



Behavioural and electrophysiological support for decreased visual processing following errors

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Liesbet

CHAPTER 1

INTRODUCTION

A key feature of human behaviour is the ability to select the appropriate response based on instructions or experiences. In experimental-psychological research, this ability is called cognitive control and it is often illustrated using traffic examples. For instance, when you are driving your car to work, you have a tendency to use the same route every time. However, if you encounter a road block unexpectedly, you can easily override your automatic tendency and use an alternate route. In doing so, you may experience that you need more attention, and might drive slower to make sure you select the correct alternative route.

Cognitive control is typically studied using conflict tasks. In these tasks, participants are required to selectively attend and respond to an arbitrary stimulus feature while ignoring other, irrelevant, features (see Figure 1 for an illustration of the most commonly used conflict tasks). As such, we can distinguish between two types of trials; (1) congruent trials, where both the relevant and irrelevant stimulus characteristics trigger the same response, and (2) incongruent trials, where the irrelevant stimulus characteristic trigger a different response (Cohen, Dunbar, & McClelland, 1990; Kornblum, 1994). For example, in the Simon task, participants have to respond, with the left or right hand, to the colour of stimuli that are being presented on the left or the right side of the screen. By applying cognitive control, participants can make sure their response is not automatically driven by the location of the stimulus but by the task-relevant colour. Incongruent stimuli typically result in slower and more error-prone responses than congruent stimuli (Lu & Proctor, 1995; MacLeod, 1991; Simon, 1969). In these tasks, conflict is thus operationalized as response competition.

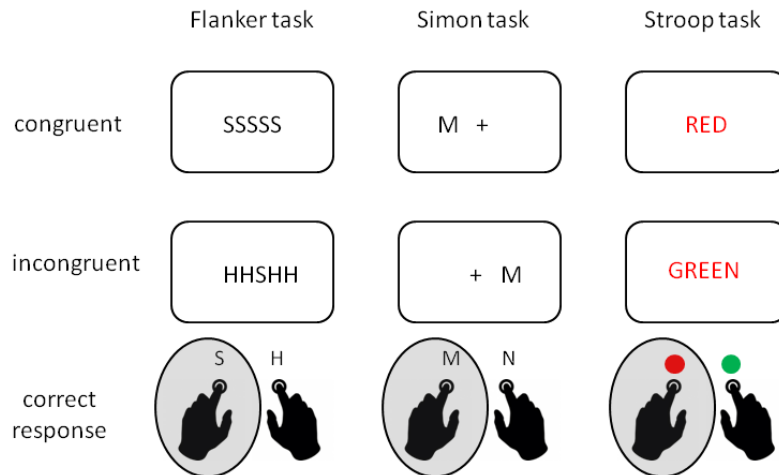


Figure 1. An illustration of a congruent and incongruent trial in a two alternative forced choice flanker task, Simon task and Stroop task and their associated correct response.

Even though humans are quite successful in selecting the appropriate behaviour even when conflicting information is present, instances occur when the optimization of the system and selection of the relevant signals fail, resulting in an error. As cognitive control is the ability to overcome conflicting information in selecting the correct response, making an error equals a failure in selecting the correct response. For some reason the incorrect conflicting information has a stronger activation, influencing behaviour. While it might be difficult to deduce exactly why an error is made, an error in itself is a strong signal to adapt subsequent behaviour due to people not wanting to repeat non-favourable outcomes. Error monitoring as well as post-error adaptation of behaviour thus contains a great deal of information about cognitive control and the performance monitoring system leading to a merge of cognitive control and error research (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Holroyd & Coles, 2002), which only recently has started to diverge again

(Danielmeier & Ullsperger, 2011; Jentsch & Dudschig, 2009; Notebaert et al., 2009).

Error monitoring and post-error behaviour have been investigated in a variety of tasks such as time estimation tasks, colour or tone discrimination tasks or mental arithmetic tasks (Desmet et al., 2012; Houtman, Núñez Castellar, & Notebaert, 2012; Jentsch & Dudschig, 2009). However, because of the inherent link between errors and conflict, conflict tasks are also widely used to study post-error adaptation.

In this introduction I will first discuss the behavioural measures of post-error adaptation as well as the electrophysiological correlates of error monitoring. I will then discuss theories of error monitoring, distinguishing between functional and nonfunctional accounts. Finally, I will present an overview of the studies presented in this doctoral dissertation.

POST-ERROR BEHAVIOURAL ADAPTATIONS

POST-ERROR SLOWING

An intensively studied marker of post-error adaptation is post-error slowing (PES), i.e. participants slow down following an error (Laming, 1979; Patrick Rabbitt & Rodgers, 1977). PES occurs with and without use of external feedback signals (Houtman et al., 2012). Within participants, PES has been shown to be quite reliable over time (Segalowitz et al., 2010), even when retesting occurs several months later (Danielmeier & Ullsperger, 2011). However, the amount of PES is also dependent on the inter-trial interval. When a short inter-trial interval is used (e.g. 100 ms), larger PES is found (Danielmeier & Ullsperger, 2011; Jentsch & Dudschig, 2009). Interestingly, participants tend to slow down only following self-committed errors, and not after inserted or externally induced errors (de Bruijn, Mars, & Hulstijn, 2004; Logan & Crump, 2010; Steinhauser & Kiesel, 2011). Interestingly, while conflict

adaptation is specific for a certain task set, PES generalizes over task sets (Forster & Cho, 2014; Notebaert & Verguts, 2011).

The amount of PES also seems to be influenced by context and personality characteristics as reducing belief in intentional control also reduces the amount of PES (Rigoni, Wilquin, Brass, & Burle, 2013). Additionally, comparing both punishment and reward contexts, Stürmer, Nigbur, Schacht, and Sommer (2011) found larger PES in the reward block than in the punishment block while Boksem, Tops, Kostermans, and De Cremer, (2008) showed larger PES for individuals with high punishment sensitivity in a context where errors were being punished. However, these findings are not straightforward since more often than not, PES is not influenced by context or individual differences such as anxiety and punishment sensitivity (Boksem, Tops, Wester, Meijman, & Lorist, 2006; Hajcak, McDonald, & Simons, 2003a; Rigoni, Pourtois, & Brass, 2014; Weinberg, Olvet, & Hajcak, 2010).

Even though the occurrence of PES is quite robust, there appear to be some instances in which PES is not found. For example when errors are not infrequent, these errors are not followed by significant PES (Houtman et al., 2012; Notebaert et al., 2009; Núñez Castellar, Kühn, Fias, & Notebaert, 2010). Additionally when investigating unperceived errors, using error awareness tasks, again no significant PES is found (Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001; Wessel, Danielmeier, & Ullsperger, 2011).

While the occurrence of PES is not controversial in itself, there has been some debate on how to reliably measure PES. Dutilh and colleagues (2012) quite convincingly showed that quantifying PES as the difference in response time between post-error trials and post-correct trials is often confounded by global changes in performance, i.e. participants tend to make (streaks of) errors when local performance is deteriorated.

Interestingly, by quantifying PES as the difference in response time between post-error trials and post-correct trials *preceding an error*, PES can be more reliably estimated making this measure immune to global fluctuations in performance.

POST-ERROR ACCURACY

The findings on PES are quite consistent, however, the reported pattern in the literature in terms of post-error accuracy is less clear. Post-error accuracy increase (PIA, Danielmeier, Eichele, Forstmann, Tittgemeyer, & Ullsperger, 2011; Maier, Yeung, & Steinhauser, 2011), as well as no difference in accuracy between post-correct and post-error trials (King, Korb, von Cramon, & Ullsperger, 2010; Ridderinkhof, 2002) or even decreased accuracy following errors (Bombeke, Schoupe, Duthoo, & Notebaert, 2013; Carp & Compton, 2009; Houtman et al., 2012) is reported. Often PES and post-error accuracy are investigated together, with the prevalent view that a speed-accuracy trade-off is expected, i.e. participants slow down in order to improve their performance on the subsequent trials. While this expected pattern of results is not clearly found in the literature, recent research suggests that the inter-trial interval may play an important role. Indeed, when using a short inter-trial interval (i.e. 100 ms), Jentsch and Dudschig (2009) found large PES and post-error accuracy *decrease*. However, when a longer inter-trial interval of 1000 ms was used, they found reduced PES and significant PIA.

POST-ERROR REDUCTION OF INTERFERENCE

Because of the use of conflict tasks, a third behavioural measure can be studied. In conflict tasks, the interference effect (i.e., the difference between incongruent and congruent trials) can be compared following erroneous and correct responses. This measure was first investigated by Ridderinkhof (2002) who showed post-error *reduction* of interference (PERI). This initial result is explained by a heightened cognitive control

following errors, resulting in post-error focusing. While PERI has been observed in some studies (King et al., 2010; Ridderinkhof et al., 2002), other studies have failed to replicate this effect (Carp & Compton, 2009; Orr, Carp, & Weissman, 2012), or even found increased interference following errors (Bombeke et al., 2013). Interestingly, while this effect mirrors the congruency sequence effect (i.e., smaller interference effect following incongruent trials than following congruent trials), most studies ignore the influence of the preceding congruency completely. As errors are mostly made on incongruent trials, this factor might influence previous reports of PERI. One exception thereof is a study by Maier, Yeung, and Steinhauser (2011) who calculated PERI following incongruent trials only. They showed a reduction of interference following flanker errors (responding to the irrelevant flanker feature), relative to correct trials or non-flanker errors (responses to neither the target nor the flanker).

ELECTROPHYSIOLOGICAL MARKERS OF ERROR COMMISSION

In more recent years, error detection in the human brain has frequently been investigated using non-invasive techniques. Overall findings in performance monitoring research using functional neuro-imaging show the importance of the posterior mesial frontal cortex (pmMFC, for an overview see Ullsperger, Danielmeier, & Jocham, 2014). Additionally, using an electro-encephalogram (EEG) the time course of brain waves, i.e. the electrical activity of the brain along the scalp, related to error commission can be investigated. These event-related potentials (ERP) are averaged voltages following specific events such as stimuli or responses. While ERPs convey less information regarding the anatomical origin of the brain waves, they do represent neural manifestations of specific processing. Depending on the experimental variables of the tasks, functional interpretations of these components can be made.

THE ERROR-RELATED NEGATIVITY

The error-related negativity (ERN) is a negative brain potential at fronto-central electrode sites peaking between 50 to 100 ms after error commission (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991; Gehring, Goss, & Coles, 1993). The origin of the ERN has been linked to the pMFC (for an overview see Ullsperger, Danielmeier, & Jocham, 2014). Interestingly, when using Laplacian transformation, which allows spatial deblurring of EEG (Babiloni, Cincotti, Carducci, Rossini, & Babiloni, 2001), a similar, but smaller, negativity can be found for correct responses, the correct-related negativity (CRN, Allain, Carbonnell, Falkenstein, Burle, & Vidal, 2004; Vidal, Hasbroucq, Grapperon, & Bonnet, 2000). Using independent component analysis (ICA, Makeig, Jung, Bell, Ghahremani, & Sejnowski, 1997), it has been shown that both negativities arise from overlapping generator structures (Gentsch, Ullsperger, & Ullsperger, 2009; Roger, Bénar, Vidal, Hasbroucq, & Burle, 2010). This finding has been supported by research using principal components analysis (PCA) which revealed a central factor, underlying both the CRN and ERN, sensitive to response correctness and task difficulty (Endrass, Klawohn, Gruetzmann, Ischebeck, & Kathmann, 2012). While it has been suggested that the CRN reflects partial error processing on correct trials (Coles, Scheffers, & Holroyd, 2001; Pailing & Segalowitz, 2004; Scheffers & Coles, 2000), partial error execution is not a prerequisite for the appearance of the CRN (Vidal, Burle, Bonnet, Grapperon, & Hasbroucq, 2003). It is therefore more probably that the amplitude of both the ERN and CRN reflect the accumulation of evidence about error commission, thereby signaling the need for adjustments (Bartholow et al., 2005; Ullsperger et al., 2014).

When external feedback signals are used, a similar deflection can be found locked to the onset of the feedback stimulus. The feedback-related negativity (FRN) peaks 200 to 300 ms after feedback and is larger for negative than for positive feedback (Gruendler, Ullsperger, & Huster, 2011; Holroyd & Krigolson, 2007; Miltner, Braun, & Coles, 1997). There

is additional evidence that the ERN and the FRN are functionally equivalent as both these components can be related to highly overlapping generator structures (Gentsch et al., 2009; Holroyd & Coles, 2002; Miltner et al., 1997). Interestingly, correlations have been found between ERN and FRN amplitude and the hemodynamic response in the anterior midcingulate cortex (aMCC, part of the pMFC) with more negative amplitudes associated with stronger aMCC responses (Debener et al., 2005; Huster et al., 2011). Recently it has been hypothesized that these components all originate from the same general pMFC processes that are reflected on the scalp in increased frontal theta power (Cavanagh, Zambrano-Vazquez, & Allen, 2012).

In several experiments the amount of PES has been related to the ERN amplitude (Debener et al., 2005; W. Gehring et al., 1993; West & Travers, 2008). However, the relation between PES and the ERN remains equivocal (Endrass, Reuter, & Kathmann, 2007; Hajcak, McDonald, & Simons, 2003b; Hewig, Coles, Trippe, Hecht, & Miltner, 2011; Núñez Castellar et al., 2010).

THE ERROR POSITIVITY

Following the ERN/CRN a slow positive wave with maximum amplitude between 200 and 400 ms and a more diffuse scalp distribution is observed (*error positivity*, Pe, Falkenstein et al., 1991). This component has been linked to error awareness (Endrass et al., 2007; Nieuwenhuis et al., 2001; O'Connell et al., 2007; Shalgi, Barkan, & Deouell, 2009; Wessel et al., 2011). There is some support that the Pe is made up of two subcomponents (Arbel & Donchin, 2009; Endrass, Klawohn, Preuss, & Kathmann, 2012; Endrass et al., 2007; Van Veen & Carter, 2002), where only the late Pe is seemingly related to error awareness (Endrass, Klawohn, Preuss, et al., 2012). The early fronto-central Pe seems to be instigated by the same generators as the ERN (Debener et al., 2005; Van

Veen & Carter, 2002) while the late posterior Pe is attributed to the parietal cortex and rostral ACC (Herrmann, Römmler, Ehlis, Heidrich, & Fallgatter, 2004; Van Veen & Carter, 2002; for an overview see Ullsperger et al., 2014).

Interestingly the Pe shares many characteristics with the P300, or P3, a positive stimulus-locked slow wave appearing between 200 and 400 ms after stimulus onset (Ridderinkhof, Ramautar, & Wijnen, 2009). The P3 has generally been associated with the processing of unexpected and motivationally significant events (for a review, see Nieuwenhuis, Aston-Jones, & Cohen, 2005) and has been divided into two subcomponents. The P3a is an earlier occurring component with a frontal/central scalp distribution (Polich & Comerchero, 2003) and is more sensitive to the novelty of events. The P3b on the other hand is a later component with a parietal scalp distribution and is sensitive to the amount of attentional resources allocated to a stimulus (Polich & Comerchero, 2003; Polich, 2007).

THEORIES OF ERROR MONITORING

Two types of theories can be discerned. Functional theories explain PES as a strategic adaptation to improve performance on the subsequent trials. However, the lack of accuracy improvement after errors gave rise to so-called non-functional accounts of PES. These theories explain PES as a result of ongoing error processing or an attentional dip following errors, which can be accompanied by decreased performance. Interestingly, as is generally the case in science, both functional and non-functional accounts need not be mutually exclusive, especially when taking into account different findings depending on the duration of the response-stimulus interval (Danielmeier & Ullsperger, 2011; Jentsch & Dudschig, 2009). I will briefly discuss the most relevant theories for this dissertation. However, please note that this is neither an exclusive list of theories of error monitoring nor a detailed overview.

CONFLICT-MONITORING THEORY

A very influential functional theory is the conflict-monitoring theory (CMT, Botvinick et al., 2001). This model focuses on a monitoring system which detects response conflict, i.e. when two competing response tendencies are activated. When conflict is detected control is upregulated. The conflict monitor is believed to be located in the anterior cingulate cortex (ACC) while the upregulation of control is implemented by the dorsolateral prefrontal cortex (DLPFC). While CMT in essence does not focus on error detection and post-error adaptation, it does postulate that errors, just as incongruent trials, elicit conflict because on most errors the correct response will also be slightly activated leading to co-activation of two competing responses. Following error trials, cognitive control is thus increased and should lead to slower and more accurate performance. Additionally, CMT predicts reduced interference effects following errors since this heightened cognitive control would also lead to attentional focusing, limiting the influence of irrelevant stimulus characteristics. As already mentioned, this is usually not what empirical data show.

Computational models show that the conflict monitoring theory can predict and explain behavioural effects of response conflict (Botvinick et al., 2001; Botvinick, Cohen, & Carter, 2004; Yeung, Botvinick, & Cohen, 2004) and fMRI studies show that the pMFC is indeed engaged when response conflict occurs (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Kerns et al., 2004; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004). While this account is still under debate (Burle, Allain, Vidal, & Hasbroucq, 2005; Burle, Roger, Allain, Vidal, & Hasbroucq, 2008; Grinband et al., 2011; Steinhauser, Maier, & Hübner, 2008; Yeung, Cohen, & Botvinick, 2011), it is a highly influential account since concrete predictions for speeded reaction time tasks, especially conflict tasks, can be made.

REINFORCEMENT LEARNING THEORY

A second functional theory is the reinforcement learning theory (Holroyd & Coles, 2002), which integrates findings on reward processing and reinforcement learning. This theory is based on the law of effect of Thorndike (1917/1970) which states that actions that are followed by a positive outcome are more likely to be repeated than actions which are followed by a negative outcome. The reinforcement learning theory posits the existence of a monitoring system which makes an assessment of the current events, predicting an expected outcome. Afterwards the actual outcome can be compared against these predictions resulting in temporal difference errors. As such we can distinguish a positive prediction error, i.e. the actual outcome was better than expected, and a negative prediction error, i.e. the actual outcome was worse than expected. These prediction errors result in a further adjustment of the system with the reinforcing or inhibiting of behaviour. As errors are usually outcomes which are worse than expected, PES can therefore be explained as an inhibition of the motor system following a negative prediction error, with larger post-error slowing when the prediction and the actual outcome differ more. Similar to CMT, an increased performance in terms of accuracy is expected since this is a strategic adjustment of the system to heighten the possibility of a favourable outcome.

Again, in this theory, the ACC is believed to be the receiver of learning signals while the monitor, the adaptive critic, is located in the basal ganglia. Additionally, this theory is based on findings that reward-guided learning, as investigated in primates, is related to dopamine release in the midbrain, with a phasic increase or decrease in activity when events are better or worse than expected (Bayer & Glimcher, 2005; Hollerman & Schultz, 1998; Matsumoto & Hikosaka, 2009).

While this theory incorporates interesting ideas about the role of dopamine in cognitive control, its predictions are quite difficult to test in

humans. However, this theory also proved to be an interesting stepping stone to expand the idea of reinforcement learning to a more general response-outcome performance monitoring not only depended on reward and error signals (Alexander & Brown, 2011).

THE ORIENTING ACCOUNT

The orienting account (Notebaert et al., 2009) states that errors are infrequent and salient events. The occurrence of an error thus triggers an orienting response hindering subsequent processing. In this regard, post-error slowing is the result of a nonspecific reflex following error detection. In line with this idea, slowing can be found following infrequent signals (Barcelo, Escera, Corral, & Periañez, 2006; Notebaert et al., 2009). Indeed, using a design in which the amount of errors was manipulated, Notebaert and colleagues (2009) showed that PES occurred when errors were infrequent, i.e. 25% of the trials. However, they showed post-*correct* slowing when correct responses were infrequent. In the initial study feedback was used, making it impossible to discern whether differences in post-error slowing could be attributed to the infrequent nature of the feedback rather than an internal detection system. However, Houtman and colleagues (2012) showed that post-error slowing increased when errors were infrequent, regardless of the use of external feedback signals. While the differences in error rates in previous reported studies were rather large, even among highly-accurate individuals (differing from 94% to 99% between groups) a significant difference in PES can be found (Steinborn, Flehmig, Bratzke, & Schröter, 2012).

In line with the idea that errors trigger an orienting response, it has been shown that errors increase autonomic arousal, which is related to orienting reflexes to novel and significant stimuli, (Barceló, Hall, & Gale, 1995; Steiner & Barry, 2011; Wessel et al., 2011) and reduce alpha power, which can reflect heightened arousal or orienting responses (Carp

& Compton, 2009). Additionally, it has been shown that errors and novel events have a common underlying processing system (Wessel, Danielmeier, Morton, & Ullsperger, 2012). Patients with lesions to this prefrontal cingulate performance-monitoring network show decreased error-related ERP-components as well as decreased novelty-related components. They also show less slowing following errors or unexpected events (Wessel, Klein, Ott, & Ullsperger, 2014). Because of the negative relationship between PES and motor activity (Danielmeier et al., 2011; King et al., 2010), it has been suggested that PES reflects the inhibitory component of an orienting response (Ullsperger et al., 2014).

The initial pattern of results, with PES when errors were infrequent but post-*correct* slowing when correct responses were infrequent, was replicated and investigated in relation to electrophysiological measures (Núñez Castellar et al., 2010). Interestingly, neither the ERN nor the FRN correlated with post-error or post-correct slowing. However the feedback-locked P3 showed the same pattern, with a higher amplitude on error trials when errors were infrequent but significantly higher amplitudes on correct trials when correct responses were infrequent. These results corroborate the idea that infrequent salient events capture attention resulting in slower reaction times. This finding also provides a more elaborate theoretical framework based on the idea that the P3 reflects activity of the locus coeruleus norepinephrine (LC-NE) system (Nieuwenhuis et al., 2005). The LC-NE system is hypothesized to increase the orienting response to salient events. Recently, it has been shown that the amount of PES increases with active transcutaneous vagus nerve stimulation (tVNS), which increases NE concentrations in the brain (Sellaro, Leusden, & Tona, 2015).

To further investigate post-error accuracy, without relying on double errors and speeded forced choice tasks, Houtman and Notebaert (2013) investigated the effect of an error on target detection in a rapid visual presentation task (RSVP). Their design was based on an attentional blink paradigm, where two targets are presented shortly after each other in a

stream of non-target stimuli. This design typically makes it harder to identify the second target (T2) when it is presented within 200 – 500 ms after the first target (T1). This effect, called the attentional blink, has also been related to the LC-NE system. The silent period following LC-NE activation is believed to be responsible for this phenomenon (Sander Nieuwenhuis, Gilzenrat, Holmes, & Cohen, 2005). Using error commission, both with and without an external feedback signal, in a speeded flanker task as T1, Houtman and Notebaert showed worse target detection following an error than following a correct response. This error-induced blink therefore corroborates the idea that an error is a salient event, capturing attention and resulting in worse performance when rapid subsequent stimuli processing is necessary.

Even though the orienting account primarily aims to explain PES, post-error accuracy decrease can thus be expected when the inter-trial interval is short. Additionally, being distracted from the task entails that attentional selection (prioritizing task relevant information) is disturbed. Therefore, increased interference of irrelevant stimulus characteristics following an error (inverse PERI), rather than decrease of interference, would be expected.

THE BOTTLENECK ACCOUNT

To explain the finding of PES as well as decreased accuracy following an error when the inter-trial interval is short, the bottleneck account (Jentsch & Dudschig, 2009) proposes an error monitoring system, requiring time and resources. Based on findings in dual task paradigms, it has been shown that there is a central bottleneck stage postponing high-order processing, e.g. stimulus identification and response selection, of the second stimulus, as reflected in longer reaction times. Interestingly, following response execution, a monitoring process might be active occupying this central bottleneck stage. However, when an error is made,

the detection of conflict and what went wrong increases the amount of time needed, occupying the central bottleneck for a larger amount of time, therefore delaying subsequent event processing resulting in slower responses and more error-prone responses immediately following the error. Indeed Jentzsch and Dudschig (2009) showed that PES was accompanied by post-error accuracy *decrease* when the inter-trial interval was short (i.e. 100 ms). But post-error accuracy *increase*, as well as PES, was found when a longer inter-trial interval was used (i.e. 1000 ms).

Additionally, this account hypothesizes that perceptual processes could occur parallel to a central processing stage. This implies that when the interval is short, low-level perceptual processing can occur simultaneously with the error monitoring process, limiting the influence of irrelevant stimulus characteristics (i.e., reduced interference following an error). Indeed when using a task with a dark and light stimulus, a significant contrast-effect was found following an error, but only when the inter-trial interval was long, while the contrast-effect following a correct response was significant irrespective of the inter-trial interval (Jentzsch & Dudschig, 2009). However, in tasks where the irrelevant task characteristic is linked to a possible response, such as conflict tasks, the perceptual processing of stimulus characteristics will occur without the capacity-taking attentional weighting, again leading to larger congruency effects.

While recent findings seem to imply that nonfunctional accounts can at least partly explain PES, it is quite difficult to distinguish both the orienting account and the bottleneck account as they generally make the same predictions. However, while Houtman and Notebaert (2013) showed worse target detection following (infrequent) errors, a follow-up experiment in this study showed that the presentation of a red T1 target, compared to a green T1 target, was always, irrespective of frequency, followed by impaired T2-detection. Based on the idea that in our society, the colour red is often used as an error signal, the bottleneck account can explain these results with the assumption that the red F automatically

triggers the error processing mechanism. This finding is somewhat more difficult to explain for the orienting account; however, as saliency might be just as important as novelty in triggering an orienting response, a similar line of reasoning can be followed.

THE CURRENT DISSERTATION

I predominantly investigate predictions of the orienting account on post-error adaptations, both behaviourally and electrophysiologically, with the intention to further separate conflict- and error-related adaptations. Based on nonfunctional accounts, we predict worse performance, i.e. post-error accuracy *decrease*, following an error. However, in line with previous research, this deterioration of performance should be predominantly found when the inter-trial interval is short. Additionally, removing the confound of previous congruency in conflict tasks, we expect to find post-error *increase* of interference rather than PERI. Furthermore, as the orienting account predicts that an error triggers an orienting response, visuo-attentional processing for subsequent events should be diminished, while information at the time of an error could benefit from this attentional boost.

A second goal of this dissertation focuses on methodological advances. For the behavioural studies, linear mixed models were used to analyze the data. Just like repeated measures by ANOVA, they are an extension of the linear model and account for intercorrelations between repeated measures. They do so by estimating subject-specific effects for the repeated factors (random effects). Unlike repeated measures by ANOVA, linear mixed models are not restricted to perfectly balanced designs, as is seldom the case in error research since errors are usually infrequent events and the amount of errors differs over participants. Additionally, this method of analysis is also more suited when investigating (post-

error) accuracy. Typically, accuracy, which is a binomial variable, has no normal distribution. As such, using generalized linear mixed models, which can be parametrized to work under the binomial distribution, are much more appropriate for this measure. Electrophysiologically, it has been shown that Laplacian transformation can improve the spatial resolution by filtering out spatially broad features of the data (Cohen, 2014). Using Laplacian transformation makes it thus possible to further differentiate components. For instance, by using this technique, the CRN, a negative component similar to the ERN but on correct trials, can be revealed. CHAPTER 5 shows the added value of this technique when investigating ERN/CRN and the Pe. Additionally, we used this technique in CHAPTER 6 and 7 when investigating early visuo-attentional components as reducing spatial overlap also leads to enhanced temporal resolution as the peaks of components can be better discerned.

POST-ERROR ADAPTATIONS: THE ROLE OF THE INTER-TRIAL INTERVAL

The idea that functional and nonfunctional accounts of PES are not mutually exclusive (Danielmeier & Ullsperger, 2011) is based on the finding that the inter-trial interval influences post-error adaptations. The finding that PES decreases over time might indicate that PES in tasks with a short inter-trial interval reflects an attentional dip or bottleneck rather than strategic slowing. While the amount of PES found with a longer inter-trial interval might reflect the recruitment of cognitive control leading to slower responses but post-error accuracy *increase* (Jentsch & Dudschig, 2009).

Interestingly, the amount of PES is also highly different over individuals. Based on the orienting account, this could be interpreted in terms of error saliency. It stands to reason that error saliency would be increased in more anxious or punishment sensitive individuals. As such, an error would trigger a larger orienting response, and these participants would

show longer after-effects following an error. We therefore investigated the influence of anxiety and punishment sensitivity on post-error adaptations, and investigated whether this influence depends on the inter-trial interval (CHAPTER 2).

SEPARATING POST-ERROR AND POST-CONFLICT ADAPTATIONS

Post-error behavioural adaptations are often investigated using conflict tasks. While this is not necessary to investigate PES and post-error accuracy (Desmet et al., 2012; Houtman et al., 2012; Jentsch & Dudschig, 2009), it is an essential factor to investigate PERI. As previously stated, in this research the factor previous congruency is usually not included in the analysis, and is therefore a possible confound when investigated this measure of adaptation. We therefore investigated this effect in a Simon task based on the study of Ridderinkhof (2002) in which PERI was first reported. We analyzed the results both with and without the factor previous congruency. The results of this experiment can be found in CHAPTER 3.

In CHAPTER 4, we investigated PERI in two different conflict tasks, a Stroop and prime-target task. By combining two alternative forced choice tasks (resp. on odd en even trials), we could exclude contingency learning and feature repetition which have been shown to influence post-conflict adaptation.

VISUAL PROCESSING FOLLOWING AN ERROR

Recently, Houtman and Notebaert (2013) demonstrated that participants showed impaired target detection following an error in an unrelated flanker task. These findings support the idea that the occurrence or processing of unexpected error-like events interfere with subsequent information processing (Notebaert et al., 2009; Jentsch & Dudschig,

2009). In CHAPTER 6, we investigated the effect of errors on early visual ERP components. For this purpose we combined a flanker and a visual discrimination task. Additionally the inter-trial interval between both tasks was manipulated to investigate the duration of these negative after-effects.

In CHAPTER 7, we re-analyzed the dataset from CHAPTER 5 to investigate the effect of an error on early visual conflict processing within a flanker task, thereby adding to the research on the occurrence of post-error focusing as an explanation of PERI.

AN ADVANTAGE OF ORIENTING TO AN ERROR?

While most chapters of this dissertation elaborate on the detrimental effects of an error, I would like to conclude this dissertation with an advantage related to error detection. When making an error in real life, the exact moment where you realized your error is sometimes etched in your memory; similar to a flash-bulb memory. Interestingly, surprising feedback in a general knowledge test leads to an improvement in memory for both the surface features and the content of the feedback (Fazio & Marsh, 2009). Based on the idea that in cognitive tasks, errors are surprising (the orienting account, Notebaert et al., 2009), we tested whether error feedback would be better remembered than correct feedback. Coloured words were presented as feedback signals in a flanker task, where the colour indicated the accuracy. Subsequently, these words were again presented during a recognition task (Experiment 1) or a lexical decision task (Experiment 2 and 3). The results of these experiments can be found in CHAPTER 8.

As a general discussion for this dissertation, I will give an overview of the results in CHAPTER 9. Additionally these findings will be compared with previous findings and theories before drawing general conclusions and suggesting some novel ideas for future research.

REFERENCES

- Alexander, W. H., & Brown, J. W. (2011). Medial prefrontal cortex as an action-outcome predictor. *Nature Neuroscience*, *14*(10), 1338–1344. doi:10.1038/nn.2921
- Allain, S., Carbonnell, L., Falkenstein, M., Burle, B., & Vidal, F. (2004). The modulation of the Ne-like wave on correct responses foreshadows errors. *Neuroscience Letters*, *372*(1-2), 161–6. doi:10.1016/j.neulet.2004.09.036
- Arbel, Y., & Donchin, E. (2009). Parsing the componential structure of post-error ERPs: a principal component analysis of ERPs following errors. *Psychophysiology*, *46*(6), 1179–1189. doi:10.1111/j.1469-8986.2009.00857.x
- Babiloni, F., Cincotti, F., Carducci, F., Rossini, P. M., & Babiloni, C. (2001). Spatial enhancement of EEG data by surface Laplacian estimation: the use of magnetic resonance imaging-based head models. *Clinical Neurophysiology*, *112*(5), 724–727. doi:10.1016/S1388-2457(01)00494-1
- Barcelo, F., Escera, C., Corral, M. J., & Periáñez, J. a. (2006). Task switching and novelty processing activate a common neural network for cognitive control. *Journal of Cognitive Neuroscience*, *18*(10), 1734–48. doi:10.1162/jocn.2006.18.10.1734
- Barceló, F., Hall, M., & Gale, a. (1995). A psychophysiological inquiry into the nature of the Sokolovian orienting response comparator model: skin conductance and EEG data. *Biological Psychology*, *41*(2), 147–66. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/8534789>
- Bartholow, B. D., Pearson, M. a, Dickter, C. L., Sher, K. J., Fabiani, M., & Gratton, G. (2005). Strategic control and medial frontal negativity: beyond errors and response conflict. *Psychophysiology*, *42*(1), 33–42. doi:10.1111/j.1469-8986.2005.00258.x
- Bayer, H. M., & Glimcher, P. W. (2005). Midbrain dopamine neurons encode a quantitative reward prediction error signal. *Neuron*, *47*(1), 129–41. doi:10.1016/j.neuron.2005.05.020
- Boksem, M. a S., Tops, M., Kostermans, E., & De Cremer, D. (2008). Sensitivity to punishment and reward omission: evidence from error-related ERP components. *Biological Psychology*, *79*(2), 185–92. doi:10.1016/j.biopsycho.2008.04.010
- Boksem, M. a S., Tops, M., Wester, A. E., Meijman, T. F., & Lorist, M. M. (2006). Error-related ERP components and individual differences in punishment and reward sensitivity. *Brain Research*, *1101*(1), 92–101. doi:10.1016/j.brainres.2006.05.004

- Bombeke, K., Schoupe, N., Duthoo, W., & Notebaert, W. (2013). The effect of alcohol and placebo on post-error adjustments. *Frontiers in Human Neuroscience*, 7(3). doi:10.3389/fnhum.2013.00003
- Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, 108(3), 624–652. doi:10.1037/0033-295X.108.3.624
- Botvinick, M. M., Cohen, J. D., & Carter, C. S. (2004). Conflict monitoring and anterior cingulate cortex: an update. *Trends in Cognitive Sciences*, 8(12), 539–46. doi:10.1016/j.tics.2004.10.003
- Botvinick, M., Nystrom, L. E., Fissell, K., Carter, C. S., & Cohen, J. D. (1999). Conflict monitoring versus selection-for-action in anterior cingulate cortex. *Nature*, 402(6758), 179–81. doi:10.1038/46035
- Burle, B., Allain, S., Vidal, F., & Hasbroucq, T. (2005). Sequential compatibility effects and cognitive control: does conflict really matter? *Journal of Experimental Psychology. Human Perception and Performance*, 31(4), 831–7. doi:10.1037/0096-1523.31.4.831
- Burle, B., Roger, C., Allain, S., Vidal, F., & Hasbroucq, T. (2008). Error negativity does not reflect conflict: a reappraisal of conflict monitoring and anterior cingulate cortex activity. *Journal of Cognitive Neuroscience*, 20(9), 1637–55. doi:10.1162/jocn.2008.20110
- Carp, J., & Compton, R. J. (2009). Alpha power is influenced by performance errors. *Psychophysiology*, 46, 336–343. doi:10.1111/j.1469-8986.2008.00773.x
- Cavanagh, J. F., Zambrano-Vazquez, L., & Allen, J. J. B. (2012). Theta lingua franca: a common mid-frontal substrate for action monitoring processes. *Psychophysiology*, 49(2), 220–238. doi:10.1111/j.1469-8986.2011.01293.x
- Cohen, J. D., Dunbar, K., & McClelland, J. L. (1990). On the control of automatic processes: a parallel distributed processing account of the Stroop effect. *Psychological Review*, 97(3), 332–361.
- Cohen, M. X. (2014). *Analyzing neural time series data: Theory and practice*. The MIT Press.
- Coles, M. G., Scheffers, M. K., & Holroyd, C. B. (2001). Why is there an ERN/Ne on correct trials? Response representations, stimulus-related components, and the theory of error-processing. *Biological Psychology*, 56(3), 173–89. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/11399349>
- Danielmeier, C., Eichele, T., Forstmann, B. U., Tittgemeyer, M., & Ullsperger, M. (2011). Posterior medial frontal cortex activity predicts post-error adaptations in task-related visual and motor areas. *The Journal of Neuroscience*, 31(5), 1780–1789. doi:10.1523/JNEUROSCI.4299-10.2011
- Danielmeier, C., & Ullsperger, M. (2011). Post-error adjustments. *Frontiers in Psychology*, 2, 233. doi:10.3389/fpsyg.2011.00233
- De Bruijn, E. R. A. De, Mars, R. B., & Hulstijn, W. (2004). It wasn't me ... or was it? How false feedback affects performance, 118–124.

- Debener, S., Ullsperger, M., Siegel, M., Fiehler, K., von Cramon, D. Y., & Engel, A. K. (2005). Trial-by-trial coupling of concurrent electroencephalogram and functional magnetic resonance imaging identifies the dynamics of performance monitoring. *The Journal of Neuroscience*, *25*(50), 11730–11737. doi:10.1523/JNEUROSCI.3286-05.2005
- Desmet, C., Imbo, I., De Brauwer, J., Brass, M., Fias, W., & Notebaert, W. (2012). Error adaptation in mental arithmetic. *Quarterly Journal of Experimental Psychology*, *65*(6), 1059–1067. doi:10.1080/17470218.2011.648943
- Dutilh, G., van Ravenzwaaij, D., Nieuwenhuis, S., van der Maas, H. L. J., Forstmann, B. U., & Wagenmakers, E.-J. (2012). How to measure post-error slowing: A confound and a simple solution. *Journal of Mathematical Psychology*, *56*(3), 208–216. doi:10.1016/j.jmp.2012.04.001
- Endrass, T., Klawohn, J., Gruetzmann, R., Ischebeck, M., & Kathmann, N. (2012). Response-related negativities following correct and incorrect responses: evidence from a temporospatial principal component analysis. *Psychophysiology*, *49*(6), 733–743. doi:10.1111/j.1469-8986.2012.01365.x
- Endrass, T., Klawohn, J., Preuss, J., & Kathmann, N. (2012). Temporospatial dissociation of Pe subcomponents for perceived and unperceived errors. *Frontiers in Human Neuroscience*, *6*, 178. doi:10.3389/fnhum.2012.00178
- Endrass, T., Reuter, B., & Kathmann, N. (2007). ERP correlates of conscious error recognition: aware and unaware errors in an antisaccade task. *The European Journal of Neuroscience*, *26*(6), 1714–20. doi:10.1111/j.1460-9568.2007.05785.x
- Falkenstein, M., Hohnsbein, J., Hoormann, J., & Blanke, L. (1991). Effects of crossmodal divided attention on late ERP components. II. Error processing in choice reaction tasks. *Electroencephalography and Clinical Neurophysiology*, *78*, 447–455. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/1712280>
- Fazio, L. K., & Marsh, E. J. (2009). Surprising feedback improves later memory. *Psychonomic Bulletin & Review*, *16*(1), 88–92. doi:10.3758/PBR.16.1.88
- Forster, S. E., & Cho, R. Y. (2014). Context specificity of post-error and post-conflict cognitive control adjustments. *PloS One*, *9*(3), e90281. doi:10.1371/journal.pone.0090281
- Gehring, W., Goss, B., & Coles, M. (1993). A neural system for error detection and compensation. *Psychological Science*, *4*(6), 385–390. Retrieved from <http://pss.sagepub.com/content/4/6/385.short>
- Gentsch, A., Ullsperger, P., & Ullsperger, M. (2009). Dissociable medial frontal negativities from a common monitoring system for self- and externally caused failure of goal achievement. *NeuroImage*, *47*(4), 2023–2030. doi:10.1016/j.neuroimage.2009.05.064

- Grinband, J., Savitskaya, J., Wager, T. D., Teichert, T., Ferrera, V. P., & Hirsch, J. (2011). The dorsal medial frontal cortex is sensitive to time on task, not response conflict or error likelihood. *NeuroImage*, *57*(2), 303–311. doi:10.1016/j.neuroimage.2010.12.027
- Gruendler, T. O. J., Ullsperger, M., & Huster, R. J. (2011). Event-related potential correlates of performance-monitoring in a lateralized time-estimation task. *PLoS One*, *6*(10), e25591. doi:10.1371/journal.pone.0025591
- Hajcak, G., McDonald, N., & Simons, R. F. (2003a). Anxiety and error-related brain activity. *Biological Psychology*, *64*(1-2), 77–90. doi:10.1016/S0301-0511(03)00103-0
- Hajcak, G., McDonald, N., & Simons, R. F. (2003b). To err is autonomic: Error-related brain potentials, ANS activity, and post-error compensatory behavior. *Psychophysiology*, *40*(6), 895–903. doi:10.1111/1469-8986.00107
- Herrmann, M. J., Römmler, J., Ehlis, A.-C., Heidrich, A., & Fallgatter, A. J. (2004). Source localization (LORETA) of the error-related-negativity (ERN/Ne) and positivity (Pe). *Cognitive Brain Research*, *20*(2), 294–299. doi:10.1016/j.cogbrainres.2004.02.013
- Hewig, J., Coles, M. G. H., Trippe, R. H., Hecht, H., & Miltner, W. H. R. (2011). Dissociation of Pe and ERN/Ne in the conscious recognition of an error. *Psychophysiology*, *48*(10), 1390–1396. doi:10.1111/j.1469-8986.2011.01209.x
- Hollerman, J. R., & Schultz, W. (1998). Dopamine neurons report an error in the temporal prediction of reward during learning, *J*(4).
- Holroyd, C. B., & Coles, M. G. H. (2002). The neural basis of human error processing: Reinforcement learning, dopamine, and the error-related negativity. *Psychological Review*, *109*(4), 679–709. doi:10.1037//0033-295X.109.4.679
- Holroyd, C. B., & Krigolson, O. E. (2007). Reward prediction error signals associated with a modified time estimation task. *Psychophysiology*, *44*(6), 913–917. doi:10.1111/j.1469-8986.2007.00561.x
- Houtman, F., & Notebaert, W. (2013). Blinded by an error. *Cognition*, *128*(2), 228–236. doi:10.1016/j.cognition.2013.04.003
- Houtman, F., Núñez Castellar, E., & Notebaert, W. (2012). Orienting to errors with and without immediate feedback. *Journal of Cognitive Psychology*, *24*(3), 278–285. doi:10.1080/20445911.2011.617301
- Huster, R. J., Eichele, T., Enriquez-Geppert, S., Wollbrink, a, Kugel, H., Konrad, C., & Pantev, C. (2011). Multimodal imaging of functional networks and event-related potentials in performance monitoring. *NeuroImage*, *56*(3), 1588–97. doi:10.1016/j.neuroimage.2011.03.039
- Jentsch, I., & Dudschig, C. (2009). Why do we slow down after an error? Mechanisms underlying the effects of posterror slowing. *Quarterly Journal of Experimental Psychology*, *62*(2), 209–218. doi:10.1080/17470210802240655

- Kerns, J. G., Cohen, J. D., MacDonald, A. W., Cho, R. Y., Stenger, V. A., & Carter, C. S. (2004). Anterior cingulate conflict monitoring and adjustments in control. *Science*, *303*, 1023–1026. doi:10.1126/science.1089910
- King, J. a, Korb, F. M., von Cramon, D. Y., & Ullsperger, M. (2010). Post-error behavioral adjustments are facilitated by activation and suppression of task-relevant and task-irrelevant information processing. *The Journal of Neuroscience*, *30*(38), 12759–12769. doi:10.1523/JNEUROSCI.3274-10.2010
- Kornblum, S. (1994). The way irrelevant dimensions are processed depends on what they overlap with: The case of Stroop-and Simon-like stimuli. *Psychological Research*, *56*, 130–135.
- Laming, D. (1979). Choice reaction performance following an error. *Acta Psychologica*, *43*, 199–224. Retrieved from <http://www.sciencedirect.com/science/article/pii/000169187990026X>
- Logan, G. D., & Crump, M. J. C. (2010). Cognitive illusions of authorship reveal hierarchical error detection in skilled typists. *Science (New York, N.Y.)*, *330*(6004), 683–6. doi:10.1126/science.1190483
- Lu, C., & Proctor, R. W. (1995). The influence of irrelevant location information on performance: A review of the Simon and spatial Stroop effects. *Psychonomic Bulletin & Review*, *2*(2), 174–207.
- MacLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin*, *109*(2), 163–203. doi:10.1037//0033-2909.109.2.163
- Maier, M. E., Yeung, N., & Steinhauser, M. (2011). Error-related brain activity and adjustments of selective attention following errors. *NeuroImage*, *56*, 2339–2347. doi:10.1016/j.neuroimage.2011.03.083
- Makeig, S., Jung, T., Bell, A. J., Ghahremani, D., & Sejnowski, T. J. (1997). Blind separation of auditory event-related brain responses into independent components. *Proceedings of the National Academy of Sciences of the United States of America*, *94*(September), 10979–10984. Retrieved from <http://www.pnas.org/content/94/20/10979.short>
- Matsumoto, M., & Hikosaka, O. (2009). Two types of dopamine neuron distinctly convey positive and negative motivational signals. *Nature*, *459*(7248), 837–41. doi:10.1038/nature08028
- Miltner, W., Braun, C., & Coles, M. (1997). Event-related brain potentials following incorrect feedback in a time-estimation task: Evidence for a “generic” neural system for error detection. *Journal of Cognitive Neuroscience*, *9*(6), 788–798.
- Nieuwenhuis, S., Aston-Jones, G., & Cohen, J. D. (2005). Decision making, the P3, and the locus coeruleus-norepinephrine system. *Psychological Bulletin*, *131*(4), 510–32. doi:10.1037/0033-2909.131.4.510

- Nieuwenhuis, S., Gilzenrat, M. S., Holmes, B. D., & Cohen, J. D. (2005). The role of the locus coeruleus in mediating the attentional blink: a neurocomputational theory. *Journal of Experimental Psychology. General*, *134*(3), 291–307. doi:10.1037/0096-3445.134.3.291
- Nieuwenhuis, S., Ridderinkhof, K. R., Blom, J., Band, G. P., & Kok, a. (2001). Error-related brain potentials are differentially related to awareness of response errors: evidence from an antisaccade task. *Psychophysiology*, *38*(5), 752–60. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/11577898>
- Notebaert, W., Houtman, F., Opstal, F. Van, Gevers, W., Fias, W., & Verguts, T. (2009). Post-error slowing: an orienting account. *Cognition*, *111*, 275–279. doi:10.1016/j.cognition.2009.02.002
- Notebaert, W., & Verguts, T. (2011). Conflict and error adaptation in the Simon task. *Acta Psychologica*, *136*, 212–216. doi:10.1016/j.actpsy.2010.05.006
- Núñez Castellar, E., Kühn, S., Fias, W., & Notebaert, W. (2010). Outcome expectancy and not accuracy determines posterror slowing: ERP support. *Cognitive, Affective, & Behavioral Neuroscience*, *10*(2), 270–278. doi:10.3758/CABN.10.2.270
- O’Connell, R. G., Dockree, P. M., Bellgrove, M. a, Kelly, S. P., Hester, R., Garavan, H., ... Foxe, J. J. (2007). The role of cingulate cortex in the detection of errors with and without awareness: a high-density electrical mapping study. *The European Journal of Neuroscience*, *25*(8), 2571–2579. doi:10.1111/j.1460-9568.2007.05477.x
- Orr, J. M., Carp, J., & Weissman, D. H. (2012). The influence of response conflict on voluntary task switching: a novel test of the conflict monitoring model. *Psychological Research*, *76*(1), 60–73. doi:10.1007/s00426-011-0324-9
- Pailing, P. E., & Segalowitz, S. J. (2004). The effects of uncertainty in error monitoring on associated ERPs. *Brain and Cognition*, *56*(2), 215–233. doi:10.1016/j.bandc.2004.06.005
- Polich, J. (2007). Updating P300: an integrative theory of P3a and P3b. *Clinical Neurophysiology*, *118*(10), 2128–2148. doi:10.1016/j.clinph.2007.04.019
- Polich, J., & Comerchero, M. D. (2003). P3a from visual stimuli: typicality, task, and topography. *Brain Topography*, *15*(3), 141–52. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/12705810>
- Rabbitt, P., & Rodgers, B. (1977). What does a man do after he makes an error? an analysis of response programming. *Quarterly Journal of Experimental Psychology*, *29*(4), 727–743. doi:10.1080/14640747708400645
- Ridderinkhof, K. R. (2002). Micro- and macro-adjustments of task set: activation and suppression in conflict tasks. *Psychological Research*, *66*(4), 312–323. doi:10.1007/s00426-002-0104-7

- Ridderinkhof, K. R., de Vlugt, Y., Bramlage, A., Spaan, M., Elton, M., Snel, J., & Band, G. P. H. (2002). Alcohol consumption impairs detection of performance errors in mediofrontal cortex. *Science*, *298*, 2209–2211. doi:10.1126/science.1076929
- Ridderinkhof, K. R., Ramautar, J. R., & Wijnen, J. G. (2009). To P(E) or not to P(E): a P3-like ERP component reflecting the processing of response errors. *Psychophysiology*, *46*(3), 531–8. doi:10.1111/j.1469-8986.2009.00790.x
- Ridderinkhof, K. R., Ullsperger, M., Crone, E. a., & Nieuwenhuis, S. (2004). The role of the medial frontal cortex in cognitive control. *Science (New York, N.Y.)*, *306*(5695), 443–7. doi:10.1126/science.1100301
- Rigoni, D., Pourtois, G., & Brass, M. (2014). “Why should I care?” Challenging free will attenuates neural reaction to errors. *Social Cognitive and Affective Neuroscience*, *1–28*. Retrieved from <http://scan.oxfordjournals.org/content/early/2014/06/15/scan.nsu068.short>
- Rigoni, D., Wilquin, H., Brass, M., & Burle, B. (2013). When errors do not matter: weakening belief in intentional control impairs cognitive reaction to errors. *Cognition*, *127*(2), 264–9. doi:10.1016/j.cognition.2013.01.009
- Roger, C., Bénar, C. G., Vidal, F., Hasbroucq, T., & Burle, B. (2010). Rostral Cingulate Zone and correct response monitoring: ICA and source localization evidences for the unicity of correct- and error-negativities. *NeuroImage*, *51*(1), 391–403. doi:10.1016/j.neuroimage.2010.02.005
- Scheffers, M. K., & Coles, M. G. H. (2000). Performance monitoring in a confusing world: Error-related brain activity, judgments of response accuracy, and types of errors. *Journal of Experimental Psychology: Human Perception and Performance*, *26*(1), 141–151. doi:10.1037//0096-1523.26.1.141
- Segalowitz, S. J., Santesso, D. L., Murphy, T. I., Homan, D., Chantziantoniou, D. K., & Khan, S. (2010). Retest reliability of medial frontal negativities during performance monitoring. *Psychophysiology*, *47*(2), 260–70. doi:10.1111/j.1469-8986.2009.00942.x
- Sellaro, R., Leusden, J. van, & Tona, K. (n.d.). Transcutaneous vagus nerve stimulation (tVNS) enhances post-error slowing. *Sandernieuwenhuis.nl*, 1–22. Retrieved from http://www.sandernieuwenhuis.nl/pdfs/Sellaro_JoCN.pdf
- Shalgi, S., Barkan, I., & Deouell, L. Y. (2009). On the positive side of error processing: error-awareness positivity revisited. *The European Journal of Neuroscience*, *29*(7), 1522–32. doi:10.1111/j.1460-9568.2009.06690.x
- Simon, J. R. (1969). Reactions toward the source of stimulation. *Journal of Experimental Psychology*, *81*(1), 174–176.

- Steinborn, M. B., Flehmig, H. C., Bratzke, D., & Schröter, H. (2012). Error reactivity in self-paced performance: Highly-accurate individuals exhibit largest post-error slowing. *Quarterly Journal of Experimental Psychology*, *65*(4), 624–31. doi:10.1080/17470218.2012.660962
- Steiner, G. Z., & Barry, R. J. (2011). Pupillary responses and event-related potentials as indices of the orienting reflex. *Psychophysiology*, *48*(12), 1648–55. doi:10.1111/j.1469-8986.2011.01271.x
- Steinhauser, M., & Kiesel, A. (2011). Performance monitoring and the causal attribution of errors. *Cognitive, Affective & Behavioral Neuroscience*, *11*(3), 309–20. doi:10.3758/s13415-011-0033-2
- Steinhauser, M., Maier, M., & Hübner, R. (2008). Modeling behavioral measures of error detection in choice tasks: response monitoring versus conflict monitoring. *Journal of Experimental Psychology: Human Perception and Performance*, *34*(1), 158–76. doi:10.1037/0096-1523.34.1.158
- Stürmer, B., Nigbur, R., Schacht, A., & Sommer, W. (2011). Reward and punishment effects on error processing and conflict control. *Frontiers in Psychology*, *2*(335). doi:10.3389/fpsyg.2011.00335
- Ullsperger, M., Danielmeier, C., & Jocham, G. (2014). Neurophysiology of performance monitoring and adaptive behavior. *Physiological Reviews*, *94*(1), 35–79. doi:10.1152/physrev.00041.2012
- Van Veen, V., & Carter, C. S. (2002). The timing of action-monitoring processes in the anterior cingulate cortex. *Journal of Cognitive Neuroscience*, *14*(4), 593–602. doi:10.1162/08989290260045837
- Vidal, F., Burle, B., Bonnet, M., Grapperon, J., & Hasbroucq, T. (2003). Error negativity on correct trials: a reexamination of available data. *Biological Psychology*, *64*(3), 265–282. doi:10.1016/S0301-0511(03)00097-8
- Vidal, F., Hasbroucq, T., Grapperon, J., & Bonnet, M. (2000). Is the “error negativity” specific to errors? *Biological Psychology*, *51*(2-3), 109–128. doi:10.1016/S0301-0511(99)00032-0
- Weinberg, A., Olvet, D. M., & Hajcak, G. (2010). Increased error-related brain activity in generalized anxiety disorder. *Biological Psychology*, *85*(3), 472–80. doi:10.1016/j.biopsycho.2010.09.011
- Wessel, J. R., Danielmeier, C., Morton, J. B., & Ullsperger, M. (2012). Surprise and error: common neuronal architecture for the processing of errors and novelty. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *32*(22), 7528–37. doi:10.1523/JNEUROSCI.6352-11.2012
- Wessel, J. R., Danielmeier, C., & Ullsperger, M. (2011). Error awareness revisited: accumulation of multimodal evidence from central and autonomic nervous systems. *Journal of Cognitive Neuroscience*, *23*(10), 3021–3036. doi:10.1162/jocn.2011.21635

- Wessel, J. R., Klein, T. a, Ott, D. V. M., & Ullsperger, M. (2014). Lesions to the prefrontal performance-monitoring network disrupt neural processing and adaptive behaviors after both errors and novelty. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, *50*, 45–54. doi:10.1016/j.cortex.2013.09.002
- West, R., & Travers, S. (2008). Tracking the temporal dynamics of updating cognitive control: an examination of error processing. *Cerebral Cortex*, *18*(5), 1112–1124. doi:10.1093/cercor/bhm142
- Yeung, N., Botvinick, M. M., & Cohen, J. D. (2004). The Neural Basis of Error Detection: Conflict Monitoring and the Error-Related Negativity. *Psychological Review*, *111*(4), 931–959. doi:10.1037/0033-295X.111.4.931
- Yeung, N., Cohen, J. D., & Botvinick, M. M. (2011). Errors of interpretation and modeling: a reply to Grinband et al. *NeuroImage*, *57*(2), 316–9. doi:10.1016/j.neuroimage.2011.04.029

CHAPTER 2

KEEP CALM AND BE PATIENT: THE INFLUENCE OF ANXIETY AND TIME ON POST-ERROR ADAPTATIONS¹²

Individual differences in anxiety and punishment sensitivity have an impact on electrophysiological markers of error processing and the orienting of attention to threatening information. However, it remains unclear how these individual differences influence behavioural adaptations to errors. Therefore, we set out to investigate the influence of anxiety and punishment sensitivity on post-error adaptations, and whether this influence depends on the time people get to adapt. We tested 99 participants using a Simon task with randomized inter-trial intervals. Significant post-error slowing (PES) was found at all time intervals. However, in line with previous research, PES reduced over time. While PES did not interact with anxiety, or punishment sensitivity, the pattern of post-error accuracy depended on anxiety. There is clear post-error accuracy *decrease* at the shortest interval, but individuals with a low score on trait anxiety showed a reversed effect (i.e., post-error accuracy *increase*) at a longer interval. These results suggest that people have trouble to disengage attention from an error, which can be overcome with time and low anxiety.

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²This study was co-authored by Senne Braem, Michaël Stevens, and Wim Notebaert.

INTRODUCTION

While errors have traditionally been described as cognitive information processing failures, a growing number of studies started to focus on the emotional aspects of error processing. For example, the amplitude of the error-related negativity (ERN; Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991), a negative brain-potential peaking 50 ms after an erroneous response, correlates positively with anxiety or punishment sensitivity (e.g., Boksem, Tops, Kostermans, & De Cremer, 2008; Hajcak, McDonald, & Simons, 2003a; Moser, Moran, Schroder, Donnellan, & Yeung, 2013). Besides the components of error processing itself, research has also focused on behavioral adaptations following an error. It is a well-documented observation that people slow down following error commission (Rabbitt & Rodgers, 1977) and post-error slowing (PES) has also been linked to individual differences in punishment sensitivity. Boksem and colleagues (2008) reported increased PES in a punishment condition for individuals scoring high on punishment sensitivity. Significant relations between PES and anxiety however, were not observed (Hajcak et al., 2003a; Weinberg, Olvet, & Hajcak, 2010).

PES is often explained as part of a strategic adaptation process resulting in increased task performance (Botvinick, Braver, Barch, Carter, & Cohen, 2001). However, recent studies demonstrate that PES not always leads to increased task performance (for an overview, see Danielmeier & Ullsperger, 2011). The combination of slowing and accuracy decrease following errors inspired non-functional accounts of post-error slowing such as the orienting account (Notebaert et al., 2009) which states that errors are infrequent and salient events. The occurrence of an error would thus trigger an orienting response hindering subsequent processing. In this regard, post-error slowing is the result of a nonspecific reflex

following error detection. For instance, errors increase autonomic arousal and prime defensive reflexes (Hajcak & Foti, 2008; Hajcak et al., 2003b; Wessel, Danielmeier, & Ullsperger, 2011). Typically autonomic arousal is related to orienting reflexes to novel and significant stimuli (Barceló, Hall, & Gale, 1995; Barry, MacDonald, De Blasio, & Steiner, 2013; Steiner & Barry, 2011), again suggesting that errors indeed trigger an orienting response. Based on the idea that the saliency of an error influences the intensity of this orienting response, personality traits that index differences in perceived error salience, such as punishment sensitivity or trait anxiety, should influence post-error performance.

Interestingly, individual differences in anxiety have been linked to how attention is directed to threatening information. The attentional control theory (Eysenck, Derakshan, Santos, & Calvo, 2007) posits that anxiety impairs attentional control, with high-anxious individuals allocating more attentional resources to threat-related information. For example, in an emotional Stroop task, anxious participants are slower to name the colour of a threatening word (Richards, French, Johnson, Naparstek, & Williams, 1992). In a similar fashion, trait anxious participants show an attentional bias towards threatening locations (Derryberry & Reed 2002), however this attentional bias was apparent when using a short interval of 250 ms, but turned towards the safe location when the interval was 500 ms (when participants showed good attentional control).

The results of Derryberry and Reed (2002) also point out the importance of intertrial interval when investigating the directing of attention. While this component is often neglected when investigating post-error adaptations, it could reconcile the ambiguous results concerning post-error slowing and post-error accuracy. When taking inter-trial interval into account, the integration of functional and non-functional accounts can offer a comprehensive explanation of post-error adaptations. When the processing time between tasks is quite short, the effect of the still ongoing orienting response triggered by the error, on behaviour is

measured. Strategic adaptation can only take place after this initial error detection. In line with this idea, research has shown that post-error adaptations depend on the intertrial interval (ITI) as PES decreases (Danielmeier & Ullsperger, 2011; Jentsch & Dudschig, 2009) and post-error accuracy increases with increasing ITIs (Jentsch & Dudschig, 2009).

In the present study, we therefore tested the influence of anxiety and punishment sensitivity on post-error performance over different ITIs. To this end, we measured punishment sensitivity by means of the Behavioral Inhibition Scale (BIS; Carver & White, 1994) and anxiety by the State-Trait Anxiety Inventory (STAI; Spielberger, 1983). Additionally, as Derryberry and Reed (2002) demonstrated that the influence of anxiety can further depend on an individual's degree of attentional control, we also included the Attentional Control Scale as a control measure (ACS; Derryberry & Reed, 2002). Additionally, we used linear mixed models to analyze the data. Just like repeated measures by ANOVA they are an extension of the linear model that can handle observations that are correlated because of repeated measures. They do so by estimating subject-specific effects for the repeated factors (random effects). Unlike repeated measures by ANOVA, linear mixed models are not restricted to perfectly balanced designs, as is seldom the case in error research since errors are usually infrequent events and the amount of errors differs over participants. Additionally this method of analysis is also more suited when investigating (post-error) accuracy. Typically, accuracy, which is a binomial variable, has no normal distribution. Generalized linear mixed models can be parametrized to work with binomial distributions.

In line with previous research, we predict that people will show larger PES and post-error accuracy decrease at shorter ITIs, consistent with the idea that people experience difficulties with disengaging attention from the error shortly after error commission. Second, we predict that

individual differences in punishment sensitivity or anxiety will determine the development of this attentional bias over time: while low punishment-sensitive or low anxious people will adapt and show improved performance over time, high punishment-sensitive or high anxious people will show a prolonged attentional bias, and have more difficulties in adapting performance, even when time allows for it.

METHOD

PARTICIPANTS

All 99 participants were students at Ghent University (25 male) participated in this study (mean age = 18.8 years, $SD = 1.8$ years). Eight participants were left-handed. All participants gave written informed consent. The participants earned course credits in exchange for participation.

STIMULI AND PROCEDURE

Stimuli were presented on a 17-inch computer screen. The stimulus was a white M or N (0.5 cm x 0.5 cm) presented 4 cm left or right from a white fixation cross in the middle. All stimuli were presented against a black background. Responses were recorded by a Cedrus response box. The experiment was conducted using Tscope software (Stevens, Lammertyn, Verbruggen, & Vandierendonck, 2006).

A Simon task was used in which the participants had to respond to the identity of the letter M or N, presented at the left or right side of the screen. The index finger of the left hand was used to respond to the M, while the index finger of the right hand corresponded with the letter N or vice versa (counterbalanced between subjects). A trial started with the presentation of the letter M or N for 200 ms followed by a blank screen with white fixation cross for a maximum of 1300 ms. The response

deadline was 1500 ms, starting from stimulus onset. After the response deadline or when a response was given, there was an ITI of 250, 500 or 1000 ms. These intervals were randomized over trials. A white fixation cross stayed on the screen during the entire inter-trial interval. Participants were instructed to respond as accurately and as quickly as possible to the presented letter. After instructions, participants first performed a practice block of 25 trials. The experiment itself consisted of 12 blocks of 100 trials and lasted approximately 40 minutes.

QUESTIONNAIRES

At the end of the experiment all participants first completed the BIS/BAS scale (Carver & White, 1994) based on the proposition of two interacting motivational systems: the behavioural approach system (BAS) and the behavioural inhibition system (BIS) (Gray, 1987). BIS is sensitive to punishment and results in inhibiting behaviour leading to aversive or harmful outcomes (7 items, Cronbach's $\alpha = 0.73$). Possible responses on BIS-items were: "totally disagree", "slightly disagree", "slightly agree", and "totally agree". Scores on BIS ranged from 12 till 28 ($M = 21$, $SD = 3$). Participants then completed the STAI (Spielberger, 1983) measuring individual differences in trait anxiety (20 items, Cronbach's $\alpha = 0.89$). Possible responses on STAI-items were: "not at all", "a little", "somewhat", and "very much so". The anxiety scores of the participants varied between 25 and 62 ($M = 42$, $SD = 9$). Finally, participants also filled in the ACS (Derryberry & Reed, 2002; 20 items, cronbachs $\alpha = 0.80$). Possible responses on ACS-items were: "(almost) never", "sometimes", "often", and "always". ACS scores of the participants varied ranged from 30 till 70 ($M = 48$, $SD = 7$).

BIS and trait anxiety strongly correlated with each other, both $r_s \geq 0.53$, both $p_s \leq 0.001$, suggesting that these are highly interrelated constructs. Furthermore, attentional control also correlated with BIS, $r(99) = -0.27$, p

< 0.01 and trait anxiety, $r(99) = -0.37$, $p < 0.001$, showing that participants with a lower score on punishment sensitivity and anxiety, tend to exhibit higher attentional control.

RESULTS

DATA TRIMMING AND ANALYSIS

To ensure a reliable measure of post-error adaptations, we selected trials present in specific local sequences (i.e., trials following a correct trial and preceding an error for post-correct trials, and trials following an error for post-error trials). When all trials originate from moments close to each other in time, these post-error estimations can be more reliably estimated rendering the analyses immune to global performance fluctuations (Dutilh et al., 2012; Navarro-Cebrian, Knight, & Kayser, 2013; Van der Borgh, Braem, & Notebaert, 2014). PES and post-error accuracy were assessed by comparing the average reaction time and accuracy on trials following an error and trial following a correct, but preceding an erroneous, response.

The first and last trials of each block, responses faster than 100 ms or exceeding the response deadline, as well as the subsequent or preceding trials, were excluded from analysis. In total, 78% of the data was excluded. On average 258 trials ($SD = 109$) were included in the analysis. The mean response time was 566 ms ($SD = 44$ ms). The mean accuracy was 85% ($SD = 9\%$).

The results were analyzed using linear mixed effects models as implemented in the R-package lme4 (Bates, Maechler, Bolker, & Walker, 2013). Accuracy was analyzed using a logistic link function. The base model consisted of the fixed factors previous accuracy and ITI and a random effect for subject. Additionally, each fixed variable, i.e. previous accuracy and ITI, was also added as a random slope to the model and

tested, using likelihood ratio tests, to see if this addition further improved the model.

Finally, to determine which covariates should be included in the model, anxiety and punishment sensitivity were first added separately to the model. Using a likelihood ratio test, the extended model was then compared to the base model. If this extended model was significantly better, the alternative covariate (e.g., anxiety if the extended model with punishment sensitivity was significantly better and vice versa) and attentional control were added separately to test whether this improved the model further.

REACTION TIME

Adding previous accuracy and ITI separately both improved the model, both $ps \leq 0.001$. A model with both these factors as random slopes, but not their interaction as this model did not converge, further improved the model significantly, both $ps \leq 0.001$.

Adding trait anxiety did not significantly improve the base model, $\chi^2(6) = 5.24$, $p = 0.51$. Adding punishment sensitivity resulted in a significantly better model than the base model, $\chi^2(6) = 13.86$, $p < 0.05$. Additionally adding trait anxiety or attentional control however, did not significantly improve our extended model, resp. $\chi^2(12) = 14.59$, $p = 0.26$ and $\chi^2(12) = 8.41$, $p = 0.75$. Therefore the extended model with previous accuracy, interval and punishment sensitivity as predicting factors was further analyzed.

There was a significant main effect of previous accuracy, $\chi^2(1) = 9.65$, $p < 0.01$, showing post-error slowing (64 ms). There was also a main effect of ITI, $\chi^2(2) = 100.29$, $p < 0.001$, showing longer responses when the intertrial interval was short (587 ms) compared with the medium (555 ms) and long (554 ms) interval. The main effect of punishment sensitivity

was not significant, $\chi^2(1) = 1.10$, $p = 0.29$. There was a significant interaction between ITI and previous accuracy, $\chi^2(2) = 20.24$, $p < 0.001$ (see Figure 1), showing larger PES with short and medium ITI (71 and 72 ms respectively) compared to the long ITI (52 ms), both $ps < 0.001$. The amount of PES in the short and medium ITI did not differ significantly, $\chi^2(1) = 0.002$, $p = 0.96$. All other interactions were not significant, all $ps \geq 0.09$.

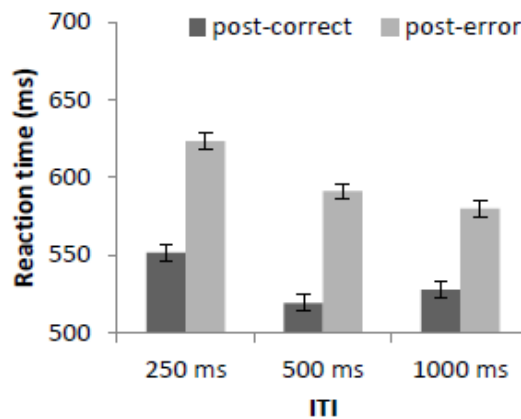


Figure 1. Average reaction time (in ms) for post-error and post-correct trials for each inter-trial interval. Error bars represent 95% confidence intervals around the means.

ACCURACY

Adding previous accuracy and ITI separately both did not improve the model, both $ps \geq 0.09$, therefore no random slopes were added.

Adding punishment sensitivity did not significantly improve the base model, $\chi^2(6) = 3.08$, $p = 0.80$. Adding trait anxiety resulted in a significantly better model than the base model, $\chi^2(6) = 13.90$, $p < 0.05$. Including punishment sensitivity or attentional control however, did not significantly improve our extended model, resp. $\chi^2(12) = 5.35$, $p = 0.95$ and $\chi^2(12) = 14.90$, $p = 0.25$. The extended model with previous

accuracy, interval and trait anxiety as predicting factors was further analyzed.

There was no significant main effect of previous accuracy, $\chi^2(1) = 2.16, p = 0.14$, ITI, $\chi^2(2) = 4.21, p = 0.12$ or trait anxiety, $\chi^2(1) = 2.71, p = 0.10$. There was a significant interaction between ITI and previous accuracy, $\chi^2(2) = 11.68, p < 0.01$ (see Figure 2a), showing significant post-error accuracy decrease following the short ITI (-3%), $\chi^2(1) = 11.87, p < 0.001$, but not after the medium ITI (0%), $\chi^2(1) = 0.21, p = 0.65$, and nonsignificant post-error accuracy increase following the long ITI (+1%), $\chi^2(1) = 1.26, p = 0.26$. All other two-way interactions were not significant, all $ps \geq 0.82$. Importantly, there was also a significant interaction between previous accuracy, ITI and trait anxiety, $\chi^2(2) = 10.97, p < 0.01$. In order to interpret this interaction, we looked at the correlation between trait anxiety and post-error accuracy (post-error accuracy minus post-correct accuracy) increase for each interval. For the short interval (250 ms) and the medium interval (500 ms) this correlation was not significant, resp. $r(99) = 0.13, p = 0.20$ and $r(99) = 0.12, p = 0.22$. For the long interval (1000 ms) however, there was a significant negative correlation between post-error accuracy increase and trait anxiety, $r(99) = -0.32, p = 0.001$ (see Figure 2b), indicating that participants with low anxiety showed post-error accuracy increase. Importantly, a partial correlation between trait anxiety and post-error accuracy increase in the longest ITI that controls for attentional control was also significant, $r(96) = -0.22, p < 0.05$.

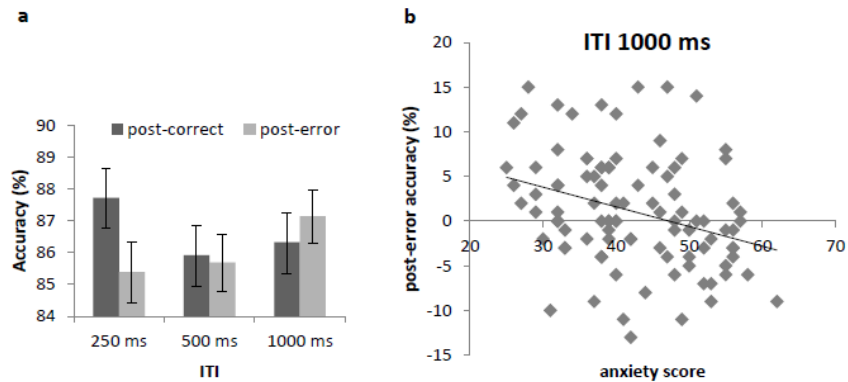


Figure 2. (a) Average accuracy (in percentage) for post-error and post-correct trials for each inter-trial interval. Error bars represent 95% confidence intervals around the means. (b) Scatter plot for the correlation of trait anxiety score and post-error increase of accuracy in the longest inter-trial interval (1000 ms).

DISCUSSION

Our results document two important findings. First, consistent with previous research (Danielmeier & Ullsperger, 2011; Jentzsch & Dudschig, 2009), post-error behavioural adaptations demonstrated a clear evolution over time. Significant PES was observed at all ITIs, but reduced over time as the amount of PES was significantly smaller at the longest ITI. Similarly, there was clear post-error accuracy *decrease* in the shortest interval, while post-error accuracy *increase* was observed in the longest interval. Together, these findings seem to suggest that participants are surprised and show biased attention at first, but do adapt to their errors over time. Secondly, however, we demonstrated how this pattern was modulated by trait anxiety, but not punishment sensitivity. Specifically, only the low-anxiety group, but not the high-anxiety group, showed improved post-error accuracies over time. We will discuss each of these findings in turn.

In line with previous research (Jentzsch & Dudschig, 2009) a longer ITI did reduce post-error slowing combined with significant post-error

accuracy increase. These results support the idea that both control adjustments and the orienting response are reflected in PES in short intervals, while the use of longer intervals limits the influence of the orienting response on post-error performance (Danielmeier & Ullsperger, 2011; Forster & Cho, 2014; Marco-pallarés, Camara, Münte, & Rodríguez-Fornells, 2008).

Our results also show the importance of personality characteristics in predicting this evolution of post-error adaptations over time. In our experiment, only low-anxious participants showed an improvement in performance when the interval was sufficiently long, indicating that participants have trouble disengaging from an error, which can only be overcome with time and low anxiety. Previous research did not find a relation between anxiety and post-error adaptations, however post-error accuracy was usually not investigated (Hajcak et al., 2003a; Weinberg et al., 2010). It is interesting to note that a different model was selected for analyzing post-error slowing and post-error accuracy. This distinction again illustrates that the relation between both measures of post-error adaptation is not as straight forward as generally assumed.

In line with previous research (Boksem et al., 2008) the model which included punishment sensitivity was significantly better when analyzing reaction times. However, punishment sensitivity did not show an impact on post-error adaptations. While Boksem et al. (2008) did find increased PES for individuals scoring high on punishment sensitivity, this relation was only apparent in the punishment condition. Highly punishment-sensitive people also show larger post-punishment slowing (Braem, Duthoo, & Notebaert, 2013), irrespective of previous performance, so Boksem and colleagues (2008) might have measured post-punishment rather than post-error slowing instead. Therefore, while post-error adaptations can be observed with and without feedback (Houtman, Núñez Castellar, & Notebaert, 2012), it is possible that the impact of punishment

sensitivity only becomes apparent in a punishment context (i.e., where punishment signals are being used).

Interestingly, while Derryberry and Reed (2002) demonstrated the influence of attentional control on anxiety-related attentional biases, we did not observe such a relation. In our dataset, the models in which those measures were incorporated were not the most efficient or significantly better than the base model. Also, even when we fitted extended models with both anxiety and attentional control, in line with Derryberry and Reed, the four-way interaction was not significant for reaction times ($\chi^2(1) = 1.06, p = 0.59$), nor accuracy ($\chi^2(1) = 0.83, p = 0.66$).

An alternative explanation for our results can be found in the questionnaire that was used to assess anxiety. It has been shown that the STAI also measures depression (Bieling, Antony, & Swinson, 1998) and depression has indeed been related to post-error performance deficits (Compton et al., 2008; Schroder, Moran, Infantolino, & Moser, 2013). When we repeated our analysis with the two subscales that measure anxious and depression components (Bieling et al., 1998), a significant three-way interaction was found with both the anxiety and depression subscale, $p \leq 0.01$. It is thus possible that a depression-related component influenced our results as well as anxiety.

Taken together, our findings illustrate the influence of the intertrial interval on post-error adaptations as well as the modulation of post-error accuracy by anxiety. These results are in line with the idea that error detection first triggers an orienting response (Notebaert et al., 2009) resulting in a non-strategic slowing and post-error accuracy *decrease*. However, low-anxious participants can counteract this detrimental effect in accuracy when the intertrial interval is sufficiently long.

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REFERENCES

- Barceló, F., Hall, M., & Gale, a. (1995). A psychophysiological inquiry into the nature of the Sokolovian orienting response comparator model: skin conductance and EEG data. *Biological Psychology*, *41*(2), 147–66.
- Barry, R. J., MacDonald, B., De Blasio, F. M., & Steiner, G. Z. (2013). Linking components of event-related potentials and autonomic measures of the orienting reflex. *International Journal of Psychophysiology: Official Journal of the International Organization of Psychophysiology*, *89*(3), 366–73. doi:10.1016/j.ijpsycho.2013.01.016
- Bates, D., Maechler, M., Bolker, B., & Walker, S. (2013). lme4: Linear mixed-effects models using Eigen and S4., R package version 1.0–5. Retrieved from <http://cran.r-project.org/package=lme4>
- Bieling, P. J., Antony, M. M., & Swinson, R. P. (1998). The State--Trait Anxiety Inventory, Trait version: structure and content re-examined. *Behaviour Research and Therapy*, *36*(7-8), 777–788. doi:10.1016/S0005-7967(98)00023-0
- Boksem, M. a S., Tops, M., Kostermans, E., & De Cremer, D. (2008). Sensitivity to punishment and reward omission: evidence from error-related ERP components. *Biological Psychology*, *79*(2), 185–92. doi:10.1016/j.biopsycho.2008.04.010
- Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, *108*(3), 624–652. doi:10.1037/0033-295X.108.3.624
- Braem, S., Duthoo, W., & Notebaert, W. (2013). Punishment sensitivity predicts the impact of punishment on cognitive control. *PloS One*, *8*(9), e74106. doi:10.1371/journal.pone.0074106
- Carver, C., & White, T. (1994). Behavioral inhibition, behavioral activation, and affective responses to impending reward and punishment: The BIS/BAS scales. *Journal of Personality and Social Psychology*, *67*(2), 319–333.
- Compton, R. J., Lin, M., Vargas, G., Carp, J., Fineman, S. L., & Quandt, L. C. (2008). Error detection and posterror behavior in depressed undergraduates. *Emotion*, *8*(1), 58–67. doi:10.1037/1528-3542.8.1.58
- Danielmeier, C., & Ullsperger, M. (2011). Post-error adjustments. *Frontiers in Psychology*, *2*, 233. doi:10.3389/fpsyg.2011.00233
- Derryberry, D., & Reed, M. A. (2002). Anxiety-related attentional biases and their regulation by attentional control. *Journal of Abnormal Psychology*, *111*(2), 225–236. doi:10.1037//0021-843X.111.2.225

- Dutilh, G., van Ravenzwaaij, D., Nieuwenhuis, S., van der Maas, H. L. J., Forstmann, B. U., & Wagenmakers, E.-J. (2012). How to measure post-error slowing: A confound and a simple solution. *Journal of Mathematical Psychology*, *56*(3), 208–216. doi:10.1016/j.jmp.2012.04.001
- Eysenck, M. W., Derakshan, N., Santos, R., & Calvo, M. G. (2007). Anxiety and cognitive performance: attentional control theory. *Emotion*, *7*(2), 336–353. doi:10.1037/1528-3542.7.2.336
- Falkenstein, M., Hohnsbein, J., Hoormann, J., & Blanke, L. (1991). Effects of crossmodal divided attention on late ERP components. II. Error processing in choice reaction tasks. *Electroencephalography and Clinical Neurophysiology*, *78*, 447–455.
- Forster, S. E., & Cho, R. Y. (2014). Context specificity of post-error and post-conflict cognitive control adjustments. *PloS One*, *9*(3), e90281. doi:10.1371/journal.pone.0090281
- Gray, J. (1987). Perspectives on anxiety and impulsivity: A commentary. *Journal of Research in Personality*, *21*, 493–509.
- Hajcak, G., & Foti, D. (2008). Errors are aversive: defensive motivation and the error-related negativity. *Psychological Science*, *19*(2), 103–8. doi:10.1111/j.1467-9280.2008.02053.x
- Hajcak, G., McDonald, N., & Simons, R. F. (2003a). Anxiety and error-related brain activity. *Biological Psychology*, *64*(1-2), 77–90. doi:10.1016/S0301-0511(03)00103-0
- Hajcak, G., McDonald, N., & Simons, R. F. (2003b). To err is autonomic: Error-related brain potentials, ANS activity, and post-error compensatory behavior. *Psychophysiology*, *40*(6), 895–903. doi:10.1111/1469-8986.00107
- Houtman, F., Núñez Castellar, E., & Notebaert, W. (2012). Orienting to errors with and without immediate feedback. *Journal of Cognitive Psychology*, *24*(3), 278–285. doi:10.1080/20445911.2011.617301
- Jentsch, I., & Dudschig, C. (2009). Why do we slow down after an error? Mechanisms underlying the effects of posterror slowing. *Quarterly Journal of Experimental Psychology*, *62*(2), 209–218. doi:10.1080/17470210802240655
- Marco-pallarés, J., Camara, E., Münte, T. F., & Rodríguez-Fornells, A. (2008). Neural Mechanisms Underlying Adaptive Actions after Slips. *Journal of Cognitive Neuroscience*, *20*(9), 1–16.
- Moser, J. S., Moran, T. P., Schroder, H. S., Donnellan, M. B., & Yeung, N. (2013). On the relationship between anxiety and error monitoring: a meta-analysis and conceptual framework. *Frontiers in Human Neuroscience*, *7*, 466. doi:10.3389/fnhum.2013.00466

- Navarro-Cebrian, A., Knight, R. T., & Kayser, A. S. (2013). Error-Monitoring and Post-Error Compensations: Dissociation between Perceptual Failures and Motor Errors with and without Awareness. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *33*(30), 12375–83. doi:10.1523/JNEUROSCI.0447-13.2013
- Notebaert, W., Houtman, F., Opstal, F. Van, Gevers, W., Fias, W., & Verguts, T. (2009). Post-error slowing: an orienting account. *Cognition*, *111*, 275–279. doi:10.1016/j.cognition.2009.02.002
- Rabbitt, P., & Rodgers, B. (1977). What does a man do after he makes an error? an analysis of response programming. *Quarterly Journal of Experimental Psychology*, *29*(4), 727–743. doi:10.1080/14640747708400645
- Richards, A., French, C., Johnson, W., Naparstek, J., & Williams, J. (1992). Effects of mood manipulation and anxiety on performance of an emotional Stroop task. *British Journal of Psychology*, *83*, 479–491. Retrieved from <http://onlinelibrary.wiley.com/doi/10.1111/j.2044-8295.1992.tb02454.x/full>
- Schroder, H. S., Moran, T. P., Infantolino, Z. P., & Moser, J. S. (2013). The relationship between depressive symptoms and error monitoring during response switching. *Cognitive, Affective & Behavioral Neuroscience*, *13*(4), 790–802. doi:10.3758/s13415-013-0184-4
- Spielberger, C. D. (1983). Manual for the State-Trait Anxiety Inventory Stai (form Y). *Palo Alto, CA: Consulting Psychologists Press*.
- Steiner, G. Z., & Barry, R. J. (2011). Pupillary responses and event-related potentials as indices of the orienting reflex. *Psychophysiology*, *48*(12), 1648–55. doi:10.1111/j.1469-8986.2011.01271.x
- Stevens, M., Lammertyn, J., Verbruggen, F., & Vandierendonck, A. (2006). Tscope: A C library for programming cognitive experiments on the MS windows platform. *Behavior Research Methods*, *38*(2), 280–286.
- Van der Borgh, L., Braem, S., & Notebaert, W. (2014). Disentangling posterror and postconflict reduction of interference. *Psychonomic Bulletin & Review*, *21*(6), 1530–1536. doi:10.3758/s13423-014-0628-z
- Weinberg, A., Olvet, D. M., & Hajcak, G. (2010). Increased error-related brain activity in generalized anxiety disorder. *Biological Psychology*, *85*(3), 472–80. doi:10.1016/j.biopsycho.2010.09.011
- Wessel, J. R., Danielmeier, C., & Ullsperger, M. (2011). Error awareness revisited: accumulation of multimodal evidence from central and autonomic nervous systems. *Journal of Cognitive Neuroscience*, *23*(10), 3021–3036. doi:10.1162/jocn.2011.21635

CHAPTER 3

DISENTANGLING POST-ERROR AND POST-CONFLICT REDUCTION OF INTERFERENCE¹

Conflict monitoring theory (CMT; Botvinick, Braver, Barch, Carter, & Cohen, 2001) states that response conflict, the simultaneous activation of two competing responses, increases task focus and reduces interference from irrelevant information. CMT also defines errors as conflict, and reduced interference effects have consistently been reported following errors (Ridderinkhof, 2002). However, previous computations of this post-error reduction of interference (PERI) have overlooked the congruency of the previous trial. This is problematic, because most errors are made on incongruent trials, creating a confound between (previous) accuracy and (previous) congruency. Therefore, it is likely that reduced interference following errors is in fact the congruency sequence effect (i.e., reduced interference following incongruent, relative to congruent, trials). Our results corroborate this idea by demonstrating that participants indeed showed significant PERI following a congruent trial, but inverse PERI following an incongruent trial. These findings are discussed in light of the adaptation-by-binding account (Verguts & Notebaert, 2008, 2009).

¹Van der Borgh, L., Braem, S., & Notebaert, W. (2014) Disentangling posterror and postconflict reduction of interference. *Psychonomic Bulletin & Review*, 21, 1530-1536. doi: 10.3758/s13423-014-0628-z

INTRODUCTION

Although we are continuously exposed to irrelevant and conflicting signals, we often succeed in selecting the signals that are relevant, while ignoring what is irrelevant. This quality is defined as *cognitive control*. In the laboratory, cognitive control is studied using conflict tasks. For example, in a Simon task, participants have to respond to the colour of stimuli that are being presented on the left or the right side of the screen. Incongruent stimuli (the response location and the [irrelevant] stimulus location differ) are typically found to result in slower and more error-prone responses than do congruent stimuli (Lu & Proctor, 1995; Simon, 1969).

Interestingly, this interference effect (i.e., the difference between incongruent and congruent trials) is often reduced following incongruent trials, relative to congruent trials (the *congruency sequence effect*; Frith & Done, 1986; Gratton, Coles, & Donchin, 1992). This congruency sequence effect, according to the influential conflict monitoring theory (CMT; Botvinick, Braver, Barch, Carter, & Cohen, 2001), demonstrates that response conflict triggers an adaptive mechanism that enhances task-specific processes, leading to so-called *conflict adaptation*. Response conflict is defined by, and equated with the simultaneous activation of two competing response units. On incongruent trials, one response is activated by the relevant dimension, and another by the irrelevant dimension (Cohen, Dunbar, & McClelland, 1990; Kornblum, 1994). However, the idea that the congruency sequence effect is a measure of conflict adaptation needs some nuance, since this is often confounded with feature repetition effects (Hommel, 2004; Mayr, Awh, & Laurey, 2003; Mayr & Awh, 2009, but see Duthoo & Notebaert, 2012) or contingency learning (Mordkoff, 2012; Schmidt & De Houwer, 2011).

Importantly, CMT also defines errors as conflicts, assuming that both the incorrect (executed) and correct response received activation. Consequently, CMT predicts reduced interference effects following errors. Indeed, *post-error reduction of interference* (PERI; King, Korb, von Cramon, & Ullsperger, 2010; Ridderinkhof, 2002; Ridderinkhof et al., 2002) has been observed. Other studies have failed to replicate this effect (Carp & Compton, 2009; Orr, Carp, & Weissman, 2012), or have even found increased interference following errors (Bombeke, Schoupe, Duthoo, & Notebaert, 2013). Surprisingly, none of these studies included Preceding Congruency as a factor in their analyses, even though the vast majority of errors in congruency tasks are made on incongruent trials (Hajcak, McDonald, & Simons, 2003; King et al., 2010). Therefore, what has been reported as PERI might have been confounded by the high proportions of congruent correct and incongruent incorrect trials. In order to show increased task focus following errors, we would need to account for previous congruency and demonstrate a smaller congruency effect following errors, regardless of the previous congruency (i.e., PERI after errors on both congruent and incongruent trials).

We designed two experiments that would allow us to include the factors Previous Congruency and Previous Accuracy. Experiment 1 was based on the study by Ridderinkhof (2002) in which PERI was first reported. In Experiment 2, we balanced the proportions of congruent and incongruent trials.

EXPERIMENT 1

In a paradigm based on Ridderinkhof (2002), we used a Simon task with .75/.25 probabilities for congruent/incongruent trials. A feedback mechanism encouraged participants to respond quickly while keeping accuracy above 85%. To ensure reliable numbers of errors on both congruent and incongruent trials, 2000 trials were administered.

METHOD

Participants

Twenty students at Ghent University (16 female, four male) participated (mean age = 18.7 years, SD = 1.6 years) for course credits.

Stimuli and material

Stimuli were presented on a 17-in. computer screen. The viewing distance was about 60 cm. A centrally presented black square contour (0.5×0.5 cm) was horizontally flanked by two larger black square contours (3.0 × 3.0 cm), with a center-to-center distance of 2.3cm between the middle square and the lateral squares. The stimulus was a black or a white diamond (1.6×1.6 cm), presented in one of the lateral squares. Feedback (“0”, “5” or “9”) was presented in the middle square (0.3 cm vertically and 0.2 cm horizontally). All of the stimuli were presented against a light-gray background, and responses were recorded using a Cedrus response box. The experiment was conducted using Tscope software (Stevens, Lammertyn, Verbruggen, & Vandierendonck, 2006).

Procedure

Participants had to respond to the colour of the diamond by pressing, for instance, a left key when a black diamond or a right key when a white diamond was presented (counterbalanced between subjects). The participants were informed that on 75% of the trials the location would correspond to the correct response side. However, it was stressed that the response should be based on the colour of the figure. Each trial started with the presentation of a stimulus inside one of the lateral squares, until a response was given or 2 s had passed. Following response, feedback was presented for 750 ms, after which a new trial started. Participants earned points for performing quickly and accurately. A “0” was presented

when the participant responded incorrect, and a “5” when the response was correct. When the participant was correct and faster than his or her running average reaction time, a “9” was presented. The average was updated on every trial for congruent and incongruent trials separately. An updated score was presented after each block.

After the instructions, participants performed a practice block of 32 trials. Next, they received instructions about the feedback procedure and were told that the participant with the most points would win an additional reward of €10. The experiment consisted of 20 blocks of 100 trials.

RESULTS

Responses faster than 100 ms or exceeding the response deadline, as well as their preceding and subsequent trials, were excluded from the analysis. Post-correct trials that were followed by a correct response were also discarded. On average, 276 trials ($SD = 130$) were included in the analysis. The mean reaction time was 388 ms ($SD = 47$ ms), and the mean error rate was 7% ($SD = 4\%$).

Both error rates and reaction times were first analyzed with only Previous Accuracy and Current Congruency as fixed factors. Second, we included the factor Previous Congruency as well as Stimulus Sequence (colour repetition or alternation from trial $n - 1$ to n ; see also Braem, Verguts, & Notebaert, 2011) to measure the effects of low-level stimulus repetitions on response repetition effects. Importantly, although the factor Stimulus Sequence allowed us to have an idea of the relative contribution of low-level repetitions, it did not rule out feature repetition effects, since the sequence of the irrelevant feature could not be accounted for (Hommel, 2004; Mayr et al., 2003; Mayr & Awh, 2009).

The results were analyzed using linear mixed-effects models, as implemented in the R package lme4 (Bates, Maechler, Bolker, & Walker, 2013). As was proposed by Barr, Levy, Scheepers, and Tily (2013), we

used a maximal linear mixed-effects model with a random effect for subjects. However, when we included the factors Previous Congruency and Stimulus Sequence, the model did not converge. We therefore simplified the random-effects structure by removing the random slope for previous congruency.

Error rates were analyzed using a logistic link function. For reaction times – a continuous variable - we report F statistics with Kenward-Roger adjustment of the degrees of freedom (Kenward & Roger, 1997). For binary responses, no such small-sample adjustments of the degrees of freedom have been proposed in the literature;² therefore, we adopted the standard strategy of reporting χ^2 statistics³.

PERI is calculated by subtracting the congruency effect (incongruent – congruent) following an error from the congruency effect following a correct response. Because we selected trials present in specific local sequences (i.e., C-X-E for post-correct trials and E-X for post-error trials), all trials originated from moments close to each other in time, rendering this analysis immune to global performance fluctuations (Dutilh et al., 2012). However, the significance of our results did not differ when we used all post-correct trials.

Error rates

The traditional analysis for error rates (only Previous Accuracy and Current Congruency were included) showed a main effect of current

² For binary dependent variables, small-sample inference is approximate because the number of possible outcomes is limited.

³ χ^2 and F statistics are related in the same way as z and t statistics: F and t assume a finite sample, and with increasing sample size they converge with the χ^2 and z statistics, which assume an infinite sample.

congruency, $\chi^2(1) = 282.89$, $p < 0.001$, but no significant effect of previous accuracy, $\chi^2(1) < 1$, $p = 0.37$. We observed a significant interaction of congruency and previous accuracy, $\chi^2(1) = 21.63$, $p < 0.001$, showing that the congruency effect after an error (15%) was smaller than that effect on trials following a correct response (23%).

Extending the analysis with the factors Previous Congruency and Stimulus Sequence again showed a main effect of current congruency, $\chi^2(1) = 126.60$, $p < 0.001$, indicating that participants made fewer errors on congruent (3%) than on incongruent (17%) trials. No significant effects were apparent of previous congruency, $\chi^2(1) < 1$, $p = 0.50$, or previous accuracy, $\chi^2(1) = 1.53$, $p = 0.225$. The congruency of the previous trial interacted significantly with the congruency of the current trial (16%), $\chi^2(1) = 52.57$, $p < 0.001$. However, we found no significant interaction of previous accuracy with previous congruency, $\chi^2(1) < 1$, $p = 0.94$, or with the congruency of the current trial, $\chi^2(1) < 1$, $p = 0.71$. The three-way interaction was significant, $\chi^2(1) = 53.02$, $p < 0.001$. This interaction is shown in Fig. 1a. Significant PERI occurred after a congruent trials (18%), $\chi^2(1) = 30.98$, $p < 0.001$, but after an incongruent trial significant inverse PERI emerged instead (-15%), $\chi^2(1) = 21.77$, $p < 0.001$. This pattern of results did not interact significantly with stimulus sequence, $\chi^2(1) = 1.61$, $p = 0.20$.

Reaction times

Analyzing reaction times with only Previous Accuracy and Current Congruency as factors showed main effects of both of current congruency, $F(1, 18.3) = 118.25$, $p < 0.001$, and previous accuracy, $F(1, 22.1) = 52.37$, $p < 0.001$. However, we found no significant interaction of previous accuracy and current congruency in this data set, $F(1, 4987.2) < 1$, $p = 0.57$.

When we included the factors Previous Congruency and Stimulus Sequence, a significant congruency effect was visible (55 ms), $F(1, 19.4)$

= 6.99, $p < 0.05$, as well as a significant effect of previous accuracy, $F(1, 23.8) = 42.64$, $p < 0.001$, showing post-error slowing (63 ms). The effect of previous congruency was not significant, $F(1, 4935.9) = 2.15$, $p = 0.14$. the congruency of the current trial showed a significant interaction with previous congruency, $F(1, 4943.1) = 15.32$, $p < 0.001$, indicating a congruency sequence effect (35 ms). We also observed a significant interaction of previous accuracy and previous congruency, $F(1, 4937.1) = 4.22$, $p < 0.05$, showing smaller post-error slowing following incongruent trials (54 ms) than following congruent trials (73 ms). Previous accuracy also interacted significantly with the congruency of the current trial, $F(1, 4967.4) = 6.55$, $p < 0.05$ (-22 ms, inverse PERI). Interestingly, the three-way interaction of previous congruency, previous accuracy, and current congruency was also significant, $F(1, 4944.6) = 18.15$, $p < 0.001$. This interaction is shown in Fig. 1b. For post-congruent trials, we found no significant PERI (16 ms), $F(1, 2592.43) = 2.03$, $p = 0.15$. After an incongruent trial, however, significant inverse PERI was apparent (-60 ms), $F(1, 2109.81) = 22.25$, $p < 0.001$. This pattern of results did not interact significantly with stimulus sequence, $F(1, 4953.2) < 1$, $p = 0.58$.

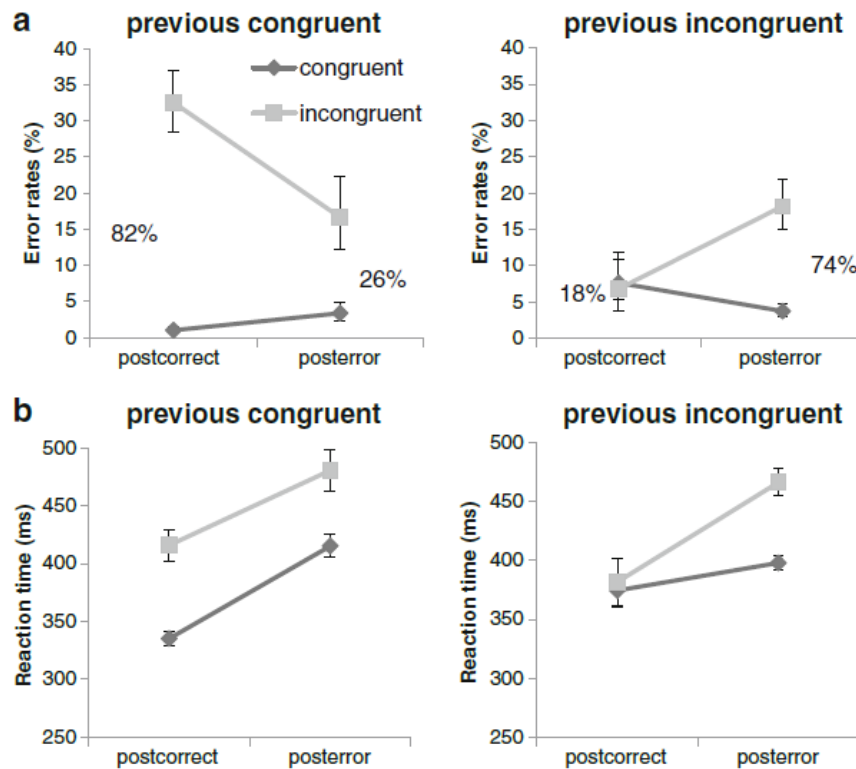


Figure 1. (a) Error rates (as percentages) and (b) reaction times (in milliseconds) dependent on previous accuracy and current congruency, following congruent and incongruent trials. Error bars represent 95% confidence intervals around the means. For each level of previous accuracy, the percentages of previous congruent and incongruent trials can be found in the graphs.

DISCUSSION

In line with the results of Ridderinkhof (2002), Experiment 1 showed significant PERI in error rates when the factor previous congruency was omitted. This effect was not replicated in reaction times. However, when previous congruency was included, a significant three-way interaction showed significant PERI following a congruent trial, but inverse PERI following an incongruent trial.

EXPERIMENT 2

The method of this experiment was identical to that of Experiment 1, with the exception that half of the trials were congruent and the other half incongruent. This balanced design served as a replication, while simultaneously controlling for contingency learning by no longer allowing participants to predict the response on the basis of the irrelevant information (Mordkoff, 2012; Schmidt & De Houwer, 2011).

Twenty students at Ghent University (17 female, three male) participated (mean age = 19.3 years, $SD = 1.8$ years) for course credits. On average, 378 trials ($SD = 154$) were included in the analysis. The mean reaction time was 364 ms ($SD = 38$ ms), and the mean error rate was 11% ($SD = 6\%$).

RESULTS

Error rates

Analyzing error rates with only Previous Accuracy and Current Congruency as factors showed a main effect of current congruency, $\chi^2(1) = 45.79$, $p < 0.001$, but no significant effect of previous accuracy, $\chi^2(1) < 1$, $p = 0.75$. We observed a significant interaction of congruency and previous accuracy, $\chi^2(1) = 5.76$, $p = 0.02$, showing that the congruency effect after an error (7%) was smaller than that effect after a correct response (11%).

Extending the analysis with the factors Previous Congruency and Stimulus Sequence again showed a main effect of current congruency, $\chi^2(1) = 38.84$, $p < 0.001$, indicating that participants made fewer errors on congruent (5%) than on incongruent (13%) trials. No significant effects were apparent of previous accuracy, $\chi^2(1) = 1.10$, $p = 0.30$, or previous congruency, $\chi^2(1) < 1$, $p = 0.63$. The congruency of the previous trial interacted significantly with the congruency of the current trial (11%),

$\chi^2(1) = 67.23, p < 0.001$. We found no significant interaction of previous accuracy and previous congruency, $\chi^2(1) = 1.12, p = 0.29$, but the interaction of previous accuracy and the congruency of the current trial was marginally significant, $\chi^2(1) = 3.65, p = 0.06$, showing a smaller congruency effect following an error (6%) than following a correct response (8%). The three-way interaction of previous accuracy, previous congruency, and current congruency was significant, $\chi^2(1) = 123.18, p < 0.001$. This interaction is shown in Fig. 2a. After a congruent trial, significant PERI emerged (20%), $\chi^2(1) = 64.34, p < 0.001$, but after an incongruent trial significant inverse PERI was seen instead (-12%), $\chi^2(1) = 48.40, p < 0.001$. This pattern of results did not interact significantly with stimulus sequence, $\chi^2(1) = 1.11, p = 0.28$.

Reaction times

Analyzing reaction times with only Previous Accuracy and Current Congruency revealed a main effect of previous accuracy, $F(1, 19) = 4.64, p < 0.05$, but not an effect of current congruency, $F(1, 19) < 1, p = 0.46$. No significant interaction of previous accuracy and current congruency was apparent, $F(1, 6542.9) < 1, p = 0.96$. When we included the factors Previous Congruency and Stimulus Sequence, a significant congruency effect emerged (27 ms), $F(1, 20.8) = 54.41, p < 0.001$, as well as a significant effect of previous accuracy, $F(1, 19.4) = 34.19, p < 0.001$, showing post-error slowing (56 ms). The effect of previous congruency was not significant, $F(1, 6538.4) < 1, p = 0.61$. The congruency of the current trial showed a significant interaction with previous congruency (35 ms), $F(1, 6501.3) = 39.67, p < 0.001$, showing a congruency sequence effect. Previous accuracy did not interact significantly with previous congruency, $F(1, 6536.4) = 2.36, p = 0.12$, or with current congruency, $F(1, 6534.7) = 1.38, p = 0.24$. The three-way interaction of previous accuracy, previous congruency, and current congruency was significant, $F(1, 6501.8) = 40.53, p < 0.001$. This interaction is shown in Fig. 2b. After a congruent trial, significant PERI was apparent (31 ms),

$F(1, 2858.59) = 13.40, p < 0.001$, but after an incongruent trial we observed significant inverse PERI instead (-45 ms), $F(1, 3620.8) = 30.12, p < 0.001$. Importantly, this effect did not interact significantly with stimulus sequence, $F(1, 6535.9) = 1.41, p = 0.24$.

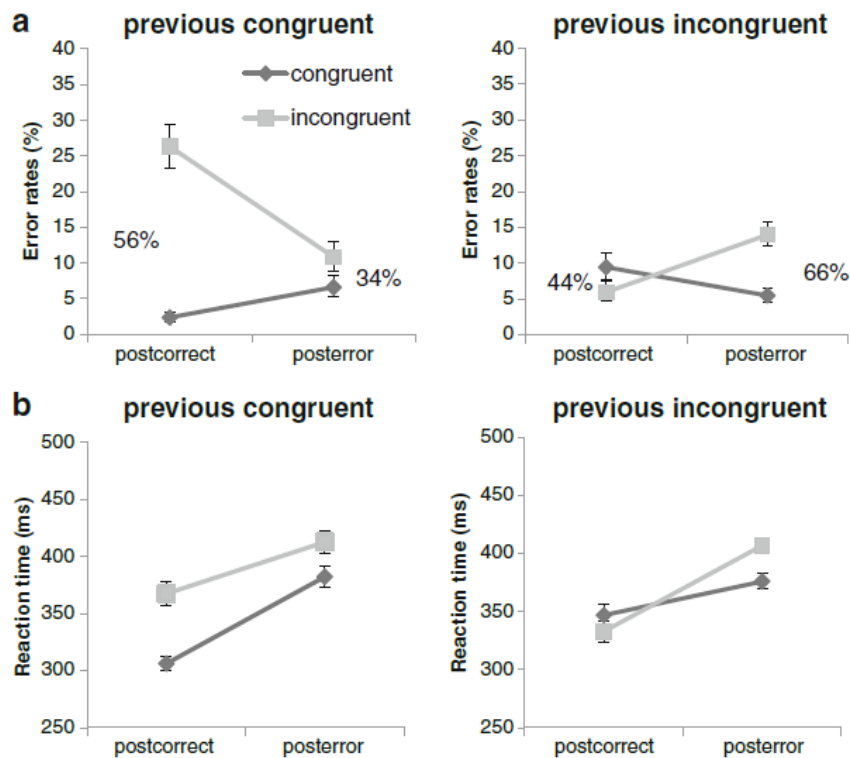


Figure 2. (a) Error rates (as percentages) and (b) reaction times (in milliseconds) dependent on previous accuracy and current congruency, following congruent and incongruent trials. Error bars represent 95% confidence intervals around the means. For each level of previous accuracy, the percentages of previous congruent and incongruent trials can be found in the graphs.

GENERAL DISCUSSION

In order to better understand behavioural adjustments following errors, we investigated the modulation of post-error reduction of interference following congruent and incongruent trials separately. Omitting the factor Previous Congruency, in line with Ridderinkhof (2002), resulted in significant PERI in the error rates from both experiments. However, when Previous Congruency was included, PERI was observed following congruent trials, but *inverse* PERI following incongruent trials, casting doubt on earlier reports of the PERI effect (King et al., 2010; Ridderinkhof, 2002; Ridderinkhof et al., 2002).

Our results thus pose a challenge for CMT. Following congruent trials, the expected pattern was observed. However, following incongruent trials, significant inverse PERI effects were demonstrated for both error rates and reaction times. Regardless of whether errors on congruent or on incongruent trials elicit more conflict (Yeung, Botvinick, & Cohen, 2004), error trials should elicit more conflict than correct trials do, and CMT would always predict PERI. One could assume that making an error on an incongruent trial induces roughly the same amount of conflict as does a correct incongruent trial, but this would still not be compatible with the finding of inverse PERI after incongruent trials. This pattern of results could, however, be described in terms of the adaptation-by-binding account (Verguts & Notebaert, 2008, 2009). This account proposes that conflict engages Hebbian learning processes on all currently active representations. This mechanism results in a stronger task focus following conflict trials, and a weaker task focus following no-conflict trials. Interestingly, both the up- and down-regulation of cognitive control occur only on correct trials, because the Hebbian mechanism requires correctly activated associations. It is rather speculative to describe the activation pattern on errors; therefore, the safest assumption is that no adjustments occur following errors. However, as compared to post-correct trials, post-error trials would show a smaller

congruency effect for congruent trials (i.e. PERI) and a larger congruency effect for incongruent trials (i.e. reversed PERI), due to the adaptation following correct trials.

Contrary to our findings, Maier, Yeung, and Steinhauser (2011) calculated PERI following incongruent trials only and showed a reduction of interference following flanker errors (responding to the irrelevant flanker feature), relative to correct trials or nonflanker errors (responses to neither the target nor the flanker). However, in their design, neutral trials were presented instead of congruent trials. Therefore, focusing on the task-irrelevant dimension was never beneficial for efficient task performance, promoting a task strategy that probably differed from the one in our paradigm. Still, further research will be needed to see under which conditions errors might indeed help conflict processing.

Our data also revealed post-error slowing (Rabbitt & Rodgers, 1977) which has traditionally been described as the result of an increase in cognitive control, and as such is predicted to be observed alongside a post-error accuracy increase (Botvinick et al., 2001). The lack of accuracy improvements after errors in the literature (Bombeke et al., 2013; Hajcak et al., 2003; King et al., 2010; Ridderinkhof, 2002) has given rise to so-called *nonfunctional* explanations for post-error slowing (Jentsch & Dudschig, 2009; Notebaert et al., 2009). Our data show an interesting dissociation between post-error slowing and PERI: Although PERI was only observed following congruent trials, post-error slowing was observed following congruent and incongruent trials. This dissociation is again an indication that the originally reported PERI effects reflected a modulation by congruency, primarily driven by congruent trials (Compton, Huber, Levinson, & Zheutlin, 2012) rather than by errors.

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REFERENCES

- Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language*, *68*(3), 255–278. doi:10.1016/j.jml.2012.11.001
- Bates, D., Maechler, M., Bolker, B., & Walker, S. (2013). lme4: Linear mixed-effects models using Eigen and S4., R package version 1.0–5. Retrieved from <http://cran.r-project.org/package=lme4>
- Bombeke, K., Schouppe, N., Duthoo, W., & Notebaert, W. (2013). The effect of alcohol and placebo on post-error adjustments. *Frontiers in Human Neuroscience*, *7*(3). doi:10.3389/fnhum.2013.00003
- Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, *108*(3), 624–652. doi:10.1037/0033-295X.108.3.624
- Braem, S., Verguts, T., & Notebaert, W. (2011). Conflict adaptation by means of associative learning. *Journal of Experimental Psychology. Human Perception and Performance*, *37*(5), 1662–1666. doi:10.1037/a0024385
- Carp, J., & Compton, R. J. (2009). Alpha power is influenced by performance errors. *Psychophysiology*, *46*, 336–343. doi:10.1111/j.1469-8986.2008.00773.x
- Cohen, J. D., Dunbar, K., & McClelland, J. L. (1990). On the control of automatic processes: a parallel distributed processing account of the Stroop effect. *Psychological Review*, *97*(3), 332–361.
- Compton, R. J., Huber, E., Levinson, A. R., & Zheutlin, A. (2012). Is “conflict adaptation” driven by conflict? Behavioral and EEG evidence for the underappreciated role of congruent trials. *Psychophysiology*, *49*(5), 583–589. doi:10.1111/j.1469-8986.2012.01354.x
- Duthoo, W., & Notebaert, W. (2012). Conflict adaptation: it is not what you expect. *Quarterly Journal of Experimental Psychology*, *65*(10), 1993–2007. doi:10.1080/17470218.2012.676655
- Dutilh, G., van Ravenzwaaij, D., Nieuwenhuis, S., van der Maas, H. L. J., Forstmann, B. U., & Wagenmakers, E.-J. (2012). How to measure post-error slowing: A confound and a simple solution. *Journal of Mathematical Psychology*, *56*(3), 208–216. doi:10.1016/j.jmp.2012.04.001
- Frith, C. D., & Done, D. J. (1986). Routes to action in reaction time tasks. *Psychological Research*, *48*, 169–177.
- Gratton, G., Coles, M., & Donchin, E. (1992). Optimizing the use of information: strategic control of activation of responses. *Journal of Experimental Psychology: General*, *121*(4), 480–506.

- Hajcak, G., McDonald, N., & Simons, R. F. (2003). To err is autonomic: Error-related brain potentials, ANS activity, and post-error compensatory behavior. *Psychophysiology*, *40*(6), 895–903. doi:10.1111/1469-8986.00107
- Hommel, B. (2004). Event files: feature binding in and across perception and action. *Trends in Cognitive Sciences*, *8*(11), 494–500. doi:10.1016/j.tics.2004.08.007
- Jentzsch, I., & Dudschig, C. (2009). Why do we slow down after an error? Mechanisms underlying the effects of posterror slowing. *Quarterly Journal of Experimental Psychology*, *62*(2), 209–218. doi:10.1080/17470210802240655
- Kenward, M. G., & Roger, J. H. (1997). Small sample inference for fixed effects from restricted maximum likelihood. *Biometrics*, *53*(3), 983–997. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/9333350>
- Kerns, J. G., Cohen, J. D., MacDonald, A. W., Cho, R. Y., Stenger, V. A., & Carter, C. S. (2004). Anterior cingulate conflict monitoring and adjustments in control. *Science*, *303*, 1023–1026. doi:10.1126/science.1089910
- King, J. a, Korb, F. M., von Cramon, D. Y., & Ullsperger, M. (2010). Post-error behavioral adjustments are facilitated by activation and suppression of task-relevant and task-irrelevant information processing. *The Journal of Neuroscience*, *30*(38), 12759–12769. doi:10.1523/JNEUROSCI.3274-10.2010
- Kornblum, S. (1994). The way irrelevant dimensions are processed depends on what they overlap with: The case of Stroop-and Simon-like stimuli. *Psychological Research*, *56*, 130–135.
- Lu, C., & Proctor, R. W. (1995). The influence of irrelevant location information on performance: A review of the Simon and spatial Stroop effects. *Psychonomic Bulletin & Review*, *2*(2), 174–207.
- Maier, M. E., Yeung, N., & Steinhauser, M. (2011). Error-related brain activity and adjustments of selective attention following errors. *NeuroImage*, *56*, 2339–2347. doi:10.1016/j.neuroimage.2011.03.083
- Mayr, U., & Awh, E. (2009). The elusive link between conflict and conflict adaptation. *Psychological Research*, *73*(6), 794–802. doi:10.1007/s00426-008-0191-1
- Mayr, U., Awh, E., & Laurey, P. (2003). Conflict adaptation effects in the absence of executive control. *Nature Neuroscience*, *6*(5), 450–452. doi:10.1038/nn1051
- Mordkoff, J. T. (2012). Observation: Three reasons to avoid having half of the trials be congruent in a four-alternative forced-choice experiment on sequential modulation. *Psychonomic Bulletin & Review*, *19*(4), 750–757. doi:10.3758/s13423-012-0257-3
- Notebaert, W., Houtman, F., Opstal, F. Van, Gevers, W., Fias, W., & Verguts, T. (2009). Post-error slowing: an orienting account. *Cognition*, *111*, 275–279. doi:10.1016/j.cognition.2009.02.002

- Orr, J. M., Carp, J., & Weissman, D. H. (2012). The influence of response conflict on voluntary task switching: a novel test of the conflict monitoring model. *Psychological Research, 76*(1), 60–73. doi:10.1007/s00426-011-0324-9
- Rabbitt, P., & Rodgers, B. (1977). What does a man do after he makes an error? an analysis of response programming. *Quarterly Journal of Experimental Psychology, 29*(4), 727–743. doi:10.1080/14640747708400645
- Ridderinkhof, K. R. (2002). Micro- and macro-adjustments of task set: activation and suppression in conflict tasks. *Psychological Research, 66*(4), 312–323. doi:10.1007/s00426-002-0104-7
- Ridderinkhof, K. R., de Vlugt, Y., Bramlage, A., Spaan, M., Elton, M., Snel, J., & Band, G. P. H. (2002). Alcohol consumption impairs detection of performance errors in mediofrontal cortex. *Science, 298*, 2209–2211. doi:10.1126/science.1076929
- Schmidt, J. R., & De Houwer, J. (2011). Now you see it, now you don't: controlling for contingencies and stimulus repetitions eliminates the Gratton effect. *Acta Psychologica, 138*(1), 176–186. doi:10.1016/j.actpsy.2011.06.002
- Simon, J. R. (1969). Reactions toward the source of stimulation. *Journal of Experimental Psychology, 81*(1), 174–176.
- Stevens, M., Lammertyn, J., Verbruggen, F., & Vandierendonck, A. (2006). Tscope: A C library for programming cognitive experiments on the MS windows platform. *Behavior Research Methods, 38*(2), 280–286.
- Verguts, T., & Notebaert, W. (2008). Hebbian learning of cognitive control: dealing with specific and nonspecific adaptation. *Psychological Review, 115*(2), 518–525. doi:10.1037/0033-295X.115.2.518
- Verguts, T., & Notebaert, W. (2009). Adaptation by binding: a learning account of cognitive control. *Trends in Cognitive Sciences, 13*(6), 252–257. doi:10.1016/j.tics.2009.02.007
- Yeung, N., Botvinick, M. M., & Cohen, J. D. (2004). The Neural Basis of Error Detection: Conflict Monitoring and the Error-Related Negativity. *Psychological Review, 111*(4), 931–959. doi:10.1037/0033-295X.111.4.931

CHAPTER 4

A NEUTRAL MEASURE FOR POST-ERROR REDUCTION OF INTERFERENCE¹²

Error commission in conflict tasks is typically followed by a range of corrective behavioural adaptations. In the present paper we focus on reports of reduced interference effects following errors. In these studies, however, such *post-error reduction of interference* (PERI) could not be interpreted unambiguously because of two confounding factors. First, lower-level memory factors were typically not controlled for. Second, the measures were always contaminated by previous congruency. In the present study, we set out to construct and test a clean measure of interference modulation. To this end, we incorporated neutral trials devoid of memory confounds in two interference tasks. In the Stroop task, significant inverse PERI was found irrespective of previous congruency. In the prime-target task, on the other hand, significant PERI was found but only following congruent trials. Overall, our data suggest that interference is not reduced after errors and that investigations of post-error reduction of interference should include previous congruency.

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INTRODUCTION

Error-monitoring and the behavioural aftereffects of errors have a long tradition in cognitive control research. These phenomena have typically been studied using congruency tasks, in which participants are required to selectively attend and respond to an arbitrary stimulus feature. By varying the congruency between this task-relevant stimulus feature and a task-irrelevant stimulus or response feature, congruent and incongruent trial types can be discerned. In the Stroop task, for example, participants are asked to respond to the ink colour of either congruent (e.g., 'RED' in red) or incongruent (e.g., 'RED' in green) stimuli. The latter typically evoke longer reaction times and higher error rates –the canonical Stroop congruency effect (Stroop, 1935; see MacLeod, 1990, for a review). Both fluctuations in the size of this Stroop effect and behavioural adaptations following error commission serve as a window onto underlying flexible control mechanisms.

Probing such post-error attentional adjustments, Ridderinkhof (2002) reported a reduced congruency effect following an erroneous response in a Simon task (i.e., post-error reduction of interference or PERI). This was interpreted in terms of improved interference resolution following error commission (see also King, Korb, von Cramon, & Ullsperger, 2010). As such, PERI bears a strong resemblance to the so-called congruency sequence effect –the finding of a smaller congruency effect following incongruent trials relative to following congruent trials (Compton, Huber, Levinson, & Zheutlin, 2012; Gratton, Coles, & Donchin, 1992; Notebaert & Verguts, 2008; Stürmer, Nigbur, Schacht, & Sommer, 2011). Both effects have typically been framed within the highly influential conflict monitoring theory (Botvinick, Braver, Barch, Carter, & Cohen, 2001). According to this theory, errors are, just like incongruent stimuli, characterized by competing response tendencies. Following detection of

this response conflict, compensatory mechanisms are triggered that enhance task focus, thereby reducing the impact of the irrelevant dimension on subsequent performance (reflected in reduced congruency effects following incongruent trials and errors).

Even though some studies have reported a significant PERI effect (King et al., 2010; Ridderinkhof, 2002; Ridderinkhof et al., 2002), other studies failed to find it (Carp & Compton, 2009; Orr, Carp, & Weissman, 2012) or even reported post-error *increase* of interference (Bombeke, Schouppe, Duthoo, & Notebaert, 2013; Schroder, Moran, Donnellan, & Moser, 2014). However, all of these studies consistently overlooked the effect of congruency on the previous trial: since most errors are made on incongruent trials, previous congruency and previous accuracy are critically confounded, and the PERI effect might actually be a congruency sequence effect.

In a recent study, we filled this gap by investigating PERI while taking the congruency of the previous trial into account (Van der Borgh, Braem, & Notebaert, 2014). Results revealed PERI following congruent trials, but *inverse* PERI following incongruent trials. This pattern of results emerged because previous congruency influenced performance on post-correct trials, leading to a larger interference effect following correct congruent trials but a smaller congruency effect following incongruent trials. It is clear that previous congruency influences PERI and one can actually conceive previous congruency as the cause of the PERI effect. In order to gain more insight in this matter it is crucial to investigate PERI after neutral trials. Interestingly, Maier, Yeung, and Steinhauser (2011) did report PERI following incongruent trials in a flanker task consisting only of neutral and incongruent trials. However, due to their focus on different error types, they did not report the congruency effect following errors made on neutral trials. Still, we believe that these post-neutral trials constitute the clearest measure of post-error reduction of interference. Similarly, Verguts, Notebaert, Kunde, and Wühr (2011) used neutral

probe trials to successfully discern post-conflict slowing from post-conflict focusing.

The present study was also set up to tackle a second shortcoming inherent to all previous investigations on the PERI effect: since these studies applied congruency tasks that were critically contaminated with lower-level memory confounds, results could not unambiguously be interpreted in terms of the proposed higher-order cognitive control mechanisms. Research on the related congruency sequence effect has spawned a large number of experiments indentifying these memory confounds (Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014b; Egner, 2007), including feature integration (Hommel, Proctor, & Vu, 2004; Mayr, Awh, & Laurey, 2003) and contingency learning (Mordkoff, 2012; J. Schmidt & De Houwer, 2011). Only recently, a series of studies reported convincing proof of conflict adaptation in paradigms devoid of such memory confounds (Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014a; Freitas & Clark, 2014; Kim & Cho, 2014; Schmidt & Weissman, 2014; Schmidt & Weissman, 2015). In line with these studies, we opted to investigate post-error adaptations in a design that, for the first time, effectively controlled for feature integration and contingency learning. One way to accomplish this is to split up a forced choice task with four response alternatives into a pair of two forced-choice tasks with separate stimulus-response mappings that alternate on a trial-by-trial basis. By doing so, stimulus features never repeat over successive trials, and stimulus-response contingencies are kept equal across all trials. We selected a Stroop task where our stimulus set was divided into two colour pairs that were presented in alternating fashion (Jiménez & Méndez, 2013, 2014; Weissman, Jiang, & Egner, 2014). Similarly in Experiment 2, we used a prime-target task where two prime-target couples were presented in alternating fashion (Schmidt & Weissman, 2014; Weissman et al., 2014).

In sum, our experiments aimed to investigate markers of post-error behavioural adaptation in an unprecedentedly clean fashion. To this end, we integrated neutral words into both a Stroop and prime-target task, and controlled for all known memory confounds *a priori*. By including neutral trials, we were able to investigate post-error adaptations of interference following neutral trials, in which the facilitating or detrimental impact of the irrelevant dimension is removed and compare this to the effect following incongruent and congruent trials.

EXPERIMENT 1

METHOD

Participants

Forty Ghent University students (36 females; mean age = 22.1 years, SD = 3.7 years) participated in the experiment, lasting approximately one hour. They provided written informed consent prior to the testing, and received 10 euro upon completion.

Stimuli and material

A program written with T-Scope software (Stevens, Lammertyn, Verbruggen, & Vandierendonck, 2006) controlled stimulus presentation and response registration. Stimuli were presented on a 17-inch computer screen. The viewing distance was approximately 50 cm. All stimuli were presented in the center of the screen in Arial 12, bold, against a black background. The stimulus set consisted of the words ‘ROOD’, ‘GROEN’, ‘BLAUW’, ‘GEEL’, ‘KRANT’ and ‘STOEL’ (i.e., the Dutch words for ‘red’, ‘green’, ‘blue’, ‘yellow’, ‘newspaper’ and ‘chair’, respectively) printed in red, RGB (255, 0, 0), green, RGB (0, 128, 0), blue, RGB (0, 0, 255) or yellow, RGB (255, 255, 0). The neutral words did not differ significantly from the colour words in terms of length,

frequency and number of neighbors (all $ps \geq 0.31$). Responses were registered by means of a Cedrus response box.

Design and procedure

A Stroop task with four colours and four response alternatives was administered. In order to exclude a contribution of feature repetition and contingency learning, the stimuli were divided into two subsets of word-colour combinations that were presented on alternating trials. On even trials, participants could, for example, see the words ‘ROOD’, ‘GROEN’ or ‘KRANT’ (i.e., the Dutch words for ‘red’, ‘green’ and ‘newspaper’, respectively) in the colours red or green, thereby creating congruent, incongruent and neutral trials. On odd trials, participant would then only see the words ‘BLAUW’, ‘GEEL’ or ‘STOEL’ (i.e., the Dutch words for ‘blue’, ‘yellow’ and ‘chair’, respectively) in the colours blue and yellow. To further ensure that participants did not become aware of this trial structure, colours used in one type of trials (odd or even) were not mapped to the same hand or the same finger. For the example above, participants were asked to press the left middle finger for ‘red’, the right index finger for ‘green’, the left index finger for ‘yellow’ and the right middle finger for ‘blue’. We created three such stimulus divisions and accompanying response mappings, which were randomized across participants.

A trial started with the presentation of a stimulus (i.e., a colour word or neutral word presented in red, green, blue or yellow). After 150 ms, this word was replaced by a blank screen until response. Starting from the onset of the stimulus, the maximum response time was 1500 ms. The inter-trial interval was set to 1000 ms. In the practice phase, the inter-trial interval was preceded by feedback: the words “juist”, “fout” or “te traag” (i.e., the Dutch words for correct, wrong and too slow, respectively) were

presented in white for 500 ms. In the experimental blocks, no feedback was provided.

Participants completed the experiment in groups of four. They first completed an unrelated task of 15 minutes. Following this experiment, instruction slides informed them that they would now see words and had to respond to the colour in which these words were presented. The response mapping was shown on the screen. Participants were asked to memorize this mapping, since it would no longer be shown during the remainder of the experiment. They first completed a practice block. This practice block consisted of 75 trials, followed by ten blocks of 156 trials. In these blocks, on both odd and even trials, 3 possible words in 2 possible colours could be shown. These 6 combinations were each repeated 13 times. In between these blocks, participants were allowed short, self-paced breaks. During these breaks, accuracy, average reaction time and percentage of too slow responses in the previous block were presented. When participants had more than 10 percent of too slow responses (i.e. exceeding the response time), there was an additional message encouraging them to respond faster.

RESULTS

Data trimming and analysis

Following the methodological guidelines put forward by Dutilh and colleagues (2012), we further restricted the analysis to a specific subset of trials (X) embedded within specific local sequences of correct (C) and erroneous (E) responses: C-X-E for post-correct trials and E-X for post-error trials. As such, our analysis is not influenced by global performance fluctuations, since all trials originate from moments close to each other in time.

Before being entered into the statistical analyses, the data were subjected to a trimming procedure. We removed the first and last trials of each

block, responses faster than 100 ms, trials in which the response deadline was not met, as well as the trial following and/or preceding these. Even though the design excluded response repetitions for correct trials, trials following an error could still entail a response repetition. These trials were also removed from the analysis. Taken together, on average 196 trials ($SD = 98$) were included in the dataset. The mean response time was 630 ms ($SD = 90$ ms). The mean accuracy was 87% ($SD = 10\%$).

For the analyses reported below, we applied a linear mixed effects model as implemented in the R-package lme4 (Bates, Maechler, Bolker, & Walker, 2013) with a random effect for subjects. Additionally each variable was added to this model and tested to see if this addition improved the model. Next the combination of every variable which significantly improved the base model was added and tested. Accuracy was analyzed using a logistic link function.

Post-error slowing (PES) and post-error accuracy were assessed by comparing the average reaction time and accuracy on trials following post-error and post-correct trials. PERI was investigated by comparing the congruency effect (incongruent – congruent), for both reaction times and accuracy, following post-error and post-correct trials.

Reaction times

There was a significant congruency effect, $\chi^2(2) = 92.67$, $p < 0.001$, indicating that participants were slower on incongruent trials (670 ms) than on congruent (614 ms), or neutral trials (634 ms). These differences in reaction time between congruency types were all significant, all $ps < 0.001$. Overall there was a main effect of previous accuracy, $\chi^2(1) = 140.56$, $p < 0.001$, indicating that participants were slower following an error (689 ms) than following a correct response (590 ms). There was a significant main effect of previous congruency, $\chi^2(2) = 14.44$, $p < 0.001$ indicating that participants responded slower following incongruent trials

(652 ms) compared to congruent (633 ms) and neutral trials (634 ms), respectively $\chi^2(1) = 11.28, p < 0.001$ and $\chi^2(1) = 9.91, p < 0.01$. Reaction time following a congruent and neutral trial did not differ significantly, $\chi^2(1) = 0.02, p = 0.89$.

There was also significant interaction effect of previous accuracy and current congruency, $\chi^2(2) = 7.71, p = 0.02$. When comparing incongruent and congruent trials, the congruency effect following an error (72 ms) was significantly larger than following a correct response (39 ms), i.e. inverse PERI, $\chi^2(1) = 7.80, p < 0.01$. Comparing incongruent and neutral trials, the difference between the congruency effect following an error (44 ms) and following a correct response (27 ms), was not significant, $\chi^2(1) = 1.88, p = 0.17$. Similarly, when congruent and neutral trials were compared, no significant difference was found (neutral min congruent, resp. 28 and 12 ms), $\chi^2(1) = 2.04, p = 0.15$. There was no significant interaction of previous congruency and previous accuracy, previous congruency and current congruency, nor a significant three-way interaction, all $ps \geq 0.42$, see Figure 1.

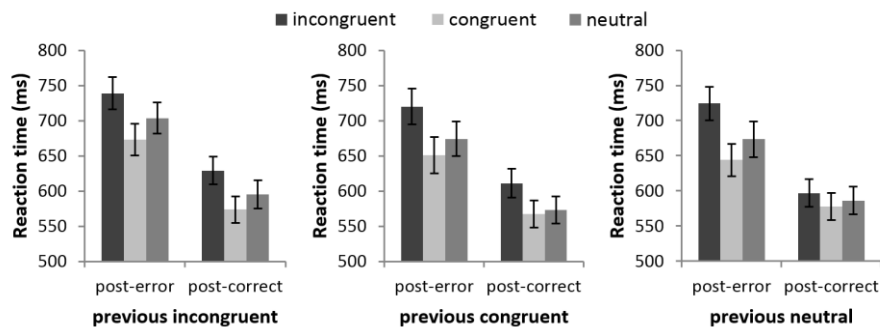


Figure 1. Average reaction time (in milliseconds) for incongruent, congruent and neutral trials following correct or erroneous responses per previous congruency type. Error bars represent 95% confidence intervals around the means.

Accuracy

There was no main effect of current congruency, $\chi^2(2) = 0.3.23, p = 0.20$ nor of previous congruency, $\chi^2(2) = 0.23, p = 0.89$. Overall there was a

main effect of previous accuracy, $\chi^2(1) = 142.04$, $p < 0.001$, indicating that participants were less correct following an error (85%) than following a correct response (93%). There was a significant interaction effect of previous congruency and previous accuracy, $\chi^2(2) = 6.26$, $p = 0.04$, as there was a larger difference between post-error and post-correct accuracy following a congruent trial (9%) compared to following an incongruent (6%) and neutral trial (6%), respectively $\chi^2(1) = 3.88$, $p < 0.05$ and $\chi^2(1) = 5.69$, $p = 0.02$. The amount of post-error accuracy decrease following an incongruent or neutral trial did not differ significantly, $\chi^2(1) = 0.24$, $p = 0.62$. The interaction of previous accuracy and current congruency, previous congruency and current congruency or the three-way interaction was not significant, all $ps \geq 0.58$, see Figure 2.

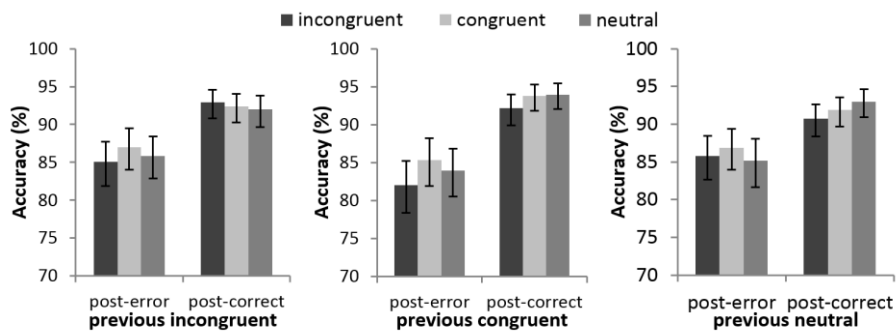


Figure 2. Average accuracy (in percentages) for incongruent, congruent and neutral trials following correct or erroneous responses per previous congruency type. Error bars represent 95% confidence intervals around the means.

DISCUSSION

Overall we found increased interference following an error, opposing the idea of post-error conflict focusing. Contrary to our expectations, previous congruency did not modulate the reported PERI effect, and contrary to our earlier study, PERI was not observed after congruent trials. However, based on our assumption that previous measures of PERI are confounded with, or even driven by, the congruency sequence effect,

it is possible that our results can be explained by our design choice. Indeed, using a design devoid of feature repetitions or contingency learning can eliminate the congruency sequence effect (Schmidt & De Houwer, 2011). As a second experiment, we therefore selected a task which has produced a reliable congruency sequence effect even when excluding feature repetition or contingency learning (Schmidt & Weissman, 2014; Weissman et al., 2014).

EXPERIMENT 2

METHOD

Participants

Forty Ghent University students (28 females, 5 left-handed; mean age = 23 years, $SD = 5.0$ years) participated in the experiment, lasting approximately one hour. They provided written informed consent prior to the testing, and received 10 euro upon completion.

Stimuli and material

A program written with T-Scope software (Stevens et al., 2006) controlled stimulus presentation and response registration. Stimuli were presented on a 17-inch computer screen. The viewing distance was approximately 50 cm. All stimuli were presented in the center of the screen in Arial 12, bold, against a black background. The stimulus set consisted of the words ‘LINKS’, ‘RECHTS’, ‘OP’, ‘NEER’, ‘KRANT’ and ‘STOEL’ (i.e., the Dutch words for ‘left’, ‘right’, ‘up’, ‘down’, ‘newspaper’ and ‘chair’, respectively) printed in white. Responses were registered by means of a Cedrus response box.

Design and procedure

The design of this prime-target task was based on the design of Schmidt and Weissman, (2014). A prime-target task with four target words and

four response alternatives was administered. In order to exclude a contribution of feature repetition and contingency learning, the stimuli were divided into two subsets of prime-target combinations that were presented on alternating trials. On even trials, participants could see the words 'LINKS', 'RECHTS' or 'KRANT' (i.e., the Dutch words for 'left', 'right' and 'newspaper', respectively) as prime and the word 'LINKS' and 'RECHTS' as target, thereby creating congruent, incongruent and neutral trials. On odd trials, participants were presented with trials consisting of the words 'OP', 'NEER' or 'STOEL' (i.e., the Dutch words for 'up', 'down' and 'chair', respectively) as prime and the word 'OP' and 'NEER' as target.

A trial started with the presentation of a fixation cross for 750 ms. Following fixation the prime was presented on screen for 133 ms and followed by a blank screen of 33 ms. Subsequently the target was presented in the middle of the screen for 133 ms and followed by a mask, '#####' for a maximum of 1360 ms. Starting from the onset of the target stimulus, the maximum response time was 1493 ms. In the practice phase, the inter-trial interval was preceded by feedback: the words "juist", "fout" or "te traag" (i.e., the Dutch words for correct, wrong and too slow, respectively) were presented in white for 500 ms. In the experimental blocks, no feedback was provided.

Participants completed the experiment in groups of four. They first completed an unrelated task of 15 minutes. Following this experiment, instruction slides informed them that they would now see words and had to respond with the appropriate response. The response mapping was shown on the screen. Participants were asked to memorize this mapping, since it would no longer be shown during the remainder of the experiment. They first completed a practice block. This practice block consisted of 48 trials, followed by ten blocks of 144 trials. In these blocks, on both odd and even trials, 3 possible primes followed by 2

possible targets could be shown. These 6 combinations were each repeated 12 times. In between these blocks, participants were allowed short, self-paced breaks. During these breaks, accuracy, average reaction time and percentage of too slow responses in the previous block were presented. When participants had more than 10 percent of too slow responses (i.e. exceeding the response time), there was an additional message encouraging them to respond faster.

RESULTS

Data trimming and analysis

We removed the first and last trials of each block, responses faster than 100 ms, trials in which the response deadline was not met, as well as the trial following and/or preceding these. Even though the design excluded response repetitions for correct trials, trials following an error could still entail a response repetition. These trials were also removed from the analysis. Taken together, on average 271 trials ($SD = 143$) were included in the dataset. The mean response time was 647 ms ($SD = 87$ ms). The mean accuracy was 86% ($SD = 13\%$).

Reaction times

There was a main effect of current congruency, $\chi^2(2) = 154.73$, $p < 0.001$, showing that participants were slower on incongruent trials (703 ms) than on congruent (602 ms), or neutral trials (659 ms). These differences in reaction time between conditions were all significant, all $ps < 0.001$. Overall there was a main effect of previous accuracy, $\chi^2(1) = 38.82$, $p < 0.001$, showing that participants were slower following an error (667 ms) than following a correct response (642 ms). There was no significant main effect of previous congruency, $\chi^2(2) = 2.61$, $p = 0.27$. There was also a significant interaction effect of previous congruency and previous accuracy, $\chi^2(2) = 14.65$, $p < 0.001$. While there was significant post-error slowing following congruent (31 ms) and neutral trials (42 ms), resp.

$\chi^2(1) = 15.63, p < 0.001$ and $\chi^2(1) = 31.53, p < 0.001$, no significant post-error slowing was found following incongruent trials, 5 ms, $\chi^2(1) = 0.78, p = 0.38$, see figure 3. There was no significant interaction of previous congruency and current congruency, previous accuracy and current congruency, nor a significant three-way interaction, all $ps \geq 0.29$.

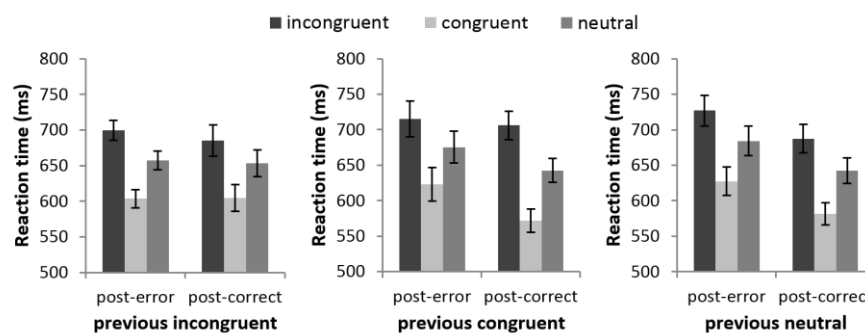


Figure 3. Average reaction time (in milliseconds) for incongruent, congruent and neutral trials following correct or erroneous responses per previous congruency type. Error bars represent 95% confidence intervals around the means.

Accuracy

There was a congruency effect, $\chi^2(2) = 259.29, p < 0.001$, showing that participants were less correct on incongruent trials (81%) than on congruent (95%), or neutral trials (93%). These differences in accuracy between conditions were significant, all $ps < 0.001$. Overall there was a main effect of previous accuracy, $\chi^2(1) = 5.09, p = 0.02$, showing that participants were less correct following an error (91%) than following a correct response (92%). There was also a main effect of previous congruency, $\chi^2(2) = 12.71, p < 0.01$, indicating that participants were more correct on trials following an incongruent trial (92%) than trials following a congruent (90%) and neutral (91%) trial, resp. $\chi^2(1) = 13.26, p < 0.001$ and $\chi^2(1) = 4.34, p = 0.04$. Accuracy following a congruent and neutral trial did not differ significantly, $\chi^2(1) = 1.96, p = 0.16$. There was no significant interaction effect of previous congruency and previous

accuracy, $\chi^2(2) = 0.10$, $p = 0.95$, nor previous congruency and current congruency $\chi^2(4) = 1.93$, $p = 0.75$. There was a significant interaction between previous accuracy and current congruency, $\chi^2(2) = 12.26$, $p < 0.001$. Interestingly this effect also interacted significantly with previous congruency, $\chi^2(4) = 9.92$, $p = 0.04$, see Figure 4.

To investigate the effect of previous congruency on PERI, current incongruent and congruent trials were selected. Again a significant three-way interaction was found between previous accuracy, previous congruency and current congruency, $\chi^2(2) = 7.21$, $p = 0.03$. Following incongruent trials, the congruency effect following error trials (13%) did not differ significantly from the congruency effect following correct trials (15%), $\chi^2(1) = 2.08$, $p = 0.15$. The same result was obtained following neutral trials, resp. 14% and 15%, $\chi^2(2) < 0.01$, $p = 0.99$. Following congruent trials however, there was significant PERI; following error trials the congruency effect was significantly smaller (9%) than following correct trials (21%), $\chi^2(2) = 14.83$, $p < 0.001$. Selecting incongruent and neutral trials, a marginally significant PERI effect was found following incongruent trials (resp. 10% and 13%), $\chi^2(1) = 3.48$, $p = 0.06$. Following congruent trials again significant PERI was present (resp. 7% and 17%), $\chi^2(2) = 14.34$, $p < 0.001$, while no significant difference was found following neutral trials, $\chi^2(2) = 0.01$, $p = 0.91$. Comparing congruent and neutral trials, no significant three-way interaction was found between previous accuracy, previous congruency and current congruency, $\chi^2(2) = 0.61$, $p = 0.74$.

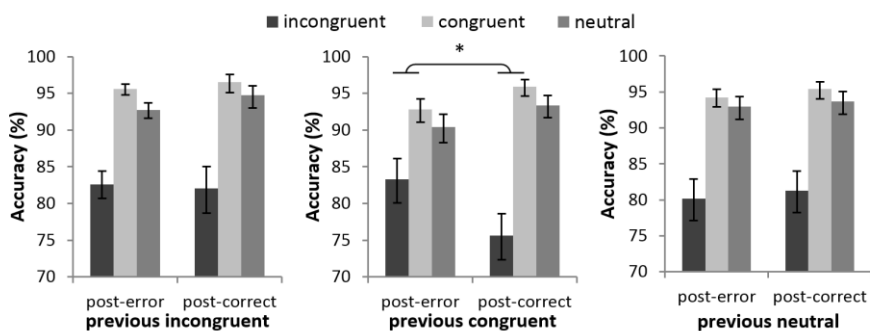


Figure 4. Average accuracy (in percentages) for incongruent, congruent and neutral trials following correct or erroneous responses per previous congruency type. Error bars represent 95% confidence intervals around the means.

Discussion

In a prime-target design we observe PERI after congruent trials, similar to our earlier study. The current results show that the occurrence of PERI is influenced, or even depending on the congruency of the previous trial. Following the idea that post-neutral trials show the cleanest measure of post-error adaptations, one has to infer that errors do not lead to reduced interference effects. Additionally, in both experiments it is clear that, when comparing congruent and incongruent trials, post-incongruent trials render the same results as post-neutral trials. Therefore, in designs without neutral trials, it would make sense to investigate PERI on post-incongruent trials.

GENERAL DISCUSSION

In the present experiments, we aimed to test post-error adaptation of interference while controlling for feature repetitions and previous congruency. As previously reported, there was a difference in the congruency effect following erroneous and correct responses. However this PERI effect was very different over the two tasks. In the Stroop task a significant *inverse* PERI was found in reaction times, but not in

accuracy, which did not depend on previous congruency. In the prime-target task on the other hand, significant PERI was found in accuracy but not in reaction time. Interestingly the effect in the prime-target task also depended on previous congruency; only following congruent trials significant PERI was observed. Interestingly the same pattern was present when looking at reaction times, even though the overall interaction with previous congruency was not significant. The difference in the congruency effect following correct and error responses was not significant following incongruent and neutral trials.

In the Stroop task, previous congruency did not influence the reported interference effect. Interestingly, post-error *increase* of interference was found. While we did not observe PERI following congruent trials, it might be the case that the influence of previous congruency on post-correct trials was diminished in our paradigm devoid of feature repetitions and contingency learning (Schmidt & De Houwer, 2011). As put forward in a recent literature review (Duthoo, Abrahamse, Braem, Böhler, & Notebaert, 2014), only in such optimized design, one is able to reliably tap into pure measures of attentional adjustments. Therefore, we strongly recommend future investigations of PERI to pursue this research strategy.

In the prime-target task, we replicated our previous results only partially (Van der Borgh et al., 2014) as we did find a significant PERI effect following congruent trials but not a significant inverse PERI effect following incongruent trials. Based on the idea that conflict adaptation drives the PERI effect, this inversed PERI would be expected in terms of increased performance for incongruent trials only after correct incongruent trials. However, as already indicated, there is now increasing support for the idea that actual adaptation is more effective after congruent trials (Compton et al., 2012; Lamers & Roelofs, 2011).

Our results are at odds with the conflict monitoring theory (Botvinick et al., 2001), according to which people will strategically slow down and increase their task focus following an error in order to avoid another misstep. The theory posits that error trials are associated with strong response conflict, and therefore trigger compensatory mechanisms aimed to reduce subsequent interference. The inverse PERI and post-error accuracy decrease reported here speak against this hypothesis. Interestingly, our previous results, in which we found PERI following congruent trials but inverse PERI following incongruent trials, could be explained by the adaptation-by-binding account (Verguts & Notebaert, 2008, 2009). The rationale of this account is that conflict strengthens all currently active representations through Hebbian learning, resulting in a stronger task focus following conflict compared to following no-conflict trials. Because this is an ongoing process, both an up- and down-regulation of cognitive control can be predicted on correct trials. This explains the above-mentioned pattern where PERI is found following congruent trials, because post-correct congruent trials lead to an increased congruency effect. Similarly inverse PERI following incongruent trials can be attributed to the reduced congruency effect following post-correct incongruent trials. However this account also highlights the difference between errors and conflict. While conflict trials lead to increased binding of task-relevant units, it is unclear what to predict when an error is made. Minimally, error trials are associated with incorrect activation patterns, leading to a far less reliable post-error task-focusing component.

In line with findings in non-conflict tasks (Houtman & Notebaert, 2013; Houtman, Núñez Castellar, & Notebaert, 2012; Steinborn, Flehmig, Bratzke, & Schröter, 2012), we found post-error accuracy *decrease* and post-error slowing in both experiments. While previous congruency influenced the amount of post-error accuracy *decrease* in the Stroop task, post-error slowing was influenced by previous congruency in the prime-

target task, with significant PES following congruent and neutral trials but nonsignificant PES following incongruent trials. Overall performance is decreased following error commission: participants slowed down and made more errors.

Interestingly, the lack of PES following incongruent trials in the prime-target task can be explained by the orienting account (Notebaert et al., 2009). This account argues that an error, as an infrequent and salient event, triggers an orienting response away from the task, thereby hampering the processing of subsequent stimuli (Houtman & Notebaert, 2013). One prediction of this account is that the amount of PES is influenced by the amount of errors. Indeed Notebaert and colleagues (2009) showed post-error slowing when errors were infrequent but post-correct slowing when correct responses were infrequent. Even when differences in accuracy are small, this relationship with PES is found (Steinborn et al., 2012). In the prime-target task, a significant accuracy difference can be found on incongruent, congruent and neutral trials, with most errors on incongruent trials. Therefore the reported results of PES might actually reflect the influence of frequency rather than previous congruency. That this effect is not found in the Stroop task, where also no differences in accuracy are found between congruency types, is in line with this idea. It remains speculative what the orienting account (Notebaert et al., 2009), which primarily aims to explain PES, predicts in terms of interference of irrelevant stimulus features. Still, being distracted from the task includes that attentional selection (prioritizing task relevant information) is disturbed. Therefore, increased interference of irrelevant stimulus characteristics following an error (inverse PERI) could be expected.

Even though the present findings do not speak in favour of improved performance following errors, this does not necessary imply that people never adapt and learn from their mistakes. Indeed, as indicated by Danielmeier and Ullsperger (2011), functional and non-functional

accounts are far from mutually exclusive. In this respect, it is conceivable that there is a short-lived attentional dip and/or impaired processing immediately following an error, especially when this error came unexpected or was very salient (Jentzsch & Dudschig, 2009; Notebaert et al., 2009). The error's disruptive effect would then be reflected in slower and less accurate responding, as well as reduced attentional filtering. The magnitude and duration of this attentional dip seem to be dependent on task demands. However, with more time, compensatory cognitive processes might kick in and exert their influence (Danielmeier & Ullsperger, 2011; Jentzsch & Dudschig, 2009). Interestingly, we used a rather long inter-trial interval (respectively 1000 and 750 ms), yet failed to find evidence for such strategic adaptation. Jentzsch and Dudschig (2009) did show PIA and reduced PES using the same inter-trial interval. Since our tasks were substantially more difficult, it is possible that non-functional task interference, be it distraction or a bottleneck, lingered on for a longer period of time.

In conclusion, our results show that previous congruency can influence the occurrence of PERI even when a design devoid of contingency learning and feature repetition is used. By including neutral trials, it is clear that investigating PERI following incongruent trials, rather than congruent trials, reflect the cleanest measure for this behavioural adaptation.

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REFERENCES

- Bates, D., Maechler, M., Bolker, B., & Walker, S. (2013). lme4: Linear mixed-effects models using Eigen and S4., R package version 1.0–5. Retrieved from <http://cran.r-project.org/package=lme4>
- Bombeke, K., Schoupe, N., Duthoo, W., & Notebaert, W. (2013). The effect of alcohol and placebo on post-error adjustments. *Frontiers in Human Neuroscience*, 7(3). doi:10.3389/fnhum.2013.00003
- Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, 108(3), 624–652. doi:10.1037/0033-295X.108.3.624
- Carp, J., & Compton, R. J. (2009). Alpha power is influenced by performance errors. *Psychophysiology*, 46, 336–343. doi:10.1111/j.1469-8986.2008.00773.x
- Compton, R. J., Huber, E., Levinson, A. R., & Zheutlin, A. (2012). Is “conflict adaptation” driven by conflict? Behavioral and EEG evidence for the underappreciated role of congruent trials. *Psychophysiology*, 49(5), 583–589. doi:10.1111/j.1469-8986.2012.01354.x
- Danielmeier, C., & Ullsperger, M. (2011). Post-error adjustments. *Frontiers in Psychology*, 2, 233. doi:10.3389/fpsyg.2011.00233
- Duthoo, W., Abrahamse, E. L., Braem, S., Boehler, C. N., & Notebaert, W. (2014a). The congruency sequence effect 3.0: A critical test of conflict adaptation. *PLoS One*.
- Duthoo, W., Abrahamse, E. L., Braem, S., Boehler, C. N., & Notebaert, W. (2014b). The heterogeneous world of congruency sequence effects: an update. *Frontiers in Psychology*, 5(1001). doi:10.3389/fpsyg.2014.01001
- Dutilh, G., van Ravenzwaaij, D., Nieuwenhuis, S., van der Maas, H. L. J., Forstmann, B. U., & Wagenmakers, E.-J. (2012). How to measure post-error slowing: A confound and a simple solution. *Journal of Mathematical Psychology*, 56(3), 208–216. doi:10.1016/j.jmp.2012.04.001
- Egner, T. (2007). Congruency sequence effects and cognitive control. *Cognitive, Affective & Behavioral Neuroscience*, 7(4), 380–390. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/18189011>
- Freitas, A. L., & Clark, S. L. (2014). Generality and specificity in cognitive control: conflict adaptation within and across selective-attention tasks but not across selective-attention and Simon tasks. *Psychological Research*, [Epub ahead of print]. doi:10.1007/s00426-014-0540-1
- Gratton, G., Coles, M., & Donchin, E. (1992). Optimizing the use of information: strategic control of activation of responses. *Journal of Experimental Psychology: General*, 121(4), 480–506.

- Hommel, B., Proctor, R. W., & Vu, K.-P. L. (2004). A feature-integration account of sequential effects in the Simon task. *Psychological Research*, *68*(1), 1–17. doi:10.1007/s00426-003-0132-y
- Houtman, F., & Notebaert, W. (2013). Blinded by an error. *Cognition*, *128*(2), 228–236. doi:10.1016/j.cognition.2013.04.003
- Houtman, F., Núñez Castellar, E., & Notebaert, W. (2012). Orienting to errors with and without immediate feedback. *Journal of Cognitive Psychology*, *24*(3), 278–285. doi:10.1080/20445911.2011.617301
- Jentzsch, I., & Dudschig, C. (2009). Why do we slow down after an error? Mechanisms underlying the effects of posterror slowing. *Quarterly Journal of Experimental Psychology*, *62*(2), 209–218. doi:10.1080/17470210802240655
- Jiménez, L., & Méndez, A. (2013). It is not what you expect: dissociating conflict adaptation from expectancies in a Stroop task. *Journal of Experimental Psychology. Human Perception and Performance*, *39*(1), 271–284. doi:10.1037/a0027734
- Jiménez, L., & Méndez, A. (2014). Even with time, conflict adaptation is not made of expectancies. *Frontiers in Psychology*, *5*(1042). doi:10.3389/fpsyg.2014.01042
- Kim, S., & Cho, Y. S. (2014). Congruency sequence effect without feature integration and contingency learning. *Acta Psychologica*, *149*, 60–68. doi:10.1016/j.actpsy.2014.03.004
- King, J. a, Korb, F. M., von Cramon, D. Y., & Ullsperger, M. (2010). Post-error behavioral adjustments are facilitated by activation and suppression of task-relevant and task-irrelevant information processing. *The Journal of Neuroscience*, *30*(38), 12759–12769. doi:10.1523/JNEUROSCI.3274-10.2010
- Lamers, M. J. M., & Roelofs, A. (2011). Attentional control adjustments in Eriksen and Stroop task performance can be independent of response conflict. *Quarterly Journal of Experimental Psychology*, *64*(6), 1056–1081. doi:10.1080/17470218.2010.523792
- Maier, M. E., Yeung, N., & Steinhauser, M. (2011). Error-related brain activity and adjustments of selective attention following errors. *NeuroImage*, *56*, 2339–2347. doi:10.1016/j.neuroimage.2011.03.083
- Mayr, U., Awh, E., & Laurey, P. (2003). Conflict adaptation effects in the absence of executive control. *Nature Neuroscience*, *6*(5), 450–452. doi:10.1038/nn1051
- Mordkoff, J. T. (2012). Observation: Three reasons to avoid having half of the trials be congruent in a four-alternative forced-choice experiment on sequential modulation. *Psychonomic Bulletin & Review*, *19*(4), 750–757. doi:10.3758/s13423-012-0257-3

- Notebaert, W., Houtman, F., Opstal, F. Van, Gevers, W., Fias, W., & Verguts, T. (2009). Post-error slowing: an orienting account. *Cognition*, *111*, 275–279. doi:10.1016/j.cognition.2009.02.002
- Notebaert, W., & Verguts, T. (2008). Cognitive control acts locally. *Cognition*, *106*(2), 1071–1080. doi:10.1016/j.cognition.2007.04.011
- Orr, J. M., Carp, J., & Weissman, D. H. (2012). The influence of response conflict on voluntary task switching: a novel test of the conflict monitoring model. *Psychological Research*, *76*(1), 60–73. doi:10.1007/s00426-011-0324-9
- Ridderinkhof, K. R. (2002). Micro- and macro-adjustments of task set: activation and suppression in conflict tasks. *Psychological Research*, *66*(4), 312–323. doi:10.1007/s00426-002-0104-7
- Ridderinkhof, K. R., de Vlugt, Y., Bramlage, A., Spaan, M., Elton, M., Snel, J., & Band, G. P. H. (2002). Alcohol consumption impairs detection of performance errors in mediofrontal cortex. *Science*, *298*, 2209–2211. doi:10.1126/science.1076929
- Schmidt, J., & De Houwer, J. (2011). Now you see it, now you don't: controlling for contingencies and stimulus repetitions eliminates the Gratton effect. *Acta Psychologica*, *138*(1), 176–186. doi:10.1016/j.actpsy.2011.06.002
- Schmidt, J. R., & Weissman, D. H. (2014). Congruency Sequence Effects without Feature Integration or Contingency Learning Confounds. *PloS One*, *9*(7), e102337. doi:10.1371/journal.pone.0102337
- Schmidt, J., & Weissman, D. (2015). Contingent attentional capture triggers the congruency sequence effect. *Acta Psychologica*, (JANUARY). Retrieved from <http://www.sciencedirect.com/science/article/pii/S0001691815300044>
- Schroder, H. S., Moran, T. P., Donnellan, M. B., & Moser, J. S. (2014). Mindset induction effects on cognitive control: A neurobehavioral investigation. *Biological Psychology*, *103*, 27–37. doi:10.1016/j.biopsycho.2014.08.004
- Steinborn, M. B., Flehmig, H. C., Bratzke, D., & Schröter, H. (2012). Error reactivity in self-paced performance: Highly-accurate individuals exhibit largest post-error slowing. *Quarterly Journal of Experimental Psychology*, *65*(4), 624–31. doi:10.1080/17470218.2012.660962
- Stevens, M., Lammertyn, J., Verbruggen, F., & Vandierendonck, A. (2006). Tscope: A C library for programming cognitive experiments on the MS windows platform. *Behavior Research Methods*, *38*(2), 280–286.
- Stürmer, B., Nigbur, R., Schacht, A., & Sommer, W. (2011). Reward and punishment effects on error processing and conflict control. *Frontiers in Psychology*, *2*(335). doi:10.3389/fpsyg.2011.00335
- Van der Borgh, L., Braem, S., & Notebaert, W. (2014). Disentangling posterror and postconflict reduction of interference. *Psychonomic Bulletin & Review*. doi:10.3758/s13423-014-0628-z

- Verguts, T., & Notebaert, W. (2008). Hebbian learning of cognitive control: dealing with specific and nonspecific adaptation. *Psychological Review*, *115*(2), 518–525. doi:10.1037/0033-295X.115.2.518
- Verguts, T., & Notebaert, W. (2009). Adaptation by binding: a learning account of cognitive control. *Trends in Cognitive Sciences*, *13*(6), 252–257. doi:10.1016/j.tics.2009.02.007
- Verguts, T., Notebaert, W., Kunde, W., & Wühr, P. (2011). Post-conflict slowing: cognitive adaptation after conflict processing. *Psychonomic Bulletin & Review*, *18*, 76–82. doi:10.3758/s13423-010-0016-2
- Weissman, D. H., Jiang, J., & Egner, T. (2014). Determinants of congruency sequence effects without learning and memory confounds. *Journal of Experimental Psychology: Human Perception and Performance*, *40*(5), 2022–37. doi:10.1037/a0037454

CHAPTER 5

DISTINGUISHING THE INFLUENCE OF TASK DIFFICULTY ON ERROR-RELATED ERPs USING SURFACE LAPLACIAN TRANSFORMATION¹²

Electrophysiologically, errors are characterized by a negative deflection, the error related negativity (ERN) and subsequently the error positivity (Pe). However, it has been suggested that this latter components consists of two subcomponents, with an early frontocentral Pe reflecting a continuation of the ERN and centro-parietal Pe reflecting error awareness. Using laplacian transformed averages, a correct-related negativity (CRN), similar to the ERN, can be found on correct trials. As this technique allows the unmixing of the recorded scalp potentials and better dissociates the underlying brain activities, we used Laplacian transformation to differentiate between both the ERN/CRN and both Pe components. Additionally, task difficulty was manipulated. Our results show a clearly distinguishable early and late Pe. Both the ERN/CRN and the early Pe varied with task difficulty, showing decreased ERN/early Pe in the difficult condition. However, the late Pe was not influenced by our difficulty manipulation. This suggests that the early and the late Pe reflect qualitatively different processes.

¹Manuscript submitted for publication

²This study was co-authored by Femke Houtman, Boris Burle, and Wim Notebaert.

INTRODUCTION

In order to behave adaptively to the requirements of the environment it is necessary to monitor signals that point out the need for adjustment. Although many signals indicate that performance is suboptimal and cognitive adjustments are required, the detection of an error is probably the most important signal. Electrophysiological investigations have demonstrated a negative brain potential at frontocentral electrode sites, peaking between 0 to 100 ms, after error commission (*error-related negativity*, ERN, Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991; Gehring, Goss, & Coles, 1993). The origin of the ERN has been linked to the posterior medial frontal cortex (for an overview see Ullsperger, Danielmeier, & Jocham, 2014). Using Laplacian transformation, which allows spatial deblurring of EEG (Babiloni, Cincotti, Carducci, Rossini, & Babiloni, 2001), previous research demonstrated that a similar negativity (of smaller amplitude though, often referred to as CRN), can be discerned on correct responses (Allain, Carbonnell, Falkenstein, Burle, & Vidal, 2004; Vidal, Hasbroucq, Grapperon, & Bonnet, 2000). This challenges the idea that the ERN is specific for errors but rather reflects a more general response evaluation (Bonini et al., 2014). In line with this idea, CRN amplitude increases with higher uncertainty (Pailing & Segalowitz, 2004). Although it has been argued that ERN and CRN might reflect different mechanisms (Coles, Scheffers, & Holroyd, 2001; Endrass, Klawohn, Gruetzmann, Ischebeck, & Kathmann, 2012), there is now strong evidences that they reflect the same modulated underlying processes (Bonini et al., 2014; Roger, Bénar, Vidal, Hasbroucq, & Burle, 2010).

Following the ERN a slow positive wave with maximum amplitude between 200 and 400 ms and a more diffuse scalp distribution is observed (*error positivity*, Pe, Falkenstein et al., 1991) and has been attributed to

error recognition or error awareness (Endrass, Reuter, & Kathmann, 2007; Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001; O'Connell et al., 2007; Shalgi, Barkan, & Deouell, 2009; Wessel, Danielmeier, & Ullsperger, 2011). Interestingly the Pe shares many characteristics with the P300, a positive stimulus-locked slow wave appearing between 200 and 400 ms after stimulus onset. The P300 has generally been associated with the processing of unexpected and motivationally significant events (for a review, see Nieuwenhuis, Aston-Jones, & Cohen, 2005) and has been subdivided into two subcomponents. The P3a occurs first with a frontocentral scalp distribution (Polich & Comerchero, 2003) and is mainly sensitive to the novelty of events. The P3b on the other hand is a later component with a parietal scalp distribution and is sensitive to the amount of attentional resources allocated to a stimulus (Polich & Comerchero, 2003; Polich, 2007). Similarly, there is support that the Pe is made up out of two subcomponents (Arbel & Donchin, 2009; Endrass, Klawohn, Preuss, & Kathmann, 2012; Endrass et al., 2007; Van Veen & Carter, 2002), where only the late Pe is seemingly related to error awareness (Endrass, Klawohn, Preuss, et al., 2012). The early frontocentral Pe seems to be generated by the same generators as the ERN (Debener et al., 2005; Van Veen & Carter, 2002) while the late posterior Pe is attributed to the parietal cortex and rostral ACC (Herrmann, Römmler, Ehlis, Heidrich, & Fallgatter, 2004; Van Veen & Carter, 2002; for an overview see Ullsperger et al., 2014).

Consistent with the idea that the ERN reflects an outcome evaluation, a relation with task difficulty, as indexed by increased perceptual difficulty, has been reported, showing decreased ERN magnitude when task difficulty increases (Endrass, Klawohn, Gruetzmann, et al., 2012; Hoffmann & Falkenstein, 2010; Pailing & Segalowitz, 2004). Also when comparing different tasks (i.e., Stroop, flanker and go/no-go task) a smaller amplitude for the ERN was found for the Stroop task, which was also associated with the highest error rate (Riesel, Weinberg, Endrass,

Meyer, & Hajcak, 2013). However, when task difficulty in conflict tasks is manipulated by increasing the number of stimuli, and their associated response, no influence on the ERN or CRN has been reported (Compton, Bissey, & Worby-Selim, 2014; Pailing & Segalowitz, 2004).

Limited research investigating the relationship between the early and late Pe and task difficulty suggests that the late Pe is sensitive to error saliency. Arbel and Donchin (2009) showed that only the posterior positive deflection was sensitive to the accuracy instruction, and was larger when accuracy was stressed compared to a neutral condition. Similarly, Endrass, Klawohn, Gruetzmann, and colleagues (2012), using spatio-temporal Principal Component Analysis, showed that a centroparietal component in the time range of the Pe varied significantly with perceptual difficulty while a frontocentral component in the same time range was not. Both studies also observed that the ERN was affected by task instruction/difficulty, with more pronounced ERN for the easier condition. That the ERN is affected and not the early Pe goes against the hypothesis that the early Pe is a continuation of the ERN (Wessel, 2012).

In the present study, we manipulated task difficulty by means of the complexity of the mapping rule and investigate its effect on the ERN/CRN, early Pe and late Pe. Because we manipulate task difficulty by increasing stimulus-response mappings, we do not expect to find a modulation of the ERN or CRN (Compton et al., 2014; Pailing & Segalowitz, 2004). Based on previous research and the idea that the early Pe is a continuation of the ERN, no modulation of this component is expected. Our difficulty modulation, however, should result in a difference in error saliency, which decreases with higher error rates and more difficult task requirements. We therefore expect to find a larger late Pe component in the easy condition. Based on the orienting account (Notebaert et al., 2009) this difference in error saliency should also be reflected in the amount of post-error slowing since infrequent or salient

events trigger a larger orienting response which interferes with subsequent processing.

An overview of the literature reveals that while some studies did report an early and late Pe (Endrass et al., 2007; Van Veen & Carter, 2002), this differentiation is not always observed (Hajcak, McDonald, & Simons, 2003; Nieuwenhuis et al., 2001; Shalgi et al., 2009; Wessel et al., 2011) unless additional techniques are used such as independent component analysis (Debener et al., 2005) or principal component analysis (Arbel & Donchin, 2009; Endrass, Klawohn, Gruetzmahn, et al., 2012; Endrass, Klawohn, Preuss, et al., 2012). As a matter of fact, volume conduction effect tend to distort brain activities, and when they are temporally and spatially close, volume conduction results in a temporal-spatial mixture at scalp level preventing their dissociation (Burle et al., 2015). The use of Laplacian transformation allows the unmixing of the recorded scalp potentials, and hence better dissociates the underlying brain activities, and provides more physiologically interpretable activities. Since early and late Pe have slightly different topographies and time course, we anticipate that Laplacian will allow to dissociate them.

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.

MATERIAL AND PROCEDURE

A classical flanker task was modified in order to create two conditions that varied in difficulty. 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. In the difficult condition there were 8 possible stimuli, namely {, }, [,], (,), | and †. Two pairs of brackets were arbitrarily mapped on the left or the right response button, resulting in a four to one mapping. Congruent trials always consisted of 5 identical brackets, while flanking stimuli on incongruent trials were always stimuli needing another response; i.e. response-incongruent. Congruent and incongruent trials were presented equally often and in random order.

The participants were seated in a comfortable armchair in a lightdimmed and sound-attenuated room. They were tested on a Pentium IV personal computer with a 17-inch monitor running Tscope (Stevens, 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 stimulus was presented centrally on a blank screen until a response button was pressed with a maximum of 145 ms. For the remainder of the response deadline, 800 ms, a blank screen was presented. 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.

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 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.

EEG ACQUISITION AND PREPROCESSING

EEG data were recorded using the BioSemi ActiveTwo system (Biosemi, Amsterdam, Netherlands). 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. EEG analyses were done in Matlab (www.mathworks.com) with the academic freeware toolboxes EEGLAB (<http://scn.ucsd.edu/eeglab>) and ERPLAB (<http://erpinfo.org/erplab>).

The data was offline resampled 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 400 ms before until 1000 ms after the response. The epochs were baseline-corrected using the 400 till 200 ms pre-response window. Additional EMG activity per epoch was removed with blind source separation (BSS) using the AAR toolbox (http://www.germangh.com/eeglab_plugin_aar). The use of Laplacian transformation is very sensitive to local artifacts, therefore epochs were manually inspected and rejected if necessary. On average 11% of the data was rejected ($SD = 5.5$). Next, EEG epochs were averaged across

participants according to the different conditions and for error and correct responses separately. Next the monopolar averages were then transformed using the CSD toolbox for Laplacian transformation (Kayser & Tenke, 2006, <http://psychophysiology.cpmc.columbia.edu/software/CSDtoolbox>), thereby enhancing the spatial resolution and intensity of ERP components. Current source densities (CSDs) were calculated according to the spherical spline algorithm of Perrin, Pernier, Bertrand, and Echallier (1989), using a default smoothing constant of 1.0^{-5} and a head radius of 10 cm. Note that transformation via CSDs results in reference-free ERP data.

RESULTS

BEHAVIOURAL DATA

Both error rates and correct reaction times were analyzed with repeated measures ANOVAs. The within-subject factors were condition and previous accuracy.

For accuracy there was a significant difference between conditions, $F(1,15) = 26.34$, $p < 0.001$, showing that participants made more errors in the hard condition (29%) than in the easy condition (20%). There was no significant effect of previous accuracy, i.e. no post-error accuracy increase or decrease, $F(1,15) = 0.72$, $p = 0.41$, or interaction between previous accuracy and condition, $F(1,15) = 0.00$, $p = 0.996$.

For correct reaction times there was again a significant difference between conditions, $F(1,15) = 39.09$, $p < 0.001$, showing faster responses in the easy condition (462 ms) than in the hard condition (508 ms). There was a significant effect of previous accuracy, $F(1,15) = 10.14$, $p < 0.01$, showing post-error slowing (13 ms). However the interaction of previous

accuracy and condition was not significant, $F(1,15) = 0.31$, $p = 0.59$, indicating that our difficulty manipulation did not influence PES.

ERPS

ERN/CRN

The ERN and CRN were measured at electrode FCz as the mean amplitude in a time window between 0 and 100 ms after response execution using the pre-response window from 400 till 200 ms as a baseline. A 2 (condition: easy, difficult) by 2 (accuracy: correct, error) repeated measures ANOVA showed no significant main effect for condition, $F(1,15) = 0.16$, $p = 0.70$. There was a main effect of accuracy, $F(1,15) = 30.09$, $p < 0.001$. The mean amplitude of the ERN was more negative ($-0.17 \mu\text{V}/\text{cm}^2$) than the mean amplitude of the CRN ($-0.04 \mu\text{V}/\text{cm}^2$). The interaction between the condition and the accuracy of the response was also significant, $F(1,15) = 9.27$, $p < 0.01$. The difference between the ERN and the CRN was larger in the easy condition ($0.17 \mu\text{V}/\text{cm}^2$, error: $-0.20 \mu\text{V}/\text{cm}^2$ vs. correct: $-0.03 \mu\text{V}/\text{cm}^2$) than in the difficult condition ($0.10 \mu\text{V}/\text{cm}^2$, error: $-0.15 \mu\text{V}/\text{cm}^2$ vs. correct: $-0.05 \mu\text{V}/\text{cm}^2$), as can be seen on Figure 1. This smaller difference in the hard condition seems to be influenced by both a decrease in ERN and an increase in CRN amplitude; however both the CRN and ERN did not differ significantly over conditions, both $ps \geq 0.15$.

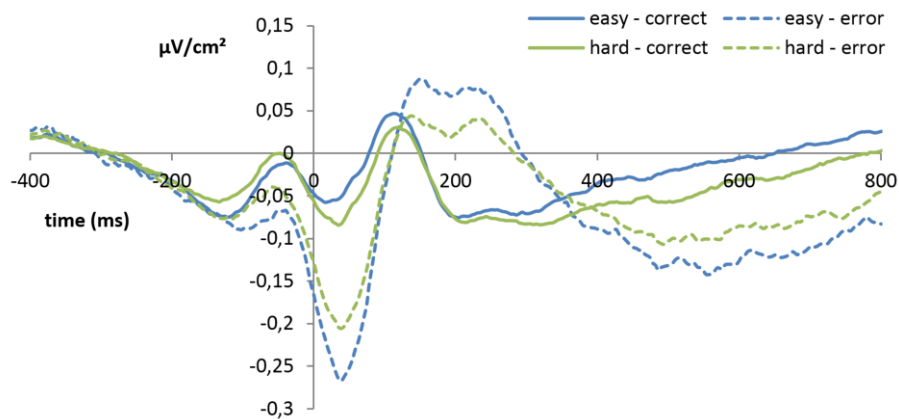


Figure 1. Laplacian transformed grand average ERP waveforms of the ERN/CRN measured at FCz, between 0 and 100 ms, as a function of accuracy and difficulty condition.

Pe

Inspection of the waveforms across electrodes allowed to identify two components: an early one peaking around 150 ms at Cz, and a later broader component peaking around 450 ms at POz, as reported in the literature (Endrass et al., 2007; Van Veen & Carter, 2002) (see figure 2). Similar to the occurrence of a CRN on correct trials, there was also an early and late correct-related positivity similar to the Pe. We therefore analyzed any interactions with previous accuracy separately. For the early Pe/Pc, mean amplitude was extracted from the averaged waveforms for correct and error trials in both conditions in a window from 100 to 200 ms following response at Cz. The late Pe/Pc was measured from 300 to 600 ms following response at POz.

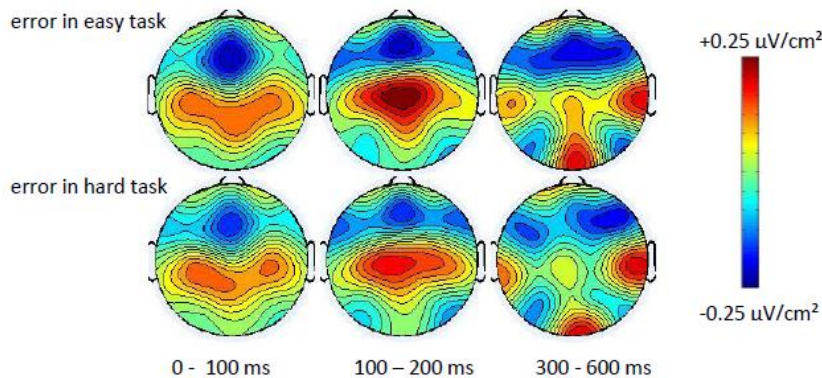


Figure 2. Scalp topographies of errors in both difficulty conditions for different time windows (ERN: 0-100ms, early Pe: 100-200 ms, late Pe: 300-600 ms).

For the early Pe/Pc, there was a significant main effect of condition, $F(1, 15) = 6.12, p < .05$, showing overall higher activation in the easy condition ($0.26 \mu\text{V}/\text{cm}^2$) than in the difficult condition ($0.21 \mu\text{V}/\text{cm}^2$). There was a significant effect of accuracy, $F(1, 15) = 7.75, p < 0.02$, with the mean amplitude after an error more positive ($0.27 \mu\text{V}/\text{cm}^2$) than after a correct response ($0.20 \mu\text{V}/\text{cm}^2$). Most importantly, there was a significant interaction of condition and accuracy, $F(1, 15) = 12.32, p < .01$. As can be seen on Figure 3, the difference in early Pe/Pc was larger in the easy condition ($0.10 \mu\text{V}/\text{cm}^2$, error: $0.31 \mu\text{V}/\text{cm}^2$ vs. correct: $0.21 \mu\text{V}/\text{cm}^2$) than in the difficult condition ($0.04 \mu\text{V}/\text{cm}^2$, error: $0.23 \mu\text{V}/\text{cm}^2$ vs. correct: $0.19 \mu\text{V}/\text{cm}^2$). Interestingly, there was no difference between conditions in amplitude for the correct-related positivity, $F(1, 15) = 0.43, p = 0.52$. The difference in Pe between conditions however was significant, $F(1, 15) = 13.98, p < 0.01$.

For the late Pe/Pc, there was a marginally significant effect of condition, $F(1, 15) = 4.14, p = 0.06$, again showing overall higher activation in the easy condition ($0.19 \mu\text{V}/\text{cm}^2$) than in the difficult condition ($0.13 \mu\text{V}/\text{cm}^2$). There was a significant effect of accuracy, $F(1, 15) = 7.12, p < 0.02$, showing a more positive mean amplitude after an error (0.19

$\mu\text{V}/\text{cm}^2$) than after a correct response ($0.13 \mu\text{V}/\text{cm}^2$). Most importantly, there was no significant interaction of condition and accuracy, $F(1, 15) = 1.31, p = 0.27$ (Fig. 3).

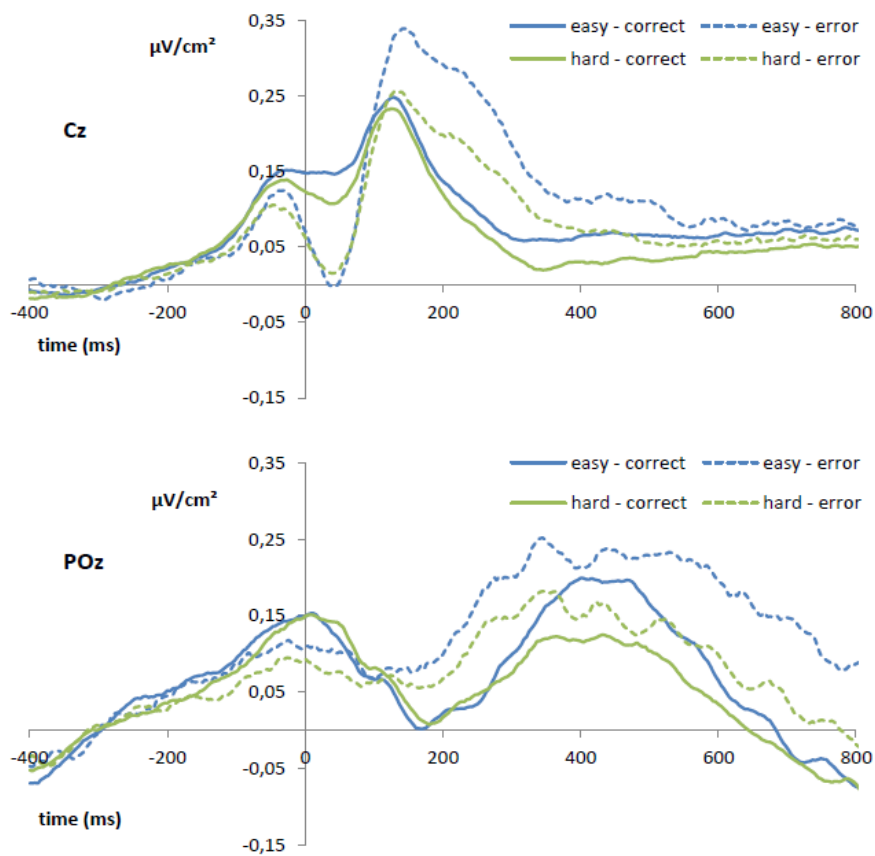


Figure 3. Laplacian transformed grand average ERP waveforms of the early Pe measured Cz (top figure), between 100 and 200 ms, and the late Pe measured at POz (bottom figure), between 300 and 600 ms, as a function of accuracy and difficulty condition.

CORRELATIONS

In the easy condition there was a significant correlation between error rates and amount of PES, $r(16) = -0.52$, $p = 0.04$, indicating that participants with more errors showed less PES. This correlation was also observed in the hard condition, $r(16) = -0.65$, $p < 0.001$. The difference in error rates between conditions (hard – easy) did not correlate with the difference in PES or post-error accuracy, both $ps \geq 0.12$.

Brain-behaviour correlations revealed that in the easy condition, there was a marginally significant correlation between error rates and the early Pe difference (Pe-Pc), $r(16) = -0.48$, $p = 0.06$, showing that higher error rates were related to a smaller early Pe/Pc difference. In the hard condition, there was a significant correlation between error rates and the difference in ERN/CRN, $r(16) = 0.52$, $p = 0.04$, showing that higher error rates were related to a smaller difference in ERN/CRN. Additionally in this condition, the difference in late Pe (Pe-Pc) correlated marginally significantly with error rates, $r(16) = -0.49$, $p = 0.06$ and PES, $r(16) = 0.48$, $p = 0.06$, indicating that participants with a larger difference in late Pe/Pc also made less errors and showed more PES. No other correlations were significant, all $ps \geq 0.10$. Comparing the difference in conditions (hard – easy) for both error-related components and behavioural measures, there were no significant correlations, all $ps \geq 0.09$.

DISCUSSION

In this ERP-study, task difficulty was manipulated in order to investigate neural correlates of error processing and Laplacian transformation was used to distinguish between an early frontocentral and a late parietal Pe. The difficulty manipulation was established by creating an easy condition with a 2:1 stimulus response mapping and a difficult condition with a 4:1 stimulus response mapping. As expected, the hard condition revealed more errors and longer reaction times compared to the easy condition.

Importantly, the Laplacian transformation clearly distinguished between the early from the late Pe. In line with the literature the early Pe is a more central component, peaking around 150 ms while the late Pe is apparent at parietal electrode sites from 300 to 600 ms (Endrass et al., 2007; Van Veen & Carter, 2002).

Unexpectedly, post-error slowing did not differ between conditions, even though there is a significant difference in error frequency between both conditions (20% in the easy condition vs. 29% in the difficult condition). Based on the orienting account (Notebaert et al., 2009), error frequency determines PES since the infrequent or salient characteristic of the error triggers an orienting response, which in turn interferes with subsequent processing, leading to worse performance following an error. Therefore, one would expect that overall PES is smaller in the difficult condition than in the easy condition. However, it is possible that the difference of 9% errors between both conditions was not sufficiently large to impact PES on a group level since in previous studies where error frequency was manipulated (Houtman, Núñez Castellar, & Notebaert, 2012; Notebaert et al., 2009; Núñez Castellar, Kühn, Fias, & Notebaert, 2010), the difference in error frequency was substantially larger ($\geq 20\%$). Indeed when looking at correlations between accuracy and PES in both conditions, participants with fewer errors showed more PES.

Because task difficulty was manipulated by using different response mappings, no influence on the ERN or CRN was expected (Compton et al., 2014; Pailing & Segalowitz, 2004). However, it has been suggested that not task difficulty in itself, but the amount of perceptual difficulty attenuates the ERN (Scheffers & Coles, 2000). Therefore the use of highly similar brackets in the difficult condition could have lead to a higher perceptual difficulty in addition to a more difficult stimulus-response mapping. This higher perceptual difficulty might have increased

participant's uncertainty about the outcome, thereby increasing CRN amplitude and decreasing ERN amplitude (Pailing & Segalowitz, 2004).

Similar to the occurrence of the CRN, an early and late positive deflection can be found on correct trials. Given that the early Pe is hypothesized to be a continuation of the ERN (Wessel, 2012), or rather processes underlying the ERN, it is possible that this component also, at least partly, reflect a response evaluation, independent of outcome. Interestingly, the ERN/CRN difference and the early Pe, were more pronounced in the easy condition than in the difficult condition. That both the ERN and the early Pe are similarly enhanced when error rates are low is again in line with the idea that the early Pe is a continuation of the ERN (Wessel, 2012). However, that both difference scores did not correlate significantly and that the early Pe but not the ERN significantly differs between conditions seem to indicate that both components are not completely related.

Moreover, the difficulty manipulation did not influence the late Pe. This finding is at odds with earlier reports that the late Pe was affected by perceptual difficulty (Endrass, Klawohn, Gruetzmann, et al., 2012) or accuracy instructions (Arbel & Donchin, 2009). The manipulations used in these tasks (i.e., accuracy ratings or instructions), however, could have increased participant's overall error awareness, boosting differences in the late Pe. Indeed a larger Pe can be found when a rating procedure is used (Grützmann, Endrass, Klawohn, & Kathmann, 2013). In these experiments error rate difference between conditions was also much larger, i.e. double the amount of errors or a difference of 16%, again suggesting that the difference in error rated induced by our manipulation was not sufficiently large to influence late Pe amplitude. Additionally, there is evidence that the classical Pe is related to PES. In a study where unperceived errors were not followed by PES also no Pe was found (Nieuwenhuis et al., 2001) while Hajcak and colleagues (2003) showed a significant positive correlation between PES and Pe-amplitude.

Interestingly, a significant correlation was found between Pe/Pc difference and PES, but only in the hard interval condition. Based on the differences with previous research and in line with a presumed relationship with PES (Hajcak et al., 2003; Nieuwenhuis et al., 2001; Núñez Castellar et al., 2010), it is not surprising that late Pe was not influenced by our difficulty manipulation. Interestingly that a, small, late positivity is also present on correct trials, adds to the idea that this component reflects a P3b-like component, which is related to memory-updating (Polich, 2007).

Our difficulty manipulation did result in a difference in error rates. The differences between conditions can therefore be attributed to a probability effect. However dividing our participants in two groups; one with a large difference in error rates (i.e. $\geq 7\%$) and one with a small difference in error rate, the same pattern of results is found with no difference between groups (all $ps \geq 0.17$). Additionally the difference in error rates between conditions did not correlate significantly with the differences in any of the ERP measures. These results suggest that the presented modulations of ERP components are not strictly the result of a probability effect. Furthermore the main result of our study is that there is a differential sensitivity for the early Pe and late Pe, while the confound of a probability effect related to differences in error rates between conditions should have influenced all ERP components.

Taken together, using Laplacian transformation, an early and late Pe could be distinguished. Both the early Pe and the ERN/CRN were modulated by the difficulty manipulation, adding to evidence that the early Pe shares a common generator with the ERN (Debener et al., 2005; Van Veen & Carter, 2002). The late Pe however was not influenced by our difficulty manipulation.

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REFERENCES

- Allain, S., Carbonnell, L., Falkenstein, M., Burle, B., & Vidal, F. (2004). The modulation of the Ne-like wave on correct responses foreshadows errors. *Neuroscience Letters*, *372*(1-2), 161–6. doi:10.1016/j.neulet.2004.09.036
- Arbel, Y., & Donchin, E. (2009). Parsing the componential structure of post-error ERPs: a principal component analysis of ERPs following errors. *Psychophysiology*, *46*(6), 1179–1189. doi:10.1111/j.1469-8986.2009.00857.x
- Babiloni, F., Cincotti, F., Carducci, F., Rossini, P. M., & Babiloni, C. (2001). Spatial enhancement of EEG data by surface Laplacian estimation: the use of magnetic resonance imaging-based head models. *Clinical Neurophysiology*, *112*(5), 724–727. doi:10.1016/S1388-2457(01)00494-1
- Bonini, F., Burle, B., Liégeois-Chauvel, C., Régis, J., Chauvel, P., & Vidal, F. (2014). Action monitoring and medial frontal cortex: leading role of supplementary motor area. *Science (New York, N.Y.)*, *343*(6173), 888–91. doi:10.1126/science.1247412
- Burle, B., Spieser, L., Roger, C., Casini, L., Hasbroucq, T., & Vidal, F. (2015). Spatial and temporal resolutions of EEG: Is it really black and white? A scalp current density view. *International Journal of Psychophysiology: Official Journal of the International Organization of Psychophysiology*. doi:10.1016/j.ijpsycho.2015.05.004
- Coles, M. G., Scheffers, M. K., & Holroyd, C. B. (2001). Why is there an ERN/Ne on correct trials? Response representations, stimulus-related components, and the theory of error-processing. *Biological Psychology*, *56*(3), 173–89. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/11399349>
- Compton, R. J., Bissey, B., & Worby-Selim, S. (2014). Task motivation influences alpha suppression following errors. *Psychophysiology*. doi:10.1111/psyp.12212
- Debener, S., Ullsperger, M., Siegel, M., Fiehler, K., von Cramon, D. Y., & Engel, A. K. (2005). Trial-by-trial coupling of concurrent electroencephalogram and functional magnetic resonance imaging identifies the dynamics of performance monitoring. *The Journal of Neuroscience*, *25*(50), 11730–11737. doi:10.1523/JNEUROSCI.3286-05.2005
- Endrass, T., Klawohn, J., Gruetzmann, R., Ischebeck, M., & Kathmann, N. (2012). Response-related negativities following correct and incorrect responses: evidence from a temporospatial principal component analysis. *Psychophysiology*, *49*(6), 733–743. doi:10.1111/j.1469-8986.2012.01365.x
- Endrass, T., Klawohn, J., Preuss, J., & Kathmann, N. (2012). Temporospatial dissociation of Pe subcomponents for perceived and unperceived errors. *Frontiers in Human Neuroscience*, *6*, 178. doi:10.3389/fnhum.2012.00178

- Endrass, T., Reuter, B., & Kathmann, N. (2007). ERP correlates of conscious error recognition: aware and unaware errors in an antisaccade task. *The European Journal of Neuroscience*, *26*(6), 1714–20. doi:10.1111/j.1460-9568.2007.05785.x
- Falkenstein, M., Hohnsbein, J., Hoormann, J., & Blanke, L. (1991). Effects of crossmodal divided attention on late ERP components. II. Error processing in choice reaction tasks. *Electroencephalography and Clinical Neurophysiology*, *78*, 447–455. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/1712280>
- Gehring, W., Goss, B., & Coles, M. (1993). A neural system for error detection and compensation. *Psychological Science*, *4*(6), 385–390. Retrieved from <http://pss.sagepub.com/content/4/6/385.short>
- Grützmann, R., Endrass, T., Klawohn, J., & Kathmann, N. (2013). Response accuracy rating modulates ERN and Pe amplitudes. *Biological Psychology*, *96C*, 1–7. doi:10.1016/j.biopsycho.2013.10.007
- Hajcak, G., McDonald, N., & Simons, R. F. (2003). To err is autonomic: Error-related brain potentials, ANS activity, and post-error compensatory behavior. *Psychophysiology*, *40*(6), 895–903. doi:10.1111/1469-8986.00107
- Herrmann, M. J., Römmler, J., Ehlis, A.-C., Heidrich, A., & Fallgatter, A. J. (2004). Source localization (LORETA) of the error-related-negativity (ERN/Ne) and positivity (Pe). *Cognitive Brain Research*, *20*(2), 294–299. doi:10.1016/j.cogbrainres.2004.02.013
- Hoffmann, S., & Falkenstein, M. (2010). Independent component analysis of erroneous and correct responses suggests online response control. *Human Brain Mapping*, *31*(9), 1305–1315. doi:10.1002/hbm.20937
- Houtman, F., Núñez Castellar, E., & Notebaert, W. (2012). Orienting to errors with and without immediate feedback. *Journal of Cognitive Psychology*, *24*(3), 278–285. doi:10.1080/20445911.2011.617301
- Kayser, J., & Tenke, C. E. (2006). Principal components analysis of Laplacian waveforms as a generic method for identifying ERP generator patterns: I. Evaluation with auditory oddball tasks. *Clinical Neurophysiology*, *117*(2), 348–368. doi:10.1016/j.clinph.2005.08.034
- Nieuwenhuis, S., Aston-Jones, G., & Cohen, J. D. (2005). Decision making, the P3, and the locus coeruleus-norepinephrine system. *Psychological Bulletin*, *131*(4), 510–32. doi:10.1037/0033-2909.131.4.510
- Nieuwenhuis, S., Ridderinkhof, K. R., Blom, J., Band, G. P., & Kok, a. (2001). Error-related brain potentials are differentially related to awareness of response errors: evidence from an antisaccade task. *Psychophysiology*, *38*(5), 752–60. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/11577898>
- Notebaert, W., Houtman, F., Opstal, F. Van, Gevers, W., Fias, W., & Verguts, T. (2009). Post-error slowing: an orienting account. *Cognition*, *111*, 275–279. doi:10.1016/j.cognition.2009.02.002

- Núñez Castellar, E., Kühn, S., Fias, W., & Notebaert, W. (2010). Outcome expectancy and not accuracy determines posterror slowing: ERP support. *Cognitive, Affective, & Behavioral Neuroscience, 10*(2), 270–278. doi:10.3758/CABN.10.2.270
- O’Connell, R. G., Dockree, P. M., Bellgrove, M. a, Kelly, S. P., Hester, R., Garavan, H., ... Foxe, J. J. (2007). The role of cingulate cortex in the detection of errors with and without awareness: a high-density electrical mapping study. *The European Journal of Neuroscience, 25*(8), 2571–2579. doi:10.1111/j.1460-9568.2007.05477.x
- Pailing, P. E., & Segalowitz, S. J. (2004). The effects of uncertainty in error monitoring on associated ERPs. *Brain and Cognition, 56*(2), 215–233. doi:10.1016/j.bandc.2004.06.005
- Perrin, F., Pernier, J., Bertrand, O., & Echallier, J. F. (1989). Spherical splines for scalp potential and current density mapping. *Electroencephalography and Clinical Neurophysiology, 72*(2), 184–187. doi:10.1016/0013-4694(89)90180-6
- Polich, J. (2007). Updating P300: an integrative theory of P3a and P3b. *Clinical Neurophysiology, 118*(10), 2128–2148. doi:10.1016/j.clinph.2007.04.019
- Polich, J., & Comerchero, M. D. (2003). P3a from visual stimuli: typicality, task, and topography. *Brain Topography, 15*(3), 141–52. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/12705810>
- Riesel, A., Weinberg, A., Endrass, T., Meyer, A., & Hajcak, G. (2013). The ERN is the ERN is the ERN? Convergent validity of error-related brain activity across different tasks. *Biological Psychology, 93*(3), 377–85. doi:10.1016/j.biopsycho.2013.04.007
- Roger, C., Bénar, C. G., Vidal, F., Hasbroucq, T., & Burle, B. (2010). Rostral Cingulate Zone and correct response monitoring: ICA and source localization evidences for the unicity of correct- and error-negativities. *NeuroImage, 51*(1), 391–403. doi:10.1016/j.neuroimage.2010.02.005
- Scheffers, M. K., & Coles, M. G. H. (2000). Performance monitoring in a confusing world: Error-related brain activity, judgments of response accuracy, and types of errors. *Journal of Experimental Psychology: Human Perception and Performance, 26*(1), 141–151. doi:10.1037//0096-1523.26.1.141
- Shalgi, S., Barkan, I., & Deouell, L. Y. (2009). On the positive side of error processing: error-awareness positivity revisited. *The European Journal of Neuroscience, 29*(7), 1522–32. doi:10.1111/j.1460-9568.2009.06690.x
- Stevens, M., Lammertyn, J., Verbruggen, F., & Vandierendonck, A. (2006). Tscope: A C library for programming cognitive experiments on the MS windows platform. *Behavior Research Methods, 38*(2), 280–286.

- Ullsperger, M., Danielmeier, C., & Jocham, G. (2014). Neurophysiology of performance monitoring and adaptive behavior. *Physiological Reviews*, *94*(1), 35–79. doi:10.1152/physrev.00041.2012
- Van Veen, V., & Carter, C. S. (2002). The timing of action-monitoring processes in the anterior cingulate cortex. *Journal of Cognitive Neuroscience*, *14*(4), 593–602. doi:10.1162/08989290260045837
- Vidal, F., Hasbroucq, T., Grapperon, J., & Bonnet, M. (2000). Is the “error negativity” specific to errors? *Biological Psychology*, *51*(2-3), 109–128. doi:10.1016/S0301-0511(99)00032-0
- Wessel, J. R. (2012). Error awareness and the error-related negativity: evaluating the first decade of evidence. *Frontiers in Human Neuroscience*, *6*, 88. doi:10.3389/fnhum.2012.00088
- Wessel, J. R., Danielmeier, C., & Ullsperger, M. (2011). Error awareness revisited: accumulation of multimodal evidence from central and autonomic nervous systems. *Journal of Cognitive Neuroscience*, *23*(10), 3021–3036. doi:10.1162/jocn.2011.21635

CHAPTER 6

ERRORS DISRUPT SUBSEQUENT EARLY ATTENTIONAL PROCESSES¹²

Recently, Houtman and Notebaert (2013) demonstrated that participants show impaired target detection following an error in an unrelated flanker task. These findings support the idea that the occurrence or processing of unexpected error-like events interfere with subsequent information processing (Notebaert et al., 2009; Jentsch & Dudschig, 2009). In the present study, we investigated the effect of errors on early visual ERP components. For this purpose we combined a flanker and a visual discrimination task. Additionally, the intertrial interval between both tasks was manipulated to investigate the duration of these negative after-effects. The results of the visual discrimination task indicated that the amplitude of the late N1 component, which is related to endogenous attention, was significantly decreased following an error than following a correct response, irrespective of the intertrial interval. Additionally, P3 amplitude was attenuated after an erroneous trial, but only in the long-interval condition. These results are in line with the idea that an error is a surprising event, and provides evidence for the idea that low-level attentional processing following an error is impaired.

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² This study was co-authored by Hanne Schevernels, Boris Burle, and Wim Notebaert.

INTRODUCTION

Inherently linked to human behaviour is that humans make errors. Errors signal the need for adaptation, illustrating the need for a well-developed error monitoring system. For several decades, post-error adaptation has been investigated using behavioural measures with the most robust finding being a slowing in reaction time following an error (Rabbitt, 1979). Interestingly, this post-error slowing (PES) is reliable within participants when re-tested, suggesting that PES reflects a personal response to the error (Danielmeier & Ullsperger, 2011; Segalowitz et al., 2010).

PES has been hypothesized to reflect a strategic adaptation in order to reduce the probability of making more errors (Botvinick, Braver, Barch, Carter, & Cohen, 2001). Yet, although decreased error rates following errors have been observed (Danielmeier, Eichele, Forstmann, Tittgemeyer, & Ullsperger, 2011; Jentsch & Dudschig, 2009; Maier, Yeung, & Steinhauser, 2011), many other studies have found increased error rates following errors (Bombeke, Schoupe, Duthoo, & Notebaert, 2013; Carp & Compton, 2009; Houtman, Núñez Castellar, & Notebaert, 2012). Therefore, non-functional accounts were postulated which explain PES as a nonspecific result of attention orienting or error processing itself (Jentsch & Dudschig, 2009; Notebaert et al., 2009). One of these theories is the orienting account (Notebaert et al., 2009). This account states that errors are infrequent and motivationally salient events which trigger an orienting response. This orienting response interferes with subsequent processing leading to PES and, if the inter-trial interval is short, to a post-error accuracy *decrease*. In line with this idea, Notebaert et al. (2009) demonstrated that PES is found when errors are infrequent but *post-correct* slowing when correct responses are infrequent. Similarly, accuracy differences between blocks or participants are

reflected in smaller PES when less errors are made (Houtman et al., 2012; Steinborn, Flehmig, Bratzke, & Schröter, 2012). A second nonfunctional theory is the bottleneck account (Jentsch & Dudschig, 2009). This theory posits that error-monitoring requires time and resources from a capacity-limited cognitive system and therefore interferes with the task at hand. Because of this central bottleneck, responses are slower and more error-prone immediately following an error.

Investigating post-error accuracy as a behavioural measure of post-error adaptation also has a more practical problem. Since experiments are usually designed to increase error rates, they lead to streaks of errors (Danielmeier & Ullsperger, 2011; Notebaert et al., 2009). To investigate post-error performance without relying on double-errors, Houtman and Notebaert (2013) used a speeded flanker task, to elicit a large amount of errors, and followed this task with a rapid serial visual presentation (RSVP) task in which participants had to indicate whether they saw a letter, and if so which one, embedded in a visual series of numbers. Houtman and Notebaert (2009) showed decreased target detection following infrequent errors with and without error feedback. This design was based on an attentional blink (AB) paradigm in which two targets are presented in rapid succession in a stream of non-target stimuli. Typically, results indicate that it is harder to identify the second target (T2) when it is presented within 200 to 500 ms after the first target (T1). The error-induced impaired detection resembles an emotional AB in which reduced target detection follows the onset of an emotional stimulus. Just as the error-induced AB, the emotional-induced AB does not show lag 1 sparing (McHugo, Olatunji, & Zald, 2013), in contrast to the classical AB where a neutral T1 and T2 are used, target detection is not impaired when T2 follows T1 within 100 ms of the first target (Potter, Staub, & O'Connor, 2002). The error-induced AB might therefore rely on similar mechanisms as the emotional AB. This emotional AB is believed to illustrate the ability of highly salient items to capture attention and reflects competition for resources during perceptual processing (Most & Wang, 2011; Wang,

Kennedy, & Most, 2012). Furthermore, recent research indicates that arousal rather than valence is critical in generating this attentional capture (for a review see, McHugo, Olatunji, & Zald, 2013).

Based on the finding of an error-induced AB, possibly explained by reduced perceptual resources, we further investigated early visual processing following an error with EEG. In a typical AB task, previous studies have found that early visual components related to attention (N1, P1) do not differ for detected and undetected T2-targets while the P3 amplitude has been shown to be reduced for undetected T2 targets (Sergent, Baillet, & Dehaene, 2005; Vogel et al., 1998). The P3 is typically related to the updating of working memory (Polich, 2007). Because of the finding of an error-induced AB, we would similarly expect an attenuated P3 following an error. However, to verify whether perceptual processing following an error is impaired, as indicated by the absence of a lag-1, we will additionally investigate how an error affects subsequent early visual components, such as the P1 and N1.

In the current study, we implemented a dual task in which a speeded flanker task was followed by a visual discrimination task. In order to investigate the effect of errors on visual processing, we used a very basic visual discrimination task in which participants had to indicate whether they saw a triangle or a diamond shape. This task required only a limited amount of effort while participants still had to discriminate between stimuli and respond accordingly. Since P3 amplitude is largely influenced by stimulus frequency with larger amplitudes for infrequent stimuli (Gonsalvez & Polich, 2002), the two targets were presented with a different frequency with one of these figures appearing frequently, i.e. 80% of the trials, while the other figure was presented in only 20% of the trials. Additionally, participants were divided in two conditions. These conditions differed only in the amount of time between the two tasks. In line with the orienting account, we hypothesized that the early visual

components (P1, N1) as well as the P3 would be attenuated following an error. These effects should be more pronounced in the short-interval condition than in the long-interval condition. Additionally, error-related components, such as the error-related negativity (ERN) and subsequent the early and late positive deflections (Pe), related to the flanker task were investigated.

METHOD

PARTICIPANTS

Thirty healthy right-handed participants with normal vision or corrected-to-normal vision participated in the experiment (three male; mean age 20 years, range 18-23 years). All participants were neurologically and psychiatrically healthy and each gave written informed consent. The study was approved by the ethical committee of the Faculty of Psychology and Educational Sciences of Ghent University. Participants were compensated at 15€ per hour.

STIMULI AND PROCEDURE

A flanker task and a visual discrimination task were combined to investigate early visual ERP components. Stimuli of the flanker task consisted of four possible letters: H, S, X, Z. In the flanker task participants had to respond by pressing a button with the index or middle finger of the right hand according to the identity of the central letter. Two letters were (randomly) mapped on each button resulting in six possible response mappings which were counterbalanced over the participants. In the visual discrimination task, a response had to be given with the index or middle finger of the left hand. Two possible figures were used, a diamond or a triangle, which were presented with either 80% or 20% frequency. Which figure was presented infrequently, i.e. in 20% of the trials, was counterbalanced over participants. There were two possible

response mappings for the frequency task, which was also counterbalanced over participants.

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 (Stevens, Lammertyn, Verbruggen, & Vandierendonck, 2006). Participants gave a manual response with the left and right index fingers of both hands using a Cedrus response box. Stimuli were presented centrally in white on a black background. A trial started with the presentation of the stimuli of the flanker task for 100 ms. Next, a mask was presented (#####) for 150 ms followed by a blank screen until a response was given or the response deadline was exceeded (750 ms from stimulus onset). Subsequently, a blank screen was presented for 500 ms for one group of participants (i.e. short interval) or 1000 ms for the other group of participants (i.e. long interval). Accordingly, the visual discrimination task started with the presentation of a figure (diamond or triangle) during 500 ms followed by a blank screen with a duration of 500 ms. When a response was given within the response deadline of 1000 ms the stimuli disappeared and a blank screen was presented for the remaining time. At the end of each trial, a fixation stimulus was displayed (+) for a randomly selected time interval of 200 to 500 ms.

Participants were asked to refrain from blinking during trials. The response mapping for both tasks was explained followed by a practice block for both tasks separately. Each practice session included 140 trials and feedback informed participants about their performance. Subsequently, the experiment consisting of 16 runs of 70 trials, was performed. During each break response mappings were repeated and overall performance during the last block was shown (i.e. accuracy levels and the percentage of too slow responses in both tasks). When

participants gave more than 10 % too slow responses, an additional message was shown to encourage participants to respond faster.

EEG ACQUISITION AND PREPROCESSING

We recorded EEG activity with a Biosemi ActiveTwo measurement system (BioSemi, Amsterdam, Netherlands) with scalp electrodes (64 Ag-AgCl attached in an elastic cap) arranged according to the standard international 10-20 system. Additionally, five external electrodes were attached to the head: left and right mastoid, which were used for later offline re-referencing, beneath the right eye and a bilateral electro-oculogram (EOG) electrode pair next to the outer canthi of the eyes referenced to each other to measure horizontal eye movements. Signals were amplified and digitized with a sampling rate of 512 Hz. EEG data was processed using EEGLAB and the ERPLAB plugin (<http://erpinfo.org/erplab>), running on MATLAB. Data of one electrode (TP7) was removed for all participants since this electrode malfunctioned in more than half of the participants. Independent component analysis (ICA) was conducted to identify and remove stereotypical eye blink components. Firstly, to investigate error-related components, epochs were created locked to the response on the flanker task, starting from 400 ms before response onset until 1600 ms after response onset. The epochs were baseline-corrected using the 400 to 200 ms pre-stimulus window. Secondly, to explore visual components in the visual discrimination task, epochs were created time-locked to the onset of the stimulus of the frequency task, including a 200 ms pre-stimulus period that was used for baseline correction and a 800 ms post-stimulus interval. Hence, the total time window of these epoched ERPs was 1000 ms. Additional EMG activity per epoch was removed with blind source separation (BSS) using the [AAR](http://www.germangh.com/eeglab_plugin_aar/index.html) toolbox (http://www.germangh.com/eeglab_plugin_aar/index.html). As in a previous study, we used Laplacian transformation, which allows spatial deblurring of EEG (Babiloni, Cincotti, Carducci, Rossini, & Babiloni,

2001), to dissociate the early from the late Pe-component (Van der Borgh, Houtman, Burle, & Notebaert, 2015). Given that the use of Laplacian transformation enhances local artifacts, epochs were manually inspected and rejected if necessary. On average respectively 10 and 8 % of the epochs were excluded. EEG epochs were averaged across participants according to the different conditions. The monopolar averages were then transformed using the CSD toolbox for Laplacian transformation (Kayser & Tenke, 2006, <http://psychophysiology.cpmc.columbia.edu/software/CSDtoolbox>), thereby enhancing the spatial resolution and intensity of ERP components. Current source densities (CSDs) were calculated according to the spherical spline algorithm of Perrin, Pernier, Bertrand, and Echallier (1989), using a default smoothing constant of 1.0^{-5} and a head radius of 10 cm. Note that transformation via CSDs results in reference-free ERP data

EEG ANALYSES

Mean amplitudes were derived over a number of electrodes within a certain time-window as defined by previous literature and inspected on ERP waveforms and topographic maps collapsed across conditions. For error-related components, the ERN and CRN were measured at electrode FCz in a time window between 0 and 100 ms after response execution in the flanker task. As reported in the literature, the Pe consisted of two subcomponents (Endrass, Reuter, & Kathmann, 2007; Van der Borgh, Houtman, Burle, & Notebaert, 2015.; Van Veen & Carter, 2002); one early component maximal between 80 and 180 ms at Cz, and a later broader component measured between 300 and 500 ms at POz.

In the visual discrimination task we analyzed the stimulus-locked P1 component which was quantified at posterior electrodes PO7 and PO8 between 80 and 130 ms. This component was followed by a negative

wave (N1) over the same electrodes from 130 to 180 ms. Additionally, an earlier negative wave (N1_e), was quantified at Oz, between 90 and 140 ms. Furthermore, P3 was quantified at Pz between 400 and 600 ms.

Amplitudes for error-related components were examined using a repeated-measures analysis of variance (rANOVA) with the between-subjects factor interval condition (short or long) and the within-subjects factor previous accuracy (correct, error). In relation to stimulus-locked components, the between-subjects factor interval condition and the within-subjects factors previous accuracy (in the flanker task) and stimulus frequency (frequent, infrequent) of the visual discrimination task, were included. Trials with exceptionally fast (< 100 ms) or no responses were excluded (i.e., exceeding the response deadline), since it is unclear whether the stimulus was perceived in this case. Additionally, we used the Pearson correlation coefficient (r) to examine the relationship between early visual components and error-related components as well as behavioural measures.

RESULTS

BEHAVIOURAL DATA

Flanker task

On average, participants responded correctly in 80 % ($SD = 11$ %) of the trials in the flanker task and the average correct reaction time was 589 ms ($SD = 71$ ms). Furthermore, we did not observe a significant difference between both interval conditions, both $ps \geq 0.54$.

Visual discrimination task

Looking at reaction time, there was no significant difference between interval conditions, $F(1,28) = 1.43$, $p = 0.24$. Yet, we did detect a significant effect of frequency, $F(1,28) = 467.88$, $p < 0.001$, showing slower responses for an infrequent target (485 ms) than for a frequent

target (352 ms). There was also a main effect of previous accuracy, $F(1,28) = 14.59$, $p = 0.001$, indicating post-error slowing (15 ms). The interaction of frequency and previous accuracy also reached significant levels, $F(1,28) = 22.06$, $p < 0.001$. More specifically, reaction time in trials with frequent stimuli did not differ significantly, $F(1,28) = 0.04$, $p = 0.84$, when following a correct response (351 ms) or an erroneous response (352 ms) while reaction time in trials with infrequent stimuli was significantly slower following an error (500 ms) than following a correct response in the flanker task (470 ms), $F(1,28) = 25.45$, $p < 0.001$. Additionally, the interaction of previous accuracy and interval was marginally significant, $F(1,28) = 3.17$, $p = 0.08$, showing larger PES in the short interval condition (22 ms) compared to the long interval condition (8 ms). All other interactions were not significant $p \geq 0.63$.

We did not find a significant difference in accuracy between interval conditions, $F(1,28) = 0.20$, $p = 0.66$. However, there was a significant effect of frequency, $F(1,28) = 99.21$, $p < 0.001$, with impaired performance in trials with infrequent targets (70%) compared to frequent targets (99%). Also, a main effect of previous accuracy was detected, $F(1,28) = 12.97$, $p = 0.001$, showing post-error decrease in accuracy (-4%). Interestingly, the interaction of frequency and previous accuracy was also significant, $F(1,28) = 14.25$, $p = 0.001$. Specifically, for frequent targets there was no influence of previous accuracy, $F(1,28) = 0.44$, $p = 0.51$, yet performance in trials with infrequent targets was significantly reduced following an error, (66%) than following a correct response (75%), $F(1,28) = 13.66$, $p = 0.001$. All other interactions were not significant $p \geq 0.67$.

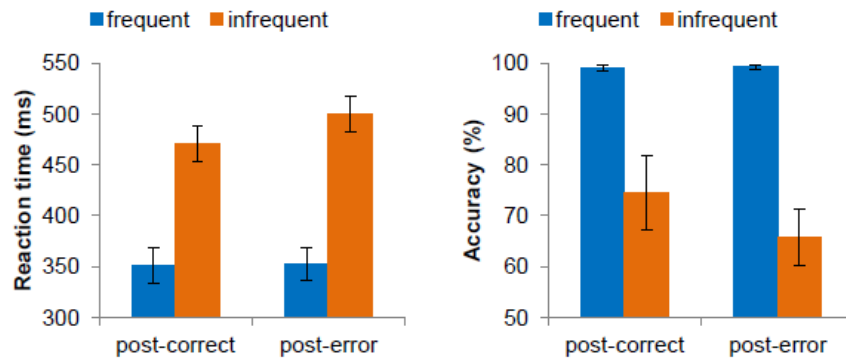


Figure 1. Average accuracy (in percentages) and reaction time (in milliseconds) in trials with frequent and infrequent stimuli following correct and erroneous trials. Error bars represent 95% confidence intervals around the means.

Additionally, we calculated a sensitivity measure d' (Macmillan & Creelman, 2005). An average d' of zero indicates chance performance, while d' becomes larger when the ability to discriminate between the signals increases. For every participant, a correct response on trials with infrequent targets was identified as a hit, while an incorrect response on trials with frequent targets was registered as a false alarm. Using the z-transformed hit and false alarm rates, d' was calculated as the difference between the hit and the false alarm rate. There was no significant main effect of interval condition, $F(1,28) = 0.64$, $p = 0.33$, however we did detect a significant effect of previous accuracy, $F(1,28) = 26.35$, $p < 0.001$, indicating a smaller d' following an error (2.74), than following a correct response (3.22). The interaction between interval condition and previous accuracy was marginally significant, $F(1,28) = 3.78$, $p = 0.06$, showing that the difference in d' was larger in the short interval condition (0.67, post-correct: 3.42, post-error: 2.75) than in the long interval condition (0.30, post-correct: 3.03, post-error, 2.3).

ERROR-RELATED COMPONENTS ON THE FLANKER TASK

Related to the mean amplitude of the ERN and CRN, no significant main effect of the factor interval condition was observed, $F(1,28) = 0.58$, $p = 0.45$. However, a main effect of accuracy on the current trial was found, $F(1,28) = 14.22$, $p = 0.001$, with the mean amplitude of the ERN (Fig. 2a) being more negative ($-0.10 \mu\text{V}/\text{cm}^2$) compared to the mean amplitude of the CRN ($-0.04 \mu\text{V}/\text{cm}^2$). The interaction between the factors interval condition and accuracy of the current response was not significant, $F(1,28) = 0.98$, $p = 0.33$.

When turning to the the early Pe/Pc components (Fig. 2b), no significant main effect of interval condition was detected, $F(1, 28) = 0.24$, $p = 0.63$. There was a significant effect of accuracy, $F(1, 28) = 7.79$, $p < 0.01$, with the mean amplitude being more positive in trials with an erroneous ($0.28 \mu\text{V}/\text{cm}^2$) than a correct response ($0.24 \mu\text{V}/\text{cm}^2$). Moreover, the interaction between the factors interval condition and accuracy did not reach significance, $F(1, 28) = 2.03$, $p = 0.17$.

The mean amplitude of the late Pe/Pc (Fig. 2c) again did not show a significant effect of interval condition, $F(1, 28) = 0.51$, $p = 0.48$. Also, there was no significant effect of accuracy, $F(1, 28) = 2.68$, $p = 0.11$, nor a significant interaction between interval condition and previous accuracy, $F(1, 28) = 0.26$, $p = 0.61$.

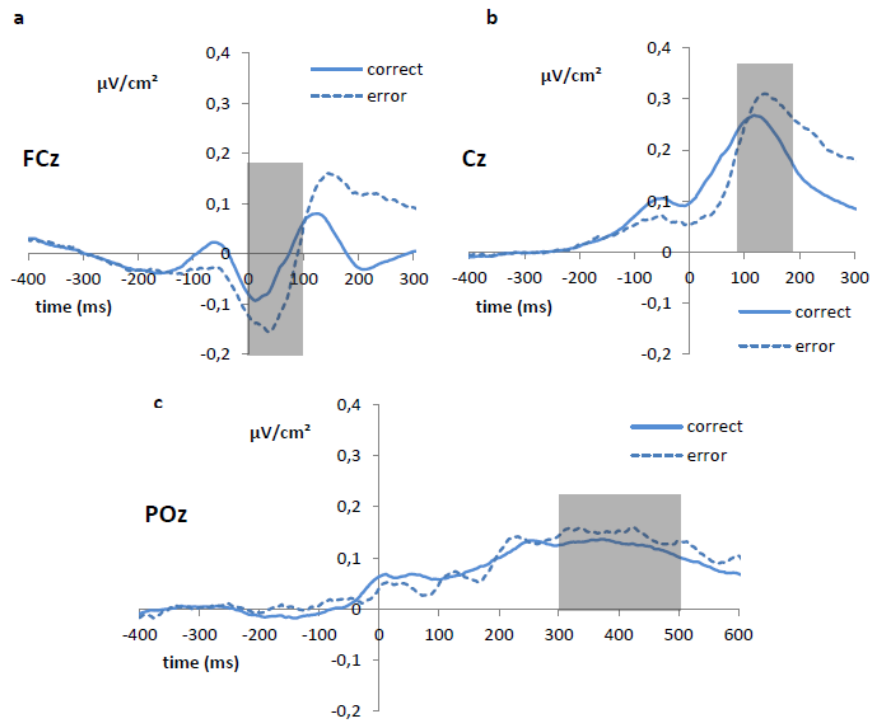


Figure 2. Laplacian transformed grand average (in $\mu\text{V}/\text{cm}^2$) response-locked ERP waveforms showing the (a) ERN/CRN (measured between 0 and 100 ms at Fcz), (b) the early Pe/Pc (measured between 80 and 180 ms at Cz) and (c) the late Pe/Pc (measured between 300 and 500 ms at POz) as a function of current accuracy.

STIMULUS-RELATED COMPONENTS IN THE VISUAL DISCRIMINATION TASK

Results indicated a significant main effect of frequency on P1 mean amplitude, $F(1,28) = 6.06$, $p = 0.02$, showing more positive values for trials with frequent stimuli ($0.19 \mu\text{V}/\text{cm}^2$) than for trials with infrequent stimuli ($0.16 \mu\text{V}/\text{cm}^2$). No other significant effects were observed, all $ps \geq 0.09$.

Mean amplitude of the early N1 (at Oz) was significantly different between interval conditions, $F(1,28) = 8.04$, $p < 0.01$, with more negative-going waves in the long interval condition ($-0.12 \mu\text{V}/\text{cm}^2$) then

in the short interval condition ($0.05 \mu\text{v}/\text{cm}^2$), see figure 3. Other main effects or interactions were not significant, all $ps \geq 0.17$.

For to the late N1 (at PO7 and PO8), we again observed a significant effect of interval condition, $F(1,28) = 7.71$, $p = 0.01$, showing more negative values in the long interval condition ($-0.16 \mu\text{v}/\text{cm}^2$) than in the short interval condition ($0.07 \mu\text{v}/\text{cm}^2$). Furthermore, there was a significant effect of frequency, $F(1,28) = 23.15$, $p < 0.001$, given that trials with infrequent stimuli show increased negative amplitudes ($-0.09 \mu\text{v}/\text{cm}^2$) than trials with frequent stimulus ($-0.01 \mu\text{v}/\text{cm}^2$). There was also a significant effect of previous accuracy, $F(1,28) = 5.06$, $p = 0.03$, showing more negative values following a correct ($-0.06 \mu\text{v}/\text{cm}^2$) compared to an erroneous response ($-0.04 \mu\text{v}/\text{cm}^2$), see figure 3. The interaction between previous accuracy and frequency was not significant, $F(1,28) = 0.09$, $p = 0.76$, as were the interactions with the factor interval condition, all $ps \geq 0.62$.

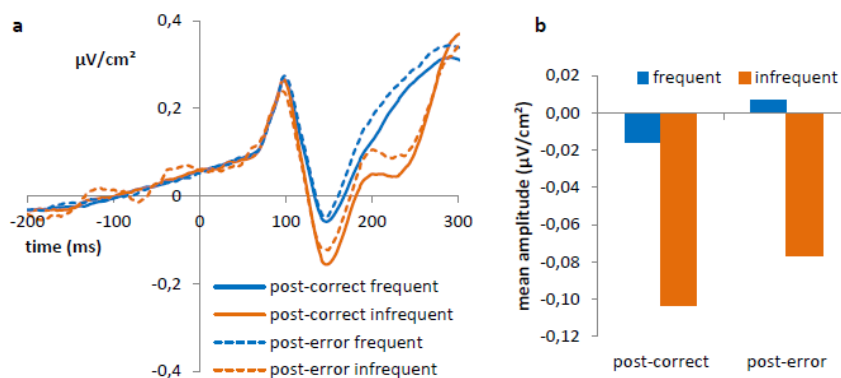


Figure 3. Left side of the figure (a) shows the Laplacian transformed grand average ERP waveforms at PO7 and PO8 showing the P1 (measured between 80 and 130 ms) and N1 (measured between 130 and 180 ms) as a function of previous accuracy and frequency. On the right side (b) average amplitude (in $\mu\text{V}/\text{cm}^2$) of the N1, for frequent and infrequent stimuli following correct and erroneous trials are shown.

We detected a significant main effect of frequency on P3 amplitudes, $F(1,28) = 92.86, p < 0.001$. As clearly illustrated in fig 4a, positive values were observed for infrequent stimuli ($0.16 \mu\text{V}/\text{cm}^2$) but not for frequent stimuli ($-0.07 \mu\text{V}/\text{cm}^2$). Interestingly, this effect interacted with interval condition, $F(1,28) = 4.71, p = 0.04$ (see fig. 4b), showing that the difference between frequent and infrequent targets was larger in the short interval condition ($0.28 \mu\text{V}/\text{cm}^2$, frequent: $-0.12 \mu\text{V}/\text{cm}^2$, infrequent: $16\mu\text{V}/\text{cm}^2$) than in the long interval condition ($0.18 \mu\text{V}/\text{cm}^2$, frequent: $-0.01 \mu\text{V}/\text{cm}^2$, infrequent: $16\mu\text{V}/\text{cm}^2$). Furthermore, there was no significant main effect of interval condition or previous accuracy, both $ps \geq 0.16$, but there was a marginally significant interaction between the factors interval condition and previous accuracy, $F(1,28) = 3.68, p = 0.07$ (see figure 4). Specifically, in the short condition the effect of previous accuracy was not significant (post-correct: $0.01 \mu\text{V}/\text{cm}^2$, post-error: $0.02 \mu\text{V}/\text{cm}^2$), $F(1,28) = 0.10, p = 0.75$. In the long condition however, amplitudes following a correct response ($0.10 \mu\text{V}/\text{cm}^2$) were significantly higher than following an error ($0.05 \mu\text{V}/\text{cm}^2$), $F(1,28) = 5.71, p = 0.03$ (see fig. 4c). Results indicated no other significant main effects or interactions, all $ps \geq 0.21$.

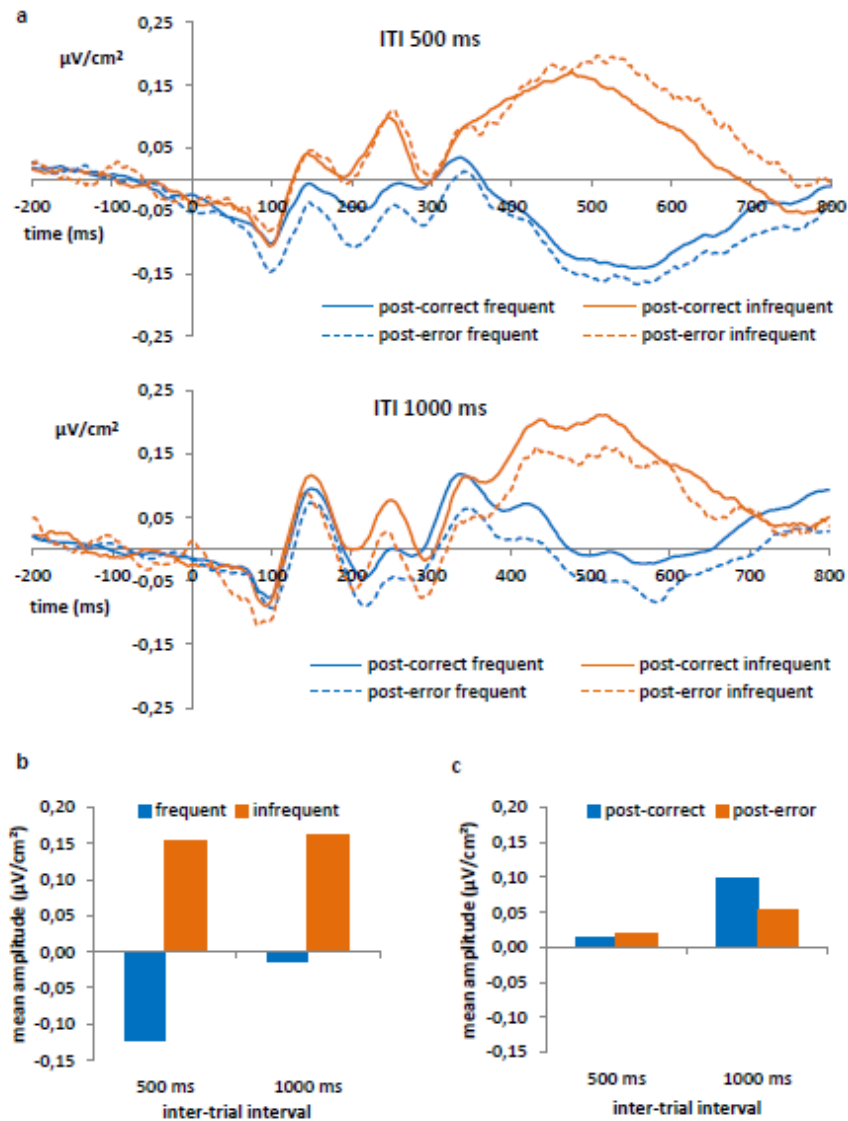


Figure 4. (a) Laplacian transformed grand average ERP waveforms at Pz, measured between 400 and 600 ms, as a function of accuracy and frequency, separately for interval condition. (b) Average P3 amplitudes (in $\mu\text{V}/\text{cm}^2$) for frequent and infrequent stimuli in both conditions are shown. (c) Average amplitude (in $\mu\text{V}/\text{cm}^2$) of the P3, for post-correct and post-error trials in both conditions.

CORRELATIONS³

We did not observe a significant correlation between any of the error-related components during the flanker task and the effects in the visual discrimination task, all $ps \geq 0.25$. Moreover, the late N1 effect did not correlate significantly with any of the behavioural measures (d' , PES or accuracy changes), all $ps \geq 0.50$.

The P3 effect in the long RSI condition correlated significantly with the effect on accuracy, $r(15) = 0.52$, $p < 0.05$, and marginally significant with PES, $r(15) = 0.49$, $p = 0.07$, indicating that participants with a larger P3 amplitude following an error (compared to a correct response), showed less post-error accuracy decrease and larger PES. However, deleting two online outliers rendered both correlations non-significant, resp. $r(13) = -0.01$, $p = 0.98$ and $r(13) = 0.17$, $p = 0.57$. There were no significant correlations in the short interval condition, all $ps \geq 0.49$.

Based on the idea that the late Pe/Pc is a P3-like component (Davies, Segalowitz, Dywan, & Pailing, 2001; Ridderinkhof, Ramautar, & Wijnen, 2009), we looked at the correlations between these components for each interval condition, separately for correct and error trials. Interestingly, in the short interval condition there was a significant negative correlation between late Pe/Pc amplitude and P3-amplitude, resp. $r(15) = -0.72$, $p < 0.01$ and $r(15) = -0.65$, $p < 0.01$, showing that increased late Pe/Pc amplitude resulted in a smaller P3 amplitude. Similarly, in the long interval condition a marginal significant correlation was observed for the late Pe and P3 amplitude following an error, $r(15) = -0.47$, $p = 0.08$, and also a significant correlation between late the

³ The difference scores for the N1 amplitude, P3 amplitude, post-error slowing and post-error accuracy were calculated by subtracting the post-correct value from the post-error value, both averaged over frequency.

amplitude of these components following a correct response, $r(15) = -0.67, p < 0.01$.

DISCUSSION

In this experiment, we investigated the effect of errors on subsequent visuo-attentional processes by combining a flanker and a visual discrimination task. Additionally, the intertrial interval between both tasks was manipulated to be able to explore the duration of these negative after-effects. As previously reported, the ERN/CRN was followed by an early and late Pe/Pc in the flanker task (Endrass et al., 2007; Van der Borgh et al., 2015; Van Veen & Carter, 2002). While the early Pe/Pc was significantly larger for errors, there was no significant difference in late Pe/Pc amplitude between erroneous and correct trials. Since the late Pe/Pc is believed to be related to error awareness (Endrass et al., 2007; Shalgi, Barkan, & Deouell, 2009; Wessel, Danielmeier, & Ullsperger, 2011), it is possible that participants did not consciously know when they made an error. Even so, the amplitude of the late N1 amplitude in the visual discrimination task was significantly decreased after an erroneous compared to a correct response in the flanker task, irrespective of the intertrial interval, suggesting diminished visual attention to the task-relevant stimulus after an error. Additionally, P3 amplitude was also attenuated following an error, but only in the long condition.

After committing an error in the flanker task, the late N1 but not the P1 amplitude locked to the target of the visual discrimination task was attenuated. This is in line with the idea that the P1 represents early sensory processing in a location where attention is already focused while the N1 rather reflects the orienting of attention to task-relevant stimuli (Hopfinger & West, 2006; Luck, Heinze, Mangun, & Hillyard, 1990). Because the stimulus of the visual discrimination task was presented in

the center of the screen, as were the stimuli in the flanker task, it is therefore not surprising that bottom-up attention is not influenced. However frequent stimuli did elicit a larger P1 component, indicating that bottom-up attention is suppressed when more top-down attention is recruited, as illustrated by a larger late N1 amplitude for infrequent stimuli.

That the late N1 is reduced following an error illustrates that participants have less resources to actively focus attention on the stimulus of the visual discrimination task, irrespective of frequency. Interestingly, only performance on infrequent stimuli was impaired following an error. While we cannot directly link the effect of previous accuracy on the late N1 to any of the behavioural measures, as there were no significant correlations; this suggests that frequent stimuli might have been processed rather automatically and with a minimum of resources, while the processing of infrequent stimuli did suffer of this decreased attentional resources resulting in PES and post-error accuracy decrease.

Interestingly, the results also indicate an attenuation of P3 amplitude following errors, but only in the long interval condition. In combination with the finding that values for both the early and late N1 were more negative in the long than in the short interval condition, one can infer that effects of previous accuracy are reduced in this interval, even though there was no main indication of an overall P3 attenuation in the short interval condition. Hence, besides decreased visual attention following an error, as indicated by the N1 component, the P3-related results indicate that memory updating seems to be impaired following an error. Additionally, in line with the idea that the late Pe/Pc reflects P3-like processing of the response outcome (Davies et al., 2001; Ridderinkhof et al., 2009), a significant negative correlation is found between the late Pe/Pc on the flanker task and the stimulus-locked P3 in the visual discrimination task.

While an AB-like effect can be found following errors (Houtman & Notebaert, 2013), our results show that the mechanism behind the classic AB and the error-induced blink are most likely not the same since previous research showed that only P3 amplitude, and not the N1, is attenuated in classical AB tasks (Sergent et al., 2005; Vogel et al., 1998) suggesting an impairment in a postperceptual stage of processing. However, similar to the idea that an emotional AB occurs through competition for perceptual resources (Most & Wang, 2011; Wang et al., 2012), our results show that an error is followed by a decrease in attentional resources, as indexed by a decrease in late N1 amplitude. These results are in line with the orienting account (Notebaert et al., 2009); attention to the task and the amplitude of the stimulus-locked P3 component is reduced following an error. These results suggest that an error is an infrequent event which triggers an orienting response away from the task. Our finding of an attenuated N1 following errors seems to contradict a second nonfunctional account, the bottleneck account (Jentsch & Dudschig, 2009), which assumes that a capacity-limited error monitoring process follows error detection. This bottleneck is present in central processing stages, leaving perceptual processing unhindered following an error. This account would therefore predict similar results as found for the classic attentional blink effect. However, it can still be hypothesized that awareness is limited because error processing occupies the central bottleneck stage. Since, the visual N1 has been related to endogenous attention (Hopfinger & West, 2006) the bottleneck account can explain attenuation of this component following errors.

Taken together, our results show that visual attention following an error, as indexed by the N1 component, is attenuated. This suggests that attention is directed away from the task, due to the triggering of an error-related orienting response or further error processing (Jentsch & Dudschig, 2009; Notebaert et al., 2009). Additionally, memory-updating,

as indexed by the P3 component is reduced following an error, implying that the initial attenuation of attention might also influence higher order processing. Interestingly P3 amplitude also correlated negatively with late Pe amplitude, supporting the idea that the late Pe/Pc reflects a P3-like reaction to response outcome.

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REFERENCES

- Babiloni, F., Cincotti, F., Carducci, F., Rossini, P. M., & Babiloni, C. (2001). Spatial enhancement of EEG data by surface Laplacian estimation: the use of magnetic resonance imaging-based head models. *Clinical Neurophysiology, 112*(5), 724–727. doi:10.1016/S1388-2457(01)00494-1
- Bombeke, K., Schouppe, N., Duthoo, W., & Notebaert, W. (2013). The effect of alcohol and placebo on post-error adjustments. *Frontiers in Human Neuroscience, 7*(3). doi:10.3389/fnhum.2013.00003
- Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108*(3), 624–652. doi:10.1037/0033-295X.108.3.624
- Carp, J., & Compton, R. J. (2009). Alpha power is influenced by performance errors. *Psychophysiology, 46*, 336–343. doi:10.1111/j.1469-8986.2008.00773.x
- Danielmeier, C., Eichele, T., Forstmann, B. U., Tittgemeyer, M., & Ullsperger, M. (2011). Posterior medial frontal cortex activity predicts post-error adaptations in task-related visual and motor areas. *The Journal of Neuroscience, 31*(5), 1780–1789. doi:10.1523/JNEUROSCI.4299-10.2011
- Danielmeier, C., & Ullsperger, M. (2011). Post-error adjustments. *Frontiers in Psychology, 2*, 233. doi:10.3389/fpsyg.2011.00233
- Davies, P. L., Segalowitz, S. J., Dywan, J., & Pailing, P. E. (2001). Error-negativity and positivity as they relate to other ERP indices of attentional control and stimulus processing. *Biological Psychology, 56*(3), 191–206. doi:10.1016/S0301-0511(01)00080-1
- Endrass, T., Reuter, B., & Kathmann, N. (2007). ERP correlates of conscious error recognition: aware and unaware errors in an antisaccade task. *The European Journal of Neuroscience, 26*(6), 1714–20. doi:10.1111/j.1460-9568.2007.05785.x
- Gonsalvez, C. L., & Polich, J. (2002). P300 amplitude is determined by target-to-target interval. *Psychophysiology, 39*(3), 388–96. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/12212658>
- Hopfinger, J. B., & West, V. M. (2006). Interactions between endogenous and exogenous attention on cortical visual processing. *NeuroImage, 31*(2), 774–89. doi:10.1016/j.neuroimage.2005.12.049
- Houtman, F., & Notebaert, W. (2013). Blinded by an error. *Cognition, 128*(2), 228–236. doi:10.1016/j.cognition.2013.04.003
- Houtman, F., Núñez Castellar, E., & Notebaert, W. (2012). Orienting to errors with and without immediate feedback. *Journal of Cognitive Psychology, 24*(3), 278–285. doi:10.1080/20445911.2011.617301
- Jentsch, I., & Dudschig, C. (2009). Why do we slow down after an error? Mechanisms underlying the effects of posterror slowing. *Quarterly Journal of Experimental Psychology, 62*(2), 209–218. doi:10.1080/17470210802240655

- Kayser, J., & Tenke, C. E. (2006). Principal components analysis of Laplacian waveforms as a generic method for identifying ERP generator patterns: I. Evaluation with auditory oddball tasks. *Clinical Neurophysiology*, *117*(2), 348–368. doi:10.1016/j.clinph.2005.08.034
- Luck, S., Heinze, H., Mangun, G., & Hillyard, S. (1990). Visual event-related potentials index focused attention within bilateral stimulus arrays. II. Functional dissociation of P1 and N1 components. *Electroencephalography and Clinical Neurophysiology*, *75*, 528–542. Retrieved from <http://www.sciencedirect.com/science/article/pii/001346949090139B>
- Macmillan, N., & Creelman, C. (2005). *Detection theory: A user's guide*. Mahwah: Lawrence Erlbaum.
- Maier, M. E., Yeung, N., & Steinhauser, M. (2011). Error-related brain activity and adjustments of selective attention following errors. *NeuroImage*, *56*, 2339–2347. doi:10.1016/j.neuroimage.2011.03.083
- McHugo, M., Olatunji, B. O., & Zald, D. H. (2013). The emotional attentional blink: what we know so far. *Frontiers in Human Neuroscience*, *7*, 151. doi:10.3389/fnhum.2013.00151
- Most, S. B., & Wang, L. (2011). Dissociating spatial attention and awareness in emotion-induced blindness. *Psychological Science*, *22*(3), 300–5. doi:10.1177/0956797610397665
- Notebaert, W., Houtman, F., Opstal, F. Van, Gevers, W., Fias, W., & Verguts, T. (2009). Post-error slowing: an orienting account. *Cognition*, *111*, 275–279. doi:10.1016/j.cognition.2009.02.002
- Perrin, F., Pernier, J., Bertrand, O., & Echallier, J. F. (1989). Spherical splines for scalp potential and current density mapping. *Electroencephalography and Clinical Neurophysiology*, *72*(2), 184–187. doi:10.1016/0013-4694(89)90180-6
- Polich, J. (2007). Updating P300: an integrative theory of P3a and P3b. *Clinical Neurophysiology*, *118*(10), 2128–2148. doi:10.1016/j.clinph.2007.04.019
- Potter, M. C., Staub, A., & O'Connor, D. H. (2002). The time course of competition for attention: Attention is initially labile. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(5), 1149–1162. doi:10.1037//0096-1523.28.5.1149
- Rabbitt, P. (1979). How old and young subjects monitor and control responses for accuracy and speed. *British Journal of Psychology*, *70*(2), 305–311.
- Ridderinkhof, K. R., Ramautar, J. R., & Wijnen, J. G. (2009). To P(E) or not to P(E): a P3-like ERP component reflecting the processing of response errors. *Psychophysiology*, *46*(3), 531–8. doi:10.1111/j.1469-8986.2009.00790.x

- Segalowitz, S. J., Santesso, D. L., Murphy, T. I., Homan, D., Chantziantoniou, D. K., & Khan, S. (2010). Retest reliability of medial frontal negativities during performance monitoring. *Psychophysiology*, *47*(2), 260–70. doi:10.1111/j.1469-8986.2009.00942.x
- Sergent, C., Baillet, S., & Dehaene, S. (2005). Timing of the brain events underlying access to consciousness during the attentional blink. *Nature Neuroscience*, *8*(10), 1391–400. doi:10.1038/nn1549
- Shalgi, S., Barkan, I., & Deouell, L. Y. (2009). On the positive side of error processing: error-awareness positivity revisited. *The European Journal of Neuroscience*, *29*(7), 1522–32. doi:10.1111/j.1460-9568.2009.06690.x
- Steinborn, M. B., Flehmig, H. C., Bratzke, D., & Schröter, H. (2012). Error reactivity in self-paced performance: Highly-accurate individuals exhibit largest post-error slowing. *Quarterly Journal of Experimental Psychology*, *65*(4), 624–31. doi:10.1080/17470218.2012.660962
- Stevens, M., Lammertyn, J., Verbruggen, F., & Vandierendonck, A. (2006). Tscope: A C library for programming cognitive experiments on the MS windows platform. *Behavior Research Methods*, *38*(2), 280–286.
- Van der Borgh, L., Houtman, F., Burle, B., & Notebaert, W. (2015). *Distinguishing the influence of task difficulty on error-related ERPs using surface Laplacian transformation*. Manuscript submitted for publication.
- Van Veen, V., & Carter, C. S. (2002). The timing of action-monitoring processes in the anterior cingulate cortex. *Journal of Cognitive Neuroscience*, *14*(4), 593–602. doi:10.1162/08989290260045837
- Vogel, E. K., Luck, S. J., Chun, M., Lollo, V. Di, Egeth, H., Maki, B., & Raymond, J. (1998). Electrophysiological Evidence for a Postperceptual Locus of Suppression During the Attentional Blink, *24*(6), 1656–1674.
- Wang, L., Kennedy, B. L., & Most, S. B. (2012). When emotion blinds: a spatiotemporal competition account of emotion-induced blindness. *Frontiers in Psychology*, *3*(November), 438. doi:10.3389/fpsyg.2012.00438
- Wessel, J. R., Danielmeier, C., & Ullsperger, M. (2011). Error awareness revisited: accumulation of multimodal evidence from central and autonomic nervous systems. *Journal of Cognitive Neuroscience*, *23*(10), 3021–3036. doi:10.1162/jocn.2011.21635

CHAPTER 7

ERRORS DISTURB SUBSEQUENT CONFLICT PROCESSING¹

Whereas it was traditionally conceived that errors lead to improved performance on subsequent trials, a series of recent studies question this adaptive point of view. For instance, we recently demonstrated that errors leads to impaired early visual attention and impaired memory updating in a visual discrimination task (Van der Borgh, Schevernels, Burle, & Notebaert, 2015). In the present study, we investigate visual processes by means of EEG within a conflict task in order to investigate early visuo-attentional and conflict related processes. The amplitude of attention-related components differed depending on congruency, with increased P1-amplitude for congruent stimuli and increased late N1-amplitude for incongruent stimuli. Interestingly, this effect was only observed following a correct response in the easy condition. Additionally, P3-amplitude, related to memory updating, was attenuated following an error. Our results indicate that errors do not trigger adaptive processes and that subsequent visuo-attentional processes in regard with conflict are disturbed.

¹ This chapter is based on a reanalysis of the data of CHAPTER 5. Note that the experiment was originally designed to answer a different research question and might therefore be suboptimal for the present one.

INTRODUCTION

The finding that people slow down following an error (PES) is typically interpreted in terms of participants slowing down in order to decrease the chance of making an error again (Botvinick, Braver, Barch, Carter, & Cohen, 2001). In more recent years, however, it has become clear that PES is more often than not accompanied by post-error accuracy decrease, especially when the inter-trial interval is short (for an overview, see Danielmeier & Ullsperger, 2011). Even when post-error accuracy was investigated in a task where no speeded response was required, there was worse target detection following errors (Houtman & Notebaert, 2013). In line with these findings, non-functional accounts were postulated which explain PES as a nonspecific result of orienting of attention or error-processing itself (Jentsch & Dudschig, 2009; Notebaert et al., 2009). The orienting account, for instance, states that errors are infrequent, and motivationally salient, events that trigger an orienting response. This orienting response interferes with subsequent processing leading to PES and, if the inter-trial interval is short, post-error accuracy *decrease* (Houtman, Núñez Castellar, & Notebaert, 2012; Notebaert et al., 2009; Steinborn, Flehmig, Bratzke, & Schröter, 2012).

While post-error behaviour is often investigated, electrophysiological research usually focuses on error-related components during or shortly after the error, but not on the post-error trial. These studies revealed hallmark potentials such as the error-related negativity (ERN, Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991; Gehring, Goss, Coles, Meyer, & Donchin, 1993) and subsequent positive deflections (the early Pe, with a frontocentral location, and the late Pe at parietal electrodes, Endrass, Klawohn, Preuss, & Kathmann, 2012; Van Veen & Carter, 2002). In order to increase our understanding of error-related changes in behaviour, we investigated early visual and attentional

components on trials following errors. We showed that early visual processing as reflected in N1-amplitude, as well as the P3, which is related to memory updating, is attenuated following an error and that these effects linger on for a fairly long period of time (Van der Borgh, Schevernels, Burle, & Notebaert, 2015).

In our previous study, error-related changes in stimulus processing were investigated in a dual-task design. The errors were evoked in difficult flanker task, and subsequent stimulus processing was investigated in a very easy visual discrimination task. It has been argued that errors also change the way we process conflicting information. Ridderinkhof (2002) for instance demonstrated that the congruency effect, i.e. the influence of task-irrelevant stimuli characteristics, is smaller following an error than following a correct response. However, we recently showed that this post-error reduction of interference (PERI) is confounded with previous congruency and when controlling for this factor no post-error focusing, as reflected in PERI, is found (Van der Borgh, Braem, & Notebaert, 2014; Van der Borgh, Duthoo, & Notebaert, 2015). In order to gain more insight into error-related changes in conflict processing, we investigate the influence of errors on visuo-attentional and conflict components in a conflict task. We therefore re-analyzed a previous dataset in which the influence of task difficulty on error-related ERP components was investigated (Van der Borgh, Houtman, Burle, & Notebaert, 2015).

We investigate the influence of errors on stimulus-locked early visual components P1 and N1. The P1 is believed to reflect mainly bottom-up attention, i.e. early sensory processing in a location where attention is already focused, while the N1 rather reflects the orienting of attention to task-relevant stimuli (Hopfinger & West, 2006; Luck, Heinze, Mangun, & Hillyard, 1990). In a flanker task, these early visual components are typically not influenced by congruency (Appelbaum, Smith, Boehler, Chen, & Woldorff, 2011). However, modulations by context, as shown in larger amplitudes for incongruent trials following incongruent trials, have been shown as early as the P1 (Scerif, Worden, Davidson, Seiger, &

Casey, 2006). We also investigate the effect of errors on the subsequent N2, which indexes the amount of response conflict and is generally used as a measure of cognitive control with lower amplitudes on congruent trials and following incongruent trials (Clayson & Larson, 2011; Folstein & Van Petten, 2008; Larson, Clayson, & Baldwin, 2012; Van Veen & Carter, 2002), and the P3 which is related to memory updating (Polich, 2007).

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.

MATERIAL AND PROCEDURE

A classical flanker task was modified in order to create two conditions that varied in difficulty. The easy condition had four possible stimuli { , }, [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. In the difficult condition there were 8 possible stimuli, namely { , }, [,], (,), | and †. Two pairs of brackets were arbitrarily mapped on the left or the right response button, resulting in a four to one mapping. Congruent trials always consisted of 5 identical brackets, while flanking stimuli on incongruent trials were always stimuli needing another response; i.e.

response-incongruent. Congruent and incongruent trials were presented equally often and in random order.

The participants were seated in a comfortable armchair in a lightdimmed and sound-attenuated room. They were tested on a Pentium IV personal computer with a 17-inch monitor running Tscope (Stevens, 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 stimulus was presented centrally on a blank screen for 145 ms, followed by a blank screen for a maximum of 655 ms. Participants thus 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.

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 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.

EEG ACQUISITION AND PREPROCESSING

EEG data were recorded using the BioSemi ActiveTwo system (Biosemi, Amsterdam, Netherlands). 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. EEG 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 data was offline resampled to 256 Hz. Independent component analysis (ICA) was conducted to identify and remove stereotypical eye blink components.

Two kinds of epochs were created. To investigate error-related components, epochs were created response-locked to the response on the flanker task, starting from 400 ms before until 1000 ms after the response. The epochs were baseline-corrected using the 400 till 200 ms pre-response window. To investigate the visual and conflict related components following correct or error trials, epochs were created time-locked to the onset of the stimulus, including a 200 ms pre-stimulus period that was used for baseline correction. The total time window of these epoched ERPs was 1000 ms. Additional EMG activity per epoch was removed with blind source separation (BSS) using the AAR toolbox (http://www.germangh.com/eeglab_plugin_aar). The use of Laplacian transformation is very sensitive to local artifacts, therefore epochs were manually inspected and rejected if necessary. On average 11% of the data was rejected. EEG epochs were averaged across participants according to the different conditions and for error and correct responses separately. Next the monopolar averages were then transformed using the CSD toolbox for Laplacian transformation (Kayser & Tenke, 2006, <http://psychophysiology.cpmc.columbia.edu/software/CSDtoolbox>), thereby enhancing the spatial resolution and intensity of ERP components. Current source densities (CSDs) were calculated according to the spherical spline algorithm of Perrin, Pernier, Bertrand, and

Echallier (1989), using a default smoothing constant of 1.0^{-5} and a head radius of 10 cm. Note that transformation via CSDs results in reference-free ERP data.

EEG ANALYSES

For the error-related components, the ERN and CRN were measured at electrode FCz in a time window between 0 and 100 ms after response execution. The early Pe was measured between 80 and 180 ms at Cz, and a later broader Pe-component was measured between 200 and 500 ms at POz. For the stimulus-locked components P1 was quantified at posterior electrodes PO7 and PO8 between 80 and 130 ms. This component was followed by a negative wave (N1) over the same electrodes from 160 to 210 ms. Additionally we investigated the occurrence of an earlier negative wave ($N1_e$), quantified at Oz, between 80 and 120 ms. The conflict N2 peaked around 300 ms and was measured at FCz between 260 and 340 ms. P3 was quantified at CPz, between 300 and 700 milliseconds.

Amplitudes of error-related components were examined using a repeated-measures analysis of variance (rANOVA) with the within subjects factor difficulty (easy or hard), current accuracy and current congruency. To investigate stimulus-locked components the within subjects factor of the rANOVA were difficulty, previous accuracy, previous congruency and current congruency. Because we were interested in error-related components and early visual components, trials with both erroneous and correct responses were included. Very early (< 100 ms) or no responses were excluded.

RESULTS

BEHAVIOURAL DATA

Both correct reaction times and error rates were analyzed with repeated measures ANOVAs. The within-subject factors were difficulty, previous accuracy, previous congruency and current congruency.

Reaction times

For reaction times there was a significant effect of difficulty, $F(1,15) = 34.27$, $p < 0.001$, showing that participants were slower in the hard condition (511 ms) than in the easy condition (465 ms). There was a significant effect of previous accuracy, $F(1,15) = 8.20$, $p = 0.01$, showing that participants were slower following an error (494 ms) than following a correct response (482 ms). There was also a significant effect of congruency, $F(1,15) = 46.84$, $p < 0.001$, indicating that participants were slower on an incongruent trial (511 ms) than on a congruent trial (465 ms). There was also a significant interaction of previous congruency and current congruency, $F(1,15) = 5.41$, $p = 0.03$, showing a smaller congruency-effect following an incongruent trial (10 ms) than following a congruent trial (14 ms). No other main effects or interactions were significant, all $ps \geq 0.12$.

Error rates

There was again a significant effect of difficulty, $F(1,15) = 24.45$, $p < 0.001$, showing that participants made less errors in the easy condition (20%) than in the hard condition (29%). There was no significant effect of previous accuracy, $F(1,15) = 0.26$, $p = 0.62$, or previous congruency, $F(1,15) = 0.47$, $p = 0.50$. There was a significant effect of congruency, $F(1,15) = 66.19$, $p < 0.001$, showing that participants made less errors on congruent trials (17%) than on incongruent trials (32%). There was a significant interaction of previous congruency and current congruency,

$F(1,15) = 7.09, p = 0.02$, showing a smaller congruency-effect following an incongruent trial (14%) than following a congruent trial (16%). There was a marginal significant interaction of difficulty and current congruency, $F(1,15) = 3.82, p = 0.07$, showing a larger congruency effect in the easy condition (18%) than in the hard condition (13%). This effect also interacted marginally with previous accuracy, $F(1,15) = 3.76, p = 0.07$, indicating that the difference between the congruency-effect following a correct response (19%) and an error (16%) was marginally significant in the easy condition, $F(1,15) = 3.50, p = 0.08$, indicating PERI, but not in the hard condition (resp. 12 and 13%), $F(1,15) = 1.03, p = 0.33$. However, the four-way interaction was also significant, $F(1,15) = 15.01, p = 0.001$, see figure 1. Following incongruent trials, the interaction of difficulty, previous accuracy and current congruency was not significant, $F(1,15) = 3.39, p = 0.09$. Following congruent trials however, there was a significant interaction, $F(1,15) = 10.41, p < 0.01$. In the easy condition, the congruency-effect was significantly smaller following an error (14%) than following a correct response (22%) (i.e. PERI), $F(1,15) = 5.29, p = 0.04$. In the hard condition, the congruency-effect was significantly larger following an error (18%) than following a correct response (12%) (i.e. inverse PERI), $F(1,15) = 5.55, p = 0.03$. Post-hoc comparisons show that the congruency-effect following error trials did not differ between difficulty conditions, $F(1,15) = 0.81, p = 0.38$, while there was a significant difference in congruency effect for post-correct trials, $F(1,15) = 13.06, p < 0.01$.

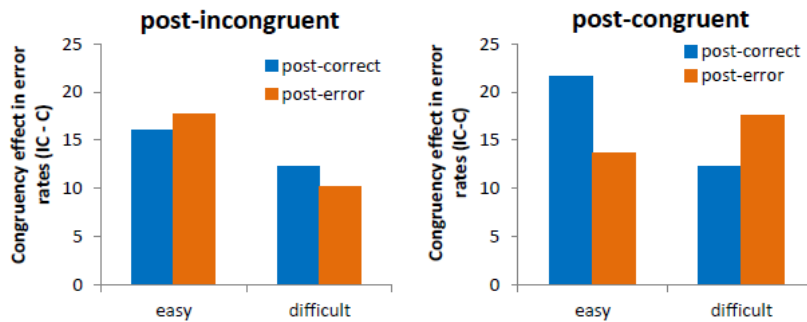


Figure 1. The congruency effect in error rates (incongruent minus congruent trials) for post-error and post-correct trials in the easy and hard condition, separate for post-congruent and post-incongruent trials.

ERPS

Response-locked

Looking at the ERN and CRN, there was no significant main effect for difficulty, $F(1,15) = 0.98$, $p = 0.34$, or congruency, $F(1,15) = 2.03$, $p = 0.18$. There was a main effect of accuracy, $F(1,15) = 35.85$, $p < 0.001$. The mean amplitude of the ERN was more negative ($-0.20 \mu\text{V}/\text{cm}^2$) than the mean amplitude of the CRN ($-0.05 \mu\text{V}/\text{cm}^2$). The interaction between difficulty and the accuracy of the response was also significant, $F(1,15) = 13.40$, $p < 0.01$. The difference between the ERN and the CRN was larger in the easy condition ($0.19 \mu\text{V}/\text{cm}^2$, error: $-0.23 \mu\text{V}/\text{cm}^2$ vs. correct: $-0.04 \mu\text{V}/\text{cm}^2$) than in the hard condition ($0.10 \mu\text{V}/\text{cm}^2$, error: $-0.16 \mu\text{V}/\text{cm}^2$ vs. correct: $-0.06 \mu\text{V}/\text{cm}^2$). There was also a significant interaction of accuracy and congruency, $F(1,15) = 17.19$, $p = 0.01$ as there was no significant difference in CRN between congruent ($-0.04 \mu\text{V}/\text{cm}^2$) and incongruent trials ($-0.05 \mu\text{V}/\text{cm}^2$), $F(1,15) = 0.78$, $p = 0.39$, while ERN-amplitude was larger for congruent trials ($-0.22 \mu\text{V}/\text{cm}^2$) than incongruent trials ($-0.17 \mu\text{V}/\text{cm}^2$), $F(1,15) = 8.38$, $p = 0.01$. No other interactions were significant, all $ps \geq 0.26$.

For the early Pe/Pc, there was a significant main effect of difficulty, $F(1, 15) = 8.03$, $p = .01$, showing overall higher amplitude in the easy condition ($0.27 \mu\text{V}/\text{cm}^2$) than in the difficult condition ($0.21 \mu\text{V}/\text{cm}^2$). There was a significant main effect of accuracy, $F(1, 15) = 8.58$, $p = 0.01$, with the mean amplitude after an error more positive ($0.28 \mu\text{V}/\text{cm}^2$) than after a correct response ($0.20 \mu\text{V}/\text{cm}^2$). There was also a significant main effect of congruency; overall amplitude was more positive for a congruent trial ($0.26 \mu\text{V}/\text{cm}^2$) than for an incongruent trial ($0.22 \mu\text{V}/\text{cm}^2$). $F(1, 15) = 5.68$, $p = .03$. Most importantly, there was a significant interaction of difficulty and accuracy, $F(1, 15) = 10.23$, $p < 0.01$. The difference in early Pe/Pc was larger in the easy condition ($0.12 \mu\text{V}/\text{cm}^2$, error: $0.33 \mu\text{V}/\text{cm}^2$ vs. correct: $0.21 \mu\text{V}/\text{cm}^2$) than in the hard condition ($0.04 \mu\text{V}/\text{cm}^2$, error: $0.23 \mu\text{V}/\text{cm}^2$ vs. correct: $0.19 \mu\text{V}/\text{cm}^2$). No other interactions were significant, all $ps \geq 0.10$.

For the late Pe/Pc, there was a marginally significant effect of difficulty, $F(1, 15) = 3.92$, $p = 0.07$, showing more positive amplitudes in the easy condition ($0.19 \mu\text{V}/\text{cm}^2$) than in the hard condition ($0.12 \mu\text{V}/\text{cm}^2$). There was a significant effect of accuracy, $F(1, 15) = 11.99$, $p < 0.01$, showing a more positive mean amplitude after an error ($0.19 \mu\text{V}/\text{cm}^2$) than after a correct response ($0.12 \mu\text{V}/\text{cm}^2$). No other main effects or interactions were significant, all $ps \geq 0.11$.

Stimulus-locked

PI. There was no significant effect of difficulty, previous accuracy, previous congruency or current congruency on mean P1 amplitudes, all $ps \geq 0.09$. There was a significant interaction of previous accuracy and current congruency, $F(1,15) = 4.72$, $p < 0.05$. Interestingly, this effect interacted significantly with difficulty, $F(1,15) = 14.29$, $p < 0.01$. In the easy condition, the interaction of previous accuracy and current congruency was significant, $F(1,15) = 10.16$, $p < 0.01$. Following correct trials, the mean amplitude was more positive for congruent trials ($0.14 \mu\text{V}/\text{cm}^2$) than for incongruent trials ($0.11 \mu\text{V}/\text{cm}^2$), $F(1,15) = 5.36$, $p =$

0.04. Following error trials, mean amplitude differed only marginally significant with larger amplitudes for incongruent trials ($0.15 \mu\text{V}/\text{cm}^2$) than congruent trials ($0.11 \mu\text{V}/\text{cm}^2$), $F(1,15) = 3.45$, $p = 0.08$. In the hard condition the interaction between previous accuracy and congruency was not significant, $F(1,15) = 1.12$, $p = 0.31$. There was also a marginally significant interaction of previous accuracy, previous congruency and difficulty, $F(1,15) = 3.81$, $p = 0.07$. The interaction of previous accuracy and previous congruency was not significant for the easy condition, $F(1,15) = 0.94$, $p = 0.35$. However, in the hard condition, this interaction was marginally significant, $F(1,15) = 4.03$, $p = 0.06$. For post-congruent trials, there was no significant difference in amplitude between post-error and post-correct trials, $F(1,15) = 1.94$, $p = 0.18$. Following post-incongruent trials, mean amplitude was marginally significantly higher following a correct response ($0.13 \mu\text{V}/\text{cm}^2$) than following an error ($0.11 \mu\text{V}/\text{cm}^2$), $F(1,15) = 3.75$, $p = 0.07$. No other interactions were significant, all $ps \geq 0.25$.

NI. For the mean amplitude of the early N1 (at Oz), there were no significant main effect or interactions, all $ps \geq 0.19$. For the late N1 (at PO7 and PO8), there was no significant main effect of difficulty, previous accuracy, previous congruency or current congruency, all $ps \geq 0.14$. There was a marginally significant interaction of previous accuracy and current congruency, $F(1,15) = 4.05$, $p = 0.06$. Interestingly, this effect interacted significantly with difficulty, $F(1,15) = 6.17$, $p = 0.03$. In the easy condition, there was a significant interaction of previous accuracy and congruency $F(1,15) = 6.14$, $p = 0.03$. More specifically, following a correct response, mean amplitude was more negative for incongruent trials ($-0.16 \mu\text{V}/\text{cm}^2$) than congruent trials ($-0.12 \mu\text{V}/\text{cm}^2$), $F(1,15) = 10.15$, $p < 0.01$. Following an error, mean amplitude did not differ between congruent and incongruent trials (resp. -0.14 and $-0.12 \mu\text{V}/\text{cm}^2$), $F(1,15) = 0.46$, $p = 0.51$. In the hard condition, this interaction between

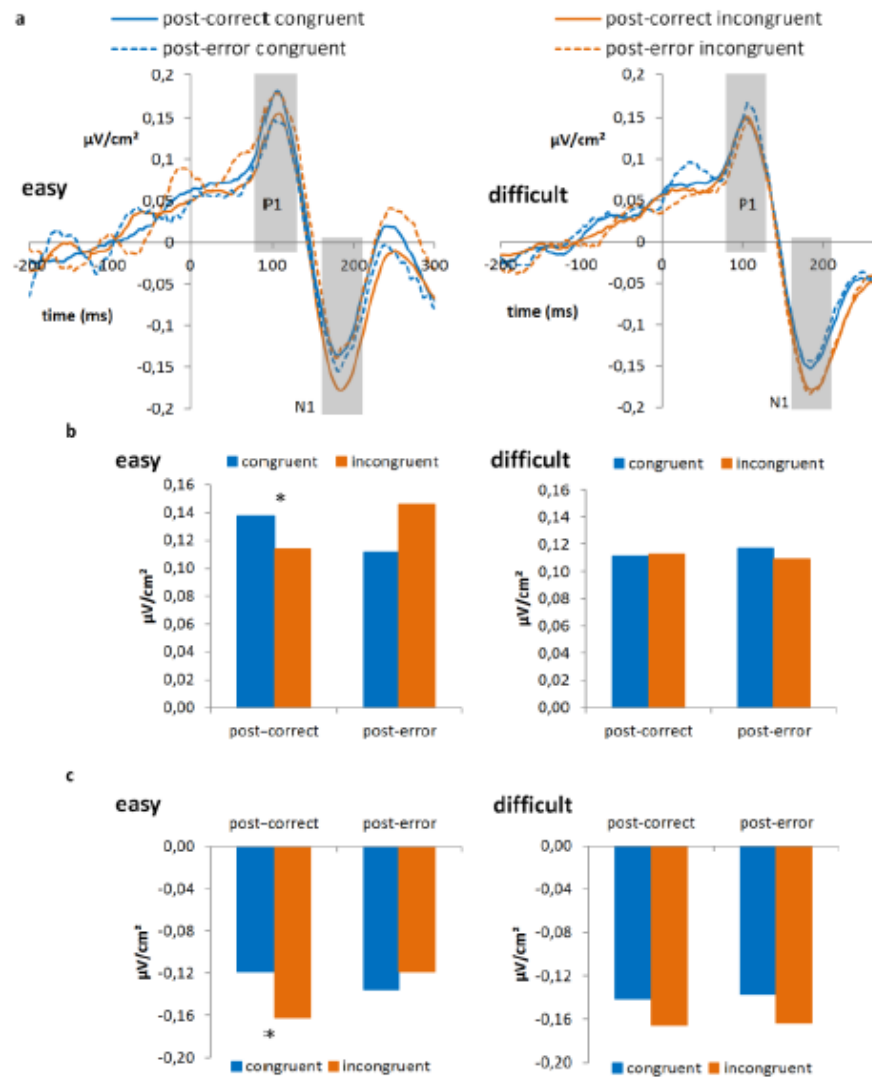


Figure 2. (a) Laplacian transformed grand average ERP waveforms at PO7 and PO8 showing the P1 (measured between 80 and 130 ms) and N1 (measured between 160 and 210 ms) as a function of previous accuracy and congruency separate for difficulty condition. On the bottom, average amplitude (in $\mu\text{V}/\text{cm}^2$) of the P1 (b) and late N1 (c) for congruent and incongruent stimuli following correct and erroneous trials are shown, separate for difficulty condition.

previous accuracy and current congruency was not significant. $F(1,15) = 0.03$, $p = 0.86$. No other interactions were significant, all $ps \geq 0.20$. These

results indicate that top-down attentional modulation by stimulus characteristics is disturbed after errors.

N2. There were no significant main effects or interactions for N2 amplitude, all $ps \geq 0.11$.

P3. Looking at P3-amplitude, there was a significant main effect of previous accuracy, $F(1,15) = 10.49$, $p < 0.01$, showing that mean amplitude was more positive following correct trials ($0.22 \mu\text{V}/\text{cm}^2$) than following error trials ($0.18 \mu\text{V}/\text{cm}^2$). There was also a marginally significant main effect of current congruency, $F(1,15) = 3.60$, $p = 0.08$, showing a more positive amplitude for congruent trials ($0.21 \mu\text{V}/\text{cm}^2$) than for incongruent trials ($0.19 \mu\text{V}/\text{cm}^2$). The interaction of previous accuracy and current congruency was also significant, $F(1,15) = 5.45$, $p = 0.03$. Following correct trials, there was no significant difference in amplitude for congruent and incongruent trials (resp. 0.22 and $0.22 \mu\text{V}/\text{cm}^2$), $F(1,15) = 0.29$, $p = 0.59$. Following an error however, P3-amplitude for congruent trials ($0.20 \mu\text{V}/\text{cm}^2$) was significantly higher for congruent trials ($0.20 \mu\text{V}/\text{cm}^2$) than for incongruent trials ($0.16 \mu\text{V}/\text{cm}^2$), $F(1,15) = 5.66$, $p = 0.03$. There was also a marginally significant interaction of difficulty and previous congruency, $F(1,15) = 3.92$, $p = 0.07$. In the easy condition, there was no significant difference in P3-amplitude following incongruent and congruent trials, (resp. 0.20 and $0.20 \mu\text{V}/\text{cm}^2$), $F(1,15) = 0.15$, $p = 0.70$. In the hard condition, P3-amplitude was significantly higher following congruent trials ($0.22 \mu\text{V}/\text{cm}^2$) than following incongruent trials ($0.20 \mu\text{V}/\text{cm}^2$), $F(1,15) = 5.69$, $p = 0.03$. No other main effect or interactions were significant, all $ps \geq 0.20$.

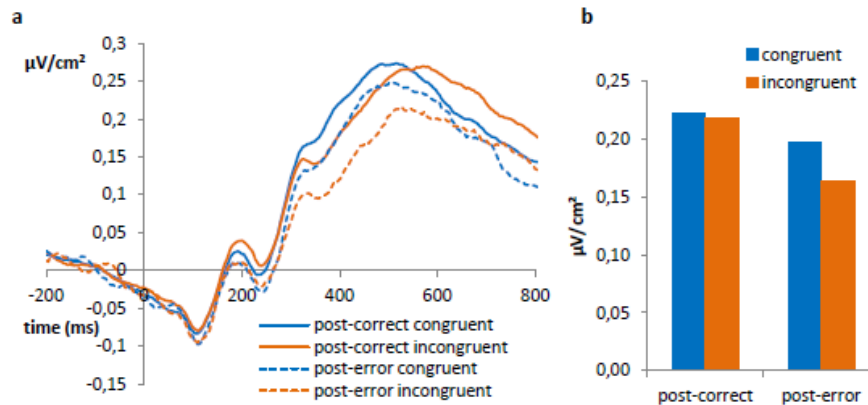


Figure 3. (a) Laplacian transformed grand average ERP waveforms at CPz, measured between 300 and 700 ms, as a function of accuracy and congruency. On the right side (b) average amplitude (in $\mu\text{V}/\text{cm}^2$) of the P3 for congruent and incongruent stimuli following correct and erroneous trials are shown.

CORRELATIONS

In the easy condition, we did not observe a significant correlation between any of the error-related components and the observed error-related changes on the P1 and late N1, all $ps \geq 0.66$. There was however, a significant correlation between P3 and the late Pe, $r(16) = -0.58$, $p = 0.02$. Importantly, removing one on-line outlier rendered this correlation nonsignificant, $r(15) = -0.37$, $p = 0.17$. There was no significant correlation between P3 and ERN or early Pe, both $p \geq 0.36$. The P1-effect (larger P1 for congruent trials following correct trials) did correlate significantly with the effect in error rates (larger congruency effect following correct trials), $r(16) = 0.55$, $p = 0.03$, however, when removing one outlier, this correlation turned nonsignificant, $r(15) = 0.45$, $p = 0.09$. Neither the late N1 nor P3 effect correlated significantly with any of the behavioural measures, all $ps \geq 0.24$.

In the hard condition, there was no significant correlation between the ERN or late Pe and the P1, late N1 and P3, all $ps \geq 0.10$. These components did correlate significantly with the early Pe, respectively;

$r(16) = 0.52, p = 0.04, r(16) = 0.59, p = 0.02$ and $r(16) = -0.61, p = 0.01$. However removing one outlier, because of a rather large negative value for the early Pe, rendered all these correlations nonsignificant, all $ps \geq 0.18$. Moreover, the P1, late N1 and P3 effect did not correlate significantly with the observed effects in reaction times and error rates, all $ps \geq 0.40$.

DISCUSSION

We investigated the effect of errors on conflict processing in an easy and difficult flanker task. Behaviourally, there was post-error slowing, which did not differ over conditions. More errors were made on incongruent trials in the easy condition than in the hard condition. In line with previous reported results, a modulation of the congruency effect by previous accuracy was only found following congruent trials (Van der Borgh, Duthoo, et al., 2015) and was predominantly influenced by post-*correct* rather than post-error trials.

The ERN/CRN and early Pe/Pc difference was smaller in the hard condition than in the easy condition in line with the idea that these components decrease when uncertainty about the response increases (Endrass, Klawohn, Gruetzmann, Ischebeck, & Kathmann, 2012; Endrass, Klawohn, Preuss, et al., 2012; Pailing & Segalowitz, 2004). This difference between conditions was not found for the late Pe/Pc, indicating that this component reflects a different process, such as error awareness (Endrass, Klawohn, Preuss, et al., 2012), than the early Pe/Pc, which is believed to be a continuation of the ERN (Wessel, 2012) reflecting response evaluation independent of outcome. However, the ERN and early Pe cannot be completely related, as the ERN was also influenced by current congruency with larger amplitudes on congruent trials (Scheffers & Coles, 2000), whereas the early Pe was not.

Surprisingly, we did not find an effect of congruency nor previous congruency on N2-amplitude. The N2 indexes the amount of conflict and significant differences have been reported between congruent and incongruent trials (Clayson & Larson, 2011; Larson et al., 2012; Van Veen & Carter, 2002). However, ambiguous stimulus sets also elicit response conflict, as reflected in an enhanced N2-amplitude (Szmalec et al., 2008). Additionally, as N2-amplitude was not influenced by previous accuracy, this indicates that there was also no modulation of cognitive control following an error and subsequently, present reported results of PERI in the easy condition cannot be unambiguously linked to increased cognitive control following an error.

Interestingly in the easy condition, there is an effect of congruency following correct trials for both the P1 and N1. While P1-amplitude is enhanced for congruent trials, N1-amplitude is more negative for incongruent trials. Previous research indicated that N1-amplitude is influenced by endogenous attention while P1 amplitude can be influenced by both exogenous and endogenous attention (Hopfinger & West, 2006). Our results therefore suggest that more attention was directed to the incongruent trials while participants relied more on exogenous attention on congruent trials. Surprisingly, this pattern of results is only found in the easy condition. At this stage, we cannot give a conclusive explanation for why this pattern is not observed in the difficult condition as there are several important differences. In the easy condition, only two types of brackets were used (i.e. “{ } []”), which were more visually distinguishable, and easier in terms of response mappings. In the hard condition stimulus ambiguity was increased by the usage of four types of brackets (i.e., “{ } [] | | ()”) and multiple response mappings which changed after each block. Perhaps the overall difficulty, both in terms of visual processes and in terms of response selection, was so demanding that no differences between congruent and incongruent trials were observed. Most important, in the easy condition, the modulation of the P1 and N1 by congruency disappears after an error. This suggests that any

influence of conflict on early visual processing is disturbed following an error.

While these early visual components are seldom investigated in conflict tasks, contrary to our findings, Scerif and colleagues (2006) found enhanced P1 amplitude for incongruent trials following incongruent trials, thereby concluding that context-driven cognitive control can modulate early stimulus processing. Interestingly, we did find a marginally significant increase in P1 amplitudes following incongruent trials in the hard condition, but only for post-correct trials, indicating that any influence of cognitive control on attention is disturbed following an error.

Overall there was no clear modulation of late N1 by previous accuracy. While our main goal was to investigate conflict-related processing following errors, we still expected to find some overall modulation by previous accuracy in this task as the results of our dual task paradigm did not reveal differences between the short (500 ms) and the long (1000 ms) inter-trial interval condition. However, it is possible that the attenuated attention previously found, is at least partly related to the switching of task-sets since the use of a rather long intertrial interval in this task, might have given participants the time to re-orient their attention to the task at hand, which could be a longer process when task demands change between trials.

Similar to our previous finding, the P3 amplitude was significantly smaller following an erroneous trial than following a correct trial, indicating that memory updating is worse following an error. Interestingly, for this component a difference is found for congruent and incongruent trials but only following an erroneous response. However, contrary to previous findings (Clayson & Larson, 2011) P3-amplitude

was reduced for incongruent trials. This result again reflects impaired conflict processing following an error.

It is worth noting that while the PERI-effect in error rates was modulated by previous congruency, with significant PERI in the easy condition and inverse PERI in the hard condition but only following congruent trials, in line with the idea that conflict adaptation is more effective after congruent trials (Compton, Huber, Levinson, & Zheutlin, 2012; Lamers & Roelofs, 2011), no such modulations were found in the reported ERPs. Interestingly however, the conflict sequence effect is also, at least partly, influenced by lower-level memory confounds such as contingency learning and feature repetition (Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014; Hommel, Proctor, & Vu, 2004; Mordkoff, 2012; Schmidt & De Houwer, 2011). While using a design devoid of feature repetitions or contingency learning can eliminate the conflict sequence effect (Schmidt & De Houwer, 2011), we recently illustrated that this can also eliminate the difference between post-congruent and post-incongruent trials in terms of the PERI-effect (Van der Borgh, Duthoo, et al., 2015). As we did not control for these confounds in the current experiment, the reported four-way interaction in error rates can therefore be driven by those confounds.

Overall our results show that differential early visual processing of congruent and incongruent trials disappears following an error, indicating reduced influence of conflict processing. Additionally, N2-amplitude did not differ following a correct or an erroneous trial, contrasting the idea that cognitive control is heightened following an error. Interestingly, while early visuo-attentional processes did differ in the easy condition, overall N2 amplitude might have been influenced by the characteristics of the difficult condition, indicating that participants did not discern between the easy and difficult blocks as separate tasks and entertained an overall task set of increased cognitive control. While there is no evidence that overall early visual processing is increased or decreased on post-error trials, our results indicate that early visual processing following an error

is less impaired when the inter-trial interval is sufficiently long while visuo-attentional processing related to conflict and memory updating is reduced following an error, possibly leading to PERI as post-correct early visual processing is influenced by conflict.

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REFERENCES

- Appelbaum, L. G., Smith, D. V., Boehler, C. N., Chen, W. D., & Woldorff, M. G. (2011). Rapid modulation of sensory processing induced by stimulus conflict. *Journal of Cognitive Neuroscience*, 23(9), 2620–8. doi:10.1162/jocn.2010.21575
- Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, 108(3), 624–652. doi:10.1037/0033-295X.108.3.624
- Clayson, P. E., & Larson, M. J. (2011). Conflict adaptation and sequential trial effects: support for the conflict monitoring theory. *Neuropsychologia*, 49(7), 1953–61. doi:10.1016/j.neuropsychologia.2011.03.023
- Compton, R. J., Huber, E., Levinson, A. R., & Zheutlin, A. (2012). Is “conflict adaptation” driven by conflict? Behavioral and EEG evidence for the underappreciated role of congruent trials. *Psychophysiology*, 49(5), 583–589. doi:10.1111/j.1469-8986.2012.01354.x
- Danielmeier, C., & Ullsperger, M. (2011). Post-error adjustments. *Frontiers in Psychology*, 2, 233. doi:10.3389/fpsyg.2011.00233
- Duthoo, W., Abrahamse, E. L., Braem, S., Boehler, C. N., & Notebaert, W. (2014). The heterogeneous world of congruency sequence effects: an update. *Frontiers in Psychology*, 5(1001). doi:10.3389/fpsyg.2014.01001
- Endrass, T., Klawohn, J., Gruetzmann, R., Ischebeck, M., & Kathmann, N. (2012). Response-related negativities following correct and incorrect responses: evidence from a temporospatial principal component analysis. *Psychophysiology*, 49(6), 733–743. doi:10.1111/j.1469-8986.2012.01365.x
- Endrass, T., Klawohn, J., Preuss, J., & Kathmann, N. (2012). Temporospatial dissociation of Pe subcomponents for perceived and unperceived errors. *Frontiers in Human Neuroscience*, 6, 178. doi:10.3389/fnhum.2012.00178
- Falkenstein, M., Hohnsbein, J., Hoormann, J., & Blanke, L. (1991). Effects of crossmodal divided attention on late ERP components. II. Error processing in choice reaction tasks. *Electroencephalography and Clinical Neurophysiology*, 78, 447–455. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/1712280>
- Folstein, J. R., & Van Petten, C. (2008). Influence of cognitive control and mismatch on the N2 component of the ERP: a review. *Psychophysiology*, 45(1), 152–70. doi:10.1111/j.1469-8986.2007.00602.x
- Gehring, W., Goss, B., & Coles, M. (1993). A neural system for error detection and compensation. *Psychological Science*, 4(6), 385–390. Retrieved from <http://pss.sagepub.com/content/4/6/385.short>

- Hommel, B., Proctor, R. W., & Vu, K.-P. L. (2004). A feature-integration account of sequential effects in the Simon task. *Psychological Research*, *68*(1), 1–17. doi:10.1007/s00426-003-0132-y
- Hopfinger, J. B., & West, V. M. (2006). Interactions between endogenous and exogenous attention on cortical visual processing. *NeuroImage*, *31*(2), 774–89. doi:10.1016/j.neuroimage.2005.12.049
- Houtman, F., & Notebaert, W. (2013). Blinded by an error. *Cognition*, *128*(2), 228–236. doi:10.1016/j.cognition.2013.04.003
- Houtman, F., Núñez Castellar, E., & Notebaert, W. (2012). Orienting to errors with and without immediate feedback. *Journal of Cognitive Psychology*, *24*(3), 278–285. doi:10.1080/20445911.2011.617301
- Jentsch, I., & Dudschig, C. (2009). Why do we slow down after an error? Mechanisms underlying the effects of posterror slowing. *Quarterly Journal of Experimental Psychology*, *62*(2), 209–218. doi:10.1080/17470210802240655
- Lamers, M. J. M., & Roelofs, A. (2011). Attentional control adjustments in Eriksen and Stroop task performance can be independent of response conflict. *Quarterly Journal of Experimental Psychology*, *64*(6), 1056–1081. doi:10.1080/17470218.2010.523792
- Larson, M. J., Clayton, P. E., & Baldwin, S. a. (2012). Performance monitoring following conflict: internal adjustments in cognitive control? *Neuropsychologia*, *50*(3), 426–33. doi:10.1016/j.neuropsychologia.2011.12.021
- Luck, S., Heinze, H., Mangun, G., & Hillyard, S. (1990). Visual event-related potentials index focused attention within bilateral stimulus arrays. II. Functional dissociation of P1 and N1 components. *Electroencephalography and Clinical Neurophysiology*, *75*, 528–542. Retrieved from <http://www.sciencedirect.com/science/article/pii/001346949090139B>
- Mordkoff, J. T. (2012). Observation: Three reasons to avoid having half of the trials be congruent in a four-alternative forced-choice experiment on sequential modulation. *Psychonomic Bulletin & Review*, *19*(4), 750–757. doi:10.3758/s13423-012-0257-3
- Notebaert, W., Houtman, F., Opstal, F. Van, Gevers, W., Fias, W., & Verguts, T. (2009). Post-error slowing: an orienting account. *Cognition*, *111*, 275–279. doi:10.1016/j.cognition.2009.02.002
- Pailing, P. E., & Segalowitz, S. J. (2004). The effects of uncertainty in error monitoring on associated ERPs. *Brain and Cognition*, *56*(2), 215–233. doi:10.1016/j.bandc.2004.06.005
- Polich, J. (2007). Updating P300: an integrative theory of P3a and P3b. *Clinical Neurophysiology*, *118*(10), 2128–2148. doi:10.1016/j.clinph.2007.04.019
- Ridderinkhof, K. R. (2002). Micro- and macro-adjustments of task set: activation and suppression in conflict tasks. *Psychological Research*, *66*(4), 312–323. doi:10.1007/s00426-002-0104-7

- Scerif, G., Worden, M. S., Davidson, M., Seiger, L., & Casey, B. J. (2006). Context modulates early stimulus processing when resolving stimulus-response conflict. *Journal of Cognitive Neuroscience*, *18*(5), 781–92. doi:10.1162/jocn.2006.18.5.781
- Scheffers, M. K., & Coles, M. G. H. (2000). Performance monitoring in a confusing world: Error-related brain activity, judgments of response accuracy, and types of errors. *Journal of Experimental Psychology: Human Perception and Performance*, *26*(1), 141–151. doi:10.1037//0096-1523.26.1.141
- Schmidt, J., & De Houwer, J. (2011). Now you see it, now you don't: controlling for contingencies and stimulus repetitions eliminates the Gratton effect. *Acta Psychologica*, *138*(1), 176–186. doi:10.1016/j.actpsy.2011.06.002
- Steinborn, M. B., Flehmig, H. C., Bratzke, D., & Schröter, H. (2012). Error reactivity in self-paced performance: Highly-accurate individuals exhibit largest post-error slowing. *Quarterly Journal of Experimental Psychology*, *65*(4), 624–31. doi:10.1080/17470218.2012.660962
- Szmalec, A., Verbruggen, F., Vandierendonck, A., De Baene, W., Verguts, T., & Notebaert, W. (2008). Stimulus ambiguity elicits response conflict. *Neuroscience Letters*, *435*(2), 158–162. doi:10.1016/j.neulet.2008.02.023
- Van der Borght, L., Braem, S., & Notebaert, W. (2014). Disentangling posterror and postconflict reduction of interference. *Psychonomic Bulletin & Review*. doi:10.3758/s13423-014-0628-z
- Van der Borght, L., Duthoo, W., & Notebaert, W. (2015). *A neutral measure for post-error reduction of interference*. Manuscript submitter for publication.
- Van der Borght, L., Houtman, F., Burle, B., & Notebaert, W. (2015). *Distinguishing the influence of task difficulty on error-related ERPs using surface Laplacian transformation*. Manuscript submitted for publication.
- Van der Borght, L., Schevernels, H., Burle, B., & Notebaert, W. (2015). *Errors disrupt subsequent early attentional processes*. Manuscript in preparation.
- Van Veen, V., & Carter, C. S. (2002). The timing of action-monitoring processes in the anterior cingulate cortex. *Journal of Cognitive Neuroscience*, *14*(4), 593–602. doi:10.1162/08989290260045837
- Wessel, J. R. (2012). Error awareness and the error-related negativity: evaluating the first decade of evidence. *Frontiers in Human Neuroscience*, *6*, 88. doi:10.3389/fnhum.2012.00088

CHAPTER 8

IMPROVED MEMORY FOR ERROR FEEDBACK¹

Surprising feedback in a general knowledge test leads to an improvement in memory for both the surface features and the content of the feedback (Fazio & Marsh, 2009). Based on the idea that in cognitive tasks, error are surprising (the orienting account, Notebaert et al., 2009), we tested whether error feedback would be better remembered than correct feedback. Coloured words were presented as feedback signals in a flanker task, where the colour indicated the accuracy. Subsequently, these words were again presented during a recognition task (Experiment 1) or a lexical decision task (Experiment 2 and 3). In all experiments, memory was improved for words seen as error feedback. These results are compared to the attentional boost effect (Spataro et al., 2013) and related to the orienting account for post-error slowing (Notebaert et al., 2009).

¹Van der Borgh, L, Schoupe, N, & Notebaert, W. (in press). Improved memory for error feedback. *Psychological Research*.

INTRODUCTION

Goal-directed behaviour requires constant monitoring of action outcomes and in this respect external performance feedback is invaluable. How people process performance feedback and how they adapt their behaviour accordingly has been the subject of an extensive set of studies. Learning from errors or error feedback has typically been measured in choice reaction tasks by calculating reaction time and accuracy differences between post-error and post-correct trials. In these tasks, it is typically postulated that error detection leads to an upregulation of cognitive control which in turns leads to strategically slowing following an error (i.e. post-error slowing, PES) in order to increase accuracy (Botvinick, Braver, Barch, Carter, & Cohen, 2001). However post-error accuracy increase (PIA) is not unequivocally found in the literature (for an overview see Danielmeier & Ullsperger, 2011). In response to this lack of evidence for a speed-accuracy trade-off, a recent theoretical framework has in fact tied errors and error feedback to attention processes. More specifically, Notebaert and colleagues (2009) have postulated that errors are surprising, causing an attentional orienting towards these events and consequently distracting participants from the task and thereby causing PES (i.e., *the orienting account*; see also Houtman & Notebaert, 2013). Interestingly a correlation between PES and the P3a, an electrophysiological component linked to attention (Polich, 2007; Simons, Graham, Miles, & Chen, 2001), has been found (Núñez Castellar, Kühn, Fias, & Notebaert, 2010). Ernst and Steinhauser (2012) found a similar relation between the P3a and P3b and learning from corrective feedback, suggesting that attentional orienting to feedback is crucial for learning.

A logical prediction from the orienting account is that the attention-grabbing error feedback should be better remembered compared to the

less salient correct feedback. Interestingly this prediction resembles a well-known phenomenon in memory literature called the hypercorrection effect (Butterfield & Metcalfe, 2006). This effect shows that when using a general knowledge test with corrective feedback, high-confidence errors are more likely to be corrected after feedback than low confidence errors. Butterfield and Metcalfe (2006) demonstrated that this effect is best explained by enhanced attentional capture due to the surprising or unexpected feedback. Interestingly increased attention to feedback also influences memory for the feedback's appearance. Indeed Fazio & Marsh (2009) demonstrated that feedback for high confidence errors and low-confidence correct answers led to an improvement in memory for both the surface features (ink colour) as well as the content of the surprising feedback.

General knowledge tests (e.g., "What is the longest river in South America?") differ substantially from the serial reaction time tasks typically used to investigate post-error slowing. In experiments in which corrective feedback is used (e.g., "The Amazon is the longest river in South America"), the feedback presents novel (and unexpected) information to the participant. In serial reaction time tasks, however, the feedback merely indicates whether the answer was correct or wrong. Research shows that participants might not even rely on this external feedback signal as post-error adaptations are present with and without feedback (Houtman, Núñez Castellar, & Notebaert, 2012). Finding improved memory for error feedback, or characteristics of this error feedback, would indicate that error or error feedback, in serial reaction time tasks trigger an automatic attentional capture, as postulated by the orienting account.

To explicitly test the hypothesis that memory for error feedback is better than memory for correct feedback, we first administered a flanker task (Eriksen & Eriksen, 1974) in which we presented irrelevant coloured words as feedback stimuli. The colour of the words conveyed information on the accuracy of the responses, while the meaning was completely

irrelevant. Participants were informed that the words were presented in 3 colours, one colour for error feedback, one for correct feedback and one colour, white, did not convey information about the accuracy. In a subsequent phase the words seen as error or correct feedback were tested using a recognition task (Experiment 1) or a lexical decision task (Experiment 2 and 3).

EXPERIMENT 1

METHOD

Participants

Forty students at Ghent University (2 males) participated in this study (mean age = 23 years, $SD = 4.2$ years). Their native language was Dutch and the participants reported not to be colour-blind. The participants were paid 10 Euros for approximately an hour.

Stimuli and material

Stimuli were presented on a 17-inch computer screen. The viewing distance was about 50 cm. The stimuli of the flanker task consisted of 5 arrows (e.g., <<<<<) presented in white on a black screen. Four lists of 20 words (see Appendix A) were selected based on the list of Hermans & Houwer (1994), in which words received an affective rating from 1 (negative) to 7 (positive). Target words were selected to be as neutral as possible ($M = 4.0$, $SD = 0.49$). The lists were matched on affective score, frequency, number of neighbors and length (all $ps \geq 0.90$). A filler list of 100 words was also selected. These words did not differ significantly from the 80 target words for frequency, number of neighbors and length (all $ps \geq 0.22$). The four lists of words were randomized using a latin square design to ensure that every list could be seen following an error or

a correct response or as new stimuli in the last task. Words were presented in white, cyan (RGB: 0, 255, 255) or yellow (RGB: 255, 255, 0). Responses were recorded using a Cedrus response box. The experiment was conducted using Tscope software (Stevens, Lammertyn, Verbruggen, & Vandierendonck, 2006).

Procedure

The experiment consisted of three tasks and lasted approximately 15 minutes in total. For the remainder of the hour an unrelated experiment was conducted. In the flanker task participants had to respond to the middle arrow by pressing the left (right) key when the arrow pointed to the left (right). All four flanker stimuli always had the same direction. Both congruent (all stimuli point to the same direction) and incongruent trials (target stimulus points to a different direction) were presented with the same probability. Each trial started with a fixation cross for 500 ms. Subsequently five arrows were presented for 100 ms followed by a mask (#####) for 150 ms. Participants had to respond within 700 ms of stimulus presentation. In the practice block, consisting of 50 trials, participants were presented with feedback. When no response was given the words “te traag” (“too slow” in Dutch) were printed in white on the screen. For a correct response the participants saw “juist” (“correct” in Dutch) or “fout” (“wrong” in Dutch) either in cyan or yellow. The feedback was presented for 150 ms, starting directly after response execution, after which a blank screen was presented for 500 ms. A new trial started with the presentation of the fixation cross for 500 ms, resulting in an inter-trial interval of 1000 ms. In the experimental phase, feedback consisted of Dutch words in three possible colours (cyan, yellow or white). Participants were informed that white words did not convey any information about the accuracy. Twenty words were presented in cyan after a correct response, while twenty different words were presented in yellow following an error. The exact colour was counterbalanced and matched the colour of the feedback in the practice block. Because participants usually make fewer errors than correct

responses, on average only one of three correct trials was followed by a coloured word. These trials were selected randomly. Following the other trials, as well as trials on which participants responded very fast (< 100 ms), irrespective of the correctness of their response, and when all relevant words following an error or correct response were seen, a white filler word was presented. In total, the flanker task consisted of 500 trials, with a break after every 200 trials, however when all 40 relevant words were seen by the participant the experiment terminated. As in the practice phase, when no response was given “te traag” (“too slow” in Dutch) was presented.

As an unrelated filler task, participants filled in the Dutch version of the BIS/BAS questionnaire (Carver & White, 1994; Franken, Muris, & Rassin, 2005) on the computer. Following this questionnaire a recognition task was administered consisting of the 40 words (20 as correct feedback and 20 as error feedback) seen in the flanker task and 40 new words, all presented in white. Participants were instructed to press right when a new word was presented and left when an old word was presented or vice versa. A trial started with the presentation of a fixation cross for 500 ms followed by the presentation of a word until a response was given.

RESULTS

In the flanker task, trials faster than 100 ms and trials exceeding the response deadline as well as subsequent trials were discarded. The first trial was also removed. In total 10% of the data was removed. The mean response time was 407 ms ($SD = 51$ ms). The mean accuracy rate was 73% ($SD = 14\%$). On average participants needed 133 trials ($SD = 63$) to see all relevant feedback words. In 85% of the cases, fillerwords ($SD = 18\%$) were presented following a correct response.

For the recognition task, trials where a response occurred earlier than 100 ms and trials where the reaction time exceeded 2.5 SD from the participant's mean RT (calculated for each condition) were discarded. In total 2.8 % of the data was removed. The mean response time in the recognition task was 751 ms ($SD = 172$ ms). The mean accuracy rate was 58% ($SD = 8\%$).

The results of the flanker task were analyzed using linear mixed effects models as implemented in the R-package lme4 (Bates, Maechler, Bolker, & Walker, 2013). A maximal linear mixed effects model with a random effect for subject was used (Barr, Levy, Scheepers, & Tily, 2013). Error rates were analyzed using a logistic link function. For reaction times F -statistics with Kenward-Roger adjustment of the degrees of freedom (Kenward & Roger, 1997) are reported. Additionally, we investigated correlations between post-error adjustments on the flanker task and differences between words seen as error feedback and correct feedback on the recognition task. For uniformity all difference scores are calculated as the performance following an error reduced with the performance following a correct response.

When looking at post-error adaptations in the flanker task, we did not find a significant difference in accuracy, $\chi^2(1) = 1.55$, $p = 0.21$, nor did we find a significant difference in reaction time, $F(1,38.75) = 0.09$, $p = 0.76$. Hence, in general, we did not find evidence for an overall post-error increase in accuracy effect, nor overall post-error slowing. There was a significant correlation between PES and overall accuracy on the flanker task, $r(40) = 0.43$, $p < 0.01$, indicating that participants with higher overall accuracy produced more PES. This correlation is in line with the orienting account which predicts more PES when accuracy is high (Houtman et al., 2012; Steinborn, Flehmig, Bratzke, & Schröter, 2012). The correlation between PIA and overall accuracy was not significant, $r(40) = -0.16$, $p = 0.34$.

We calculated d' (Macmillan & Creelman, 2005) to evaluate whether participants could discern between old and new words. For every participant, a correct 'old' response on old words was identified as a hit, while an 'old' response on a new word was counted as a false alarm. Using the z-transformed hit and false alarm rates, d' was calculated as the difference between the hit and the false alarm rate. An average d' of zero indicates chance performance, while d' becomes larger when the ability to discriminate between the signals increases. Not surprisingly, participants were able to discriminate between old and new words ($d' = 0.46$), $t(39) = 5.37$, $p < 0.001$. Next we calculated d' separately for words seen after an error and after a correct response, e.g. for d' error feedback a correct 'old' response on words previously seen as an error was counted as a hit, while the false alarm rate again corresponds to an 'old response' for a new word. Using a paired samples t -test, the difference in d' between words seen following an error (0.53) and words seen following a correct response (0.39) was significant, $t(39) = 2.58$, $p < 0.05$ (see figure 1a). This difference in d' did not correlate with PIA, $r(40) = -0.12$, $p = 0.46$. There was however a significant correlation with PES in the flanker task, $r(40) = 0.35$, $p < 0.05$. Participants with more PES also showed a larger difference in d' (see Figure 1b). This correlation remained significant even when selecting only flanker trials following relevant feedback, $r(40) = 0.35$, $p < 0.05$.

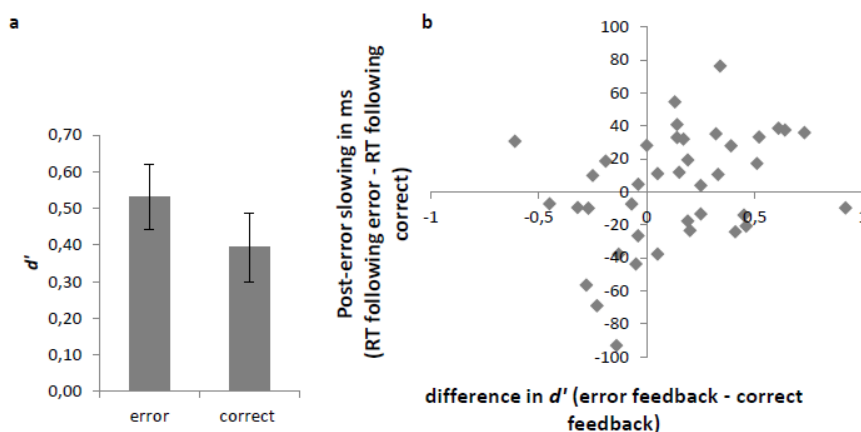


Figure 1. (a) Average d' for error feedback and correct feedback. d' is calculated as the z-score of hits, i.e. correct old responses, minus the z-score of false alarms, i.e. incorrect old responses, for words seen as error or correct feedback in the flanker task separately. Error bars represent 95% confidence intervals around the means. (b) Scatter plot of post-error slowing in the flanker task and the difference in d' for words seen as error feedback and correct feedback. Larger post-error slowing is correlated with a larger difference in d' .

EXPERIMENT 2

In Experiment 1 we used a recognition task to test memory for feedback signals. The results showed that memory for error feedback was indeed improved. Additionally, this improvement was related to the amount of PES in the preceding flanker task. To follow up on these results, and replicate our effect using a different memory task, we conducted Experiment 2, where memory for feedback words was tested using a lexical decision task.

METHOD

Participants

Forty students at Ghent University (8 males) participated in this study (mean age = 22 years, $SD = 4.7$ years). Their native language was Dutch

and the participants reported not to be colour-blind. The participants were paid 10 Euros for approximately an hour.

Stimuli and procedure

Stimuli and material were identical to Experiment 1. The same lists of words (see Appendix A) were used. To ensure the same duration as Experiment 1, only 20 new words were added for the lexical decision task therefore each participant did not see one particular list. Also, 80 nonwords were constructed using WinWordGen (Duyck, Desmet, Verbeke, & Brysbaert, 2004). These words were matched with the target words for number of neighbors and length (both $p \geq 0.94$).

The procedure was identical to Experiment 1 but now a lexical decision task was administered consisting of 60 nonwords, 40 words seen in the flanker task and 20 new words. Participants were instructed to press right when a word was presented and left when a nonword was presented or vice versa. The assignment of button presses (left vs. right) to word type (word vs. nonword) was counterbalanced across participants. A trial started with the presentation of a fixation cross for 500 ms followed by the presentation of a word or nonword until the response deadline was exceeded. There was a short break after 60 trials.

RESULTS

One participant was removed from the dataset due to an unusual low accuracy score (> 3 SD) on the lexical decision task.

In the flanker task, trials faster than 100 ms or trials exceeding the response time as well as subsequent trials were discarded. The first trial was also removed. In total 20% of the data was removed. The mean response time of the remaining 39 participants was 388 ms ($SD = 67$ ms). The mean accuracy rate was 72% ($SD = 12\%$). On average participants

needed 125 trials ($SD = 51$) to view all relevant words. Fillerwords were presented mostly following a correct response (86%, $SD = 18\%$).

For the lexical decision task, trials where a response occurred earlier than 100 ms and trials where the reaction time exceeded 2.5 SD from the participant's mean RT (calculated for each condition) were discarded. In total 2.8% of the data was removed. The mean response time of the remaining 39 participants was 632 ms ($SD = 111$ ms). The mean accuracy rate was 95% ($SD = 3\%$).

The results were again analyzed using a maximal linear mixed effects model with a random effect for subject (Barr, Levy, Scheepers, & Tily, 2013). For the analysis of the lexical task a random effect for item was included.

When considering post-error adaptations in the flanker task, we did not find a significant difference in accuracy, $\chi^2(1) = 0.11$, $p = 0.74$. There was a significant difference in reaction time, $F(1,37.48) = 6.36$, $p < 0.05$, showing slower reaction times following an error (396 ms) than following a correct response (386 ms). The correlation between PES and overall accuracy on the flanker task was marginally significant, $r(39) = 0.31$, $p = 0.06$, again indicating that participants with higher overall accuracy showed more post-error slowing. The correlation between PIA and overall accuracy was not significant, $r(39) = 0.19$, $p = 0.24$.

The results of the lexical decision task showed that there was a significant difference in reaction time between words and nonwords, $F(1,56.18) = 41.80$, $p < 0.001$, with faster responses for words (573 ms) compared to nonwords (660 ms). Comparing new words and words previously seen in the flanker task, there was again a significant difference in reaction time, $F(1,38.76) = 10.45$, $p < 0.01$, showing slower responses for new words (592 ms) than old words (565 ms). Finally there was no significant difference between error feedback (564 ms) and correct feedback words (565 ms), $F(1,35.03) = 0.02$, $p = 0.90$ (see figure 2).

Looking at accuracy, there was no significant difference between words (98%) and nonwords (97%), $\chi^2(1) = 0.83$, $p = 0.36$, or between new words (97%) and words previously seen in the flanker task (98%), $\chi^2(1) = 2.88$, $p = 0.09$. Interestingly, when comparing error feedback vs. correct feedback words, we found a significant difference in accuracy, $\chi^2(1) = 15.94$, $p < 0.001$, showing a higher accuracy for words seen following an error (99%) than words seen following a correct response (97%), see figure 2. There were no significant correlations between this difference in accuracy and post-error adaptations in the flanker task, all $ps \geq 0.62$. The difference in reaction time between words seen after an error and words seen after a correct response also did not correlate significantly with PES, $r(39) = -0.08$, $p = 0.63$. There was however a marginally significant correlation with PIA, $r(39) = 0.30$, $p = 0.06$, indicating that participants displaying post-error accuracy *increase* responded slower to words seen as error feedback than words seen as correct feedback. However selecting only flanker trials following relevant feedback made this correlation nonsignificant, $r(39) = -0.22$, $p = 0.18$.

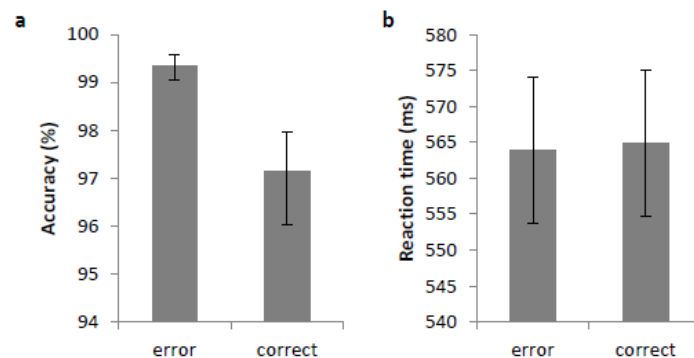


Figure 2. (a) Average accuracy (in percentages) and (b) reaction time (in milliseconds) for error feedback and correct feedback. Error bars represent 95% confidence intervals around the means.

EXPERIMENT 3

In Experiment 2 we used a lexical decision task to test memory for feedback. The results showed that accuracy was higher for words used as error feedback than for words used as correct feedback. There was no effect in reaction times. In a lexical decision task, it is rather unusual to find an effect in accuracy only. Our lexical decision task was relatively easy with overall high accuracies and fast reaction times. We therefore repeated the experiment using in a more difficult lexical decision task.

METHOD

Participants

Forty students at Ghent University (12 males) participated in this study (mean age = 23 years, $SD = 5.0$ years). Their native language was Dutch and the participants reported not to be colour-blind. The participants were paid 10 Euros for approximately an hour.

Stimuli and procedure

Using the Dutch Lexicon project 180 infrequent nouns, i.e. between 0 en 0.2 frequency per million, based on Dutch subtitles, were selected (Keuleers, Diependaele, & Brysbaert, 2010). Interestingly this database also includes an average reaction time and accuracy for each word. We selected 80 of these words which were devised in four groups of 20 words (appendix B). These four lists did not differ in frequency, length, number of neighbors, reaction time or accuracy; all $ps \geq 0.77$. The other 100 words were used as fillers in the flanker task. These words did not differ from the 80 targetwords in number of neighbours, $F(1, 178) = 2.23$, $p = 0.14$. The fillerwords did differ from the targetwords in length, targetwords were shorter (6.1 vs. 6.8), frequency, targetwords were more frequent (0.11 vs. 0.09), reaction time, targetwords were associated with slower responses (702 ms vs. 674 ms) and accuracy, targetwords were associated with lower accuracy (76% vs. 81%), all $ps \leq 0.03$. Also, 80

nonwords based on the 80 targetwords were constructed using Wuggy, a pseudoword generator (Keuleers & Brysbaert, 2010). These nonwords were matched with the targetwords in regard with length and number of neighbours, both $ps \geq 0.87$. The procedure was identical to Experiment 2.

RESULTS

One participant was removed from the dataset because not all relevant words were seen in the flanker task. Additionally two participants were removed from the dataset due to an unusual low accuracy score (> 3 SD) in the lexical decision or flanker task.

In the flanker task, trials faster than 100 ms or trials exceeding the response time as well as subsequent trials were discarded. The first trial was also removed. In total 13% of the data was removed. The mean response time of the remaining 37 participants was 460 ms ($SD = 43$ ms). The mean accuracy rate was 87% ($SD = 8\%$). On average participants needed 211 trials ($SD = 88$) to view all relevant words. In 98% of the cases ($SD = 8\%$) fillerwords were presented following a correct response.

For the lexical decision task, trials where a response occurred earlier than 100 ms and trials where the reaction time exceeded 2.5 SD from the participant's mean RT (calculated for each condition) were discarded. In total 3.8% of the data was removed. The mean response time of the remaining 37 participants was 860 ms ($SD = 189$ ms). The mean accuracy rate was 89% ($SD = 5\%$).

When considering post-error adaptations in the flanker task, there was a significant difference in accuracy, $\chi^2(1) = 4.26$, $p = 0.04$, indicating that participants were more correct following an error (91%) than following a correct response (88%), i.e. post-error accuracy *increase*. There was also a significant difference in reaction time, $F(1, 35.66) = 15.60$, $p < 0.001$, showing slower reaction times following an error (472 ms) than

following a correct response (459 ms). The correlation between PES and overall accuracy on the flanker task was marginally significant, $r(37) = 0.28$, $p = 0.09$, again indicating that participants with higher overall accuracy showed more post-error slowing. The correlation between PIA and overall accuracy was not significant, $r(37) = 0.17$, $p = 0.30$.

The results of the lexical decision task showed that there was a significant difference in reaction time between words and nonwords, $F(1, 66.58) = 4.37$, $p = 0.04$, with faster responses for words (841 ms) compared to nonwords (886 ms). Comparing new words and words previously seen in the flanker task, there was no significant difference in reaction time, $F(1, 24.22) = 1.90$, $p = 0.18$, respectively 859 and 833 ms. Interestingly there was a marginally significant difference between error feedback (806 ms) and correct feedback words (856 ms), $F(1, 34.59) = 3.46$, $p = 0.07$. Further inspection of the data revealed that there was a lot of variability over participants in their mean reaction time, range [576 ms, 1559 ms]. This variability over participants might influence the size of the effect, with slower reaction times leading to larger effects. Therefore, we calculated the standardized reaction time score for each participant on every trial. Using this standardized reaction time measure, there was a significant difference between error and correct feedback, $F(1, 36.94) = 4.25$, $p < 0.05$ with faster responses for words seen as error feedback (-0.19) compared to words seen as correct feedback (-0.02), see figure 3.

Looking at accuracy, there was a significant difference between words (91%) and nonwords (97%), $\chi^2(1) = 11.69$, $p < 0.001$. There was also a significant difference in accuracy between new words (88%) and words previously seen in the flanker task (93%), $\chi^2(1) = 17.76$, $p < 0.001$. Comparing error feedback vs. correct feedback words, there was no significant difference in accuracy, $\chi^2(1) = 0.77$, $p = 0.38$.

There were no significant correlations between the reported difference in reaction time and post-error adaptations in the flanker task, all $ps \geq 0.16$. The difference in accuracy between words seen after an error and words

seen after a correct response also did not correlate significantly with PES or post-error accuracy increase in the flanker task, both $ps \geq 0.19$.

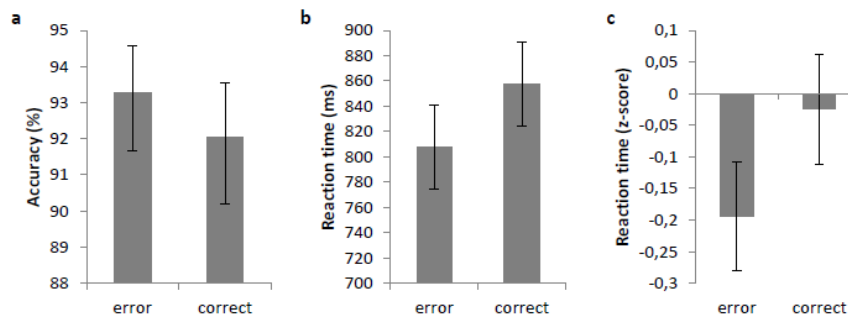


Figure 3. (a) Average accuracy (in percentages) and reaction time, respectively in milliseconds (b) and standardized (c) for error feedback and correct feedback. Error bars represent 95% confidence intervals around the means.

GENERAL DISCUSSION

The aim of this study was to investigate the processing of feedback stimuli and more specifically test the hypothesis that memory for error feedback is better than memory for correct feedback. Using a recognition task (Experiment 1) and lexical decision task (Experiment 2 and 3) in which a subset of words was previously seen as error or correct feedback in a flanker task, we could show that memory was indeed improved for words seen as error feedback. This was indicated by a larger d' in the recognition task and increased accuracy or faster reaction times in the lexical decision task for words seen as error feedback compared to words seen as correct feedback. Additionally, in Experiment 1 the difference in d' between words seen as error feedback and words seen as correct feedback was positively correlated with the amount of PES in the flanker task: the more PES, the larger the difference in d' .

In line with previous results in general knowledge tests (Butterfield & Metcalfe, 2006; Fazio & Marsh, 2009) and the orienting account

(Notebaert et al., 2009) our results shows that surprising/salient feedback automatically captures attention, thereby improving processing of irrelevant characteristics of this feedback. Additionally this effect did not rely on frequency since both coloured correct and incorrect feedback was presented equally in the flanker task. Therefore the attentional capture seems more related to salient, arousal-inducing events than merely unexpected, infrequent events.

While three types of feedback were used in the flanker task, in the second testing phase only coloured words (resp. instructed to participants as error feedback and correct feedback) were administered. As participants generally make fewer errors, these filler words were mainly seen on correct trials (resp. in 85, 86 and 98% of the trials). As such this category of words could provide useful information with regard to the influence of relative frequency as well as the necessity of instructing participants about the colour-related feedback to elicit this effect. However, in our design it was not possible to include these words in the recognition or lexical decision task as there were differences in word characteristics between the filler list and the target words and participants differed in the amount of words of the filler list seen.

Our results resemble a memory effect reported by Krebs, Boehler, De Belder, and Egner (2013). In their study participants had to identify faces that were previously presented as congruent, incongruent or neutral stimuli in a face-word Stroop task. The results showed improved memory for faces presented on incongruent trials. This effect was explained in terms of increased attention to task relevant information on incongruent trials, in line with the conflict monitoring theory (Botvinick et al., 2001). Because most of the errors in our tasks are made on incongruent trials (resp. 82% 83% and 90%), it is possible that an incongruent trial not only results in better memory for the relevant information, but also in better memory for the feedback. To test this we investigated the influence of congruency of the flanker trials on words seen as correct feedback. There was no significant effect of congruency of the flanker trial in both lexical

decision tasks, all $ps \geq 0.26$. In the recognition task d' was significantly *smaller* for correct feedback seen on incongruent trials (0.23) than correct feedback seen on congruent trials (0.52), $t(38) = -3.00$, $p < 0.01$, contrary to the results of Krebs and colleagues. Additionally, comparing correct and error feedback presented on incongruent trials again showed a larger d' -prime for error feedback (0.56) compared to correct feedback, $t(38) = 4.53$, $p < 0.001$, thereby replicating our initial findings. In sum, these additional results indicate that congruency of the flanker trial is not responsible for the observed effects².

The observed enhancement in memory for words seen as error feedback also resembles the recently described attentional boost effect, showing that stimuli occurring alongside a target stimulus are recognized better (Swallow & Jiang, 2010, 2012). Spataro, Mulligan, and Rossi-Arnaud (2013) replicated and extended this effect, showing improved explicit and implicit memory for words presented simultaneously with an infrequent target stimulus. The attentional boost effect is believed to reflect an enhancement in visual encoding elicited by the opening of an attentional gate resulting from a temporal attentional orienting response triggered by target detection (Swallow & Jiang, 2011, 2012). The event segmentation theory (Zacks, Speer, Swallow, Braver, & Reynolds, 2007), a theory of event perception, proposes that this gating mechanism is involved in the alerting to salient environmental changes, and links it to subcortical regions like the locus coeruleus or the nucleus basalis. In our Experiments, words were presented as error feedback, however only the colour of the word contained information. While word-processing is

² However, note that for these analyses we could not control for differences in word characteristics (such as frequency, number of neighbors and length) between words seen on congruent and incongruent trials.

believed to be, at least partly, automatic (e.g. standard Stroop effect, MacLeod, 1991), the additional processing of the error feedback, compared to correct feedback, can be seen as an attentional boost-like effect. This reasoning supports the idea that processing of error feedback profits from the orienting response triggered by an error. Interestingly, the locus coeruleus – norepinephrine system (LC-NE) is believed to facilitate the updating of neural representations to produce a cognitive shift, i.e. interruption of on-going behaviour and adaptation (Bouret & Sara, 2005). Because the occurrence of a novel unexpected event also triggers LC activation, it is conceivable that an orienting response towards an error or error feedback is the first step in learning and improving performance.

Although our results in general show a robust pattern, there are some aspects of the data that deserve some attention. First, surprisingly, there is no PES in Experiment 1. However, our design of the flanker task also results in rather small PES in Experiment 2 and 3 (resp. 10 and 13 ms). Moreover, in Experiment 1, PES does correlate with accuracy rate, suggesting that overall accuracy was too low to observe PES on average. Secondly, in Experiment 1, we also observed a correlation between PES and the memory effect for error feedback, while this correlation was not observed in Experiment 2 and 3, possibly due to a smaller range of PES (resp. [-27 ms, 67 ms] and [-36 ms, 49 ms] vs. [-93 ms, 76 ms] in Experiment 1). Finally, both in Experiment 2 and 3, a lexical decision task was administered to test memory for error and correct feedback. While Experiment 2 revealed an advantage for error feedback in terms of accuracy, Experiment 3 revealed an effect in reaction times. As previously noted, finding an effect only in accuracy is rather unusual for a lexical decision task (Albrecht & Vorberg, 2010; Coane & Balota, 2010; Spataro, Mulligan, & Rossi-Arnaud, 2013). We hypothesized that this might have been due to a floor effect in the reaction times. In Experiment 3, we therefore used infrequent words. In this more difficult experiment, we observed the advantage for error feedback in reaction times. This

suggests that task difficulty determines the locus of the effect. Although this certainly deserves more attention in further research, for the present purposes it is crucial that we observe a benefit for error feedback in both experiments.

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REFERENCES

- Albrecht, T., & Vorberg, D. (2010). Long-lasting effects of briefly flashed words and pseudowords in ultrarapid serial visual presentation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 36(5), 1339–45. doi:10.1037/a0019999
- Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language*, 68(3), 255–278. doi:10.1016/j.jml.2012.11.001
- Bates, D., Maechler, M., Bolker, B., & Walker, S. (2013). lme4: Linear mixed-effects models using Eigen and S4., R package version 1.0–5. Retrieved from <http://cran.r-project.org/package=lme4>
- Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, 108(3), 624–652. doi:10.1037/0033-295X.108.3.624
- Bouret, S., & Sara, S. J. (2005). Network reset: a simplified overarching theory of locus coeruleus noradrenaline function. *Trends in Neurosciences*, 28(11), 574–582. doi:10.1016/j.tins.2005.09.002
- Butterfield, B., & Metcalfe, J. (2006). The correction of errors committed with high confidence. *Metacognition and Learning*, 1(1), 69–84. doi:10.1007/s11409-006-6894-z
- Carver, C., & White, T. (1994). Behavioral inhibition, behavioral activation, and affective responses to impending reward and punishment: The BIS/BAS scales. *Journal of Personality and Social Psychology*, 67(2), 319–333.
- Coane, J. H., & Balota, D. a. (2010). Repetition priming across distinct contexts: effects of lexical status, word frequency, and retrieval test. *Quarterly Journal of Experimental Psychology (2006)*, 63(12), 2376–98. doi:10.1080/17470211003687546
- Danielmeier, C., & Ullsperger, M. (2011). Post-error adjustments. *Frontiers in Psychology*, 2, 233. doi:10.3389/fpsyg.2011.00233
- Duyck, W., Desmet, T., Verbeke, L. P. C., & Brysbaert, M. (2004). WordGen: a tool for word selection and nonword generation in Dutch, English, German, and French. *Behavior Research Methods, Instruments, & Computers*, 36(3), 488–499.
- Eriksen, B. a., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics*, 16(1), 143–149. doi:10.3758/BF03203267
- Ernst, B., & Steinhauser, M. (2012). Feedback-related brain activity predicts learning from feedback in multiple-choice testing. *Cognitive, Affective & Behavioral Neuroscience*, 12, 323–336. doi:10.3758/s13415-012-0087-9

- Fazio, L. K., & Marsh, E. J. (2009). Surprising feedback improves later memory. *Psychonomic Bulletin & Review*, *16*(1), 88–92. doi:10.3758/PBR.16.1.88
- Franken, I. H. a., Muris, P., & Rassin, E. (2005). Psychometric Properties of the Dutch BIS/BAS Scales. *Journal of Psychopathology and Behavioral Assessment*, *27*(1), 25–30. doi:10.1007/s10862-005-3262-2
- Hermans, D., & Houwer, J. De. (1994). Affective and subjective familiarity ratings of 740 Dutch words. *Psychologica Belgica*, *34*, 115–139.
- Houtman, F., & Notebaert, W. (2013). Blinded by an error. *Cognition*, *128*(2), 228–236. doi:10.1016/j.cognition.2013.04.003
- Houtman, F., Núñez Castellar, E., & Notebaert, W. (2012). Orienting to errors with and without immediate feedback. *Journal of Cognitive Psychology*, *24*(3), 278–285. doi:10.1080/20445911.2011.617301
- Kenward, M. G., & Roger, J. H. (1997). Small sample inference for fixed effects from restricted maximum likelihood. *Biometrics*, *53*(3), 983–97.
- Keuleers, E., & Brysbaert, M. (2010). Wuggy: a multilingual pseudoword generator. *Behavior Research Methods*, *42*(3), 627–33. doi:10.3758/BRM.42.3.627
- Keuleers, E., Diependaele, K., & Brysbaert, M. (2010). Practice effects in large-scale visual word recognition studies: a lexical decision study on 14,000 dutch mono- and disyllabic words and nonwords. *Frontiers in Psychology*, *1*(November), 174. doi:10.3389/fpsyg.2010.00174
- Krebs, R. M., Boehler, C. N., De Belder, M., & Egner, T. (2013). Neural Conflict-Control Mechanisms Improve Memory for Target Stimuli. *Cerebral Cortex*. doi:10.1093/cercor/bht283
- MacLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin*, *109*(2), 163–203. doi:10.1037//0033-2909.109.2.163
- Macmillan, N., & Creelman, C. (2005). *Detection theory: A user's guide*. Mahwah: Lawrence Erlbaum.
- Notebaert, W., Houtman, F., Opstal, F. Van, Gevers, W., Fias, W., & Verguts, T. (2009). Post-error slowing: an orienting account. *Cognition*, *111*, 275–279. doi:10.1016/j.cognition.2009.02.002
- Núñez Castellar, E., Kühn, S., Fias, W., & Notebaert, W. (2010). Outcome expectancy and not accuracy determines posterror slowing: ERP support. *Cognitive, Affective, & Behavioral Neuroscience*, *10*(2), 270–278. doi:10.3758/CABN.10.2.270
- Polich, J. (2007). Updating P300: an integrative theory of P3a and P3b. *Clinical Neurophysiology*, *118*(10), 2128–2148. doi:10.1016/j.clinph.2007.04.019
- Simons, R. F., Graham, F. K., Miles, M. a, & Chen, X. (2001). On the relationship of P3a and the Novelty-P3. *Biological Psychology*, *56*, 207–218.

- Spataro, P., Mulligan, N. W., & Rossi-Arnaud, C. (2013). Divided attention can enhance memory encoding: the attentional boost effect in implicit memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *39*(4), 1223–12231. doi:10.1037/a0030907
- Steinborn, M. B., Flehmig, H. C., Bratzke, D., & Schröter, H. (2012). Error reactivity in self-paced performance: Highly-accurate individuals exhibit largest post-error slowing. *Quarterly Journal of Experimental Psychology*, *65*(4), 624–31. doi:10.1080/17470218.2012.660962
- Stevens, M., Lammertyn, J., Verbruggen, F., & Vandierendonck, A. (2006). Tscope: A C library for programming cognitive experiments on the MS windows platform. *Behavior Research Methods*, *38*(2), 280–286.
- Swallow, K. M., & Jiang, Y. V. (2010). The Attentional Boost Effect: Transient increases in attention to one task enhance performance in a second task. *Cognition*, *115*(1), 118–132. doi:10.1016/j.cognition.2009.12.003
- Swallow, K. M., & Jiang, Y. V. (2011). The role of timing in the attentional boost effect. *Attention, Perception & Psychophysics*, *73*(2), 389–404. doi:10.3758/s13414-010-0045-y
- Swallow, K. M., & Jiang, Y. V. (2012). Goal-relevant events need not be rare to boost memory for concurrent images. *Attention, Perception & Psychophysics*, *74*(1), 70–82. doi:10.3758/s13414-011-0227-2
- Zacks, J. M., Speer, N. K., Swallow, K. M., Braver, T. S., & Reynolds, J. R. (2007). Event perception: a mind-brain perspective. *Psychological Bulletin*, *133*(2), 273–293. doi:10.1037/0033-2909.133.2.273

APPENDIX A

List 1	List 2	List 3	List 4
Advocaat (lawyer)	Antilope (antelope)	Adelaar (eagle)	Accent (accent)
Balpen (pen)	Beton (concrete)	Buik (belly)	Aquarium (aquarium)
Bier (beer)	Bord (plate)	Darm (intestine)	Banaan (banana)
Boter (butter)	Bril (glasses)	Doos (box)	Boog (arc)
Cirkel (circle)	Broek (pants)	Dwerg (dwarf)	Gist (yeast)
Geur (odor)	Ivoor (ivory)	Eend (duck)	Hagedis (lizard)
Kapper (hairdresser)	Keel (throat)	Eicel (egg-cell)	Hoed (hat)
Kerosine (kerosene)	Kever (beetle)	Golf (wave)	Kelder (basement)
Mand (basket)	Klas (class)	Haring (herring)	Lever (liver)
Naald (needle)	Letter (letter)	Hek (fence)	Papier (paper)
Olifant (elephant)	Pin (pin)	Honing (honey)	Parade (parade)
Piraat (pirate)	Politie (police)	Inkt (ink)	Slak (snail)
Rok (skirt)	Saffier (sapphire)	Kaas (cheese)	Snoep (candy)
Sap (juice)	Smoking (tuxedo)	Klei (clay)	Staal (steel)
Schaar (scissors)	Spinazie (spinach)	Kruid (herb)	Tas (bag)
Slager (butcher)	Stoep (doorstep)	Magazine (magazine)	Tong (tongue)

Toilet (toilet)	Streep (stripe)	Pleister (plaster)	Trompet (trumpet)
Vishaak (fishhook)	Tapijt (carpet)	Raadsel (riddle)	Venster (window)
Vogel (bird)	Vierkant (square)	Schreeuw (shout)	Vijver (pond)
Winkel (shop)	Wolk (cloud)	Stier (bull)	Vulkaan (volcano)

APPENDIX B

List 1	List 2	List 3	List 4
walm (vapour)	krib (crib)	etui (pencil case)	oker (ochre)
mees (tit)	rasp (grater)	zerk (tombstone)	spar (spruce)
vlas (flax)	teil (barrel)	vlok (flake)	perk (bed)
trema (diaeresis)	manga (manga)	stuip (spasm)	humus (humus)
fjord (fjord)	leuze (slogan)	rayon (rayon)	grief (agony)
stolp (bell jar)	ijzel (glaze)	kwark (quark)	karaf (decanter)
tralie (bar)	geloel (howling)	gewoel (rooting)	mimiek (mimic art)
aanhef (beginning)	teneur (tendency)	slalom (slalom)	lychee (lychee)
raming (estimation)	sjalot (shallot)	pastel (pastel)	sokkel (pedestal)
striem (weal)	fresco (fresco)	dracht (pregnancy)	gemaal (husband)
sliert (wisp)	tandem (tandem)	venkel (fennel)	leemte (gap)
gewest (province)	jonker (jonkheer)	grimas (smirk)	kozijn (window frame)
herdruk (reprint)	gisting (fermentation)	zijwand (sidewall)	uitbouw (expansion)
Strozak (straw-mattress)	welving (curvature)	stofjas (dust-coat)	voerman (waggoner)
pachter (leaseholder)	oogmerk (goal)	bouwsel (construction)	oorvijs (clout)

rekestok (horizontal bar)	geknars (grating)	valreep (gangway)	knokkel (knuckle)
komplot (conspiracy)	heffing (custom)	kroniek (chronicle)	slotsom (conclusion)
wasdraad (clothesline)	strohoed (boater)	voertaal (official language)	draaiing (rotation)
panfluit (panpipes)	potgrond (potting soil)	raadzaal (boardroom)	bankstel (sofa)
plakkaat (placard)	chrysent (chrysanthemum)	peignoir (dressing gown)	tweeloop (shotgun)

CHAPTER 9

GENERAL DISCUSSION

The aim of the research presented in this doctoral dissertation was to further investigate post-error adaptations by taking additional factors into account such as the inter-trial interval, personality characteristics and previous congruency. The first part of this dissertation focused on behavioural studies. In the second part, visual processing following an error was investigated electrophysiologically.

An additional goal of this dissertation was of a methodological nature. By using linear mixed models for behavioural studies, we showed the usability of this method in investigating post-error adaptations. Indeed as errors are usually infrequent, experimental designs are never perfectly balanced. This imbalance can also be found between participants, as the amount of errors can differ quite a lot. As we also analysed accuracy in each chapter, to investigate increased performance following an error, generalized linear mixed models provide a more suitable method as this model can be parametrized to work under the binomial distribution. Additionally, when using a limited set of stimuli, such as words in CHAPTER 8, item-specific effects can also be accounted for in the model.

Furthermore we used Laplacian transformation when working with ERP's. It has been shown that this technique can improve spatial, and temporal, resolution, making it possible to further differentiate components. The finding that the Pe consists of two components is quite ambiguous with some studies reporting an early and late Pe (Endrass, Reuter, & Kathmann, 2007; Van Veen & Carter, 2002), while others do not (Hajcak, McDonald, & Simons, 2003; Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001; Shalgi, Barkan, & Deouell, 2009; Wessel, Danielmeier, & Ullsperger, 2011) unless additional techniques are used

such as independent component analysis (Debener et al., 2005) or principal component analysis (Arbel & Donchin, 2009; Endrass, Klawohn, Gruetzmann, Ischebeck, & Kathmann, 2012; Endrass, Klawohn, Preuss, & Kathmann, 2012). Therefore in CHAPTER 5, we used Laplacian transformation to discern both Pe-components. In line with the literature, we observed an early Pe as a more central component, peaking around 150 ms and a late Pe at parietal electrode sites from 300 to 600 ms (Endrass et al., 2007; Van Veen & Carter, 2002). Additionally, we replicated these results when investigating error-related components in CHAPTER 6. Given that the early Pe is hypothesized to be a continuation of the ERN (Wessel, 2012), or rather processes underlying the ERN, it is possible that this component also, at least partly, reflects a response evaluation, independent of outcome. Similar to the late Pe, a small positivity was also present on correct trials. This findings corroborates the idea that the late Pe reflects a P3b-like component, which is related to memory-updating (Polich, 2007).

In this general discussion, the main empirical findings are outlined and integrated with theories of error monitoring. To conclude, some future research questions are presented.

RESEARCH OVERVIEW

POST-ERROR ADAPTATIONS: THE ROLE OF THE INTER-TRIAL INTERVAL

The finding that post-error slowing (PES) is not usually accompanied by post-error accuracy *increase* has been explained by the amount of time between trials. It has been proposed that when the inter-trial interval is short, PES reflects an attentional dip or processing bottleneck. The use of longer intervals however, limits the influence of the orienting response on

post-error performance. In this case, PES reflects strategic slowing accompanied by accuracy improvement (Danielmeier & Ullsperger, 2011; Forster & Cho, 2014; Marco-pallarés, Camara, Münte, & Rodríguez-Fornells, 2008). This idea thus integrates both functional and nonfunctional accounts. Corroborating this idea, our results in CHAPTER 2 illustrate that post-error behavioural adaptations indeed demonstrate a clear evolution over time. In line with previous reports, a longer inter-trial interval did reduce PES and numerical post-error accuracy increase was observed (Jentsch & Dudschig, 2009).

Additionally, as the amount of PES is also highly different over individuals, which is believed to be related to error saliency, we investigated whether anxious or punishment sensitive individuals show larger effects. Indeed, the pattern of results was modulated by trait anxiety with only the low-anxiety group, but not the high-anxiety group, showing improved post-error accuracy over time. This finding seems to suggest that participants are surprised and show biased attention at first, but do adapt to their errors over time. Taken together, this finding also indicates the importance of personality characteristics, next to inter-trial interval, when investigating post-error adaptations.

In Figure 1, we visually present the influence of personality. In general, with increasing the inter-trial interval, the negative effect of the orienting response decreases and more room is available for cognitive control effects. Although we have currently no information about the shape of the function, we propose an S-shaped function. One could even assume a step-wise function where control effects pop-up ones a particular inter-trial interval is reached. However, do to fluctuations in, for example, attention, trial-to-trial variability and sequence effects, we assume an S-shaped function. Figure 1 shows the effect of anxiety (for instance) as a rightward shift of the function showing that high anxious people in general need a longer inter-trial interval before cognitive control effects take over from orienting effects. However, before we can fit real data to investigate the proposed mechanism, we would first need to develop a

measure that quantifies the Y-axis, which might prove difficult. PES in itself can reflect both orienting and cognitive control, whereas the absence of post-error accuracy *increase* does not necessarily imply the absence of cognitive control.

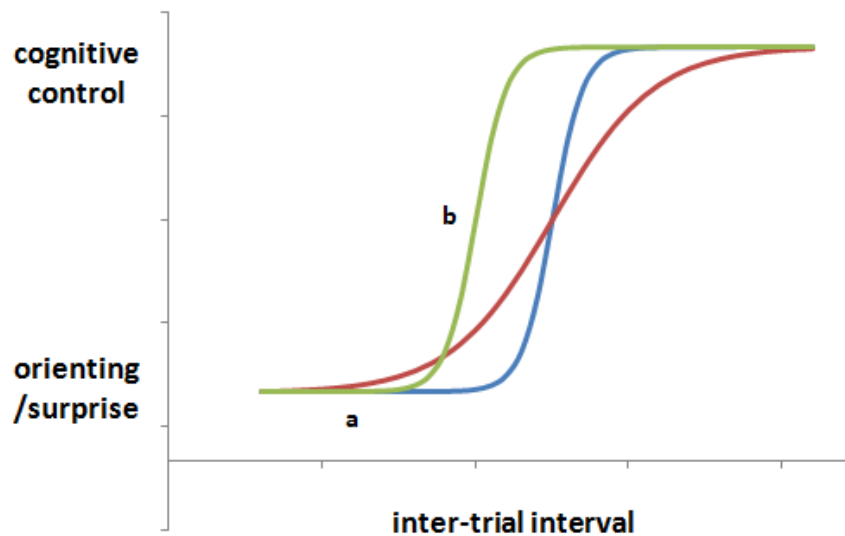


Figure 1. Depiction of how the inter-trial interval can regulate the influence of an orienting response and cognitive control on post-error adaptations. The influence of the orienting response can be prolonged depending on personality characteristics such as anxiety (a). The slope of the function (b) refers to the time needed to re-orient the attention to the task at hand and can be influenced by task difficulty. More difficult tasks typically involve more processes and therefore one can expect more trial-to-trial variation and therefore more deviation from the step-wise function.

While it is clear that time between trials influences PES and post-error accuracy, an overview of the other chapters in this dissertation seem to indicate the importance of task characteristics as well. In CHAPTER 3, similar to CHAPTER 2, a Simon task was administered. In these experiments, where an inter-trial interval of 750 ms is used, no differences in accuracy following an error and following a correct response is found, similar to the medium inter-trial interval (i.e. 500 ms)

in CHAPTER 2. However, the use of more difficult tasks in CHAPTER 4, i.e. a four alternative forced choice Stroop and prime-target task, resulted in significant post-error accuracy *decrease* even though the inter-trial interval used was moderate or even long (resp. 1000 and 750 ms). Additionally, in CHAPTER 5 a difficult flanker task was administered with an inter-trial interval of 1100 ms, however, no significant post-error accuracy changes were found. These differential results illustrate that more difficult tasks can elongate the detrimental effects of an orienting response on post-error accuracy as participants need more time to re-orient attention to the task at hand. It is therefore important to consider task characteristics when predicting the evolution of post-error adaptations over time. Figure 1 also depicts the effect of task characteristics. More difficult tasks typically involve more processes and therefore one can expect more trial-to-trial variation and therefore more deviation from the step-wise function.

SEPARATING POST-ERROR AND POST-CONFLICT ADAPTATIONS

The use of conflict tasks in error research permits us to investigate error-related modulations of conflict processing. Based on this idea, Ridderinkhof (2002) investigated the interference effect (i.e., the difference between incongruent and congruent trials) following erroneous and correct responses, and showed post-error *reduction* of interference (PERI). While this phenomenon is typically explained by a heightened cognitive control following errors, previous studies never included, or systematically examined, the influence of previous congruency on top of the factor previous accuracy. Typically most errors are made on incongruent trials. As such, the factor Previous Congruency might influence the reported PERI-effect, reflecting the rather well known the congruency sequence effect (i.e., smaller interference effect following incongruent trials than following congruent trials) than increased post-error focusing.

In CHAPTER 3 we investigated PERI using the task in which it was initially discovered (Ridderinkhof, 2002). Indeed, omitting the factor Previous Congruency, in line with Ridderinkhof (2002), resulted in significant PERI. However, when Previous Congruency was included, PERI was observed following congruent trials, but *inverse* PERI following incongruent trials, casting doubt on earlier reports of the PERI effect (King, Korb, von Cramon, & Ullsperger, 2010; Ridderinkhof, 2002; Ridderinkhof et al., 2002). Interestingly, this pattern of results emerged primarily because of a larger congruency effect following *correct* congruent trials and a smaller congruency effect following *correct* incongruent trials. This results indicates that the originally reported PERI effects reflected a modulation by congruency, primarily driven by congruent trials (Compton, Huber, Levinson, & Zheutlin, 2012) rather than by errors.

In CHAPTER 4, we further investigated PERI in two different conflict tasks, a Stroop and prime-target task. As it has been shown that the congruency sequence effect is influenced by contingency learning and feature repetition (Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014; Egner, 2007; Hommel, Proctor, & Vu, 2004; Mayr, Awh, & Laurey, 2003; Mordkoff, 2012; Schmidt & De Houwer, 2011), we combined two alternative forced choice tasks (resp. on odd en even trials) in these experiments to exclude these confounds. Additionally we included neutral trials to investigate PERI without the influence of previous congruency.

In the Stroop task a significant *inverse* PERI was found which did not depend on previous congruency. However, based on our assumption that previous measures of PERI are confounded with, or even driven by, the congruency sequence effect, it is possible that our results can be explained by our design choice. Indeed, using a design devoid of feature repetitions or contingency learning can eliminate the congruency

sequence effect (Schmidt & De Houwer, 2011). In the prime-target task on the other hand, significant PERI was found. Interestingly, this effect also depended on previous congruency; only following congruent trials significant PERI was observed. Based on the idea that conflict adaptation drives the PERI effect, we would have expected significant inverse PERI following incongruent trials, as in CHAPTER 3. However, there is now increasing support for the idea that conflict adaptation is more effective after congruent trials. Investigating the congruency-sequence effect, it has been shown that the congruency-effect following incongruent trials is similar to that following neutral trials but a larger congruency-effect can be found following congruent trials (Compton et al., 2012; Lamers & Roelofs, 2011).

In conclusion, both CHAPTER 3 and 4 show that previous congruency can influence the occurrence of PERI even when a design devoid of contingency learning and feature repetition is used. Additionally, the results of CHAPTER 4 indicate that PERI should be investigated following incongruent trials, rather than congruent trials. Interestingly, the behavioural results in CHAPTER 7 again show that PERI is highly influenced by previous congruency with only significant PERI following congruent trials in the easy condition but significant inverse PERI in the hard condition. This pattern of results was also related to post-correct trials rather than post-error trials again illustrating that the finding of PERI might not be attributed to post-error focusing, but rather post-correct adaptations triggered by the (non-)occurrence of conflict.

VISUAL PROCESSING FOLLOWING AN ERROR

Behaviourally, it is clear that performance is impaired shortly following an error. Additionally, the results of CHAPTER 3 and 4 indicate that there is no post-error focusing. We therefore used ERP's to investigate the effect of errors on subsequent visuo-attentional processes. In CHAPTER 6, we combined a flanker and a visual discrimination task. Additionally, the

inter-trial interval between both tasks was manipulated to investigate the duration of these negative after-effects. Similar to the results of CHAPTER 5, the ERN/CRN was followed by an early Pe/Pc and a late Pe/Pc. In line with the idea that these positivities reflect different processes, the early Pe/Pc was significantly larger for errors while there was no significant difference in late Pe/Pc amplitude between erroneous or correct trials. When looking at stimulus-locked components in the flanker task, the late N1 was attenuated following errors. This component reflects the orienting of attention to task-relevant stimuli (Hopfinger & West, 2006; Luck, Heinze, Mangun, & Hillyard, 1990) and illustrates that participants focus less attention on the stimulus of the visual discrimination task following an error. Additionally, P3-amplitude, a component related to memory updating (Polich, 2007), was attenuated following an error in the long interval condition. These results show that task-related memory is decreased following an error.

While an AB-like effect can be found following errors (Houtman & Notebaert, 2013), our results show that the mechanism behind the classic AB and the error-induced blink are most likely not the same, as early visual processing is not attenuated in a classical AB task (Sergent, Baillet, & Dehaene, 2005; Vogel et al., 1998). Similar to the idea that an emotional AB occurs through competition for perceptual resources (Most & Wang, 2011; Wang, Kennedy, & Most, 2012), our results show that an error is followed by a decrease in attentional resources for the stimulus of the visual discrimination task.

To follow-up the results of CHAPTER 6, we wanted to investigate this early visual components within a conflict task. In CHAPTER 7, we therefore re-analyzed the dataset from CHAPTER 5. In this dataset, we investigated the effect of error and congruency in an easy and difficult flanker task on subsequent visuo-attentional processes, conflict

processing and memory updating, thereby adding to the research on the occurrence of post-error focusing as an explanation of PERI.

Surprisingly we did not find an effect of congruency or previous accuracy on N2-amplitude, which indexes the amount of conflict. For both the P1 and N1, we did find a clear effect of congruency but only following correct trials in the easy condition. While P1-amplitude was enhanced for congruent post-correct trials, N1-amplitude was more negative for incongruent post-correct trials. Previous research indicated that N1-amplitude is influenced by endogenous attention while P1 amplitude can be influenced by both exogenous and endogenous attention (Hopfinger & West, 2006). Our results therefore suggest that more attention was directed to post-correct incongruent trials while participants relied more on exogenous attention on post-correct congruent trials. While there was no clear overall modulation of late N1 by previous accuracy, possibly related to task characteristics, the P3 amplitude was again significantly smaller following an erroneous trial than following a correct trial. This result indicates that even when visual attention is only minimally influenced by previous accuracy, memory updating is still worse following an error. Overall our results show that differential early visual processing of congruent and incongruent trials disappears following an error, indicating reduced influence of conflict processing. However, we have to be careful with this interpretation as the modulation of these early processes was not observed in the difficult condition.

Taken together, the results of CHAPTER 6 and 7 indicate that visual attention, as well as memory updating, is attenuated following errors. However, the influence of an error on the early visual components seems to be depended on the inter-trial interval. Additionally, there is no support for the idea of post-error focusing as an explanation of PERI.

AN ADVANTAGE OF AN ERROR-RELATED ORIENTING RESPONSE

The aim of the study presented in CHAPTER 8 was to investigate the processing of feedback stimuli and more specifically test the hypothesis that memory for error feedback is better than memory for correct feedback. Using a recognition task (Experiment 1) and lexical decision task (Experiment 2 and 3) in which a subset of words was previously seen as error or correct feedback in a flanker task, we could show that memory was indeed improved for words seen as error feedback. This was indicated by a larger d' in the recognition task and increased accuracy or faster reaction times in the lexical decision task for words seen as error feedback compared to words seen as correct feedback.

In line with previous results in general knowledge tests (Butterfield & Metcalfe, 2006; Fazio & Marsh, 2009) and the orienting account (Notebaert et al., 2009) our results shows that words shown as error feedback are more surprising/salient and automatically capture attention, thereby improving processing of irrelevant characteristics of this feedback.

TOWARDS A GENERAL PERFORMANCE MONITORING SYSTEM

Error monitoring and post-error adaptations have often been investigated as a part of cognitive control. As such, functional accounts, such as the conflict monitoring theory (CMT, Botvinick, Braver, Barch, Carter, & Cohen, 2001) and the reinforcement learning theory (Holroyd & Coles, 2002), have predominantly influenced predictions about post-error adaptations. Both the CMT and the reinforcement learning theory posit that an error results in heightened cognitive control leading to strategic adaptations, such as post-error slowing, to increase performance, i.e. post-error accuracy *increase*. However, the results presented in this dissertation show that post-error slowing is usually not accompanied by

post-error accuracy *increase* (see also, Bombeke, Schoupe, Duthoo, & Notebaert, 2013; Carp & Compton, 2009; Notebaert & Verguts, 2011; Steinborn, Flehmig, Bratzke, & Schröter, 2012). Additionally, heightened cognitive control following an error should also lead to increased attention as reflected in less interference from task-irrelevant characteristics. However, the results of CHAPTER 3 and 4 show that PERI is more likely to be the result of conflict-related adaptations following post-correct trials, rather than post-error trials. Additionally, CHAPTER 6 shows that early attentional processing is reduced following an error.

The more recently formulated nonfunctional accounts, such as the orienting account (Notebaert et al., 2009) and the bottleneck account (Jentzsch & Dudschig, 2009) can explain observations of worse performance following an error by the occurrence of an orienting response to an error or prolonged error processing occupying a central bottleneck. The predictions of both nonfunctional accounts are limited in time. Once attention is re-oriented to the task at hand, or central processing stages are accessible again, these accounts posit the possibility for strategic adaptations to increase performance, as it was predicted by functional accounts. Although these accounts have quite similar predictions, the finding of a decreased N1 following an error in CHAPTER 6 suggests that it is indeed early perceptual processing that is impaired, rather than a central bottleneck. However, as the N1 is believed to reflect endogenous attention (Hopfinger & West, 2006), it can still be hypothesized that awareness is limited because error processing occupies central processing stages. Interestingly, (Houtman & Notebaert, 2013), using a design inspired by classic AB tasks, showed that post-error target detection is worse following an error. However in classic AB tasks, where a neutral T1 and T2 are used, target detection is not impaired when T2 follows T1 within 100 ms of the first target (Potter, Staub, & O'Connor, 2002). The error-induced impaired detection therefore actually resembles more an emotional AB in which an emotional T1 is used, as both do not show lag 1 sparing (McHugo, Olatunji, & Zald, 2013). This

emotional AB is believed to illustrate the ability of highly salient items to capture attention and reflects competition for resources during perceptual processing (Most & Wang, 2011; Wang et al., 2012). This idea is also supported by the finding of a diminished attentional processing following an error in CHAPTER 6. Furthermore, this comparison with the emotional AB also results in a more specific prediction to investigate whether the orienting response triggered by an error is spatially specific or rather interferes with processing by occupying more central resources, as proposed by the bottleneck account (Jentsch & Dudschig, 2009). Similar to the design of Most & Wang (2011) with two spatially separate RSVP streams, we could use a task in which an error is followed by a RSVP stream on the same and a different location. As such, we could investigate whether an error-induced blink occurs in both streams, indicating a central bottleneck, or only in the stream sharing the same spatial location as the error. Alternatively, the design of CHAPTER 8 could be adjusted to spatially separate the feedback information about accuracy and the word. This design would again indicate whether the orienting response elicited by the error or error feedback is limited by the location of error commission or feedback presentation.

Overall, our findings are more in line with nonfunctional accounts. However, as post-error improvement can be found with larger inter-trial intervals, our findings thus illustrate the need of combining both functional and non-functional accounts to predict post-error performance. Interestingly, one need not be limited to error monitoring as the idea of a predicted response-outcome model is a more general performance monitoring system (Alexander & Brown, 2011). As outcomes are compared with their predictions, both positive and negative events can trigger adaptive control. Additionally, surprising outcomes, i.e. a larger deviation of the prediction, are associated with a larger learning signal. While this theory opens up performance monitoring to all sorts of task-

relevant events, it is also possible to combine this theory with non-functional accounts, with the triggering of an orienting response, due to saliency of unexpectedness of the event as the first step in this response-outcome comparison.

Recent evidence indeed suggests a common underlying structure for the processing of error and novel events (Desmet, Deschrijver, & Brass, 2014; Wessel, Danielmeier, Morton, & Ullsperger, 2012). Similarly, using EEG, the feedback-related negativity has been shown to be elicited by unexpected positive feedback (Jessup, Busemeyer, & Brown, 2010; Silvetti, Nuñez Castellar, Roger, & Verguts, 2014). Furthermore, Cavanagh, Zambrano-Vazquez, and Allen (2012) showed that error-related negativities and the stimulus-locked N2, related to conflict or novelty processing, at least partially reflect a common theta band oscillatory process related to a generic and reactive medial prefrontal cortex process. Additionally pupil size, which is a measure of cognitive surprise, is larger on correct incongruent, i.e. difficult, than on congruent trials (Braem, Coenen, Bombeke, van Bochove, & Notebaert, 2015) illustrating a positive prediction error while this pattern reversed when an error was made.

Interestingly, a link has been made between pupil dilatation and the locus coeruleus (LC, Aston-Jones & Cohen, 2005). As briefly discussed in the introduction, the LC is instrumental in the occurrence of the orienting response. The LC is believed to regulate cognitive performance by exhibiting a strong phasic increase, releasing norepinephrine (NE), during the processing of emotionally relevant stimuli. This NE-release increases the gain improving subsequent processing and behaviour. Following this phasic NE release, there is a refractory-like silent period, typically starting about 200 ms following the eliciting stimulus and lasting about 250 ms. This silent period is believed to be responsible for the attentional blink (AB) in rapid serial visual presentation (RSVP) tasks, where presenting two targets closely together, leads to worse detection of the second target. Typically, in speeded response choice tasks an inter-trial

interval of 500 ms (or less) is used. Based on the timing of LC-NE activation, it is possible that this subsequent silent period is responsible for PES and an initial decrease in performance. Indeed, the results of CHAPTER 2 show that PES is large in the short and medium interval but significantly decreased when a long inter-trial interval is used.

The idea that attention is oriented to an error, is also in line with the findings in CHAPTER 8. By using feedback words, the orienting response triggered by an error results in better memory, due to enhanced processing, for these words. However words were presented in a specific colour, related to the accuracy of their response. It is therefore still a possibility that the unexpectedness of negative feedback triggered the orienting response and subsequent processing of the feedback word. It would therefore be interesting to investigate whether the same effects would occur when no additional feedback signal was present. Additionally, increasing time between response and feedback presentation might elucidate the timeframe in which the orienting response and the silent period respectively operate and their associated effects on processing and memory.

This timing of the silent period also corroborates with the idea that the design of the dataset presented in CHAPTER 7 was less than optimal in investigating the influence of an orienting response on early visuo-attentional and conflict processing, as a rather large inter-trial interval was used (1100 ms). That we found no difference between the short and long interval condition in CHAPTER 6, with regard to decreased N1 amplitude following an error, thus seems to be partly due to the additional task-switching in this design, prolonging detrimental effects. However, both CHAPTER 6 and CHAPTER 7 do show decreased P3 amplitude following an error, indicating that memory updating is impaired following an error even when the inter-trial interval is rather long. This

result indicates that the orienting response to an error might have longer after-effects than just the initial silent period.

The idea that the first step in a general performance monitoring system is the eliciting of an orienting response, leads to the behavioural prediction that conflict, novelty and errors are initially followed by similar 'adaptations'. Indeed it is clear that post-oddball slowing exists, as infrequent events are followed by slower reaction times (Barcelo, Escera, Corral, & Periáñez, 2006; Notebaert et al., 2009). Post-conflict slowing, on the other hand, is usually not reported. However, Verguts, Notebaert, Kunde, and Wühr, (2011), showed that post-conflict slowing does occur but is masked by post-conflict focusing. Even though all these events are followed by slowing, it is quite apparent that PES is usually substantially larger than post-oddball or post-conflict slowing (Notebaert et al., 2009; Verguts et al., 2011). When comparing errors with conflict and novel events, it is important to point out that the saliency of an error is typically higher than the saliency of conflict or novelty, resulting in larger orienting responses. Indeed PES can be modulated by differences in context, as more PES is found in a reward context, i.e. making an error is more upsetting (Stürmer, Nigbur, Schacht, & Sommer, 2011), and personality characteristics, with increased PES when scoring higher on empathic personal distress (Larson, Fair, Good, & Baldwin, 2010). In line with this idea, observed PES is larger in a cooperation context than in a competition context (Núñez Castellar, Notebaert, Van den Bossche, & Fias, 2011) indicating that how participants feel about their, and others, errors influences PES, and thus possibly the orienting response.

While slowing does seem to occur following both errors and conflict, it stands to reason that these events should similarly trigger enhanced adaptive control. Indeed CHAPTER 2 illustrates that enhanced post-error performance can be found when the inter-trial interval is sufficiently long, bridging the silent period of the LC-NE. However, CHAPTER 3 and 4 illustrate that another measure of increased cognitive control, namely a smaller interference-effect following an error, cannot be reliably found,

even with a rather large inter-trial interval. This measure of post-error adaptation resembles the congruency sequence effect. This effect can easily be explained by the adaptation-by-binding account (Verguts & Notebaert, 2008, 2009) which proposes that conflict engages Hebbian learning processes on all currently active representations. This mechanism therefore results in a stronger task focus following conflict trials, and a weaker task focus following no-conflict trials. However, when looking at error trials, both correct and incorrect representations have been activated. This co-activation of correct and error representations makes it difficult to predict the expected pattern for post-error trials. As such, it is possible that incorrect representations are strengthened leading to *increased* interference following an error. However, it is also possible that increased cognitive control only exerts influence when the correct response is determined, possibly resulting in a larger processing time before PERI can be observed. Interestingly, this idea can also be traced back to the results of CHAPTER 7. While conflicting stimuli influences early visuo-attentional components on post-correct trials, this difference was not found in post-error trials. However, these findings were not reflected in a reliable PERI effect in behavioural measures. It is possibly that using a longer inter-trial interval might reveal this phenomenon.

Overall, it is clear that the orienting response triggered by an error results in, often, detrimental effects on subsequent performance. However, if this orienting response is a first step in comparing the actual response to the prediction to improve behaviour, it is clear that, when a longer inter-trial interval is used, possibly bridging a silent period from the LC-NE, adaptive processes triggered by the error detection should lead to enhanced performance. Indeed increasing the inter-trial interval does lead to post-error accuracy *increase* (Jentsch & Dudschig, 2009) and could lead to post-error focusing. However only increasing the inter-trial

interval might not be sufficient to reveal these kinds of adaptations. While measuring anxiety, and possibly empathy, as well as using a long inter-trial interval, i.e. > 1000 ms, could shed some light on these predicted post-error adaptations, we also need to critically assess the paradigms used. Most tasks in which post-error adaptations are assessed are quite restrictive in regards with appropriate behavioural adaptations. Interestingly, using a mental arithmetic task in which participants could use multiple strategies, rather than just remembering and executing the correct response mapping, Desmet and colleagues (2012) showed post-error accuracy *increase*. It might therefore prove to be fruitful to extend error research to tasks where different strategies can be adopted in order to improve performance.

CONCLUSIONS

In this thesis I aimed to widen the current perspective on post-error adaptations. The results presented in this thesis add to the idea that an error triggers an orienting response resulting in worse performance for subsequent events, both behaviourally and electrophysiologically. However, information presented at the time of an error, i.e. error feedback, can profit from this orienting response resulting in improved memory. Additionally, it is clear that post-error adaptations are influenced by time between tasks as well as personality and task characteristics. Furthermore, these chapters also present some methodological remarks such as the use of linear mixed models for behavioural studies and Laplacian transformation when working with ERP's. Additionally, the results presented in this dissertation also provide a caveat for investigating PERI, as this measure of post-error adaptation seems to be confounded by previous congruency.

REFERENCES

- Alexander, W. H., & Brown, J. W. (2011). Medial prefrontal cortex as an action-outcome predictor. *Nature Neuroscience*, *14*(10), 1338–1344. doi:10.1038/nn.2921
- Arbel, Y., & Donchin, E. (2009). Parsing the componential structure of post-error ERPs: a principal component analysis of ERPs following errors. *Psychophysiology*, *46*(6), 1179–1189. doi:10.1111/j.1469-8986.2009.00857.x
- Aston-Jones, G., & Cohen, J. D. (2005). An integrative theory of locus coeruleus-norepinephrine function: adaptive gain and optimal performance. *Annual Review of Neuroscience*, *28*, 403–50. doi:10.1146/annurev.neuro.28.061604.135709
- Barcelo, F., Escera, C., Corral, M. J., & Periáñez, J. a. (2006). Task switching and novelty processing activate a common neural network for cognitive control. *Journal of Cognitive Neuroscience*, *18*(10), 1734–48. doi:10.1162/jocn.2006.18.10.1734
- Bombeke, K., Schouppe, N., Duthoo, W., & Notebaert, W. (2013). The effect of alcohol and placebo on post-error adjustments. *Frontiers in Human Neuroscience*, *7*(3). doi:10.3389/fnhum.2013.00003
- Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, *108*(3), 624–652. doi:10.1037/0033-295X.108.3.624
- Braem, S., Coenen, E., Bombeke, K., van Bochove, M. E., & Notebaert, W. (2015). Open your eyes for prediction errors. *Cognitive, Affective & Behavioral Neuroscience*, *15*(2), 374–80. doi:10.3758/s13415-014-0333-4
- Butterfield, B., & Metcalfe, J. (2006). The correction of errors committed with high confidence. *Metacognition and Learning*, *1*(1), 69–84. doi:10.1007/s11409-006-6894-z
- Carp, J., & Compton, R. J. (2009). Alpha power is influenced by performance errors. *Psychophysiology*, *46*, 336–343. doi:10.1111/j.1469-8986.2008.00773.x
- Cavanagh, J. F., Zambrano-Vazquez, L., & Allen, J. J. B. (2012). Theta lingua franca: a common mid-frontal substrate for action monitoring processes. *Psychophysiology*, *49*(2), 220–238. doi:10.1111/j.1469-8986.2011.01293.x
- Compton, R. J., Huber, E., Levinson, A. R., & Zheutlin, A. (2012). Is “conflict adaptation” driven by conflict? Behavioral and EEG evidence for the underappreciated role of congruent trials. *Psychophysiology*, *49*(5), 583–589. doi:10.1111/j.1469-8986.2012.01354.x
- Danielmeier, C., & Ullsperger, M. (2011). Post-error adjustments. *Frontiers in Psychology*, *2*, 233. doi:10.3389/fpsyg.2011.00233

- Debener, S., Ullsperger, M., Siegel, M., Fiehler, K., von Cramon, D. Y., & Engel, A. K. (2005). Trial-by-trial coupling of concurrent electroencephalogram and functional magnetic resonance imaging identifies the dynamics of performance monitoring. *The Journal of Neuroscience*, *25*(50), 11730–11737. doi:10.1523/JNEUROSCI.3286-05.2005
- Desmet, C., Deschrijver, E., & Brass, M. (2014). How social is error observation? The neural mechanisms underlying the observation of human and machine errors. *Social Cognitive and Affective Neuroscience*, *9*(4), 427–35. doi:10.1093/scan/nst002
- Desmet, C., Imbo, I., De Brauwer, J., Brass, M., Fias, W., & Notebaert, W. (2012). Error adaptation in mental arithmetic. *Quarterly Journal of Experimental Psychology*, *65*(6), 1059–1067. doi:10.1080/17470218.2011.648943
- Duthoo, W., Abrahamse, E. L., Braem, S., Boehler, C. N., & Notebaert, W. (2014). The heterogeneous world of congruency sequence effects: an update. *Frontiers in Psychology*, *5*(1001). doi:10.3389/fpsyg.2014.01001
- Egner, T. (2007). Congruency sequence effects and cognitive control. *Cognitive, Affective & Behavioral Neuroscience*, *7*(4), 380–390. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/18189011>
- Endrass, T., Klawohn, J., Gruetzmänn, R., Ischebeck, M., & Kathmann, N. (2012). Response-related negativities following correct and incorrect responses: evidence from a temporospatial principal component analysis. *Psychophysiology*, *49*(6), 733–743. doi:10.1111/j.1469-8986.2012.01365.x
- Endrass, T., Klawohn, J., Preuss, J., & Kathmann, N. (2012). Temporospatial dissociation of Pe subcomponents for perceived and unperceived errors. *Frontiers in Human Neuroscience*, *6*, 178. doi:10.3389/fnhum.2012.00178
- Endrass, T., Reuter, B., & Kathmann, N. (2007). ERP correlates of conscious error recognition: aware and unaware errors in an antisaccade task. *The European Journal of Neuroscience*, *26*(6), 1714–20. doi:10.1111/j.1460-9568.2007.05785.x
- Fazio, L. K., & Marsh, E. J. (2009). Surprising feedback improves later memory. *Psychonomic Bulletin & Review*, *16*(1), 88–92. doi:10.3758/PBR.16.1.88
- Forster, S. E., & Cho, R. Y. (2014). Context specificity of post-error and post-conflict cognitive control adjustments. *PloS One*, *9*(3), e90281. doi:10.1371/journal.pone.0090281
- Hajcak, G., McDonald, N., & Simons, R. F. (2003). To err is autonomic: Error-related brain potentials, ANS activity, and post-error compensatory behavior. *Psychophysiology*, *40*(6), 895–903. doi:10.1111/1469-8986.00107
- Holroyd, C. B., & Coles, M. G. H. (2002). The neural basis of human error processing: Reinforcement learning, dopamine, and the error-related negativity. *Psychological Review*, *109*(4), 679–709. doi:10.1037//0033-295X.109.4.679

- Hommel, B., Proctor, R. W., & Vu, K.-P. L. (2004). A feature-integration account of sequential effects in the Simon task. *Psychological Research*, *68*(1), 1–17. doi:10.1007/s00426-003-0132-y
- Hopfinger, J. B., & West, V. M. (2006). Interactions between endogenous and exogenous attention on cortical visual processing. *NeuroImage*, *31*(2), 774–89. doi:10.1016/j.neuroimage.2005.12.049
- Houtman, F., & Notebaert, W. (2013). Blinded by an error. *Cognition*, *128*(2), 228–236. doi:10.1016/j.cognition.2013.04.003
- Jentsch, I., & Dudschig, C. (2009). Why do we slow down after an error? Mechanisms underlying the effects of posterror slowing. *Quarterly Journal of Experimental Psychology*, *62*(2), 209–218. doi:10.1080/17470210802240655
- Jessup, R. K., Busemeyer, J. R., & Brown, J. W. (2010). Error effects in anterior cingulate cortex reverse when error likelihood is high. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *30*(9), 3467–72. doi:10.1523/JNEUROSCI.4130-09.2010
- King, J. a, Korb, F. M., von Cramon, D. Y., & Ullsperger, M. (2010). Post-error behavioral adjustments are facilitated by activation and suppression of task-relevant and task-irrelevant information processing. *The Journal of Neuroscience*, *30*(38), 12759–12769. doi:10.1523/JNEUROSCI.3274-10.2010
- Lamers, M. J. M., & Roelofs, A. (2011). Attentional control adjustments in Eriksen and Stroop task performance can be independent of response conflict. *Quarterly Journal of Experimental Psychology*, *64*(6), 1056–1081. doi:10.1080/17470218.2010.523792
- Larson, M. J., Fair, J. E., Good, D. a, & Baldwin, S. a. (2010). Empathy and error processing. *Psychophysiology*, *47*(3), 415–24. doi:10.1111/j.1469-8986.2009.00949.x
- Luck, S., Heinze, H., Mangun, G., & Hillyard, S. (1990). Visual event-related potentials index focused attention within bilateral stimulus arrays. II. Functional dissociation of P1 and N1 components. *Electroencephalography and Clinical Neurophysiology*, *75*, 528–542. Retrieved from <http://www.sciencedirect.com/science/article/pii/001346949090139B>
- Marco-pallarés, J., Camara, E., Münte, T. F., & Rodríguez-Fornells, A. (2008). Neural Mechanisms Underlying Adaptive Actions after Slips. *Journal of Cognitive Neuroscience*, *20*(9), 1–16.
- Mayr, U., Awh, E., & Laurey, P. (2003). Conflict adaptation effects in the absence of executive control. *Nature Neuroscience*, *6*(5), 450–452. doi:10.1038/nn1051
- McHugo, M., Olatunji, B. O., & Zald, D. H. (2013). The emotional attentional blink: what we know so far. *Frontiers in Human Neuroscience*, *7*, 151. doi:10.3389/fnhum.2013.00151

- Mordkoff, J. T. (2012). Observation: Three reasons to avoid having half of the trials be congruent in a four-alternative forced-choice experiment on sequential modulation. *Psychonomic Bulletin & Review*, *19*(4), 750–757. doi:10.3758/s13423-012-0257-3
- Most, S. B., & Wang, L. (2011). Dissociating spatial attention and awareness in emotion-induced blindness. *Psychological Science*, *22*(3), 300–5. doi:10.1177/0956797610397665
- Nieuwenhuis, S., Ridderinkhof, K. R., Blom, J., Band, G. P., & Kok, a. (2001). Error-related brain potentials are differentially related to awareness of response errors: evidence from an antisaccade task. *Psychophysiology*, *38*(5), 752–60. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/11577898>
- Notebaert, W., Houtman, F., Opstal, F. Van, Gevers, W., Fias, W., & Verguts, T. (2009). Post-error slowing: an orienting account. *Cognition*, *111*, 275–279. doi:10.1016/j.cognition.2009.02.002
- Notebaert, W., & Verguts, T. (2011). Conflict and error adaptation in the Simon task. *Acta Psychologica*, *136*, 212–216. doi:10.1016/j.actpsy.2010.05.006
- Núñez Castellar, E., Notebaert, W., Van den Bossche, L., & Fias, W. (2011). How monitoring other's actions influences one's own performance. *Experimental Psychology*, *58*(6), 499–508. doi:10.1027/1618-3169/a000118
- Polich, J. (2007). Updating P300: an integrative theory of P3a and P3b. *Clinical Neurophysiology*, *118*(10), 2128–2148. doi:10.1016/j.clinph.2007.04.019
- Potter, M. C., Staub, A., & O'Connor, D. H. (2002). The time course of competition for attention: Attention is initially labile. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(5), 1149–1162. doi:10.1037//0096-1523.28.5.1149
- Ridderinkhof, K. R. (2002). Micro- and macro-adjustments of task set: activation and suppression in conflict tasks. *Psychological Research*, *66*(4), 312–323. doi:10.1007/s00426-002-0104-7
- Ridderinkhof, K. R., de Vlugt, Y., Bramlage, A., Spaan, M., Elton, M., Snel, J., & Band, G. P. H. (2002). Alcohol consumption impairs detection of performance errors in mediofrontal cortex. *Science*, *298*, 2209–2211. doi:10.1126/science.1076929
- Schmidt, J., & De Houwer, J. (2011). Now you see it, now you don't: controlling for contingencies and stimulus repetitions eliminates the Gratton effect. *Acta Psychologica*, *138*(1), 176–186. doi:10.1016/j.actpsy.2011.06.002
- Sergent, C., Baillet, S., & Dehaene, S. (2005). Timing of the brain events underlying access to consciousness during the attentional blink. *Nature Neuroscience*, *8*(10), 1391–400. doi:10.1038/nn1549
- Shalgi, S., Barkan, I., & Deouell, L. Y. (2009). On the positive side of error processing: error-awareness positivity revisited. *The European Journal of Neuroscience*, *29*(7), 1522–32. doi:10.1111/j.1460-9568.2009.06690.x

- Silvetti, M., Nuñez Castellar, E., Roger, C., & Verguts, T. (2014). Reward expectation and prediction error in human medial frontal cortex: An EEG study. *NeuroImage*, *84*, 376–382. doi:10.1016/j.neuroimage.2013.08.058
- Steinborn, M. B., Flehmig, H. C., Bratzke, D., & Schröter, H. (2012). Error reactivity in self-paced performance: Highly-accurate individuals exhibit largest post-error slowing. *Quarterly Journal of Experimental Psychology*, *65*(4), 624–31. doi:10.1080/17470218.2012.660962
- Stürmer, B., Nigbur, R., Schacht, A., & Sommer, W. (2011). Reward and punishment effects on error processing and conflict control. *Frontiers in Psychology*, *2*(335). doi:10.3389/fpsyg.2011.00335
- Van Veen, V., & Carter, C. S. (2002). The timing of action-monitoring processes in the anterior cingulate cortex. *Journal of Cognitive Neuroscience*, *14*(4), 593–602. doi:10.1162/08989290260045837
- Verguts, T., & Notebaert, W. (2008). Hebbian learning of cognitive control: dealing with specific and nonspecific adaptation. *Psychological Review*, *115*(2), 518–525. doi:10.1037/0033-295X.115.2.518
- Verguts, T., & Notebaert, W. (2009). Adaptation by binding: a learning account of cognitive control. *Trends in Cognitive Sciences*, *13*(6), 252–257. doi:10.1016/j.tics.2009.02.007
- Verguts, T., Notebaert, W., Kunde, W., & Wühr, P. (2011). Post-conflict slowing: cognitive adaptation after conflict processing. *Psychonomic Bulletin & Review*, *18*, 76–82. doi:10.3758/s13423-010-0016-2
- Vogel, E. K., Luck, S. J., Chun, M., Lollo, V. Di, Egeth, H., Maki, B., & Raymond, J. (1998). Electrophysiological Evidence for a Postperceptual Locus of Suppression During the Attentional Blink, *24*(6), 1656–1674.
- Wang, L., Kennedy, B. L., & Most, S. B. (2012). When emotion blinds: a spatiotemporal competition account of emotion-induced blindness. *Frontiers in Psychology*, *3*(November), 438. doi:10.3389/fpsyg.2012.00438
- Wessel, J. R. (2012). Error awareness and the error-related negativity: evaluating the first decade of evidence. *Frontiers in Human Neuroscience*, *6*, 88. doi:10.3389/fnhum.2012.00088
- Wessel, J. R., Danielmeier, C., Morton, J. B., & Ullsperger, M. (2012). Surprise and error: common neuronal architecture for the processing of errors and novelty. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *32*(22), 7528–37. doi:10.1523/JNEUROSCI.6352-11.2012
- Wessel, J. R., Danielmeier, C., & Ullsperger, M. (2011). Error awareness revisited: accumulation of multimodal evidence from central and autonomic nervous systems. *Journal of Cognitive Neuroscience*, *23*(10), 3021–3036. doi:10.1162/jocn.2011.21635

CHAPTER 10

NEDERLANDSTALIGE SAMENVATTING

Meestal zijn mensen zeer succesvol in het correct uitvoeren van een bepaald gedrag of een bepaalde handeling ondanks de aanwezigheid van conflicterende informatie. Maar toch gebeurt het dat dit systeem faalt, wat leidt tot een fout. Foutenmonitoring en gedragsadaptaties na een fout worden onderzocht in een verscheidenheid aan taken, zoals tijdschattingstaken, kleur- of toondiscriminatietaken of mentale rekentaken (Desmet et al., 2012; Houtman, Núñez Castellar, & Notebaert, 2012; Jentsch & Dudschig, 2009). Maar vanwege de link tussen fouten en conflict, worden veelal conflicttaken gebruikt.

Het doel van het onderzoek in deze doctoraatsdissertatie was het verder onderzoeken van adaptaties na een fout wanneer men rekening houdt met extra factoren zoals het inter-trial interval, persoonlijkheidskenmerken en de vorige congruentie, in een poging om conflict- en foutgerelateerde adaptatie te scheiden van elkaar. In het eerste deel werd vooral gefocust op gedragsmatige aanpassingen. In het tweede deel werd visuele verwerking na een fout elektrofysiologisch onderzocht.

Een robuuste bevinding is dat participanten vertragen nadat ze een fout gemaakt hebben (post-error slowing, PES). Volgens functionele verklaringen van foutenmonitoring is PES een strategische adaptatie om ervoor te zorgen dat de kans op een nieuwe fout vermindert (Botvinick, Braver, Barch, Carter, & Cohen, 2001). PES wordt evenwel niet altijd vergezeld door een verhoogde accuraatheid na een fout. Hierdoor werden nonfunctionele verklaringen voorgesteld, waarbij PES een gevolg is van een oriëntatierespons uitgelokt door een fout of een verwerkingsbottleneck reflecteert (Jentsch & Dudschig, 2009; Notebaert et al., 2009).

De minder eenduidige resultaten over post-error accuraatheid kunnen evenwel verklaard worden door de tijd tussen trials. Er werd reeds gesteld dat wanneer het inter-trial interval kort is, PES een aandachtsdip of een verwerkingsbottleneck reflecteert. Het gebruik van een lang inter-trial interval daarentegen, beperkt de invloed van een oriëntatierespons op post-error performantie. PES reflecteert dan net strategische vertraging, vergezeld door een verhoogde accuraatheid (Danielmeier & Ullsperger, 2011; Forster & Cho, 2014; Marco-pallarés, Camara, Münte, & Rodríguez-Fornells, 2008). Dit idee integreert dus zowel functionele als non-functionele verklaringen. Onze resultaten in HOOFDSTUK 2 ondersteunen de idee dat gedragsaanpassingen na een fout veranderen over tijd. Bij een langer inter-trial interval vonden we verminderde PES en (numeriek) verhoogde accuraatheid na een fout.

De hoeveelheid PES is ook enorm verschillend tussen participanten. Deze grootteverschillen worden gelinkt aan de saillantie van een fout. Daarom onderzochten we of angstige of strafsensitieve participanten grotere effecten vertoonden. De resultaten werden inderdaad gemoduleerd door angst daar enkel laag-angstige participanten een verbeterde accuraatheid na een fout vertoonden in het langste interval. Deze bevinding suggereert dat participanten verrast zijn en hun aandacht getrokken wordt, maar wel strategische adaptaties kunnen vertonen na verloop van tijd. Daarnaast illustreert dit ook het belang van persoonlijkheidskenmerken wanneer men gedragsaanpassingen na een fout onderzoekt.

Hoewel het duidelijk is dat het inter-trial interval PES en accuraatheid na een fout beïnvloedt, laten de resultaten in de andere hoofdstukken van dit doctoraat ook het belang van de taak zelf zien. In HOOFDSTUK 3, gelijkaardig aan HOOFDSTUK 2, werd een Simon taak gebruikt. In deze experimenten, waar een inter-trial interval van 750 ms werd gebruikt, werd geen verschil in accuraatheid gevonden na een fout of na een correcte respons. Dit resultaat komt overeen met de resultaten bij het

middelste inter-trial interval (500 ms) in HOOFDSTUK 2. In HOOFDSTUK 4 worden evenwel moeilijkere taken gebruikt, een Stroop en prime-target taak met vier alternatieven, en werd er verminderde accuraatheid na een fout gevonden hoewel het gebruikte inter-trial interval gemiddeld of zelfs lang was (resp. 1000 en 750 ms). Daarnaast werd in HOOFDSTUK 5 een moeilijke flankertaak gebruikt met een inter-trial interval van 1100 ms. Hier werden opnieuw geen significante verschillen in accuraatheid na een fout en na een correcte respons gevonden. Deze resultaten illustreren dat moeilijkere taken de negatieve effecten van een oriëntatierespons op accuraatheid na een fout kunnen verlengen gezien participanten meer tijd nodig hebben om zich te heroriënteren op de taak. Het is dus belangrijk om rekening te houden met taakkenmerken wanneer men de evolutie van gedragsaanpassingen na een fout over tijd voorspelt.

Door het gebruik van conflicttaken in foutenonderzoek kunnen we ook fout-gerelateerde modulaties van conflictverwerking onderzoeken. Ridderinkhof (2002) onderzocht het interferentie-effect (m.a.w., het verschil tussen incongruente en congruente trials) na een fout en na correcte trials en toonde aan dat er post-error *reductie* van interferentie (PERI) is. Dit fenomeen wordt typisch verklaard aan de hand van verhoogde cognitieve controle na een fout. Eerdere studies hielden evenwel nooit rekening met de invloed van vorige congruentie, hoewel de meeste fouten gemaakt worden op incongruente trials. Deze factor kan dus het PERI-effect beïnvloeden waarbij dit effect eerder het gekende congruentie-sequentie effect laat zien (m.a.w., een kleiner interferentie-effect na incongruente trials dan na congruente trials) dan verhoogde post-error focusing.

In HOOFDSTUK 3 onderzochten we PERI in de taak waarin dit effect eerst werd gevonden (Ridderinkhof, 2002). Wanneer er geen rekening werd gehouden met de factor vorige congruentie, vonden we inderdaad PERI. Wanneer deze factor wel opgenomen was in de analyses vonden we PERI na congruente trials maar inverse PERI na incongruente trials. Deze resultaten tonen aan dat eerdere rapportage van dit effect niet compleet

betrouwbaar is. (King, Korb, von Cramon, & Ullsperger, 2010; Ridderinkhof, 2002; Ridderinkhof et al., 2002). Dit patroon kon ook herleid worden naar een groter congruentie-effect na *correcte* congruente trials en een kleiner congruentie-effect na *correcte* incongruente trials. Dit impliceert dat de eerder gerapporteerde effecten van PERI eerder gemoduleerd worden door congruentie, vooral gedreven door congruente trials (Compton, Huber, Levinson, & Zheutlin, 2012), dan door fouten.

In HOOFDSTUK 4, werd PERI verder onderzocht in twee andere conflicttaken, een Stroop en prime-target taak. Aangezien het reeds aangetoond werd dat het congruentie-sequentie effect beïnvloed wordt door contingentieren en kenmerkherhaling (Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014; Egner, 2007; Hommel, Proctor, & Vu, 2004; Mayr, Awh, & Laurey, 2003; Mordkoff, 2012; Schmidt & De Houwer, 2011), werden twee taken met twee alternatieven gecombineerd (resp. op even en oneven trials) om de invloed van deze confounds uit te sluiten. Daarnaast werden ook neutrale trials aangeboden om PERI te onderzoeken zonder invloed van vorige congruentie.

In de Stroop taak vonden we significante inverse PERI die niet gemoduleerd werd door vorige congruentie. Gezien onze assumptie dat de traditionele PERI gedreven werd door het congruentie-sequentie effect is het mogelijk dat het gebruik van een design zonder contingentieren en kenmerkherhaling, wat het congruentie-sequentie effect kan elimineren (Schmidt & De Houwer, 2011), een verklaring kan bieden voor dit resultaat. In de prime-target taak was er significante PERI, maar enkel na congruente trials. In tegenstelling tot HOOFDSTUK 3 vonden we geen inverse PERI na incongruente trials. Er is evenwel evidentie dat conflictadaptatie effectiever is na congruente trials gezien het congruentie-sequentie effect vooral gedreven wordt door een groter congruentie-effect na congruente trials (Compton et al., 2012; Lamers & Roelofs, 2011).

Zowel HOOFDSTUK 3 en 4 tonen aan dat vorige congruentie PERI kan beïnvloeden. Daarnaast laten de resultaten van HOOFDSTUK 4 zien dat het betrouwbaarder is om PERI te onderzoeken na incongruente trials. De gedragsmatige resultaten van HOOFDSTUK 7 tonen opnieuw aan dat PERI beïnvloed wordt door vorige congruentie. Hier vonden we enkel significante PERI na een congruente trial in de gemakkelijke conditie en significante inverse PERI na congruente trials in de moeilijke conditie. Deze resultaten zijn ook eerder gerelateerd aan significante verschillen in post-correct trials dan verschillen in post-error trials. Deze bevinding laat opnieuw zien dat PERI niet kan toegeschreven worden aan post-error focusing maar eerder aan adaptaties na een correcte trial die veroorzaakt worden door het (niet) voorkomen van conflict.

Het is duidelijk dat de gedragsmatige prestatie daalt kort na een fout. Daarnaast tonen de resultaten van HOOFDSTUK 3 en 4 aan dat er geen post-error focusing is. We onderzochten daarom het effect van fouten op de daaropvolgende visuele aandachtsprocessen met ERP's. In HOOFDSTUK 6, combineerden we een flanker- en visuele discriminatietask. Daarnaast manipuleerden we het inter-trial interval tussen beide taken om na te gaan hoe lang deze negatieve na-effecten duren. Gelijkwaardig aan de resultaten van HOOFDSTUK 5, werd de ERN/CRN gevolgd door een vroege Pe/Pc en een late Pe/Pc. In overeenstemming met het idee dat deze positieve componenten andere processen reflecteren was de vroege Pe/Pc significant groter voor fouten terwijl er geen significant verschil in late Pe/Pc amplitude was tussen correcte en foute trials. Voor de stimulus-locked componenten vonden we dat de late N1 verminderd was na een fout. Deze component is gelinkt aan het oriënteren van aandacht naar taak-relevante stimuli (Hopfinger & West, 2006; Luck, Heinze, Mangun, & Hillyard, 1990) en illustreert dus dat participanten minder aandacht hebben voor de stimulus van de visuele discriminatietask na een fout. Daarnaast was ook P3-amplitude, een component gerelateerd aan geheugen updating (Polich, 2007), verminderd na een fout in de lange interval conditie. Dit toont aan dat er

na een fout ook verminderde taak-gerelateerde geheugen updating op de volgende trial is.

Men rapporteerde reeds een attentional blink-achtig effect na fouten (Houtman & Notebaert, 2013), maar onze resultaten tonen aan dat het mechanisme achter de klassieke attentional blink (AB) en de error-geïnduceerde blink waarschijnlijk niet dezelfde zijn, gezien vroege visuele verwerking niet verstoord is in een klassieke AB taak (Sergent, Baillet, & Dehaene, 2005; Vogel et al., 1998). Gelijkaardig aan de idee dat een emotionele AB tot stand komt door concurrentie voor perceptuele bronnen (Most & Wang, 2011; Wang, Kennedy, & Most, 2012), tonen onze resultaten aan dat een fout gevolgd wordt door een daling in aandachtsbronnen voor de stimulus van de visuele discriminatie-taak.

Als een soort follow-up na HOOFDSTUK 6, wilden we vroege visuele componenten onderzoeken in een conflicttaak. Hiervoor heranalyseerden we de dataset van HOOFDSTUK 5 in HOOFDSTUK 7. We vonden geen effect van congruentie of vorige accuraatheid op N2 amplitude, een component gerelateerd aan conflict. We vonden evenwel een effect van congruentie op zowel de P1 als de N1, maar enkel na correcte trials. P1-amplitude is groter voor congruente post-correct trials, terwijl N1-amplitude meer negatief is voor incongruente post-correct trials. Eerder onderzoek liet zien dat N1 amplitude beïnvloed wordt door endogene aandacht terwijl P1 amplitude door zowel endogene als exogene aandacht beïnvloed kan worden. (Hopfinger & West, 2006). Onze resultaten suggereren dus dat er meer aandacht gericht werd naar post-correct incongruente trials terwijl participanten meer vertrouwden op exogene aandacht bij post-correcte congruente trials. Er was geen duidelijke modulatie van de late N1 door vorige accuraatheid. P3 amplitude was opnieuw significant kleiner na een fout dan na een correcte respons. Dit resultaat laat zien dat zelfs wanneer visuele aandacht slechts minimaal

wordt beïnvloed door vorige accuraatheid, geheugenupdating nog steeds slechter is na een fout. Daarnaast verdwijnt het verschil in vroege visuele aandacht tussen congruente en incongruente trials na een fout, wat een verminderde invloed van conflict verwerking impliceert. We moeten evenwel voorzichtig zijn met deze interpretatie aangezien de modulatie van deze vroege processen niet gevonden werd in de moeilijke conditie.

Samen bekeken tonen de resultaten van HOOFDSTUK 6 en 7 aan dat visuele aandacht, net zoals geheugenupdating, verminderd is na een fout. De invloed van een fout op deze vroege visuele componenten lijkt wel af te hangen van het inter-trial interval. Daarnaast is er ook geen evidentie voor post-error focusing als verklaring voor PERI.

Het doel van de studie in HOOFDSTUK 8 was het onderzoeken van de verwerking van feedback stimulus. Hier wilden we de hypothese testen dat het geheugen voor feedback getoond na een fout beter is dan voor feedback getoond na een correcte respons. We gebruikten een herkenningstaak (Experiment 1) en een lexicale decisie taak (Experiment 2 en 3) waarin een subset van woorden eerder gezien werd als foute of correcte feedback in een flankertaak. Uit de resultaten bleek inderdaad dat participanten de woorden die werden gezien na een fout beter onthielden.

In overeenstemming met resultaten van algemene kennistests (Butterfield & Metcalfe, 2006; Fazio & Marsh, 2009) en de orienting account (Notebaert et al., 2009) tonen onze resultaten aan dat woorden die getoond worden als foutfeedback meer verrassend/saillant zijn en automatisch de aandacht trekken, waardoor de verwerking van irrelevante kenmerken van deze feedback verbetert.

De resultaten gepresenteerd in dit doctoraat dragen bij tot de idee dat een fout een oriëntatierespons uitlokt en dat dit leidt tot een slechtere performantie, zowel gedragsmatig als elektrofysiologisch. Informatie gepresenteerd op het moment van de fout kan evenwel voordeel halen uit deze oriëntatierespons, wat resulteert in een beter geheugen voor deze

informatie. Daarnaast is het duidelijk dat deze aanpassingen na een fout beïnvloed worden door de tijd tussen trials en door persoonlijkheids- en taakkenmerken. Deze hoofdstukken laten ook het methodologisch nut zien van linear mixed models en Laplacian transformation voor ERP's. Daarnaast laten de resultaten ook zien dat wanneer PERI onderzocht wordt, men zich bewust moet zijn dat de factor vorige congruentie deze kan beïnvloeden.

REFERENTIES

- Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, *108*(3), 624–652. doi:10.1037/0033-295X.108.3.624
- Butterfield, B., & Metcalfe, J. (2006). The correction of errors committed with high confidence. *Metacognition and Learning*, *1*(1), 69–84. doi:10.1007/s11409-006-6894-z
- Compton, R. J., Huber, E., Levinson, A. R., & Zheutlin, A. (2012). Is “conflict adaptation” driven by conflict? Behavioral and EEG evidence for the underappreciated role of congruent trials. *Psychophysiology*, *49*(5), 583–589. doi:10.1111/j.1469-8986.2012.01354.x
- Danielmeier, C., & Ullsperger, M. (2011). Post-error adjustments. *Frontiers in Psychology*, *2*, 233. doi:10.3389/fpsyg.2011.00233
- Desmet, C., Imbo, I., De Brauwer, J., Brass, M., Fias, W., & Notebaert, W. (2012). Error adaptation in mental arithmetic. *Quarterly Journal of Experimental Psychology*, *65*(6), 1059–1067. doi:10.1080/17470218.2011.648943
- Duthoo, W., Abrahamse, E. L., Braem, S., Boehler, C. N., & Notebaert, W. (2014). The heterogeneous world of congruency sequence effects: an update. *Frontiers in Psychology*, *5*(1001). doi:10.3389/fpsyg.2014.01001
- Egner, T. (2007). Congruency sequence effects and cognitive control. *Cognitive, Affective & Behavioral Neuroscience*, *7*(4), 380–390. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/18189011>
- Fazio, L. K., & Marsh, E. J. (2009). Surprising feedback improves later memory. *Psychonomic Bulletin & Review*, *16*(1), 88–92. doi:10.3758/PBR.16.1.88
- Forster, S. E., & Cho, R. Y. (2014). Context specificity of post-error and post-conflict cognitive control adjustments. *PloS One*, *9*(3), e90281. doi:10.1371/journal.pone.0090281
- Hommel, B., Proctor, R. W., & Vu, K.-P. L. (2004). A feature-integration account of sequential effects in the Simon task. *Psychological Research*, *68*(1), 1–17. doi:10.1007/s00426-003-0132-y
- Hopfinger, J. B., & West, V. M. (2006). Interactions between endogenous and exogenous attention on cortical visual processing. *NeuroImage*, *31*(2), 774–789. doi:10.1016/j.neuroimage.2005.12.049
- Houtman, F., & Notebaert, W. (2013). Blinded by an error. *Cognition*, *128*(2), 228–236. doi:10.1016/j.cognition.2013.04.003
- Houtman, F., Núñez Castellar, E., & Notebaert, W. (2012). Orienting to errors with and without immediate feedback. *Journal of Cognitive Psychology*, *24*(3), 278–285. doi:10.1080/20445911.2011.617301

- Jentsch, I., & Dudschig, C. (2009). Why do we slow down after an error? Mechanisms underlying the effects of posterror slowing. *Quarterly Journal of Experimental Psychology*, *62*(2), 209–218. doi:10.1080/17470210802240655
- King, J. a, Korb, F. M., von Cramon, D. Y., & Ullsperger, M. (2010). Post-error behavioral adjustments are facilitated by activation and suppression of task-relevant and task-irrelevant information processing. *The Journal of Neuroscience*, *30*(38), 12759–12769. doi:10.1523/JNEUROSCI.3274-10.2010
- Lamers, M. J. M., & Roelofs, A. (2011). Attentional control adjustments in Eriksen and Stroop task performance can be independent of response conflict. *Quarterly Journal of Experimental Psychology*, *64*(6), 1056–1081. doi:10.1080/17470218.2010.523792
- Luck, S., Heinze, H., Mangun, G., & Hillyard, S. (1990). Visual event-related potentials index focused attention within bilateral stimulus arrays. II. Functional dissociation of P1 and N1 components. *Electroencephalography and Clinical Neurophysiology*, *75*, 528–542. Retrieved from <http://www.sciencedirect.com/science/article/pii/001346949090139B>
- Marco-pallarés, J., Camara, E., Münte, T. F., & Rodríguez-Fornells, A. (2008). Neural Mechanisms Underlying Adaptive Actions after Slips. *Journal of Cognitive Neuroscience*, *20*(9), 1–16.
- Mayr, U., Awh, E., & Laurey, P. (2003). Conflict adaptation effects in the absence of executive control. *Nature Neuroscience*, *6*(5), 450–452. doi:10.1038/nn1051
- Mordkoff, J. T. (2012). Observation: Three reasons to avoid having half of the trials be congruent in a four-alternative forced-choice experiment on sequential modulation. *Psychonomic Bulletin & Review*, *19*(4), 750–757. doi:10.3758/s13423-012-0257-3
- Most, S. B., & Wang, L. (2011). Dissociating spatial attention and awareness in emotion-induced blindness. *Psychological Science*, *22*(3), 300–5. doi:10.1177/0956797610397665
- Notebaert, W., Houtman, F., Opstal, F. Van, Gevers, W., Fias, W., & Verguts, T. (2009). Post-error slowing: an orienting account. *Cognition*, *111*, 275–279. doi:10.1016/j.cognition.2009.02.002
- Polich, J. (2007). Updating P300: an integrative theory of P3a and P3b. *Clinical Neurophysiology*, *118*(10), 2128–2148. doi:10.1016/j.clinph.2007.04.019
- Ridderinkhof, K. R. (2002). Micro- and macro-adjustments of task set: activation and suppression in conflict tasks. *Psychological Research*, *66*(4), 312–323. doi:10.1007/s00426-002-0104-7

- Ridderinkhof, K. R., de Vlugt, Y., Bramlage, A., Spaan, M., Elton, M., Snel, J., & Band, G. P. H. (2002). Alcohol consumption impairs detection of performance errors in mediofrontal cortex. *Science*, *298*, 2209–2211. doi:10.1126/science.1076929
- Schmidt, J., & De Houwer, J. (2011). Now you see it, now you don't: controlling for contingencies and stimulus repetitions eliminates the Gratton effect. *Acta Psychologica*, *138*(1), 176–186. doi:10.1016/j.actpsy.2011.06.002
- Sergent, C., Baillet, S., & Dehaene, S. (2005). Timing of the brain events underlying access to consciousness during the attentional blink. *Nature Neuroscience*, *8*(10), 1391–400. doi:10.1038/nn1549
- Vogel, E. K., Luck, S. J., Chun, M., Lollo, V. Di, Egeth, H., Maki, B., & Raymond, J. (1998). Electrophysiological Evidence for a Postperceptual Locus of Suppression During the Attentional Blink, *24*(6), 1656–1674.
- Wang, L., Kennedy, B. L., & Most, S. B. (2012). When emotion blinds: a spatiotemporal competition account of emotion-induced blindness. *Frontiers in Psychology*, *3*(November), 438. doi:10.3389/fpsyg.2012.00438

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Appendix

DATA STORAGE FACT SHEETS

Data Storage Fact Sheet - CHAPTER 2

Name/identifier study: Keep calm and be patient: the influence of anxiety and time on post-error adaptations

Author: Liesbet Van der Borght

Date: 24 August 2015

1. Contact details

=====

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2. Information about the datasets to which this sheet applies

=====

* Reference of the publication in which the datasets are reported: Van der Borght, L., Braem, S., Stevens, M., & Notebaert, W. (2015). *Keep calm and be patient: the influence of anxiety and time on post-error adaptations*. Manuscript submitted for publication.

* Which datasets in that publication does this sheet apply to?: The sheet applies to all data reported in the study.

3. Information about the files that have been stored

=====

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* Have the raw data been stored by the main researcher? YES / NO
If NO, please justify:

* On which platform are the raw data stored?

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- research group file server
- other (specify): ...

* Who has direct access to the raw data (i.e., without intervention of another person)?

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- responsible ZAP
- all members of the research group
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Specify: R Scripts and See methodology and results section in the article
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- a file specifying legal and ethical provisions:
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Data Storage Fact Sheet - CHAPTER 3

Name/identifier study: Disentangling post-error and post-conflict reduction of interference

Author: Liesbet Van der Borght

Date: 29 July 2015

1. Contact details

=====

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2. Information about the datasets to which this sheet applies

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* Reference of the publication in which the datasets are reported: Van der Borght, L., Braem, S., & Notebaert, W. (2014) Disentangling posterror and postconflict reduction of interference. *Psychonomic Bulletin & Review*, 21, 1530-1536. doi: 10.3758/s13423-014-0628-z

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- main researcher
- responsible ZAP
- all members of the research group
- all members of UGent
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3b. Other files

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Data Storage Fact Sheet - CHAPTER 4

Name/identifier study: A neutral measure for post-error reduction of interference

Author: Liesbet Van der Borght

Date: 24 August 2015

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If a response is not received when using the above contact details, please send an email to data.pp@ugent.be or contact Data Management, Faculty of Psychology and Educational Sciences, Henri Dunantlaan 2, 9000 Ghent, Belgium.

2. Information about the datasets to which this sheet applies

* Reference of the publication in which the datasets are reported: Van der Borght, L., Duthoo, W., & Notebaert, W. (2015). *A neutral measure for post-error reduction of interference*. Manuscript submitted for publication.

* Which datasets in that publication does this sheet apply to?: The sheet applies to all data reported in the study

3. Information about the files that have been stored

=====

3a. Raw data

* Have the raw data been stored by the main researcher? YES / NO

If NO, please justify:

* On which platform are the raw data stored?

- researcher PC
- research group file server
- other (specify): ...

* Who has direct access to the raw data (i.e., without intervention of another person)?

- main researcher
- responsible ZAP
- all members of the research group
- all members of UGent
- other (specify): ...

3b. Other files

* Which other files have been stored?

- file(s) describing the transition from raw data to reported results.
Specify: R Scripts and See methodology and results section in the article
- file(s) containing processed data. Specify: figures in the article
- file(s) containing analyses. Specify: R scripts and see results section in the article
- files(s) containing information about informed consent:
- a file specifying legal and ethical provisions:
- file(s) that describe the content of the stored files and how this content should be interpreted. Specify: ...
- other files. Specify: ...

* On which platform are these other files stored?

- individual PC
- research group file server
- other: ...

* Who has direct access to these other files (i.e., without intervention of another person)?

- main researcher
- responsible ZAP
- all members of the research group
- all members of UGent
- other (specify): ...

4. Reproduction

* Have the results been reproduced independently?: YES / NO

* If yes, by whom (add if multiple):

- name:
- address:
- affiliation:
- e-mail:

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Data Storage Fact Sheet - CHAPTER 5

Name/identifier study: Distinguishing the influence of task difficulty on error-related ERPs using surface Laplacian transformation

Author: Liesbet Van der Borght

Date: 24 August 2015

1. Contact details

=====

1a. Main researcher

- name: Liesbet Van der Borght
- address: Henri Dunantlaan 2, 9000 Gent
- e-mail: liesbet.vanderborght@ugent.be

1b. Responsible Staff Member (ZAP)

- name: Wim Notebaert
- address: Henri Dunantlaan 2, 9000 Gent
- e-mail: wim.notebaert@ugent.be

If a response is not received when using the above contact details, please send an email to data.pp@ugent.be or contact Data Management, Faculty of Psychology and Educational Sciences, Henri Dunantlaan 2, 9000 Ghent, Belgium.

2. Information about the datasets to which this sheet applies

=====

* Reference of the publication in which the datasets are reported: Van der Borght, L., Houtman, F., Burle, B., & Notebaert, W. (2015). *Distinguishing the influence of task difficulty on error-related ERPs using surface Laplacian transformation*. Manuscript submitted for publication.

* Which datasets in that publication does this sheet apply to?: The sheet applies to all data reported in the study.

3. Information about the files that have been stored

3a. Raw data

* Have the raw data been stored by the main researcher? YES / NO

If NO, please justify:

* On which platform are the raw data stored?

- researcher PC
- research group file server
- other (specify): ...

* Who has direct access to the raw data (i.e., without intervention of another person)?

- main researcher
- responsible ZAP
- all members of the research group
- all members of UGent
- other (specify): ...

3b. Other files

* Which other files have been stored?

- file(s) describing the transition from raw data to reported results. Specify: EEGlab/ERPlab Scripts and See methodology and results section in the article
- file(s) containing processed data. Specify: Figures in the article
- file(s) containing analyses. Specify: SPSS datasets and see results section in the article
- files(s) containing information about informed consent:
- a file specifying legal and ethical provisions:
- file(s) that describe the content of the stored files and how this content should be interpreted. Specify: ...
- other files. Specify: ...

* On which platform are these other files stored?

- individual PC
- research group file server
- other: ...

* Who has direct access to these other files (i.e., without intervention of another person)?

- main researcher
- responsible ZAP
- all members of the research group
- all members of UGent
- other (specify): ...

4. Reproduction

* Have the results been reproduced independently?: YES / NO

* If yes, by whom (add if multiple):

- name:
- address:
- affiliation:
- e-mail:

Data Storage Fact Sheet – CHAPTER 6

Name/identifier study: Errors disrupt subsequent early attentional processes

Author: Liesbet Van der Borght

Date: 6 August 2015

1. Contact details

1a. Main researcher

- name: Liesbet Van der Borght
- address: Henri Dunantlaan 2, 9000 Gent
- e-mail: liesbet.vanderborght@ugent.be

1b. Responsible Staff Member (ZAP)

- name: Wim Notebaert
- address: Henri Dunantlaan 2, 9000 Gent
- e-mail: wim.notebaert@ugent.be

If a response is not received when using the above contact details, please send an email to data.pp@ugent.be or contact Data Management, Faculty of Psychology and Educational Sciences, Henri Dunantlaan 2, 9000 Ghent, Belgium.

2. Information about the datasets to which this sheet applies

* Reference of the publication in which the datasets are reported: Van der Borght, L., Schevernels, H., Burle, B., & Notebaert, W. *Errors disrupt subsequent early attentional processes*. Manuscript in preparation.

* Which datasets in that publication does this sheet apply to?: The sheet applies to all data reported in the study.

3. Information about the files that have been stored

=====

3a. Raw data

* Have the raw data been stored by the main researcher? YES / NO

If NO, please justify:

* On which platform are the raw data stored?

- researcher PC
- research group file server
- other (specify): ...

* Who has direct access to the raw data (i.e., without intervention of another person)?

- main researcher
- responsible ZAP
- all members of the research group
- all members of UGent
- other (specify): ...

3b. Other files

* Which other files have been stored?

- file(s) describing the transition from raw data to reported results. Specify: EEGlab/ERPlab Scripts and See methodology and results section in the article
- file(s) containing processed data. Specify: Figures in the article
- file(s) containing analyses. Specify: SPSS datasets and see results section in the article
- files(s) containing information about informed consent:
- a file specifying legal and ethical provisions: filled in specified ethical protocol and the approval of the project by the ethical commission
- file(s) that describe the content of the stored files and how this content should be interpreted. Specify: ...
- other files. Specify: ...

* On which platform are these other files stored?

- individual PC
- research group file server
- other: ...

* Who has direct access to these other files (i.e., without intervention of another person)?

- main researcher
- responsible ZAP
- all members of the research group
- all members of UGent
- other (specify): ...

4. Reproduction

* Have the results been reproduced independently?: YES / NO

* If yes, by whom (add if multiple):

- name:
- address:
- affiliation:
- e-mail:

Data Storage Fact Sheet – CHAPTER 7

Name/identifier study: Errors disrupt conflict processing

Author: Liesbet Van der Borgh

Date: 6 August 2015

1. Contact details

=====

1a. Main researcher

- name: Liesbet Van der Borgh
- address: Henri Dunantlaan 2, 9000 Gent
- e-mail: liesbet.vanderborgh@ugent.be

1b. Responsible Staff Member (ZAP)

- name: Wim Notebaert
- address: Henri Dunantlaan 2, 9000 Gent
- e-mail: wim.notebaert@ugent.be

If a response is not received when using the above contact details, please send an email to data.pp@ugent.be or contact Data Management, Faculty of Psychology and Educational Sciences, Henri Dunantlaan 2, 9000 Ghent, Belgium.

2. Information about the datasets to which this sheet applies

=====

* Reference of the publication in which the datasets are reported:

* Which datasets in that publication does this sheet apply to?: The sheet applies to all data reported in the study.

3. Information about the files that have been stored

3a. Raw data

* Have the raw data been stored by the main researcher? YES / NO

If NO, please justify:

* On which platform are the raw data stored?

- researcher PC
- research group file server
- other (specify): ...

* Who has direct access to the raw data (i.e., without intervention of another person)?

- main researcher
- responsible ZAP
- all members of the research group
- all members of UGent
- other (specify): ...

3b. Other files

* Which other files have been stored?

- file(s) describing the transition from raw data to reported results. Specify: EEGlab/ERPlab Scripts and See methodology and results section in the article
- file(s) containing processed data. Specify: Figures in the article
- file(s) containing analyses. Specify: SPSS datasets and see results section in the article
- files(s) containing information about informed consent:
- a file specifying legal and ethical provisions: filled in specified ethical protocol and the approval of the project by the ethical commission
- file(s) that describe the content of the stored files and how this content should be interpreted. Specify: readme.txt shows the location of the raw data and the program as these are part of another manuscript
- other files. Specify: ...

* On which platform are these other files stored?

- individual PC
- research group file server
- other: ...

* Who has direct access to these other files (i.e., without intervention of another person)?

- main researcher
- responsible ZAP
- all members of the research group
- all members of UGent
- other (specify): ...

4. Reproduction

* Have the results been reproduced independently?: YES / NO

* If yes, by whom (add if multiple):

- name:
- address:
- affiliation:
- e-mail:

Data Storage Fact Sheet – CHAPTER 8

Name/identifier study: Improved memory for error feedback

Author: Liesbet Van der Borght

Date: 31 August 2015

1. Contact details

1a. Main researcher

- name: Liesbet Van der Borght
- address: Henri Dunantlaan 2, 9000 Gent
- e-mail: liesbet.vanderborght@ugent.be

1b. Responsible Staff Member (ZAP)

- name: Wim Notebaert
- address: Henri Dunantlaan 2, 9000 Gent
- e-mail: wim.notebaert@ugent.be

If a response is not received when using the above contact details, please send an email to data.pp@ugent.be or contact Data Management, Faculty of Psychology and Educational Sciences, Henri Dunantlaan 2, 9000 Ghent, Belgium.

2. Information about the datasets to which this sheet applies

* Reference of the publication in which the datasets are reported: Van der Borght, L., Schoupe, N., & Notebaert, W. (in press). Improved memory for error feedback. *Psychological Research*.

* Which datasets in that publication does this sheet apply to?: The sheet applies to all data reported in the study.

3. Information about the files that have been stored

=====

3a. Raw data

* Have the raw data been stored by the main researcher? YES / NO

If NO, please justify:

* On which platform are the raw data stored?

- researcher PC
- research group file server
- other (specify): ...

* Who has direct access to the raw data (i.e., without intervention of another person)?

- main researcher
- responsible ZAP
- all members of the research group
- all members of UGent
- other (specify): ...

3b. Other files

* Which other files have been stored?

- file(s) describing the transition from raw data to reported results. Specify: R Scripts and See methodology and results section in the article
- file(s) containing processed data. Specify: figures in the article
- file(s) containing analyses. Specify: R scripts, SPSS datasets and see results section in the article
- files(s) containing information about informed consent:
- a file specifying legal and ethical provisions:
- file(s) that describe the content of the stored files and how this content should be interpreted. Specify: ...
- other files. Specify: ...

* On which platform are these other files stored?

- individual PC
- research group file server
- other: ...

* Who has direct access to these other files (i.e., without intervention of another person)?

- main researcher
- responsible ZAP
- all members of the research group
- all members of UGent
- other (specify): ...

4. Reproduction

* Have the results been reproduced independently?: YES / NO

* If yes, by whom (add if multiple):

- name:
- address:
- affiliation:
- e-mail:

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