (1-9). In most trials, a letter was presented on three possible positions of the RSVP (1-3-6). This was done with and without immediate feedback on the flanker task. In both experiments participants had worse target detection after an error in the flanker task. These findings support non-functional accounts for error monitoring that predict decreased post-error performance (Jentzsch & Dudschig, 2009; Dudschig & Jentzsch, 2009; Notebaert et al., 2009). In a third experiment we tried to dissociate between a bottleneck and an orienting account and showed decreased target detection after irrelevant red signals, irrespective of frequency. This result is interpreted in support for the bottleneck account (Jentzsch & Dudschig, 2009; Dudschig & Jentzsch, 2009).

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[4] Houtman, F. & Notebaert, W. Blinded by an Error. *In Press in Cognition.*

INTRODUCTION

Several behavioural and neural correlates of error commission have been described in the literature. For instance, heart rate deceleration (Danev & de Winter, 1971), pupil dilation (Critchley, Tang, Glaser, Butterworth, & Dolan, 2005) and a larger skin-conductance response (O'Connell et al., 2007) have been reported to follow an erroneous response. Event-related potential (ERP) studies on the other hand, demonstrate error-related negativity (ERN) peaking frontally within 50 to 200 ms after an error (for a recent review see Hajcak, 2012), followed by a more posterior error-related positivity that peaks between 200 and 400 ms after an error. In addition to measures taken at the time of error commission, behaviour after making an error has also been investigated thoroughly. Three hallmarks of behaviour following an error are post-error slowing, post-error reduction of interference and post-error improvement in accuracy (PIA). Post-error slowing (PES, e.g. Rabbitt, 1966; Laming, 1968; Debener et al., 2005) refers to the finding that people respond slower following an error than after a correct trial. PES has been shown to be reliable over periods ranging from 20 minutes, a couple of weeks (Segalowitz et al., 2010) to several months (Danielmeier & Ullsperger, 2011). The second behavioural post-error effect is observed in congruency tasks such as the flanker task (Eriksen & Eriksen, 1974), where participants have to categorize a centrally presented target that is flanked by stimuli associated either with the correct response (congruent) or the incorrect response (incongruent). In these tasks, it is observed that the interference effect, i.e. slower and less accurate responses to an incongruent stimulus compared to a congruent stimulus, is reduced after errors (Ridderinkhof et al., 2002). This effect is known as post-error reduction of interference (PERI). Several studies indicate that PES and PERI are independent (although Carp and Compton, 2009 found a correlation) and are produced by different neuronal networks (De Bruijn, Hulstijn, Verkes, Ruigt, & Sabbe, 2004; Ridderinkhof, 2002; King, Korb, von Cramon, & Ullsperger, 2010). The third behavioural finding is the observation that errors are followed by improved accuracy (e.g. Laming, 1968; Marco-Pallares, Camara, Munte, & Rodriguez-Fornells, 2008; Maier, Yeung, & Steinhauser, 2011). This finding, however, is not universal as some studies reported no difference between post-error and post-correct accuracy (e.g. Hajcak, McDonald, & Simons, 2003; King et al., 2010) while others reported a decline in accuracy directly after an error (e.g. Rabbitt & Rodgers, 1977; Cheyne, Carriere, & Smilek, 2009; Steinborn, Flehmig, Bratzke, & Schröter, 2012). PIA does not correlate with PERI (King et al., 2010) and also PES does not always correlate with PIA (Carp & Compton, 2009; King et al., 2010; Danielmeier, Eichele, Forstmann, Tittgemeyer, & Ullsperger, 2011; Cohen, & van Gaal, 2012). Hajcak and colleagues (2003) did find a positive correlation between PES and PIA where greater PES resulted in improved post-error accuracy. Taken together, the behavioural findings concerning PIA are not unequivocal. As Danielmeier and Ullsperger mentioned in their review (2011), PIA research is highly influenced by overall accuracy rates in an experiment as chances of committing double errors are higher when more errors are made.

Understanding post-error accuracy changes, however, is very important because it can be used to distinguish between functional and non-functional theories for PES. Functional theories hold that error processing and subsequent adjustments are intended to improve performance on the following trial(s). In this light, PES is functional in the sense that it increases response caution. Perhaps the best-known example of a functional framework is the conflict monitoring theory, although this theory is even better known for conflict monitoring (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, Cohen, & Carter, 2004). Within this framework, an error results in co-activation of two or more responses, which is recognized as conflict. Conflict detection increases cognitive control by increasing the response threshold resulting in slower and more accurate performance. Dutilh and colleagues (2012) recently provided support for increased response caution following errors in a lexical decision task, by means of diffusion modeling. The inhibition account (Ridderinkhof, 2002; Marco-Pallares et al., 2008) has much in common with the conflict monitoring theory. It states that after error commission selective suppression or inhibition of response activation occurs. In support for this account, PES correlates with an increase in beta band power that is associated with motor inhibition processes (Marco-Pallares et al., 2008; Kühn et al., 2004; Swann et al., 2009). Another well known functional theory integrates findings on reward processing and reinforcement learning (the reinforcement learning theory: Holroyd & Coles, 2002). Studies on reward processing in primates show a phasic increase or decrease in activity of the dopamine system when events are better or worse (respectively) than expected (Schultz, 2000, 2002). In most cases, errors are events that are worse than expected. These dopaminergic reinforcement signals are used for selecting and reinforcing the motor controllers to perform the ongoing task optimally. All of the functional accounts share the common idea that PES is a compensatory, adaptive mechanism aimed at improving performance.

Non-functional theories, on the other hand, explain PES in terms of reduced cognitive processing after errors. Typically, these accounts predict PES and post-error accuracy *decrease*. The bottleneck error-monitoring theory (Jentzsch & Dudschig, 2009; Dudschig & Jentzsch, 2009) claims that error monitoring requires time and resources from a capacity-limited central information processor. This bottleneck leads to slower and less accurate performance when a task immediately follows an error. However, when there is enough time between the error and the following trial, compensatory mechanisms, like the ones described above, are implemented to prevent subsequent mistakes. Another theory that predicts worse performance directly after making an error is the orienting account for PES (Notebaert et al., 2009). This theory explains PES as the consequence of an orienting response to errors. Because errors are mostly infrequent and/or salient events, attention is directed towards them and, as a consequence, performance on the next trial is disturbed. According to this account there should be an attention dip immediately after making an error. A similar explanation is postulated in the bidirectional model for attention lapses (Cheyne, Carriere, Solman, & Smilek, 2011) where errors caused by lapses in attention can on their turn induce dips in attention. A third non-functional account explains PES in terms of persistent malfunctioning (Gehring, Goss, Coles, Meyer, & Donchin, 1993; Gehring & Knight, 2000), where it is argued that the error is caused by a lapse of attention which lingers on to the following trial.

As Danielmeier and Ullsperger (2011) point out in their review on post-error adjustments, there is evidence for functional and non-functional accounts and these accounts are probably not mutually exclusive. As already indicated by Jentzsch and colleagues (Jentzsch & Dudschig, 2009; Dudschig & Jentzsch, 2009), it is conceivable that immediately following the error, non-functional effects cause post-error accuracy decrease while cognitive mechanisms only kick-in when more time elapsed. In order to understand post-error performance, it is crucial to develop a paradigm that does not rely on double errors, as traditional post-error accuracy measurements do. Here, we propose a new approach by combining two well-known tasks in cognitive psychology, the Eriksen flanker task (Eriksen & Eriksen, 1974) and the Attentional Blink Paradigm (Chun & Potter, 1995). First, a modified speeded Eriksen flanker task that is known to elicit a large amount of errors is presented, followed by a rapid serial visual presentation (RSVP) of numbers (1 to 9). In 95% of the trials one letter is presented in the RSVP and participants have to indicate whether they did or did not see a letter, and if they did, which one. The original attentional blink paradigm (Chun & Potter, 1995) was used as a means to investigate the temporal dynamics of attention processes. In numerous studies it has been shown that when two targets are presented shortly after each other in a stream of non-target stimuli, it is harder to identify the second target (T2) when it is presented within 200 – 500 ms after the first target. This failure to detect T2 is called the attentional blink effect (for a review on the attentional blink paradigm see Shapiro, Arnell, & Raymond, 1997 and Martens & Wyble, 2010). Notably, when both targets are presented within about 100 ms, T2 is detected much more often; this is referred to as lag-1 sparing (Potter, Staub, & O’Connor, 2002). By using this paradigm we can measure the effect of accuracy on subsequent target detection.

Non-functional accounts predict worse target detection (more misses and more erroneous letters reported) after errors than after correct trials. Both the bottleneck (Jentzsch & Dudschig, 2009; Dudschig & Jentzsch, 2009), the orienting (Notebaert et al., 2009) and the persistent malfunctioning account (Gehring et al., 1993; Gehring & Knight, 2000) predict reduced performance after errors. Interestingly, Gehring et al. would also predict reduced target detection prior to the error because it is reasonable to assume lapses of attention spread out over several trials. The functional accounts described above have no clear predictions about post-error target detection performance. Both the inhibition account (Ridderinkhof, 2002; Marco-Pallares et al., 2008) and the reinforcement learning account (Holroyd & Coles, 2002) state that detecting an error calls for adjustments at the response level.

EXPERIMENT 1

METHOD

Participants

Twenty students (18 females; age range = 19 - 34 years) of Ghent University participated in the study. This study was approved by the ethical committee of the Faculty of Psychology and Educational Sciences of Ghent University and was conducted in accordance with the Declaration of Helsinki. Informed consent was obtained from all participants. All participants received course credits.

Apparatus and stimuli.

The stimuli in the first part of the task consisted of a black arrow pointing to the left or the right (i.e. < or >) flanked by two black arrows both pointing in the same direction. Therefore, the four possible stimuli combinations were <<<, >>>, ><>, <><. In half of the trials the flanking arrows pointed in the same direction as the target (i.e. congruent trials) and in the other trials they pointed in the opposite direction (i.e. incongruent trials). The feedback stimulus was a green J after correct responses, a red F after erroneous responses and a black T in case of a too slow response. In the second part of the task black digits (all digits between 0 and 10 were possible) and an uppercase letter (K, L, D or S) were presented in rapid succession. This was followed by the question: “Welk van de vier letters (KLDS) heb je gezien?” (i.e. Dutch translation of “Which of the four letters (KLDS) have you seen?”). Possible responses could be K, L, D, S or the space bar. This latter response indicated that they did not see a letter in the RSVP. The participants were tested on a Pentium IV personal computer with a 17-inch colour monitor running Tscope (Stevens, Lammertyn, Verbruggen, & Vandierendonck, 2006). Responses were given on the keyboard.

Design

In the first part of the task participants were asked to respond as fast and accurately as possible to direction of the central arrow. In the second part of the task the participants had to type the letter they detected in the RSVP or, in case they did not detect a letter, press the spacebar to indicate that. There were two within-subject factors. The first within-subject factor was the accuracy of the response on the flanker task (correct or incorrect) and the second one was the position of the letter in the RSVP (1, 3, or 6). The dependent variables were the percentage misses and the percentage error detections in the RSVP.

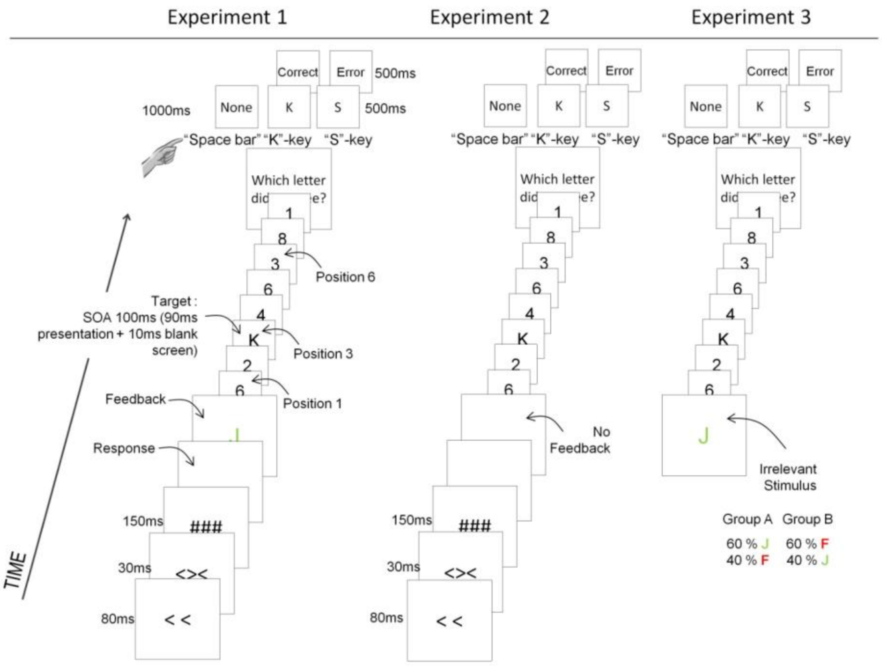


Figure 1. Example of one trial in Experiment 1 (A), Experiment 2 (B) and Experiment 3(C). For the sake of clarity only 8 distracters instead of 14 are presented.

Procedure

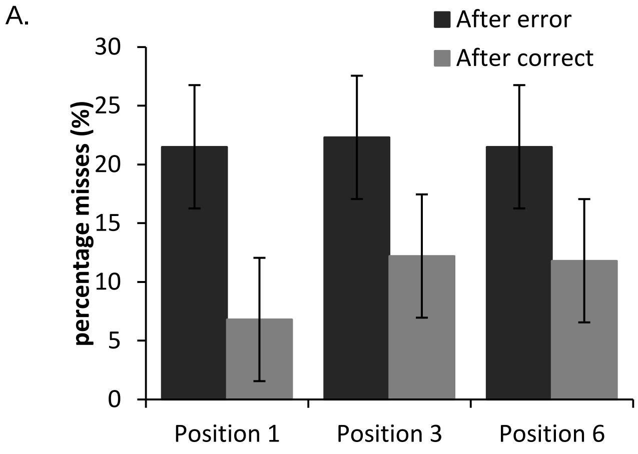
Participants entered a quiet room and sat in front of a computer and a keyboard. Instructions appeared on the screen and were supported orally by the experimenter. The task and the response mapping were explained and the participants were told that in some cases no letter would be presented in the RSPV. Participants knew they had a button to indicate that they did not see a letter. This response option was created in order to minimise guessing. There was one experimental block of 420 trials (see Figure 1 for an overview of the trial sequence) with self paced pauses after every sixtieth trial ("pause" was presented centrally on the screen). Each trial began with a central fixation cross (500 ms) followed by the presentation of the two flanking arrows (< < or > >). After 80 ms the target was presented on the screen (> or < in the middle of the flanking arrows). Thirty milliseconds later a mask was presented for 150 ms (###). Participants had to press ‘J’ on the keyboard with their right index finger when the middle arrow pointed to the right and ‘F’ with their left index finger when it pointed to the left. There was a response deadline of 1000 ms. Immediately after the response a feedback signal appeared on the screen (J in green for correct, F in red for incorrect and T in black, for too slow, corresponding to the words ‘juist’, ‘fout’ and ‘te traag’ in Dutch). This feedback signal was presented for 90 ms, followed by a blank screen for 10 ms. The blank screen was followed by an RSVP sequence. The sequence consisted of 14 characters. In 95% of the trials there were 13 digits as distracters and 1 target letter. In the remaining trials there were 14 digits. The digits were chosen randomly, with replacement, from the numbers 1-9, with the constraint that digit distracters were not repeated within a lag of two characters. The target was randomly chosen from the list K, L, D or S. The letter could appear in three possible positions: immediately after the feedback signal of the flanker task, on the third position in the RSVP or on the sixth position in the RSVP. After the RSVP a question appeared on the screen to ask the participants which of the four letters they had detected in the RSVP. There was no deadline to respond to this second task. In case they had missed the target letter, they had to press the spacebar and the word “GEEN” appeared on the screen for 1000 ms. If they did see a letter, they had to type it and the letter appeared for 500 ms on the screen. This was followed by a feedback signal presented on the screen for 500 ms (“FOUT” or “JUIST”, i.e. “wrong” and “correct” in Dutch). This was followed by an inter-trial interval of 1500 ms while the screen was blank.

RESULTS

Trials with a response time that exceeded the response deadline in the flanker task (4.6%) and trials where no letter was presented (5%) were excluded. Two participants scoring lower than chance level (i.e. 50%) on the flanker task were excluded. All analyses were done on the remaining 18 participants. Where Mauchly’s test indicated that the assumption of sphericity had been violated, Greenhouse-Geisser corrections to the degrees of freedom and p-values were used. However, only the adjusted p-values are reported for the ease of reading. Repeated measures analysis of variance (rANOVA) was done on the percentage misses (i.e. where participants indicated that they did not see a letter in the number stream) and the percentage errors (e.g. occasions where participants responded “L” when “S” was presented). Both are reported in the following sections.

Percentage misses

A significant main effect of accuracy on the flanker task was found, *F*(1, 17) = 22.083, $p < .001$, = .338. More targets were missed after making an error on the flanker task (*M* = 21.78%, *SD* = 11.95%) than after a correct flanker response (*M* = 10.27%, *SD* = 9.13%). Both the effect of the position of the letter in the RSVP and the interaction effect were not significant, both *Fs*(2, 34) < 1. To have an overview of the data, the interaction of both within-subject variables is presented in Figure 2.



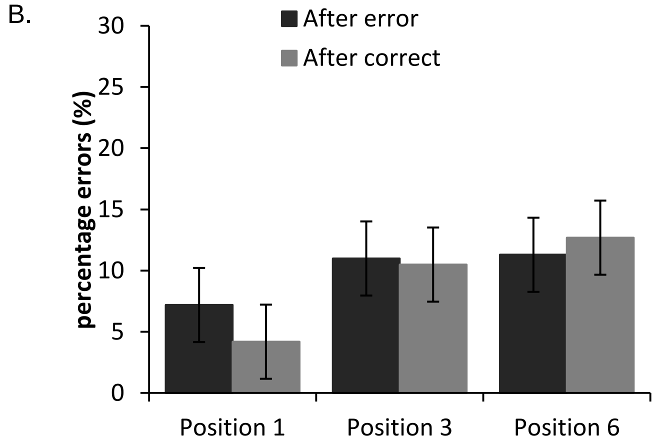


Figure 2. A. The percentage misses of the target on each of the three positions after making an error on the flanker task and after responding correctly on the flanker task in Experiment 1 where immediate feedback was given. More targets were missed after error execution. B. The percentage errors of the target on each of the three positions after making an error on the flanker task and after responding correctly on the flanker task. There was no effect on the error rates. Error bars represent 95% within-participant confidence intervals.

Percentage errors

A significant main effect of the position of the letter in the RSVP was found, $F(2, 34) = 8.435$, $p < .01$, = .332. Most errors were made when the target was presented on the sixth position ($M = 12.61\%$, $SD = 10.21\%$), less when it was presented on the third position ($M = 10.68\%$, $SD = 8.09\%$) and least when it was presented on the first position ($M = 5.17\%$, $SD = 4.22\%$). Both the effect of the accuracy on the flanker task and the interaction effect were not significant, respectively $F(1, 17) < 1$ and $F(2, 34) = 1.050$, $p = .361$.

Additional analysis

In order to check whether the effect of worse target detection after making an error was not part of a dip in attention that spread over several trials, we investigated whether errors on the flanker task were preceded by more misses on the previous RSVP than correct responses on the flanker task. An rANOVA with within-subjects factor accuracy on the flanker task was done on the percentage misses on the previous RSVP. There was no significant main effect of accuracy of the response on the flanker task, *F*(1, 17) < 1.

Analysis of Flanker task

Additionally, we analysed the correct response times and the error rates on the congruent and the incongruent stimuli. A paired sample t-test showed a congruency effect both on the response times, *t*(17) = 3.659, *p* < .01, and on the error rates, *t*(17) = 3.519, *p* < .01. Participants responded slower and made more errors on incongruent stimuli (*M* = 608.14 ms, *SD* = 155.69 and *M* = 46.34%, *SD* = 33.72) compared to on congruent stimuli (*M* = 487.24 ms, *SD* = 108.60 and *M* = 12.18%, *SD* = 12.2). The (intended) high error rates, especially for incongruent trials, were caused by presenting the flanker information first and presenting targets only for 30 ms.

DISCUSSION

The results indicate that performance was worse after errors than after correct responses and therefore support non-functional accounts. After making errors participants missed more targets than after responding correctly. Interestingly, they did not make more errors (i.e. reporting the wrong target) after errors. Further, a control analysis showed that this is an effect of committing an error and not of a prolonged dip in attention.

EXPERIMENT 2

INTRODUCTION

Because it could be argued that the blink-like effect was driven by the presentation of an external feedback signal and not by the error itself a second experiment was designed. In Experiment 2, no immediate feedback on the flanker task was presented. In a recent study where error frequency was manipulated parametrically, PES became smaller as the number of errors increased and this was observed both in a condition with and without immediate feedback (Houtman, Núñez Castellar, & Notebaert, 2012). Therefore, we expect similar effects as in Experiment 1, namely, worse target detection after making an error compared to after a correct response on the flanker task.

METHOD

Participants

Twenty students (19 females; age range = 18 - 37 years) of Ghent University participated based on their written informed consent with approval of the ethical committee of the Faculty of Psychology and Educational Sciences of Ghent University and according to the Declaration of Helsinki. They all received course credits. The participants were different persons than in the first experiment.

Apparatus and stimuli

The apparatus and the stimuli were similar as in Experiment 1. The only difference was that in this experiment no feedback signals were presented in the Flanker task.

Design and Procedure

The design was the same as in Experiment 1 except that the feedback signal was replaced by a blank screen (see Figure 1 for an overview). This was done to keep the timing of the experiment the same as in Experiment 1. After every tenth trial, feedback was given about the previous 10 responses on the flanker task.

RESULTS

Trials with a response time that exceeded the response deadline (1%) and trials without letter presentation (5%) were excluded. Two participants scoring lower than chance level (i.e. 50%) on the flanker task were excluded. All analyses were done on the remaining 18 participants. Again, rANOVAs were done on the percentages misses and the percentage errors.

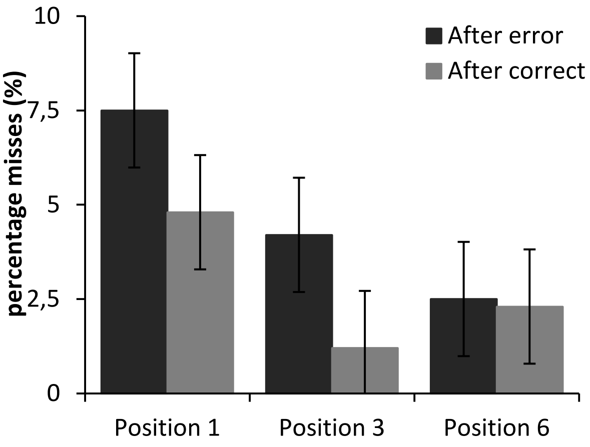
Percentage misses

Both main effects were significant, accuracy on flanker task: *F*(1, 17) = 8.841, $p < .01$, = .342, and position in RSVP: *F*(2, 34) = 8.190, $p < .01$, = .325. More targets were missed after making an error on the flanker task (*M* = 4.94%, *SD* = 3.20%) than after a correct flanker response (*M* = 2.79%, *SD* = 1.87%). The target was missed more when it was presented on the first position (*M* = 5.38%, *SD* = 4.45%), than when it was presented on the third (M = 2.03%, SD = 1.45%) or the sixth position (M = 2.43%, SD = 2.44%). The interaction effect, however, was not significant, $F(2, 34) = 1.581$, $p = .765$.

Percentage errors

A significant main effect of accuracy on the flanker task was found, $F(1, 17) = 8.691$, $p < .01$, = .338. More errors were made after making an error on the flanker task (M = 5.68%, SD = 3.84%) than after responding correctly (M = 4.09%, SD = 2.82%). In Figure 3 an overview of the data is presented. Both the position of the letter in the RSVP and the interaction effect were not significant, respectively $F(2, 34) = 1.526$, $p = .232$ and $F(2, 34) < 1$.

A.



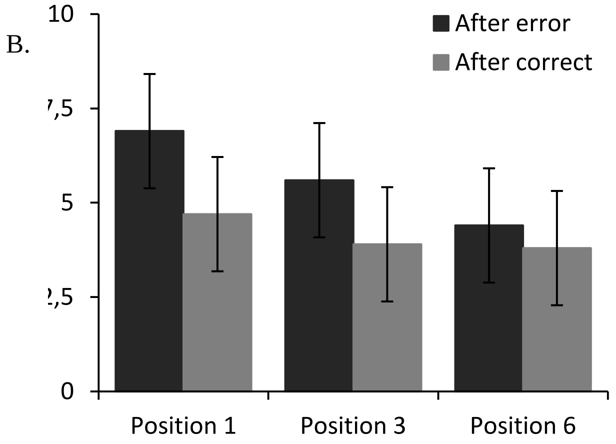


Figure 3. A. The percentage misses of the target on each of the three positions after making an error on the flanker task and after responding correctly on the flanker task in Experiment 2. More targets were missed after error execution. B. The percentage errors of the target on each of the three positions after making an error on the flanker task and after responding correctly on the flanker task in Experiment 2. More errors were made after error execution. Error bars represent 95% within-participant confidence intervals.

Additional analysis

As in Experiment 1, we investigated whether errors on the flanker task were preceded with more misses or errors on the previous RSVP than correct responses on the flanker task. An rANOVA with within-subjects factor accuracy on the flanker task was done, both on the percentage misses and the percentage error responses on the previous RSVP. There was no significant main effect of accuracy of the response on the flanker task on the percentage errors, $F(1, 17) < 1$, but there was an effect on the percentage misses, $F(1, 17) = 13.495$, $p < .01$, = .443. The percentage misses before an error ($M = 4.52\%$, $SD = 2.64\%$) was higher than before a correct response ($M = 3.22\%$, $SD = 1.95\%$). This indicates that decreased target detection *after* an error needs to be interpreted with caution.

Analysis of Flanker task

Again, we analysed the correct response times and the error rates on the congruent and the incongruent stimuli of the Flanker task. A paired sample t-test showed a congruency effect both on the response times, $t(17) = 3.597$, $p < .01$, and on the error rates, $t(17) = 6.527$, $p < .001$. Participants responded slower and made more errors on incongruent stimuli (*M* = 535.13 ms, *SD* = 165.75 and *M* = 56.20%, *SD* = 23.73) compared to on congruent stimuli (*M* = 446.19 ms, *SD* = 110.46 and *M* = 14.35%, *SD* = 11.26). As in Experiment 1, our procedure of presenting flankers first and targets only for 30 ms resulted in chance-level performance for incongruent trials.

DISCUSSION

The results of Experiment 2 further support non-functional accounts in the sense that target detection was worse after errors than after correct trials. The pattern of results, however, differs from Experiment 1, with immediate feedback. In Experiment 2, participants not only missed the target more after errors, they also reported the wrong target more frequently. However, also on the trial preceding the error, participants missed more targets compared to trials preceding correct responses. This suggests that the observed post-error attention dip might, at least partially, be the result of an attention dip that already existed before making the error and might have caused the flanker error in the first place. On the other hand, making an error did have an effect on subsequent performance. More target detection errors were made after error commission compared to after responding correctly and this difference did not exist prior to the error. The results of the two experiments combined indicate that making an error has a negative impact on performance, supporting non-functional accounts for PES. Tentatively, one could argue that with feedback more targets are missed because of perceptual limitations (interference between target and feedback), while without feedback more targets are incorrectly categorized due to central limitations (interference between error processing and letter categorization).

EXPERIMENT 3

INTRODUCTION

In Experiment 3, we wanted to dissociate between the bottleneck and the orienting account. The RSVP started with an irrelevant stimulus (a green J or a red F) that closely matched the frequency of the feedback signal in Experiment 1 and 2 (i.e. J: 60% and F: 40%). In a between subjects design the frequency of the red F and the green J was manipulated, in one group a red F was presented frequently and a green J infrequently while in other group this frequency was reversed. The orienting account predicts reduced performance after infrequent stimuli (Notebaert et al., 2009). The bottleneck account on the other hand, would predict reduced performance after red signals, irrespective of frequency. The association between red signals and errors seems to be quite robust and decreased performance after the presentation of red signals has been demonstrated (Elliot, Maier, Moller, Friedman, & Meinhardt, 2007).

METHOD

Participants

Thirty-two students (group 1: 15 females; age range = 18 - 28 years; group 2: 8 females; age range = 18 – 26 years) of Ghent University participated based on their written informed consent with approval of the ethical committee of the Faculty of Psychology and Educational Sciences of Ghent University and according to the Declaration of Helsinki. They all received course credits. The participants were different persons than in the first and the second experiment.

Apparatus and stimuli

The apparatus and the stimuli were the same as in Experiment 1 (see Figure 1 for an overview). Except that in this experiment no flanker task was presented. Each trial started with a green J or a red F. In one group (N = 16) a green J was presented in 60% of the trials and a red F was presented in 40% of the trials while in the other group a red F was presented in 60% of the trials and a green J was presented in 40% of the trials.

Design and Procedure

Apart from the exclusion of the flanker task, the design was the same as in Experiment 1. Participants were told that the RSVP would start randomly with a green J or a red F.

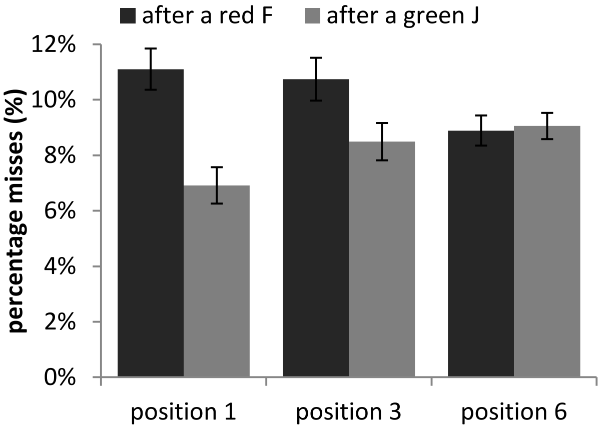
RESULTS

Split plot repeated measures ANOVAs were done both on the percentage misses and on the percentage errors.

Percentage misses

The results indicated reduced target detection after the red F, irrespective of its frequency. This is supported by the interaction between the group and the frequency of the irrelevant signal was significant, *F*(1, 30) = 10.067, $p < .01$, = .251. The data pattern showed that that T2 was missed more when it was presented after a red F (*M* = 10.50%, *SD* = 6.39) then when it was presented after a green J (*M* = 8.48%, *SD* = 5.44). This was also confirmed in a significant post-hoc paired-sample t-test that tested the difference between percentage misses after a red irrelevant signal and after a green irrelevant signal, *t*(31) = 3.136, $p < .01$. There was also a significant three-way interaction of position, frequency of the irrelevant signal and group, *F*(2, 60) = 4.441, $p = .016$, = .129.

A.



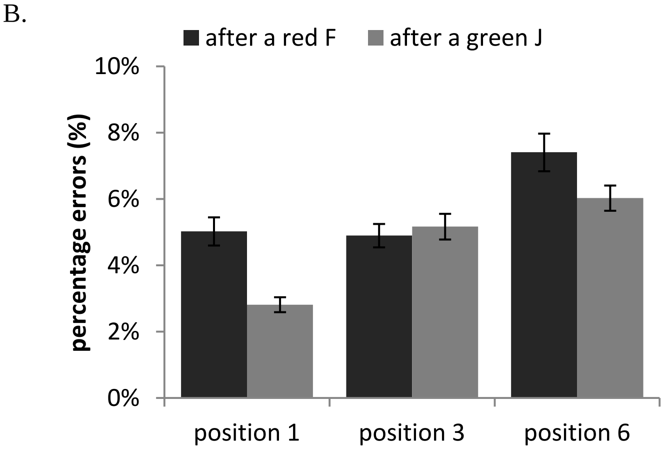


Figure 4. A. The percentage misses of the target on each of the three positions when the RSVP starts with a red F and with a green J in Experiment 3. More targets were missed after the presentation of the red F. B. The percentage errors of the target on each of the three positions. More errors were made after the presentation of the red F. Error bars represent 95% within-participant confidence intervals.

Percentage errors

There was a main effect of the position of the letter in the RSVP, $F(2, 60) = 7.828$, $p < .01$, = .207. The interaction between the group and the frequency of the irrelevant signal was significant, $F(1, 30) = 4.732$, $p = .038$, = .136. This effect boils down to the fact that more errors were made after the presentation of the letter F in red ($M = 6.01\%$, $SD = 3.93$), irrespective of the frequency of the signal, than after the presentation of the letter J in green ($M = 4.71\%$, $SD = 2.66$). None of the other main or interaction effects were significant.

DISCUSSION

The results of Experiment 3 demonstrate reduced target detection after the presentation of an irrelevant red F, irrespective of its frequency (60% or 40%). This effect supports the bottleneck account under the assumption that the red stimulus triggered error-like processes that cause a bottleneck in processing capacity and therefore lead to worse performance, in terms of more misses and more errors.

GENERAL DISCUSSION

Performance after an error was investigated using a new paradigm that combined a speeded visual discrimination task with a target detection task. In the first experiment immediate feedback was given after every response, while in the second experiment no immediate feedback was provided. In Experiment 3, the target detection task started with an irrelevant stimulus. In Experiment 1 and 2, we observed reduced performance after errors and in Experiment 3 reduced performance after a red irrelevant stimulus was observed.

In Experiment 1, feedback was given after every response on the flanker task. This feedback was immediately followed by an RSVP. Participants had to detect a letter in a stream of numbers. They could respond with the letter they detected or indicate that they did not see a target. After responding incorrectly in the flanker task and the associated negative feedback, more targets were missed than after receiving positive feedback. In Experiment 2, the immediate feedback signal was removed. More targets were missed after an error compared to after a correct response. Unlike in Experiment 1, also more targets were missed before the error indicating that participants were already distracted before the error was made. The suboptimal performance (possibly a lapse of attention) that caused the error was already present in the trial preceding it and lingered on in the trial following it (Gehring et al., 1993). In Experiment 2 more target detection errors were made after making an error. In this case, participants did notice a letter but were not able to discriminate between the letters. These findings strengthen the idea of a performance breakdown immediately after making a mistake, as proposed by non-functional theories. Both the bottleneck theory (Jentzsch & Dudschig, 2009; Dudschig & Jentzsch, 2009) and the orienting account (Notebaert et al., 2009) can interpret the described results. According to the first, error detection is a process that takes time and resources that interferes with the next task at hand. Therefore, when a target is presented shortly after making an error it is often missed or detected incorrectly. The orienting account on the other hand, states that poor target detection after errors is induced by an orienting response that has a general impact on the cognitive system. Obviously, the orienting account is more intuitive when feedback signals are presented, and orienting to infrequent feedback signals interferes with subsequent visual processing. In this respect, the high percentage of misses (20%) after errors in Experiment 1 seems to fit well with the orienting account. The results of Experiment 2, on the other hand, where no feedback signals are presented and errors seem to primarily have an effect on target discrimination seem to better fit the bottleneck account, where internal error processing interferes with target discrimination.

Experiment 3 was set up dissociate between both theoretical propositions. In each trial, the RSVP started with one of two possible stimuli. In one group a red F was presented more frequently than a green J, while in the other group a green J was presented more frequently than a red F. The results showed that more targets were missed and incorrectly reported when the RSVP started with red F, irrespective of its frequency. Hence, the results did not confirm the frequency-based predictions of the orienting account. The results of Experiment 3 therefore favour the bottleneck account under the assumption that the red F triggered the error processing mechanism and that this caused interference at central processing stages. Similarly, Elliot et al. (2007) demonstrated reduced performance after presenting red signals to participants in a series of achievement tasks. This effect was also explained in terms of the inherent error-value associated with the colour red. Consequently, it is conceivable that irrelevant red signals triggered error-processing mechanisms that interfered with subsequent target detection and categorization. The fact that this effect was short-lived, at least in percentage misses, further supports this interpretation. The red signal might initiate error processing, but no error is made and hence this process can immediately be aborted.

The results of Experiment 3 favour the bottleneck account, but can this account also explain frequency-based effects that provided initial support for the orienting account? Houtman et al. (2012) demonstrated increased PES in conditions with higher accuracy (lower error rates). Similarly, Steinborn et al. (2012) reported larger performance drops (RT and error rate increase) following errors for participants with higher accuracy rates. Within the orienting account, this has been explained in terms of the surprise associated with an error. When errors are infrequent, participants will be more surprised by the error and show increased PES. However, this frequency effect could also be explained in terms of the bottleneck account. Some participants put more resources in error processing than others and these participants will show larger performance drops immediately following the errors. However, putting more energy in analyzing (the cause of) the error will generally improve performance and result in overall higher accuracy rates. Similarly, one can assume that participants put more energy in processing errors in easy conditions than in hard conditions, where the error is often inevitable. However, what remains difficult to explain within a bottleneck account is that slowing is observed after infrequent correct trials when errors outnumber correct trials, and that slowing is observed after completely irrelevant auditory infrequent signals (Notebaert et al., 2009). It is therefore likely that both processes, orienting to salient events and performance monitoring, both contribute to PES. It is even conceivable that both processes are part of an integrated mechanism that detects and processes salient events.

CONCLUSION

In the present study we introduced a new paradigm to study behavioural changes following errors. Previous attempts to investigate accuracy changes following errors relied completely on double errors, a questionable measure. We demonstrated that target detection was worse after errors than after correct trials, with and without immediate feedback. This provides strong support for the idea that error processing interferes with subsequent information processing.

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CHAPTER 6

EFFECTS OF FEEDBACK MAGNITUDE AND FREQUENCY:

A CHALLENGE FOR THE ORIENTING ACCOUNT [5]

The orienting account for post-error slowing (PES; Notebaert et al., 2009) explains the typical slowdown in reaction times (RT) after committing an error in terms of an orienting response to infrequent errors. In the present study, we set out to investigate how the presentation of feedback signals might modulate this post-error orienting response by manipulating feedback frequency and magnitude experimentally in an arrow flanker task with different reinforcement contexts. Participants were either rewarded for correct trials, or punished for error trials. Moreover, both the reward and the punishment groups were further divided in a high and low reward/punishment condition, resulting in four between-subjects conditions. In each of these conditions, occasional infrequent feedback was presented. PES was observed in the punishment groups but not in the reward groups. However, neither the frequency nor the magnitude of the feedback signal influenced subsequent performance. The results pose a challenge for the orienting account.

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[5] Houtman, F. Van der Borght, L., Braem, S., Fias, W., & Notebaert, W. Effects of feedback magnitude and frequency: a challenge for the orienting account.

INTRODUCTION

After committing an error in a cognitive task, people typically slow down on subsequent trials. This slow down in performance is referred to as post-error slowing (PES). Cognitive control theories (for example: the conflict monitoring theory: Botvinick, Braver, Barch, Carter, & Cohen, 2001) state that this reflects strategic control applied to perform better on the next trial. However, in the literature many different results in terms of post-error accuracy have been reported. Both a better performance after an error (e.g. Laming, 1968), a worse performance (e.g. Fiehler, Ullsperger, & von Cramon, 2005) and a status quo (King, Korb, von Cramon, & Ullsperger, 2010) have been covered. Recently, the orienting account explained PES in terms of an orienting response induced by the infrequent nature of errors in most experimental tasks (Notebaert et al., 2009). Post-*error* slowing was observed in a condition with 75% correct responses and post-*correct* slowing was observed when only 35% responses were correct. In other words, participants slowed down after infrequent events.

In another experiment Notebaert et al. (2009) presented task irrelevant auditory oddballs on 25% of the trials. As has been found in other studies (Barcelo, Escera, Corral, & Perianez, 2006), participants slowed down after the appearance of an oddball, which is referred to as post-oddball slowing (POS). However, while keeping the frequency of errors and oddballs equal across experiments, PES (25 ms) was remarkably larger than POS (9 ms). One explanation for this discrepancy is that errors are more significant than irrelevant oddballs and that the orienting and the subsequent slowing depend on the significance. Additional support for our hypothesis that error significance plays a role in the size of PES comes from a social cognition study (Núñez Castellar, Notebaert, Van den Bossche, & Fias, 2011) that investigated behavioural effects after error observation. In this experiment two participants alternated in performing an arrow flanker task (Eriksen & Eriksen, 1974) while the social context was manipulated. In the competitive condition the best performing participant of a pair received a monetary reward, while in the cooperative condition, the best pair of participants among all pairs received a monetary reward. In both conditions participants slowed down after observing an error, but slowing in cooperation was twice as large as in competition (cooperation: 63 ms vs. competition: 32 ms). This can be explained by the difference in significance of the observed error in both conditions. When you observe the other participant making an error in a competitive context this has no impact on your own score. However, when you observe your partner whom you are cooperating with making an error, this also affects your score. Therefore, this observed error is more significant to you.

To specifically test whether error significance has an impact on PES, we created four between-subject conditions where the significance of the error was manipulated by implementing different reinforcement contexts; two groups were punished for making an error and two groups were rewarded for correct responses. Both groups (reward and punishment) were further subdivided in a high and low value group, resulting in a high and a low reward and a high and a low punishment group. Each group received its normal feedback on 85% of the cases, while receiving deviant feedback in 15% of the cases. Consequently, after correct trials, the high reward group received high reward in 85% of the correct trials and low reward in 15% of the correct trials, whereas the low reward group received low reward after correct trials in 85% and high reward in 15% of the cases. The same was true for the punishment groups, as the high punishment group received high punishment following errors in 85% of the cases and low punishment in 15% of the cases, and the low punishment group received low punishment following 85% of the error trials and high punishment following 15% of the errors. This manipulation enables us to test the effect of feedback frequency on subsequent performance.

Because we know that the orienting response to an event is influenced by the significance of the event (Bernstein, 1969; Bradley, 2009) more PES in the punishment than in the reward condition is predicted. In the punishment conditions, attention is directly drawn to errors and we expect errors to become more significant. In the reward conditions, attention is drawn to correct responses and error significance is reduced. Furthermore, in the punishment condition, we predict more PES in the high punishment group than in the low punishment group because errors are more significant when they are more punished. The effect of feedback frequency is expected to interact with reinforcement context and predictions are most clear in the low punishment group where we expect that infrequent high punishment will result in increased PES. In the high punishment group, one could expect increased PES after infrequent low punishment on the basis of frequency-based orienting (Notebaert et al., 2009), or decreased PES on the basis of its decreased saliency. In the reward conditions, we expect slower RTs after infrequent reward than after frequent reward.

METHOD

PARTICIPANTS

Eighty-three students (74 females, average age of 21 years and 5 months) of Ghent University participated based on their written informed consent with approval of the local ethical committee and according to the Declaration of Helsinki. They received 8€ for their participation. In every group the participant with the most accurate performance was rewarded with a 10€ voucher. Participants were randomly assigned to one of the four groups.

APPARATUS AND STIMULI

On every trial the participants had to identify the centre stimulus of a horizontal stimulus array. A centrally presented arrowhead was flanked by two arrowheads on each side (e.g. >><>>). These flanking arrowheads could point to the same direction of the central stimulus (i.e. a congruent trial) or to the opposite direction (i.e. an incongruent trial). The target and the flankers were black arrows printed on a white background. Participants had to press the left button on a cedrus-response box with their left index finger when the central arrow pointed to left and vice versa. The participants were tested on a Pentium IV personal computer with a 17-inch colour monitor running Tscope (Stevens, Lammertyn, Verbruggen, & Vandierendonck, 2006).

DESIGN

There were two within-subject factors and two between-subject factors. The within-subject factors were frequency of the feedback (frequent or infrequent) and the accuracy of the previous trial (correct or error). The first between-factor was context (reward or punishment). The second was the magnitude of the feedback (mostly high or mostly low). Combining these between-subject factors resulted in four groups. Two groups were rewarded for a correct response and two groups were punished for an error or a too slow response. Within each context one group received mostly (85%) a low value as feedback and sometimes (15%) a high value as feedback, in the other group this was vice versa (e.g. in the high value punishment feedback group participants, when punished, lost 10 points in 85% of cases and only 1 point in 15% of the cases). The magnitude of the feedback was implemented this way in order for subjects to have a relative idea of high and low magnitude.

PROCEDURE

The participants entered a slightly dimmed room and took place in front of a computer. There were two practice blocks and one experimental block. After signing the informed consent the instructions for the first practice block were given verbally by the experimenter and were printed on the screen. Important, all participants received the same instructions. Both the task and the feedback signals were explained. This first practice block consisted of 30 trials without response deadline. Each trial began with a central fixation cross (500 ms) followed by the presentation of the flankers with centrally a blank space (>> >> or << <<) for 80 ms. While the flankers stayed on the screen the target was presented for 30 ms. This presentation was masked (#####) for 150 ms. After that the participants were able to press one of the two response buttons. This was immediately followed by a feedback signal (J for correct, F for incorrect, corresponding to the words correct (i.e. juist) and error (i.e. fout) in Dutch). The feedback stimuli were presented for 500 ms, followed by a blank screen for 100 ms, resulting in an inter trial interval of 100 ms.

Before the second practice block began, the participants were told that in this block there would be a response deadline and therefore a new feedback signal, indicating too slow responses, was introduced. The second practice block consisted of 300 trials with a response deadline of 740 ms. When participants did not respond within 740 ms, a feedback signal was presented to indicate that they responded too slow (T). There was a self paced break after 80 trials.

When the experimental block started new instructions were presented on the screen. Instructions were different depending on the reinforcement group. Participants in the reward groups were told that they would win sometimes many points and sometimes a small amount of points for every correct response they gave. The one with the most points out of 20 participants would receive a 10€ voucher. The punishment groups were told that they started the experiment with 5000 points and that they would lose many or just a little bit of points for every erroneous or too slow response. The participant with the most points left at the end of the experiment would receive a 10€ voucher. All groups were asked to respond as fast and accurate as possible.

The experimental block consisted of 1200 trials. The trial sequence was the same as in the practice block, only the feedback signal differed between the four groups, see Figure 1. Both the accuracy and the points that were gained or lost were presented. In the punishment context the participant saw how much they lost in case of a wrong or too slow answer (e.g. F -1), when they responded correctly they saw the same feedback signal as in the practice block (i.e. J). In the reward context, they saw how much they gained for a right answer (e.g. J +1), after committing an error or responding too slow the same feedback signal as in the practice block was presented (i.e. T for too slow and F for incorrect response). The frequency of small reward/loss (1) and big reward/loss (10) was either 85% or 15 % (where the 15% trials were never repeated on successive trials).

RESULTS

Trials with a response time that exceeded the response deadline or that were faster than 200 ms and the immediately following trial were excluded from the data. Also the first trial after every pause was excluded. As a result, 11% of the data was excluded. From the remaining trials reaction times (RTs) more or less than three standard deviations from the mean were removed per participant.

PRACTICE BLOCK

To check whether there were a priori differences between the four groups, the data of the second practice block were analysed. Repeated measures ANOVAs were done, both on the correct RTs and on the error proportions. In both analyses the independent variables were accuracy of the previous trial (correct or incorrect), whether the participants were punished or rewarded (context) and whether this punishment/reward was high or low (magnitude).

Reaction times

There was a significant main effect of previous accuracy, *F*(1,79) = 13.020, *p* = .001. Participants responded slower after making an error, (*M* = 460.4 ms, *SD* = 78.7 ms), compared to after a correct response, (*M* = 446.9 ms, *SD* = 70.2 ms). This reflects the PES effect of 13.5 ms. All other main and interaction effects were not significant (all *F*s(1,79) < 1, *ns*).

Error proportions

The factor previous accuracy had a significant effect on the error proportions, *F*(1,79) = 16.047, *p* < .001. Error proportions after an error (*M* = 30.8%, *SD* = 13.9%) were higher compared to after a correct response (*M* = 27.7%, *SD* = 12.7%). None of the other main and interaction effects were significant (*Fs*(1,79), *ps* < .16).

EXPERIMENTAL BLOCK: OVERALL ANALYSIS

A split plot ANOVA was conducted on correct reaction times and error rates with one within-subjects factor, accuracy of the previous trial (correct, error) and two between-subjects factors reinforcement context (punishment, reward) and the magnitude of the feedback (mostly high or mostly low). Frequency was ignored in this overall analysis because in the punishment group, infrequent feedback is error feedback while in the reward condition, infrequent feedback is correct feedback.

Correct reaction times

There was a main effect of previous accuracy, *F*(1,79) = 8.005, *p* = .006. Correct RTs were longer after an error (*M* = 439.4 ms, *SD* = 60.7 ms) than after a correct trial (*M* = 432.0 ms, *SD* = 53.1 ms). We also found a two-way interaction effect of accuracy of the previous trial and the context, *F*(1,79) = 4.019, *p* < .05. In line with our first prediction, PES was larger in the punishment conditions (*M* = 12.4 ms, *SD* = 26.1 ms) than in the reward conditions (*M* = 2.1 ms, *SD* = 19.2 ms) (see Figure 1). Actually, planned comparisons showed that PES was significant in the punishment conditions (*t*(42) = 3.102, *p* < .01) and absent in the reward conditions (*t*(39) = 0.688, *p* = .496). There was no interaction between accuracy of the previous trial and the magnitude, *F*(1,79) < 1, and also the three-way interaction was not significant, *F*(1,79) = 1.732, *p* = .192. This is against our expectations of finding a modulation of the PES-effect in the punishment groups by the feedback magnitude.

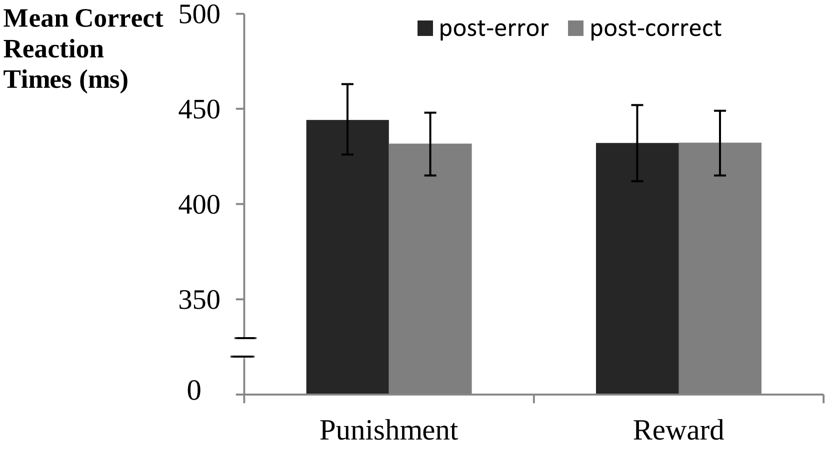

Figure 1. Mean correct RTs after errors and after correct responses in the punishment groups and in the reward groups. The error bars represent the lower and the upper bound of the 95% confidence interval. There is PES in the punishment groups but not in the reward groups.

Error proportions

The factor accuracy of the previous trial had a significant main effect on the error proportions, *F*(1,79) = 16.047, *p* < .001. Interestingly, we observed post-error accuracy decrease because error rates were higher after making an error (*M* = 27.7%, *SD* = 14.7 %) than after a correct response (*M* = 24.5%, *SD* = 15.3%). All other main and interactions effects were not significant (*F*s(1,79), *p*s < .27) (see Table 1). Consequently, error rates were the same in all groups.

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Table 2. Error rates were always higher after errors than after correct responses. Crucially, overall accuracy did not differ between punishment groups and reward groups.

	Low				High				Marginal accuracy	
Reinforcement context	After error		After correct		After error		After correct			
	M	SD	M	SD	M	SD	M	SD	M	SD
Punishment	29.0	12.5	24.8	13.9	26.7	16.7	23.8	18.4	75.1	16.0
Reward	30.4	13.4	26.2	14.0	26.4	16.1	23.5	15.7	74.3	14.7

Note. Mean error rates and standard deviations of the error rates are presented in percentages.

EXPERIMENTAL BLOCK: EFFECT OF FREQUENCY

The effect of feedback frequency was investigated by means of planned comparisons t-tests (infrequent-frequent).

Correct Reaction Times

Contrary to our predictions, no increased PES was found after infrequent high punishment in the low punishment group, *t*(20) = 0.258, *p* = .799. Also in the high punishment group, there was no difference between RTs after infrequent low punishment and frequent high punishment, *t*(21) = 1.169, *p* = .256. Therefore, we can conclude that the frequency manipulation had no effect on PES in the punishment groups. In the low reward group correct RTs after infrequent high reward were not slower than after frequent low reward, *t*(19) = 0.300, *p* = .768. In the high reward group, however, RTs after frequent high reward (*M* = 436.90ms, *SD* = 56.86) were slower than after infrequent low reward (*M* = 428.72ms, *SD* = 64.05), *t*(19) 2.285, *p* = .034.

Error Rates

Both in the low punishment group, *t*(20) = -0.839, *p* = .412, and in the high punishment group, *t*(21) = 0.237, *p* = .815, there was no difference between error rates after frequent low/high punishment and infrequent high/low punishment. Again, there was no effect of the frequency manipulation post-error accuracy decrease in both punishment groups. In the low reward group, error rates were slightly higher after frequent low reward (*M* = 26.5%, *SD* = 13.9%) than after infrequent high reward (*M* = 24.3%, *SD* = 15.1%), *t*(19) = 2.917, *p* = .009. In the high reward group, however, there was no difference in error rates, *t*(19) = -0.019, *p* = .929.

Correlations

A Pearson product-moment correlation coefficient was computed to assess the relationship between the size of the PES effect and the mean accuracy (see Figure 2). There was a significant positive correlation between the two variables, *r*(83) = 0.463, *p* < .001. Because there were no group differences in terms of accuracy rates, this correlation reflects a relation between individuals' error rates and PES, with more slowing as errors become less expected.

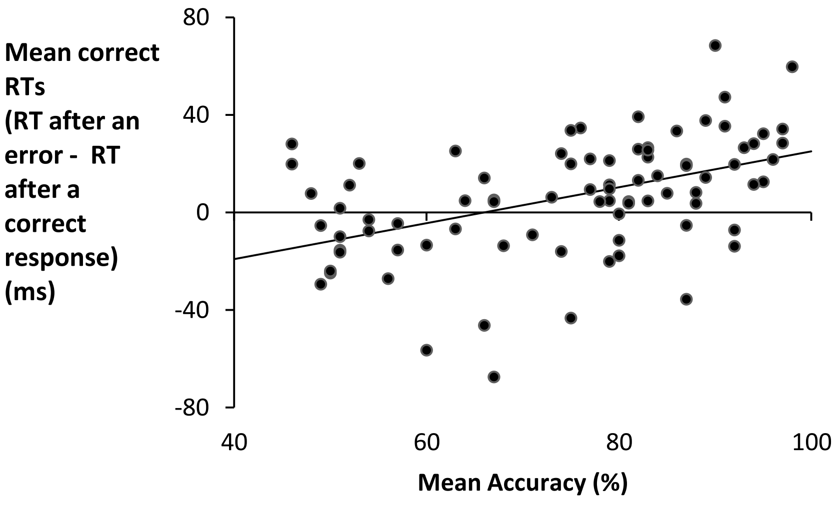

Figure 2. The scatterplot of mean accuracy and the difference between correct RTs after correct response and after errors shows that higher accuracy goes together with a larger PES effect.

DISCUSSION

In this study we investigated the influence of feedback frequency and magnitude on subsequent behaviour. We therefore created four reinforcement contexts. Half of the participants were punished for errors and half of them were rewarded for correct trials. Under the assumption that punishing errors directs more attention to errors than rewarding correct trials, we predicted more PES in the punishment group, which was confirmed. However, PES was not larger for a group that generally received larger punishment after errors, and also the frequency of the feedback signal did not systematically affect subsequent performance.

PES ONLY IN THE PUNISHMENT CONDITIONS

Studies that investigate response-locked event-related potentials (ERPs) also demonstrated an influence of punishing errors on error-related ERPs. The error-related negativity (ERN), a negative deflection that appears 50 – 200 ms after committing an error (Gehring, Goss, Coles, Meyer, & Donchin, 1993; Falkenstein, Hohnsbein, Hoormann, & Blanke, 1990) was larger for high compared to low monetary value errors and when being evaluated compared to not being evaluated (Hajcak, Moser, Yeung, & Simons, 2005). However, it should be noted that no behavioural differences were found in this study.

Delgado, Locke, Stenger and Fiez (2003) investigated the activity of the striatum following high or low rewarding or punishing feedback in an fMRI study and observed that the left dorsal striatum differentiated between reward and punishment. More precisely, the activation of the left caudate nucleus depended on the magnitude of the reward, where high reward was correlated with the highest activation and high punishment with the lowest activation. However, this pattern was only true in the 6- to 9-second interval after presenting the feedback. Earlier, in the 3- to 6-second time interval, the reversed pattern was observed, with highest activation after high punishment feedback and lowest after the high reward feedback. One of the possible explanations Delgado and colleagues put forward is an early autonomic response preceding a cognitive process. Several autonomic responses have been reported after an erroneous response (Danev & de Winter, 1971, Critchly, Tang, Glaser, Btterworth, & Dolan, 2005) and after negative feedback (Somsen, Van der Molen, Jennings, & Van Beek, 2000). These autonomic responses have been interpreted as an orienting response (see Van der Molen, Bashore, Halliday, & Callaway, 1991, for a review). In fact, the early autonomic response in Delgado and colleagues' study could be an orienting response due to the presentation of the large punishment.

The observation that PES is only observed in our punishment conditions (with no pre-existing group differences) fits the orienting account, and is in line with previous research. Alternatively, one might argue that punishment and reward induced different emotional states. While punishment might have induced a negative emotion, reward possibly induced a positive emotion. It has been argued that positive emotions reduce cognitive control processes or increase flexibility (e.g., Ashby et al., 1999; Braver & Cohen, 2000; Dreisbach & Goschke, 2004). Within the orienting account, one could argue that increased positive affect due to the reward manipulation increases flexibility and hence decreases the distraction caused by the error. Note that this argument fits well, when comparing PES scores of the reward and the punishment groups with their PES scores before the implementation of the reinforcement schedule. This comparison indicates that PES did not change in the punishment group, while PES dropped from 13.5 ms to 2.1 ms the reward group.

On the other hand, studies investigating error monitoring in short-term changes of emotion (Wiswede, Münte, Goschke, & Rüsseler, 2009) or state anxiety (Hajcak et al., 2003; Moser et al., 2005) failed to find an effect on PES. Moreover, Stürmer, Nigbur, Schacht, and Sommer (2011) observed increased ERN and PES in a reward condition. The fact that more PES was observed in the reward than the punishment condition (contrary to our findings) can be explained in terms of the specific reinforcement schedule. Stürmer et al. rewarded the 25% fastest correct responses in one condition and punished the 25% slowest correct responses in another. Crucially, errors were punished in both conditions, which was not the case in our reward condition. Punishing errors in a reward context presumably results in increased rather than decreased sensitivity to errors. Taken together, the present findings together with the results of Stürmer et al. are easier to explain in terms of error saliency rather than mood differences.

NO EFFECT OF MAGNITUDE AND HALF AN EFFECT OF FREQUENCY

In line with previous reports in our lab (Notebaert et al., 2009; Nunez Castellar, et al., 2010; Nunez Castellar, et al., 2011; Houtman, Nunez Castellar, & Notebaert, 2012), we expected increased PES when errors are more salient. Surprisingly, PES was not larger in the high punishment group than the low punishment group. In our defense, we could argue that our between-subjects manipulation of punishment magnitude went unnoticed to the participants. Note that we created our contexts by *usually* giving high or *usually* giving low reward/punishment, in order to also investigate the effect of frequency. It is also possible that this blurred the differences between our high and low conditions. In a monetary gambling task, Wu and Zhou (2009) found an effect of valence of feedback but not of the magnitude of the feedback on choice behaviour. Participants had to choose between a left and a right pile and could either win or lose 0.5 or 2.5 yuan and were more likely to select the same card when it was rewarded in the previous trial, compared to when it was punished. The size of the reward did not have an impact on this choice behaviour. However, the most stringent prediction was formulated within the low punishment group. This group occasionally received high punishment for errors, which should have led to increased slowing. The fact that this is not observed poses a real challenge for the orienting account. Moreover, a similar effect of frequency was expected in the reward conditions. However, frequent high reward was followed by slower responses than infrequent low reward in the high reward group. How do we integrate these findings with previous reports of slowing after irrelevant unexpected feedback? One possibility is that participants did not pay attention to the complex feedback signal and only relied on internal error monitoring. The fact that there is an overall difference between the punishment and the reward group does not necessarily indicate that feedback signals were processed on a trial-by-trial basis, as this information was delivered during the instructions. Still, this finding is at odds with the observation that participants were slower after infrequent feedback than after frequent feedback in the Notebaert et al., (2009) study. In the present study, feedback signals were visual, whereas Notebaert et al. used auditory stimuli. As a matter of fact, it is not the first time that we fail to find a frequency effect of visual stimuli. In Houtman et al. (submitted), we report a series of experiments where we demonstrate an attentional blink following errors. In a final experiment, we failed to find an effect of frequency of irrelevant visual signals. Similarly, in an unpublished dataset, we failed to observe post-oddball slowing after irrelevant visual signals in an otherwise identical setup as Notebaert et al. Experiment 2. These data indicate that visual feedback is perhaps less salient than auditory feedback, and that trial-by-trial differences in visual feedback can go unnoticed. Support for this claim can be found in oddball literature. The observation that distraction following oddballs (post-oddball slowing) is only observed after auditory oddballs and not after visual oddballs is in line with this suggestion (Leiva & Parmentier, 2011).

On the other hand, the present set of data again confirms that error frequency has an important impact on PES, as participants with less errors showed increased PES. This finding can be considered as the most important support for the orienting account. Note that this effect has also been observed without feedback (Houtman et al., 2012). Similarly, Steinborn, Flehmig, Bratzke, and Schröter (2012) reported that differences in accuracy (although the range was rather small, from 94% to 99%) resulted in differences in PES. When classifying participants into three groups according to their accuracy, it was shown that PES was largest in the high accurate group and smallest in the low accurate group. This leaves us to conclude that internal error detection triggers on orienting response and results in PES (in relation to the frequency of errors), that irrelevant auditory feedback signals trigger an orienting response and subsequent slowing, and that visual feedback signals do not trigger an orienting response, and do not result in slowing. It remains to be investigated whether trial-by-trial variations in auditory feedback magnitude and frequency influence subsequent behaviour.

REDUCED PERFORMANCE AFTER ERRORS

Remarkably, performance did not improve after making an error. It is important to point out that this post-error accuracy decrease is the same in all conditions although post-error RTs did change between groups. It is clear that in this case post-error RT changes were not part of a more cautious response style in order to improve performance. This is in line with recent findings of King and colleagues (2010) who also found no correlation between PES and post-error accuracy. However, they found that there was no change in accuracy after making an error compared to after responding correctly. Interestingly, they observed a negative correlation between PES and response-related sensorimotor cortex activity. Apart from an explanation in terms of a motor inhibition account (Danielmeier, Eichele, Forstmann, Tittgemeyer, & Ullsperger, 2011), it could also be that the distraction caused by the error resulted in decreased motor activation. It should be noted that Hajcak and colleagues (2003) did find a positive correlation between post-error accuracy and PES, although performance was not better after errors than after correct responses. However, in the study of Steinborn et al. (2012) post-error accuracy decrease correlated with PES. Like PES, post-error accuracy decrease was bigger in the high accuracy group than in the low accuracy group. Future research is needed to investigate this in more detail.

CONCLUSION

The present study did not reveal the expected effect of frequency and magnitude of visual feedback. In line with smaller oddball interference in the visual than the auditory domain, we suspect that visual trial-by-trial variations in feedback go unnoticed. However, post-error slowing was only observed when errors were punished, and post-error slowing correlated with error frequency, as predicted by the orienting account.

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CHAPTER 7
GENERAL DISCUSSION

In this dissertation we proposed and investigated a new account for post-error slowing. The orienting account states that post-error slowing is highly influenced by the frequency of errors in that context. The view on error processing was broadened and support for non-functional error processing theories in general was provided. In this final chapter I will give an overview of the empirical findings obtained in Chapter 2, 3, 4, 5 and 6. I will integrate these results and discuss recent literature regarding the orienting account.

THE ORIENTING ACCOUNT

In **Chapter 2** the orienting account was proposed. One of the most reported behavioural adjustments after making an error is the slowdown in reaction times. This effect is referred to as the post-error slowing effect and was originally described by Rabbitt (1966) and Laming (1968) and interpreted as a cautious response style in order to improve behaviour. The idea that post-error slowing serves as a remedial action in order to prevent further erring is also reflected in cognitive control theories. According to these theories, post-error slowing should go together with post-error accuracy improvement. However, an overview of the literature learns that this is not always the case (Hajcak & Simons, 2008; Cheyne, Carriere, & Smilek, 2009; Steinborn, Flehmig, Bratzke, & Schröter, 2012; Rabbitt & Rogers, 1977). Remarkebly, patients with a lesion in the medial prefrontal cortex (mPFC) still show post-error slowing (Stemmer, Segalowitz, Witzke, & Schönle, 2004). Starting from these observations and the observation that in typical tasks used in the laboratory errors occur only rarely we began to develop a new account for post-error slowing.

From learning psychology we know that rare events elicit an orienting response that causes attentional capture. Besides this, the orienting response also evokes some changes in the autonomic nervous system (ANS). Hajcak, Simons and McDonald (2003) reported that making an error is followed by heart rate deceleration, pupil dilation and increased skin conductance. The orienting account proposes that, in most experiments, post-error slowing is caused by an orienting response elicited by the relative infrequency of the error itself. Two hypotheses were formulated. First, slowing should occur after infrequent events, when correct responses are relatively infrequent, we would expect post-correct slowing. Second, also irrelevant events that occur during the task should have this effect in case they are infrequent.

In order to test this two experiments were set up, one to verify the first hypothesis and one to verify the second hypothesis. In Experiment 1 we used a newly designed adaptive paradigm during a four choice colour discrimination task. There were three within-subjects conditions that aimed at different levels of accuracy, respectively 35% accuracy, 55% accuracy and 75% accuracy. During each condition the darkness of the colour was adapted when the average accuracy of the previous 20 trials was not the same as the accuracy aimed for in that condition. For example, when the average accuracy of the previous 20 trials was higher than 55% in the 55% accuracy condition, the colour of the square would become slightly darker. When the average accuracy was lower than 55% correct responses then the colour would become slightly brighter and as a consequence become slightly easier to discriminate. Immediate feedback was given in the form a visual presentation of a letter (an “F” when an error was made, a “J” when the response was correct and a “T” when the response deadline was reached).

In line with the first hypothesis, post-correct slowing was found in the 35% accuracy condition. In the 75% accuracy condition post-error slowing was observed, while in the 55% accuracy condition no effect of accuracy of the previous trial on reaction times was found. It was not possible to interpret accuracy changes after errors or after correct responses because the error frequency was manipulated constantly during the experiment.

In order to investigate hypothesis 2, we designed a second experiment where an irrelevant signal substitutes the feedback signal. Our hypothesis that irrelevant infrequent stimuli would also evoke a slowing in response times was already indirectly confirmed in a study by Barcelo, Escera, Corral and Periáñez (2006) where occasionally (26 times in a block of 140 trials) a novel unique sound was presented. Reaction times were indeed slower following these novel sounds, which 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. In 75% of the trials a high or a low tone (depending on the condition the participant was in) was presented at the time where in the first experiment a feedback signal was presented. In the remaining 25% of the trials a low or a high tone was presented. 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.

One important note to make about the obtained results is that in experiment 1 feedback was given on every trial. Thus, between responding on one trial and the start of the next trial a visual signal was presented that indicated whether your response was correct, incorrect or too slow. The implications of the orienting account would be quite limiting if they would only hold in cases where external feedback is presented. However, studies investigating ANS correlates of error monitoring indicate that this is not the case. Crone, Somsen, Van Beek and Van Der Molen (2004) demonstrated heart rate deceleration after error feedback, which was also observed by Hajcak et al. (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, heart rate measurements on tasks with and without feedback indicate an important role for orienting responses towards errors and error feedback. In order to investigate this more thoroughly we designed an experiment presented in **Chapter 3**.

THE ROLE OF FEEDBACK

Imagine sitting on the train, working on a text and not noticing that you have to grab your stuff together to jump off the train. All of a sudden you do notice you have to get off and because you hurry so much you forget your scarf. In some cases, someone will shout “Hey! You forgot your scarf!”. You will walk back and gratefully get your scarf. In other cases you will have the ‘feeling’ you forgot something and walk back to your seat. In the first example you received external feedback, while in the second example you relied on your internal error monitoring system to notice your mistake.

After we tested the basic assumption of the orienting account we wanted to expand the implications of the account. The goal in **Chapter 3** was to replicate the findings presented in **Chapter 2** in a task without immediate feedback. This was done by splitting the group of participants in two. One group received feedback after every response, whereas the other group only received feedback after every fiftieth trial. Because the orienting account predicts different sizes of post-error slowing depending on the amount of errors that were made, we created three accuracy conditions: 50% accurate, 70% accurate and 90% accurate.

The same adaptive program as in **Chapter 2** was used with a slight modification. This time the stimulus discriminability was only adjusted in the beginning of the experiment until a stable level of accuracy, that was aimed for in that condition, was reached. This allowed us to measure post-error accuracy changes. The orienting account predicts a higher error rate after unexpected errors than after correct trials. When attention is drawn away from the task by an error, the obligatory shifting back to the task could result in more errors on top of response slowing. Functional theories, on the other hand, predict that accuracy improves because of the remedial post-error slowing.

Post-error slowing was largest in the 90% accuracy condition, smaller in the 70% accuracy condition and not existing in the 50% condition. These findings are in line with the hypothesis made by the orienting account, and with previous findings in **Chapter 2**. The main research question was whether this pattern was different without immediate feedback presentation. Indeed, there was no difference between both conditions. However, one limitation to this study is that feedback presentation was manipulated between subjects. It remains an open question whether the same results would be found in a within subjects design. The theoretical implication that derives from this experiment is that the orienting response to externally indicated and internally detected infrequent errors is the same. It could be that the orienting response after errors is triggered by an internal error signal. However, in studies where false error feedback is delivered, post-error slowing is present only after incorrect responses but not after correct responses (de Bruijn, Mars, & Hulstijn, 2004).

As described in **Chapter 1**, in event-related potential studies (ERP studies) it has been shown that the error-locked PE and the stimulus-locked P3 show many similarities (Overbeek, Nieuwenhuis, & Ridderinkhof, 2005; Ridderinkhof, Ramautar, & Wijnen, 2009). In an ERP study done in our research group (Nunez Castellar, Kuhn, Fias, & Notebaert, 2010) the same experiment as presented in **Chapter 2** was done. However, only the 35% accuracy and the 75% accuracy condition were used. In the first condition post-correct slowing was found and the second condition post-error slowing was found. Furthermore, it was shown that the amplitudes of the P3 correlated with slowing on the next trial, whereas the amplitudes of the ERN did not correlate.

According to the results found in this Chapter we can safely assume that the orienting response to errors with and without immediate feedback is in essence the same. Based on this assumption and the findings of the ERP study of Nunez-Castellar et al. we designed an ERP experiment presented in **Chapter 3**.

THE PE AS AN INDEX FOR ORIENTING TO ERRORS

After we confirmed that the frequency dependent orienting response to errors did not differ with or without immediate feedback, we wanted to test the relation between neural correlates of making an error and behavioural adjustments afterwards. Because it is not possible to investigate error-locked potentials when a feedback signal is presented immediately after the response, the participants were presented with a task without immediate feedback.

The two error-related potentials of interest in **Chapter 4** are the ERN, peaking between 0 and 100 ms after error commission, and the PE, a positive deflection between 200 ms and 400 ms after the error response. The same rationale as in the study of Nunez-Castellar et al., 2010, was used. Namely, participants are presented with a difficult and an easy condition. However, instead of using an adaptive program all participants saw the same stimuli. The difficulty manipulation was established by creating a condition with a 2:1 stimulus response mapping and a more difficult condition with a 4:1 stimulus response mapping. More errors were made in the difficult condition than in the easy condition, although this effect was not large (on average 9% more errors in difficult condition).

The results of this study were somewhat surprising and pose a challenge for the orienting account defended in the previous chapters. Although there was difference in error rates, there was no difference in post-error slowing at least not on group level. Correlation analyses per condition showed that there was an error frequency effect on post-error slowing on individual level. Participants with the highest error rate also showed smallest post-error slowing, in both conditions. This same correlation was reported in a study done by Steinborn and colleagues (2012). In a task with accuracies ranging from 94% to 99% it was shown that participants with the highest accuracy rates also show the most post-error slowing.

In the ERP-data we did find a difference between both conditions. Both the ERN and the P_E were more pronounced in the easy condition than in the difficult condition. This effect replicates previous findings that also report a smaller ERN and PE when participants make more errors (Santesso, Segalowitz, & Schmidt, 2006). Pailing and Segalowitz (2004) found that by increasing task difficulty, participants made more errors but this did not diminish ERN amplitude. Instead, it was the participants' certainty of having erred that predicted ERN amplitude.

When combining the ERP-data and the behavioural adjustments data we found that only the PE correlated with post-error slowing. The PE can be interpreted as an internal marker for orienting to errors. Comparable with the P3's dependency of the saliency of a presented stimulus, the PE seems to play a similar role for internally detected salient events. Our results are very similar to the ones reported by Nùñez-Castellar et al. (2010). Whereas they found the P3 to be largest after the least frequent presented feedback signal, the PE was largest in the condition with less error rates and largest for participants with the smallest error rate. As previously suggested (Falkenstein, Hoormann, Christ, & Hohnsbein, 2000) the PE might reflect the subjective significance of an error. This interpretation is in line with studies investigating EPR-correlates of unaware errors (Nieuwenhuis, Ridderinkhof, Blow, Band, & Kok, 2001; Endrass et al., 2005, 2007; O'Connell et al., 2007; Shalgi et al., 2009; Dhar, Wiersema, & Pourtois, 2011; Wessel, Danielmeier, & Ullsperger, 2011; Endrass, Klawohn, Preuss, & Kathmann, 2012). In these studies no PE is found when participants are unaware of their errors. In the study of Endrass and colleagues a choice selection task was used where errors were induced by manipulating perceptual difficulty. In that way differences in ERPs related to the awareness of the accuracy of the response could be investigated. Remarkably, the PE was not only larger for unaware errors than for aware errors, but also larger for unaware correct responses than for aware correct responses. Similarly, post-response slowing was more pronounced following perceived than following unperceived errors but reaction times were also slower following unperceived correct responses. In line with the orienting account post-error slowing was related to perceived incorrectness of a response rather than being an automatic adjustment process apart from conscious error perception.

A DROP IN ATTENTION

In **Chapter 5** we wanted to investigate a hypothesis made by the orienting account regarding the disturbance in attention you would expect after making an infrequent error. Furthermore, this would allow us to differentiate between functional and non-functional theories regarding error monitoring without having to rely on double errors. As explained in the post-error adjustments review of Danielmeier and Ullsperger (2011) the danger of relying too much on double errors is that you have to be very careful the interpret these depending on task that was used or the absolute number of errors that was made. For example, in case a subject commits only 10 errors, every single double error leads to an increase of the post-error error rate by 10%. Also in the task presented in Chapter 2 where we constantly updated the perceptual difficulty depending on the error rates, streaks of very easy trials were created when error rates became too high and streaks of very difficult trials were created when error rates became too low. Therefore, we should not make too strong conclusions about post-error improvements following the results obtained in those experiments.

We designed a new paradigm by combining a modified Eriksen flanker task (Eriksen & Eriksen, 1974) and a traditional attentional blink task (Chun & Potter, 1995). First, a modified speeded Eriksen flanker task that is known to elicit a large amount of errors is presented. The flankers were presented 150 ms before the target was presented very shortly for 30 ms. After responding on the flanker task a rapid serial visual presentation (RSVP) of numbers (1 to 9) started. In 95% of the trials one letter is presented in the RSVP and participants have to indicate whether they did or did not see a letter, and if they did, which one. By using the original attentional blink paradigm (Chun & Potter, 1995) we were able to investigate the temporal dynamics of attention processes after making an error. In numerous studies it has been shown that when two targets are presented shortly after each other in a stream of non-target stimuli, it is harder to identify the second target (T2) when it is presented within 200 – 500 ms after the first target. This failure to detect T2 is called the attentional blink effect (for a review on the attentional blink paradigm see Shapiro, Arnell, & Raymond, 1997 and Martens & Wyble, 2010).

There was only a small difference between experiment 1 and experiment 2. Whereas immediate visual feedback was presented in experiment 1, this was not the case in experiment 2. Instead a blank screen with the same duration of the feedback signal in experiment 1 was shown. Both percentage misses, when the participant indicates not having seen a letter in the number stream, and percentage errors, when the wrong letter was reported, were calculated after errors and correct responses on the flanker task. Generally, worse performance after errors compared to after correct responses was shown. Relatively more targets were missed after the presentation of error feedback than after the presentation of correct feedback. In the second experiment participants not only missed the target more after errors, they also reported the wrong target more frequently. However, also on the trial preceding the error, participants missed more targets compared to trials preceding correct responses. This could be the result of an attentional dip that maybe caused the error in the first place. Taken together, our results indicate that post-error processes interfere with task performing processes immediate after the erroneous response. Both non-functional theories of error monitoring can explain these results. According to the bottleneck theory (Jentzsch & Dudschig, 2009; Dudschig & Jentzsch, 2009) error detection is a process that takes time and resources that interferes with the next task at hand. Therefore, when a target is presented shortly after making an error it is often missed or detected incorrectly. The orienting account states that poor target detection after errors is induced by an orienting response that has a general impact on the cognitive system. It could well be that when errors are followed by feedback, orienting to these infrequent feedback signals interfere with subsequent visual processing. Whereas in case that no feedback is presented, internal error processes interfere with subsequent target discrimination. Recent findings of an ERP study (Nahum, Barcellona-Lehmann, Morand, Sander, & Schnider, 2012) are in line with the obtained results. Nahum and colleagues found that prediction errors were followed by slower reaction times and higher error rates. Also the ERP-correlate of this performance breakdown was investigated. The early visual component P1 had larger amplitude after unexpected outcomes than after expected outcomes. Both when these outcomes were unpleasant or neutral. They interpret their findings as evidence that unexpected prediction errors capture attention which leads to a decrease in performance on the subsequent trial.

In an attempt to dissociate between both non-functional theories a third experiment was carried out. In this experiment the flanker task was removed. Instead two irrelevant visual stimuli were presented. The frequency of these stimuli matched the average accuracy in the first two experiments. Half of the participants saw a red F in 60% of the trials and a green J in 40% of the trials. In the other half of the participants these frequencies were reversed. The results of this experiment were quite clear. The red F was followed be more target misses and more incorrectly reported targets, irrespective of the frequency of that red F. Based on the orienting account a performance breakdown after the infrequent stimulus is expected, irrespective of its appearance. However, in a series of achievement tasks Elliot, Maier, Moller, Friedman, & Meinhardt (2007) demonstrated that performance was reduced after presentation of red signals. These findings were explained by the fact that the colour red is associated with making errors. For example, at school most teachers will mark errors with a red pen. The performance breakdown after a red F can be the consequence of error processes, which were triggered by the red F, that interfere with subsequent target detection. The fact that this effect was short-lived, at least in percentage misses, further supports this interpretation. The red signal might initiate error processing, however, no error is made and thus this process can immediately be aborted.

It is clear that the orienting account for post-error slowing as it was originally formulated can only explain a limited set of data patterns. In the following paragraph we will present data that challenge the orienting account and move more towards a blend between the orienting account and the bottleneck account.

EFFECTS OF FREQUENCY AND MAGNITUDE THAT CHALLENGE THE ORIENTING ACCOUNT

In the last empirical chapter we wanted to investigate whether error saliency would have an impact on behavioural adjustments after an error. We started from two observations. First, in the experiments presented in **Chapter 2** we found that post-error slowing was remarkably larger (23ms) when compared to post-oddball slowing (9ms) when keeping the infrequent events (errors and oddballs) even (25%). Second, in a social cognition study (Núñez Castellar, Notebaert, Van den Bossche, & Fias, 2011) behavioural adjustments after observed errors were investigated in a competitive and in a cooperative condition. In the competitive condition the best performing participant of a pair received a monetary reward, while in the cooperative condition the best pair of participants among all pairs received a monetary reward. Post-error slowing in cooperation was twice as large as in competition (cooperation: 63 ms vs. competition: 32 ms). Both effects can be explained by a larger orienting response after more salient errors. Whereas an error is presumably more salient to you than irrelevant stimulus, the same could be said about an error that has an impact on your own score (cooperation) than an error that not affects your score (competition).

To specifically test whether error significance has an impact on post-error slowing, four between-subject conditions were created. The saliency of the error was manipulated by implementing different reinforcement contexts; two groups were punished for making an error and two groups were rewarded for correct responses. Note that all participants received immediate visual feedback on every trial. The task was a modified flanker task. Both groups (reward and punishment) were further subdivided in a high and low value group, resulting in a high and a low reward and a high and a low punishment group. Each group received its normal feedback on 85% of the cases, while receiving deviant feedback in 15% of the cases. For example, after correct trials, the high reward group received high reward in 85% of the correct trials and low reward in 15% of the correct trials, whereas the low reward group received low reward after correct trials in 85% and high reward in 15% of the cases. Both groups received error feedback after making an error. The same was true for the punishment groups, as the high punishment group received high punishment following errors in 85% of the cases and low punishment in 15% of the cases, and the low punishment group received low punishment following 85% of the error trials and high punishment following 15% of the errors. Again, after every correct response correct feedback was given. This manipulation enables us to test the effect of feedback frequency on subsequent performance. According to the orienting account more post-error slowing is expected in the punishment groups than in the reward groups. Because errors are made more salient by punishing them, while when correct responses are rewarded more attention is drawn to these correct responses. Besides this hypothesis, some more specific hypotheses were formulated. More post-error slowing is expected in het high punishment group than in the low punishment group. Errors should be more salient when they are punished more severe. Within groups larger post-error slowing would be expected after frequent feedback than after infrequent feedback. Within the reinforcement contexts we would predict larger post-error slowing after for example infrequent large punishment than after frequent small punishment.

The obtained results were challenging for the orienting account. Generally, only the hypothesis about post-error slowing being larger in the punishment groups than in the reward groups was confirmed. There was no difference in post-error slowing between the high punishment group and the low punishment group. Also, in the low punishment group there was no difference after a frequent low punishment compared to after an infrequent high punishment. As a matter of fact, in the high reward group frequent high reward was followed by slower responses than infrequent low reward.

Similarly as in the third experiment of **Chapter 5**, no effect, and in one case even a reversed effect, after infrequent events was found. Maybe the participants did not pay attention to the precise feedback they received because in the general instructions the reinforcement scheme was already presented. Unfortunately, we did not ask the participants whether or not they paid attention to the different punishment or reward signals. Although feedback was always given correctly, the amount of punishment or reward was not dependent on the sort of error that was made or the sort of trial that was solved correctly.

FUNCTIONAL VS NON-FUNCTIONAL THEORIES

Where functional theories hold that error processing and post-error adjustments aim to improve performance on the following trial(s), non-functional theories explain post-error slowing in terms of reduced cognitive processing after errors. This dissertation started with the observation that traditional accounts for error-monitoring were challenged by a growing body of empirical data. In this dissertation we provided accumulating evidence that there is a need for non-functional theories for error monitoring.

CORRELATION POST-ERROR SLOWING AND OVERALL ACCURACY

In **Chapter 3**, **Chapter 4** and **Chapter 6** a correlation between post-error slowing and accuracy is reported. The most accurate participants also show the largest slowing after errors compared to after correct responses. It is undeniable that post-error slowing is at least partly influenced by error frequency. From a functional theory perspective one could say that better cognitive functioning participants, according to their high accuracy rates, apply more cognitive control and as a result show larger post-error slowing. However, in a study of Steinborn and colleagues (2012) post-error slowing and post-error accuracy changes was reported in a group of participants with a small range of accuracy, from 94% to 99%. When classifying participants into three groups according to their accuracy, it was shown that post-error slowing was largest in the high accurate group and smallest in the low accurate group. The group with the highest accuracy had also the lowest accuracy rates after errors compared to after correct trials. This would not be expected when post-error slowing is interpreted as a cognitive control effect, a remedial action in order to perform better. When post-error slowing is seen as the result of an orienting response, increased error rates are expected as you are more startled by the infrequent error you made. The bottleneck theory, however, needs an additional assumption to explain this finding. As Steinborn and colleagues suggested this assumption could be that infrequent errors lead to a longer post-error refractory period than frequent errors. Another explanation that combines both non-functional theories is that an orienting response to the infrequent nature of the error is the source of the interference that causes the bottleneck in central processing when another task needs to be processed immediately afterwards. The size of this orienting response depends on the relative frequency.

In a study by Maylor and Rabbitt (1995), participants were divided into two groups depending on their IQ rates. Although there was no difference in mean accuracy between both groups, the group with lowest IQ rates demonstrated the largest post-error slowing. This also contradicts an explanation in terms of high functioning participants that call for more cognitive control. The orienting account can only explain the result of Maylor and Rabbitt by assuming that people with lower IQ rates are more startled by surprising events than people with higher IQ rates. The bottleneck theory has a more elegant way of explaining the results. People with lower IQ rates have presumably lower capacity of working memory which results a lower ability to do two things at the same time.

POST-ERROR PERFORMANCE

In all the empirical chapters post-error slowing was accompanied by post-error accuracy decrease. The use of double errors in order to dissociate between a functional explanation for post-error slowing and a non-functional explanation is, however, questionable (see above). When using the attentional blink task (Chun & Potter, 1995) to measure post-error performance much stronger evidence is established.

Recent fMRI studies (King, Korb, von Cramon, & Ullsperger, 2010; Danielmeier, Eichele, Forstmann, Tittgemeyer, & Ullsperger, 2011) that investigated the relation between posterior medial frontal cortex activity and post-error behaviour observed a relationship between post-error slowing and decreased motor activation. Although this could be interpreted in terms of a motor inhibition account (Danielmeier et al.), it is also possible that the distraction on the basis of the infrequent error results in decreased motor activation.

An important remark to make is that in most tasks used in error monitoring research there is not much that can be learned. The tasks are mostly quite easy to do. For example, pressing a right button when you see an arrow pointing to the right and a left button when you see an arrow pointing to the left is not that difficult to remember. The speed of the task, both the speeded presentation of the stimuli and the short response deadline, evoke many errors. A challenge for future research therefore is to come up with experiments where errors induce either an orienting response or a real strategic adjustment of behaviour in order to perform better.

This idea is nicely illustrated in an ERP study (Holroyd, Krigolson, Baker, Lee, & Gibson, 2009) that further investigated the domain of the reinforcement learning theory originally described by Holroyd and Coles (2002). The study started from the observation that the basic hypothesis made by this theory was not always confirmed. According to this theory dopaminergic reinforcement signals are used by the anterior cingulate cortex (ACC) for selecting and reinforcing the motor controllers to perform the ongoing task optimally. The reinforcement learning theory states that the impact of these dopamine signals on the ACC modulate the amplitude of the ERN. Thus the more unexpected an event is, the larger the amplitude of the ERN should be. When investigating under which circumstances this hypothesis was confirmed the researchers found that this was most convincingly the case when optimal behavior is learnable. Similarly, in an experiment of Desmet, Imbo, De Brauwer, Brass, Fias, & Notebaert (2012) participants had to solve multiplications. This enabled participants to apply a more variety of strategic adjustments than only paying more attention to the presented stimulus, which is usually the case in conflict tasks. It was demonstrated that performance improves after errors when it is possible to learn something after errors.

In my view it is therefore necessary to move more towards experiments that enable the participant to learn to perform better.

TOWARDS A UNIFIED VIEW ON ERROR MONITORING

Functional theories and non-functional theories do not need to be mutually exclusive. It could well be that the immediate reaction to an error is for a large part dependent on its frequency. The following orienting response in case of an infrequent error will cause interference in the central processor when a subsequent task is followed immediately. However, when there is time enough both processes post-error slowing can in fact be used as a remedial action in order to perform better. In a study by Jentzsch and Dudschig (2009) smaller post-error slowing was found in a condition with long intervals (1000ms) between the response of the previous trial and the stimulus of the next trial (referred to as the Response Stimulus Interval: RSI) than in a condition with short intervals (100ms). There was, however, still post-error slowing in both conditions. Interestingly, post-error performance improved slightly in the longer RSI condition compared to in the short RSI condition. In that same experiment an underadditive effect of perceptual difficulty and post-error slowing was found. Previously, it had been demonstrated that perceptual processes can be carried out in parallel to central processes (Jentzsch, Leuthold, & Ulrich, 2007). On short RSIs no effect of perceptual difficulty was found on post-error trials, while this effect was present in post-correct trials. This underadditivity effect disappeared in case of long RSIs and was accompanied by better performance after errors. This can be explained by the fact that error monitoring processes have been completed, leaving time for strategic behavioural adjustments that lead to slower and more accuracy responses. This can be done by for example inhibiting the motor system in the brain. Thus, the time available after an error is probably an important prerequisite to observe functional results of post-error slowing.

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HOOFDSTUK 8

SAMENVATTING VAN HET PROEFSCHRIFT: FOUTENMONITORING: EVIDENTIE VOOR EEN VERKLARING IN TERMEN VAN ORIËNTATIE

"Een geniaal persoon maakt geen vergissingen.
Zijn fouten zijn gewild en zijn de poorten der ontdekking"

Ullysses (1922), James Joyce (1882-1941)

FOUTEN EN DE REACTIE OP FOUTEN

Fouten maken is een essentieel onderdeel van het leven. Iedereen maakt fouten. Veel belangrijker dan het maken van een fout op zich is de manier waarop je erop reageert. Je kan erover piekeren dat je de fout gemaakt hebt en daardoor niet onderzoeken hoe die fout er gekomen is en hoe je ze in de toekomst kan vermijden. Je kan de fout ook zien als een opportuniteit om huidige werkmethoden in vraag te stellen. Dit is ook wat ze volgens een legende over ‘ivory soap’ bij Proctor en Gamble deden eind de 19de eeuw. Toen één van de werknemers op een dag lunchpauze hield, vergat hij de machine die de zeep mixte af te zetten. Op het moment dat hij terug kwam was de zeep extra luchtig geworden door de lucht die er onder gemixt was. In plaats van de fout gemixte zeep weg te gooien, besloten ze om het mengsel te houden en de zeep te verkopen. Hun drijvende zeep werd een bestseller die wereldwijd verkocht werd. Hoewel onderzoek bij Proctor en Gamble heeft uitgewezen dat de drijvende zeep een uitvinding was van één van hun chemici, blijft de legende toch een goede illustratie van hoe de reactie op een fout veel belangrijker is dan de fout op zich.

Tabel 3. Citaten over fouten van oude filosofen.

Venia dignus error est humanus
Titus Livius (59 BC - AD 17)

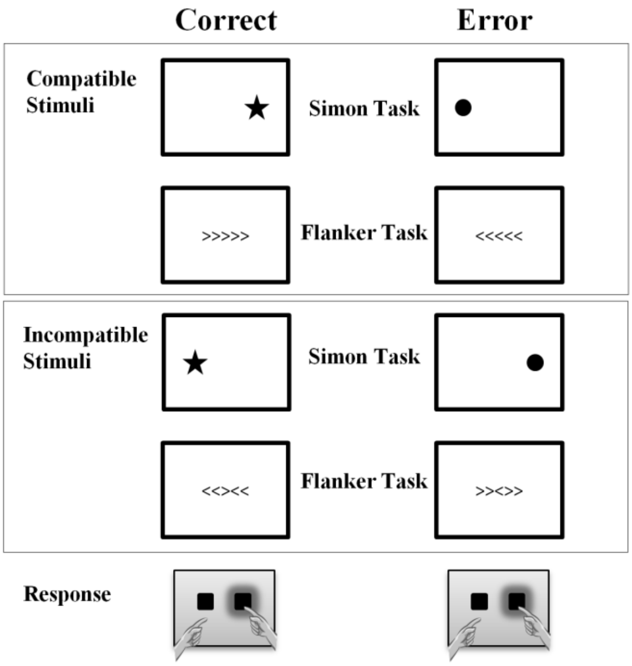
Humanum fuit errare, diabolicum est per animositatem in errore manere
Aurelius Augustinus Hipponensis (354 – 430)

Errare humanum est, perseverare
autem diabolicum, et tertium non datur
Lucius Annaeus Seneca (ca. 4 BC – AD 65)

Cuiusvis errare:insipientis nullius nisi, in errore perseverare
Marcus Tullius Cicero (106 BC - 43 BC)

In Table 1 zijn enkele citaten gepresenteerd van filosofen van soms meer dan 2000 jaar geleden. Opvallend bij deze citaten is dat ze ook meer gericht zijn op hoe er gereageerd wordt op een fout dan het maken van een fout op zich. De algemene boodschap van deze citaten is dat fouten maken menselijk is, maar dat volharden in je fouten duivels is.

In dit proefschrift wordt eerder de reactie op een fout onderzocht, dan de modaliteiten van het fouten maken op zich. Eind de jaren 60 onderzochten cognitief psychologen Rabbitt en Laming het gedrag na fouten. Beiden vonden de sindsdien vaak gerepliceerde bevinding dat mensen vertragen na het maken van een fout (Rabbitt, 1966; Laming, 1968). Deze vertraging werd oorspronkelijk aanzien als een strategische vertraging met als doel beter te presteren op de volgende oefening. Zulke verklaring noemt men een functionele verklaring van vertragen na fouten. De vertraging zelf heeft namelijk een functie. Hoewel betere prestaties na het maken van een fout af en toe zijn gerapporteerd (Laming, 1968; Marco-Pallares, Camara, Munte, & Rodriguez-Fornells, 2008; Maier, Yeung, & Steinhauser, 2011), was dit zeker niet altijd het geval. Verschillende studies rapporteren slechtere prestaties na fouten terwijl op hetzelfde moment vertraagd werd (Rabbitt & Rodgers, 1977; Cheyne, Carriere, & Smilek, 2009; Steinborn, Flehmig, Bratzke, & Schröter, 2012). Deze bevindingen waren de eerste aanleiding voor dit proefschrift. Het lijkt alsof de vertraging na een fout niet altijd functioneel is, maar soms ook zorgt voor een verstoring van de processen die nodig zijn om de volgende oefening op te lossen.



Figuur 3. Twee voorbeelden van eenvoudige conflicttaken die in het laboratorium vaak gebruikt worden om fouten te onderzoeken.

Om fouten te onderzoeken gebruikt men in het laboratorium eenvoudige conflicttaken. In Figuur 3 worden twee voorbeelden van zulke conflicttaken gegeven. Ten eerste is er de Flanker taak (Eriksen & Eriksen, 1974) waarbij je moet reageren op de richting van de middelste pijl. Deze middelste pijl wordt geflankeerd door vier andere pijlen. Deze kunnen in dezelfde richting wijzen of in de omgekeerde richting. In het eerste geval spreken we van een compatibele oefening waarbij de flankers compatibel zijn met het correcte antwoord. In het tweede geval spreken we van een incompatibele oefening waarbij de flankers niet compatibel zijn met de correcte response. Meestal zullen deelnemers aan zulke experimenten vooral fouten maken wanneer ze incompatibele oefeningen moeten oplossen.

De ‘conflict monitoring theory’ (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, Cohen, & Carter, 2004) is een functionele theorie die stelt dat er een signaal gestuurd wordt naar een conflict monitor wanneer er conflict in ons cognitief systeem opgemerkt wordt. Deze monitor zal er dan voor zorgen dat de cognitieve controle verhoogd wordt. Wanneer men een fout maakt gaat dit meestal gepaard met conflict. Zowel de correcte (niet uitgevoerde) respons zal actief zijn als de foute (uitgevoerde) respons. Het op hetzelfde moment actief zijn van beide antwoorden zorgt voor conflict. Verhoogde cognitieve controle zal ervoor zorgen dat men trager en ook beter presteert op de volgende oefening. De ‘reinforcement learning’ theorie (Holroyd & Coles, 2002) stelt dat leersignalen onder de vorm van dopamine door de anterieure cingulate cortex opgewekt worden wanneer gebeurtenissen afwijken van wat verwacht wordt. Deze signalen worden gebruikt om de gebieden die zorgen voor beweging perfect af te stellen op de taak die men aan het doen is. Verder stelt men dat de impact van deze dopamine-signalen op de ACC de grootte van de ERN (een error-specifiek potentiaal) beïnvloeden. Hoe meer onverwachts een gebeurtenis is, hoe groter de ERN zou moeten zijn. Een niet-functionele theorie die ongeveer tegelijkertijd met onze verklaring ontwikkeld werd is de flessenhals theorie voor foutenmonitoring van Jentzsch en Dudschig (Jentzsch & Dudschig, 2009; Dudschig & Jentzsch, 2009). Deze theorie stelt dat de centrale verwerker in ons brein een gelimiteerde capaciteit heeft. Wanneer men een fout maakt zijn er aan die fout gerelateerde processen bezig die ook door deze centrale processor verwerkt moeten worden. Indien een volgende oefening te snel volgt na het maken van een fout dan treedt er interferentie op. Bijgevolg zal de volgende oefening trager verwerkt worden en treedt er vertraging na fouten op. Deze theorie verwacht ook dat men, indien oefeningen elkaar in sneltempo opvolgen, slechter zal presteren na een fout dan na een juiste oefening. Indien er echter voldoende tijd is, verwacht men dat strategische aanpassingen aan het gedrag kunnen gedaan worden om beter te presteren op de volgende oefening.

EEN VERKLARING IN TERMEN VAN ORIËNTATIE

Vanuit de observatie dat vertraging na fouten niet altijd resulteert in betere prestaties zochten we naar een alternatieve verklaring voor deze vertraging. Wanneer men nagaat hoe vaak een fout wordt gemaakt in de eenvoudige taken in het laboratorium dan valt het op dat dit aantal relatief laag is. We trokken de parallel met een onverwachte gebeurtenis. Wanneer in je omgeving iets onverwachts gebeurt dan wordt je aandacht ernaar getrokken en moet je je terug re-oriënteren naar wat je op dat moment aan het doen was. Deze oriëntatie reflex werd al in 1863 beschreven door

Sechenov. Later is deze reflex veelvuldig onderzocht door toonaangevende wetenschappers (Pavlov, 1927; Sokolov, 1963). Onze hypothese is dat de vertraging die men gewoonlijk vindt in het laboratorium na fouten beïnvloed wordt door het aantal keren dat die fout is voorgekomen. Wanneer men heel weinig fouten maakt, verwacht men volgens deze hypothese dat de vertraging na een fout groter is dan wanneer men vaak fouten maakt. Om dit te onderzoeken ontworpen we een taak waarin het aantal fouten gemanipuleerd werd. Onze deelnemers moesten kleuren categoriseren. Dit betekent dat ze een bepaalde knop moesten indrukken al naargelang ze een groen, geel, blauw of rood vierkant zagen verschijnen. Om de taak moeilijker te maken werd de donkerte van de kleur aangepast. Er waren drie condities die alle deelnemers deden, een 35% correctheid, een 55% correctheid en een 75% correctheid conditie. Wanneer je bijvoorbeeld in de 55% correctheid conditie zat, dan werd er na elk antwoord op een oefening gekeken naar de gemiddelde nauwkeurigheid op de voorbije 20 oefeningen. Wanneer je meer dan 9 fouten had gemaakt dan werd de kleur lichter en dus gemakkelijker om te categoriseren. Wanneer je minder dan 9 fouten had gemaakt werd de kleur donkerder en bij gevolg moeilijker om te categoriseren. Bij 9 fouten bleef de kleur gelijk.

In lijn met onze verwachtingen vonden we inderdaad dat de vertraging na fouten in de 75% conditie het grootst was. In de 55% conditie was er geen vertraging na fouten. In de 35% conditie echter waren reacties na een correct antwoord trager dan na een fout antwoord. Dit is ook wat men op basis van een verklaring in termen van oriëntatie zou verwachten. Wanneer correct antwoorden een onverwachte gebeurtenis wordt, dan zou je inderdaad verwachten dat dit een oriëntatie reflex uitlokt waardoor je trager bent op de volgende oefening.

In een tweede experiment bleven de kleuren constant, maar nu werd er telkens ook een hoge of een lage toon gepresenteerd. De ene groep hoorde een hoge toon in 75% van de oefeningen en een lage toon in 35% van de oefeningen. De andere groep kreeg het omgekeerde te horen. Belangrijk in dit experiment is dat deze toon totaal irrelevant was voor de deelnemers. Ook nu vonden we dat reacties na een niet vaak voorkomende toon (25%) trager waren dan na het horen van de andere toon. Dit demonstreert het algemene effect dat een onverwachte gebeurtenis een vertraging uitlokt.

In het eerste experiment kregen deelnemers steeds onmiddellijke feedback na het geven van een antwoord. Wanneer ze fout waren werd er een F gepresenteerd op het scherm, wanneer ze juist waren werd er een J gepresenteerd en wanneer het antwoord te traag geven werd dan verscheen er een T. Het is dus mogelijk dat de oriëntatie reflex die we beschreven eigenlijk veroorzaakt werd door het zien van een onverwachtse visuele presentatie van de feedback en niet door het onverwachts maken van een fout of geven van een juist antwoord. In het volgende hoofdstuk wordt een experiment voorgesteld waarin we dit meer in detail onderzoeken.

ORIËNTATIE NAAR FOUTEN MET EN ZONDER ONMIDDELLIJKE FEEDBACK

Een voorbeeld om te illustreren wat fouten met en zonder externe feedback zijn is het volgende. Beeld je in dat je op de trein zit en plots merkt dat je eindstation bereikt is. In al je haast zoek je je spullen samen en vervolgens begeef je je naar de uitgang van de wagon. Je hebt echter je sjaal laten liggen op je zitplaats. Het kan zijn dat een vriendelijke medepassagier zegt: “Hee, je bent je sjaal vergeten!”. Het kan ook gebeuren dat je terwijl je je naar de uitgang begeeft beseft dat je je sjaal vergeten bent, en uit jezelf terug keert om je sjaal te halen. In het eerste voorbeeld was er een extern signaal, komende van de medepassagier, dat je wees op je fout. In het tweede voorbeeld heb je zelf ontdekt dat je fout was. In **hoofdstuk 3** onderzochten we de hypothesen van de verklaring in termen van oriëntatie wanneer er geen externe feedback gegeven wordt en deelnemers dus op zichzelf aangewezen zijn om te ontdekken dat ze fout waren. We verwachten dat de mate van onverwachts zijn van de intern ontdekte fout de grootte van de oriëntatie reflex zal bepalen en dus dat vertragingen na fouten ook hier afhankelijk zullen zijn van de onverwachtsheid van de fout.

We gebruikten hetzelfde paradigma als in **hoofdstuk 2** met enkele belangrijke wijzingen. Het adaptief algoritme werd slechts in het begin van elke conditie gebruikt om te bepalen voor elke deelnemer afzonderlijk welke donkerte nodig was om het vooraf bepaalde percentage fouten binnen die specifieke conditie te maken. Ook de condities waren lichtjes anders, in dit experiment werd er gestreefd naar 50% nauwkeurigheid, 70% nauwkeurigheid en 90% nauwkeurigheid. De helft van de deelnemers kreeg onmiddellijke feedback en de andere helft kreeg slechts na elke 50ste oefening feedback.

De resultaten waren conform de hypothese. Er werd het meest vertraagd na fouten in de 90% conditie, minder in de 70% conditie en er was geen vertraging meer in de 50% conditie. Dit effect van de frequentie van de fout op het vertragen na fouten was niet afhankelijk van onmiddellijke feedback. In beide groepen werd hetzelfde resultaat gevonden.

DE PE ALS EEN INDEX VAN INTERNE ORIËNTATIE NAAR FOUTEN

In een studie gedaan door onze onderzoeksgroep werden de elektrofysiologische correlaten van onverwachte fouten en onverwachte juiste antwoorden onderzocht (Nùñez-Castellar, Kühn, Fias, & Notebaert, 2010). Ze gebruikten dezelfde taak als die beschreven in hoofdstuk 2. De gedragsmatige bevindingen werden gerepliceerd. In de 75% nauwkeurigheid conditie vertraagden de deelnemers na fouten en in de 35% nauwkeurigheid conditie vertraagde men na het geven van een juist antwoord. Nùñez-Castellar en collega's vonden dat de P3, een aan aandacht gerelateerde ERP component, correleerde met de vertragingen. De P3 is een ERP component die gerelateerd is aan opvallende gebeurtenissen. De P3 was het sterkst na feedback die aangeeft dat je fout was in de 75% conditie en het sterkst na feedback die aangeeft dat je juist antwoordde in de 25% conditie. De ERN, een ERP component die gerelateerd is aan fouten, correleerde echter niet met reactietijden. In hoofdstuk 4 willen we gedragsmatige veranderingen na fouten correleren met ERP componenten.

In onze taak werd geen feedback gegeven. We creëerden een moeilijke en een makkelijke conditie van een flanker taak. De resultaten van deze studie waren niet helemaal volgens de verwachtingen. Ookal was er een verschil in het percentage fouten tussen beide condities, toch was er geen verschil in de vertraging na fouten. Wanneer we de data per conditie afzonderlijk gaan analyseren vonden we wel een correlatie tussen het percentage fouten en vertraging na fouten. De foutgerelateerde ERP componenten die we onderzochten waren de ERN en de PE. De ERN is een negatieve potentiaal die tussen 0 en 100 ms na het maken van een fout gemeten kan worden. De PE is een positieve potentiaal die tussen 200 en 400 ms na fout geobserveerd wordt. Zowel de ERN als de PE was het grootst in de conditie waar het minst fouten werd gemaakt, zoals al in een eerder ERP studie gevonden werd (Santesso, Segalowitz, & Schmidt, 2006).

De correlatie tussen de ERP data en de gedragsmatige veranderingen na fouten toonde aan dat enkel de PE correleerde met het vertragen na fouten. In verschillende ERP studies is het reeds aangetoond dat de PE en de P3 zeer gelijkaardige componenten zijn. De PE kan dus gezien worden als een marker voor interne oriëntatie naar fouten.

VERBLIND WORDEN DOOR EEN FOUT

Om te onderzoeken of vertraging na fouten gepaard gaat met betere prestaties wordt vaak gekeken naar het percentage fouten dat na een fout gemaakt wordt en het percentage fouten dat na een correct antwoord gemaakt wordt. Deze methode is sterk afhankelijk van zowel dubbele fouten als het aantal fouten dat gemaakt werd. In een overzichtsartikel van Danielmeier en Ullsperger (2011) kaartte men dit probleem reeds aan. Wanneer bijvoorbeeld iemand slechts 10 fouten heeft gemaakt tijdens het experiment dan zorgt elke dubbele fout voor een verhoging van 10% in het percentage fouten na fouten. We zochten dus een nieuwe manier om prestaties na fouten te gaan evalueren. Een reeds vaak gebruikt paradigma in aandachtsonderzoek is het “attentional blink” paradigma (Chun & Potter, 1995). Bij zulke experiment gaat men een heel snelle stroom van bijvoorbeeld cijfers presenteren. In die stroom van cijfers worden twee letters getoond. De taak van de deelnemer is om die twee letters te identificeren. Indien deze letters kort na elkaar getoond worden dan is het zeer moeilijk om de tweede letter in de rij te detecteren. We pasten dit paradigma aan door een flanker taak direct te laten volgend door zo een stroom van cijfers. Deelnemers reageren eerst op de flanker taak en meteen erna moeten ze een letter in een cijferstroom detecteren. In het eerste experiment werd er tussen de flanker taak en de cijferstroom ook een visueel feedback signaal gepresenteerd, in het tweede experiment werd dit vervangen door een leeg scherm. Op die manier bleef de timing in beide experimenten hetzelfde. We vonden dat een fout op de flanker taak vaker gevolgd werd door een fout in de detectie taak dan een correct antwoord op de flanker taak. Dus na het maken van een fout is er een dip in aandacht. Dit werd zowel gevonden met als zonder feedback.

Dit kan zowel verklaard worden door de flessenhals theorie voor foutenmonitoring (Jentzsch & Dudschig, 2009; Dudschig & Jentzsch, 2009) als door de verklaring in termen van oriëntatie. Het kan zowel zijn dat de aandachtsdip veroorzaakt wordt doordat er teveel processen tegelijk plaatsvinden als dat de onverwachtsheid van de fout een oriëntatie reflex uitlokt die vervolgens de aandacht verstoort.

Om een onderscheid te maken tussen beide niet-functionele verklaringen voor vertraging na fouten werd een derde experiment ontworpen. De flanker taak werd achterwege gelaten en elke stroom van cijfers begon nu met een rode F of een groene J. Dit waren de zelfde letters als de feedbacksignalen in het eerste experiment. De deelnemers werden in twee groepen verdeeld en kregen een verschillend percentage van beide letters. De ene groep zag de rode F in 60% van de oefeningen en bijgevolg de groene J in 40% van de oefeningen. De andere groep zag de groene J het vaakst (60%) en de rode F het minst (40%). Elliot, Maier, Moller, Friedman, en Meinhardt (2007) toonden reeds aan dat rode signalen gerelateerd worden met fouten. Op basis van deze kennis zou de flessenhals theorie voor foutenmonitoring verwachten dat de aandachtsdip afhankelijk zal zijn van het voorkomen van de rode F onafhankelijk van de frequentie waarmee die letter getoond wordt. De verklaring in termen van oriëntatie zou voorspellen dat de aandachtsdip het grootst zal zijn na de letter die het minst vaak voorkwam, onafhankelijk van het uitzicht van de letter.

Er werd evidentie gevonden voor de flessenhals theorie. De aandachtsdip was in beide groepen het grootst na het zien van een rode F, onafhankelijk van de frequentie van die stimulus.

EFFECTEN VAN DE FREQUENTIE EN GROOTTE VAN STRAF EN BELONING: EEN UITDAGING VOOR EEN VERKLARING IN TERMEN VAN ORIËNTATIE

In **hoofdstuk 6** onderzochten we ten slotte of de salientie van een fout gedragsmatige aanpassingen na fouten zou beïnvloeden. Een gebeurtenis kan niet vaak voorkomen en dus onverwachts zijn, maar als die helemaal onopvallend gebeurt dan zal je ze ook niet opmerken. Verder is het bekend dat de salientie van een gebeurtenis ook een invloed heeft op de oriëntatie reflex die het eventueel uitlokt (Bernstein, Scheffers, & Coles, 1995). Het startpunt van dit onderzoek was tweezijdig. Ten eerste vonden we in het tweede experiment van **hoofdstuk 2** dat de deelnemers opvallend meer vertraagden na fouten (23 ms) dan na een onverwachte stimulus (9 ms), zelfs indien de frequentie van voorkomen gelijk gehouden werd. Ten tweede hadden Nùñez-Castellar, Notebaert, Van den Bossche, en Fias (2011) gevonden dat de invloed die het observeren van een fout had op het eigen gedrag afhankelijk was van de context waarin men zich bevond. Er was een coöperatieve en een competitieve conditie. In de eerste conditie werd aan de deelnemers verteld dat het koppel met gezamenlijk het minste aantal fouten een extra beloning zou krijgen. In de competitieve conditie werd per koppel de best presterende deelnemer beloond. In de coöperatieve conditie vertraagde men twee keer zo lang als in de competitieve conditie na het zien van een fout bij de andere deelnemer (coöperatief: 63 ms vs. competitief: 32 ms). Een fout bij de andere deelnemer in een coöperatieve conditie is waarschijnlijk meer salient, meer belangrijk voor jou dan in een competitieve conditie waar de fout geen invloed heeft op jouw eigen score.

Om de salientie van de fout te manipuleren hebben we vier condities gecreëerd waarin telkens andere deelnemers deelnamen. Twee groepen werden gestraft na het maken van fout door punten te verliezen (de deelnemer met het grootst aantal overgebleven punten werd extra beloond) en twee groepen werden beloond voor het geven van juiste antwoorden door hen punten toe te kennen (de deelnemer met het grootst aantal verworven punten werd beloond). De taak was een moeilijkere versie van de flanker taak waarbij de flankers eerst getoond werden en de target pas later. De strafgroepen en de beloningsgroepen werden verder opgedeeld in een groep die meestal veel straf/beloning en soms weinig straf/beloning kreeg en een groep die meestal weinig straf/beloning kreeg en soms veel straf/beloning kreeg. Op deze manier konden we het effect van de frequentie van de feedback op het gedrag testen. Volgens de verklaring in termen van oriëntatie verwacht men meer vertraging na fouten in de strafgroepen dan in de beloningsgroepen. Aangezien men zou kunnen verwachten dat fouten meer opvallend/salient gemaakt worden door deelnemers te bestraffen bij het maken van een fout, terwijl correcte antwoorden meer aandacht krijgen wanneer je beloond wordt voor het geven van een juist antwoord. Verder verwachtten we ook meer vertraging na fouten in de groep die meestal veel straf krijgt dan in de groep die meestal weinig straf krijgt. Aangezien fouten hoogstwaarschijnlijk salienter zijn wanneer ze meer bestraft worden. Bij analyses binnen de groepen verwachtten we dat vertraging na fouten groter is na feedback die vaak gegeven wordt, dan na feedback die slechts af en toe gegeven wordt.

De resultaten vormden een uitdaging voor de verklaring in termen van oriëntatie. Enkel de hypothese dat mensen meer zouden vertragen na fouten in een straf conditie dan in een beloning conditie werd bevestigd. Er was geen verschil in vertraging na fouten in de groep die meestal veel bestraft werd en de groep die meestal weinig bestraft werd. Daarenboven vonden we in de omgekeerde effecten in de groep die vaak veel beloond werd.

Net als in het derde experiment van **hoofdstuk 5** vonden we geen effect en zelfs een omgekeerd effect na infrequente gebeurtenissen. Het is mogelijk dat de deelnemers geen aandacht gaven aan de exacte feedback die ze kregen aangezien ze al in het begin van het experiment op de hoogte waren gesteld van het feit dat ze straf/zouden krijgen. Jammer genoeg hebben we de deelnemers niet gevraagd of ze aandacht gegeven hebben aan het precieze feedback signaal.

FUNCTIONELE THEORIEËN VERSUS NIET-FUNCTIONELE THEORIEËN

Functionele theorieën voor het vertragen na fouten veronderstellen dat foutenmonitoring en gedragsmatige aanpassingen na het maken van een fout er op gericht zijn om de prestatie in de volgende oefeningen te verbeteren. Niet-functionele theorieën verklaren het vertragen na fouten aan de hand van verminderde cognitieve processen. Dit proefschrift begon bij de observatie dat het vertragen na fouten niet altijd gepaard gaat met een verbetering in prestaties. Ook werd aangetoond dat patiënten met schade aan hun frontale kwab, in gebieden die voor functionele theorieën essentieel zijn voor het strategisch aanpassen van het gedrag na fouten, nog steeds vertraging na fouten vertonen (Stemmer, Segalowitz, Witzke, & Schönle, 2004).

DE SAMENHANG TUSSEN VERTRAGEN NA FOUTEN EN ALGEMENE ACCURAATHEID

In **hoofdstuk 3, hoofdstuk 4** en **hoofdstuk 4** werd een positieve correlatie tussen het aantal correcte antwoorden in een experiment en de mate van vertraging na fouten aangetoond. Mensen die het best presteren, vertragen ook het meest na het maken van een fout. Deze bevinding maakt het onweerlegbaar dat het vertragen na fouten op zijn minst gedeeltelijk beïnvloed is door het aantal fouten dat gemaakt wordt. Een functionele verklaring voor deze bevinding zou kunnen zijn dat mensen die cognitief zeer goed functioneren en bijgevolg zeer weinig fouten maken, meer strategische controle aan de dag kunnen leggen. Met als gevolg dat ze ook meer gaan vertragen. Enkele bevindingen spreken deze verklaring tegen. Steinborn en collega's (2012) onderzochten reactietijden en accuraatheden na het maken van fouten in een groep van zeer goed scorende mensen. De gemiddelde accuraatheid ging van 94% tot 99%. De deelnemers werden in drie groepen ingedeeld, afhankelijk van hun percentage correcte antwoorden zaten ze in de minst presenterende groep, de best presenterende groep en de groep die daar tussenin valt. De best presterende groep vertoonde de grootste vertraging na het maken van een fout. De minst presenterende groep vertraagde het minst. Het was opmerkelijk dat de best scorende groep het slechtst scoorde na het maken van een fout. Deze samenhang van grootste vertraging en slechtst presteren zou je niet verwachten indien vertraging na fouten steeds tot doel heeft om beter te presteren. Een verklaring in termen van oriëntatie zou inderdaad voorspellen dat prestaties na een fout slechtst zijn in de groep waar het minst fouten voor komen, aangezien zij het meest verrast zijn van hun onverwachte fout. De flessenhals theorie zou deze bevindingen enkel kunnen verklaring indien ze de assumptie dat minder frequente fouten leiden tot een langere periode van interferentie. Een andere verklaring, die beide niet-functionele theorieën combineert, is dat onverwachtse fouten een oriëntatie reflex uitlokken en dat dit de bron is van de interferentie die de opstopping in de flessenhals veroorzaakt. De grootte van deze oriëntatie reflex hangt af van de relatieve frequentie van de fout.

In een onderzoek uitgevoerd door Maylor en Rabbitt (1995) deelde men deelnemers op in twee groepen afhankelijk van hun score op een IQ test. Hoewel er geen verschil tussen beide groepen was in het aantal fouten dat gemaakt werd, toch vertraagden de deelnemers in de groep met de laagste IQ scores meer na een fout dan de groep met de hoogste IQ scores. Deze bevinding doet opnieuw twijfelen aan een verklaring op basis van cognitief sterk presterende mensen die een grotere strategische controle over hun antwoorden hebben. De meest elegante verklaring van de bevindingen van Maylor en Rabbitt is die van de flessenhals theorie. Mensen met een lagere IQ score hebben waarschijnlijk ook een minder groot werkgeheugen waardoor ze slechter zijn in het uitvoeren van meerdere processen tegelijk.

PRESTATIES NA HET MAKEN VAN EEN FOUT

In elk empirisch hoofdstuk in dit proefschrift ging vertragen na een fout samen met een hogere fouten ratio na een fout dan na een juist antwoord. Het gebruik van dubbele fouten om een verschil te maken tussen functionele en niet-functionele theorieën werd reeds eerder in twijfel getrokken. Door de implementatie van de ‘attentional blink’ taak (Chun & Potter, 1995) hebben we veel overtuigender kunnen aantonen dat de aandacht na een fout in typische taken in het lab verstoord is.

Recente fMRI studies (King, Korb, von Cramon, & Ullsperger, 2010; Danielmeier, Eichele, Forstmann, Tittgemeyer, & Ullsperger, 2011) onderzochten de relatie tussen hersenactiviteit in de posterieure mediale frontale cortex en het gedrag na het maken van een fout. Deze studies toonden aan dat de foutspecifieke vertraging gepaard ging met een vermindering van hersenactiviteit in het gebied dat instaat voor onze bewegingen. Men zou kunnen stellen dat de afleiding die gebeurt door het maken van een onverwachte fout resulteert in een vermindering van hersenactiviteit in het bewegingsgebied.

Een belangrijke opmerking bij de meeste taken die gebruikt worden om de processen die gepaard gaan met het maken van fouten te onderzoeken, is dat er meestal niet zo heel veel kan geleerd worden. Wanneer je verkeerdelijk de rechtse knop indrukte wanneer op het midden van het scherm een pijl naar links gepresenteerd werd kan je eigenlijk enkel maar proberen om je beter te concentreren in de volgende oefening. Het veelvuldig gebruik van zulke taken kan de theorievorming van cognitieve processen beïnvloeden. Het is belangrijk om ook na te gaan of dezelfde resultaten gevonden worden wanneer een meer ecologische valide taak gebruikt wordt.

Dit wordt mooi geïllustreerd in een onderzoek van Desmet, Imbo, De Brauwer, Brass, Fias en Notebaert (2012). De deelnemers moesten vermenigvuldigingen oplossen. Dit gaf hen de kans om een meer dan een strategie te kunnen gebruiken om beter te presteren op de volgende oefening. In deze taak vond men dat deelnemers beter presteren na het maken van een fout.

In een ERP-studie van Holroyd, Krigolson, Baker, Lee, en Gibson (2009) werd ongeveer hetzelfde punt gemaakt. In deze studie wilde men het domein waarin de ‘reinforcement learning theory’ van Holroyd en Coles (2002) gaan onderzoeken. In eerder onderzoek was immers aangetoond dat hun theorie niet altijd bevestigd werd. De onderzoekers vonden dat hun hypotheses het meest overtuigend bevestigd werden wanneer men kan leren om optimaal te reageren op de taak.

Een uitdaging voor toekomstig onderzoek is dus om experimenten te ontwerpen waarbij fouten ofwel een oriëntatie reflex uitlokken ofwel een werkelijke strategische verandering in het gedrag. Experimenten die een grotere ecologische validiteit hebben.

NAAR EEN GEÜNIFICEERD BEELD VAN FOUTENMONITORING

Functionele en niet-functionele verklaringen voor vertragen na fouten hoeven elkaar niet uit te sluiten. Het zou zeer goed kunnen dat de onmiddellijke reactie na het maken van een fout voor een groot deel bepaald wordt door het relatieve aantal fouten dat gemaakt werd. De oriëntatie reflex die dan zou volgen op een weinig voorkomende fout kan dan interferentie veroorzaken in de centrale verwerker wanneer onmiddellijk daaropvolgend een taak moet gedaan worden. Maar indien er tijd genoeg is tussen beide processen dan kan de tactiek van vertraging gebruikt worden om beter te presteren. Een onderzoek van Jentzsch en Dudschig (2009) toonde aan dat vertraging na fouten kleiner is in een taak met veel tijd tussen het antwoord en de volgende taak dan in een taak waarbij er weinig tussentijd is. Hierbij aansluitend verbeterden de prestaties na het maken van een fout lichtjes bij veel tussentijd. Dus de tijd die men heeft na het maken van een fout is hoogstwaarschijnlijk een belangrijke voorwaarde om vertraging na fouten te doen resulteren in betere prestaties.

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