

# **Pre-Error Cognition: Insights into Cognitive Control through Neural Precursors of Performance Errors**

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**Robert Steinhauser**

**aus Eichstätt**

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Referent: Prof. Dr. Marco Steinhauser

Korreferent: Dr. Søren Andersen

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## Abstract

Cognitive control processes enable humans to break out of reflexive stimulus-response chains and to align their behavior towards self-imposed goals. Despite decades of research on the nature of these processes, they remain a complex and only partly comprehensible fabric of interactions and interdependencies. Three electroencephalographic studies aimed to increase knowledge about cognitive control by utilizing *error precursors* – neural activity preceding the occurrence of performance errors. Study 1 used error precursors to separate two preparatory control processes of a task-switching paradigm and to investigate their relative contribution to the emergence of task confusions. The results highlight the importance of general preparation in the form of cue encoding but also demonstrate how switch-specific preparatory activity can affect the selection of the currently relevant task set. In Study 2, preparatory processes were examined in the more complex environment of a dual-tasking paradigm. Distinct error precursors for the respective subtasks and a neural correlate of task order switches that is independent of these provide evidence for a multi-level system of control processes with advance prioritization of subtasks in dual-tasking. Study 3 finally focused on reactive control – adjustments to neural activity and behavior following unfavorable outcomes such as performance errors. Here, error precursors serve as a prerequisite to answer the question of adaptivity of post-error adjustments in visual search. The results confirm that a post-error reduction of target localization activity serves to attenuate a potential error source in this paradigm. In summary, the three studies of this doctoral thesis contribute to understanding the complex system of control processes by providing evidence for accounts that suggest well-established knowledge about control processes to be reconsidered in light of more fine-grained differentiation of the underlying subcomponents.

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## Introduction

*„It is in the nature of an experimental analysis of human behavior that it should strip away the functions previously assigned to autonomous man and transfer them one by one to the controlling environment“*

F. B. Skinner, *Beyond Freedom and Dignity*, 1971

*„The capacity for cognitive control is perhaps the most distinguishing characteristic of human behavior. [...] Understanding the mechanisms that underlie our capacity for cognitive control seems essential to unravelling the mystery of why [...] we are capable of intelligent, goal-directed behaviour“*

Jonathan D. Cohen, *The Wiley Handbook of Cognitive Control*, 2017

For many decades, experimental psychologists focused on investigating the laws of contingencies between stimuli and responses, going so far as to explain human behavior solely in terms of man being deterministically controlled by the environment (Skinner, 1973; Watson, 1919). Today's cognitive psychology and neuroscience have advanced from this reductionist approach and distinctly include internal states and goals into their endeavor to establish a more comprehensive account for the many forms of human behavior in experimental settings as well as everyday situations (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Cohen, 2017; Dehaene, 2014; Posner, Snyder, & Solso, 2004). In fact, humans exceed any other species in their ability to maintain self-set goals despite ongoing interference from conflicting distractions and flexibly adapt their behavior to changing environments. These abilities rest upon a complex set of *cognitive control processes* that monitor and adjust our current behavior, thus allowing us to break reflexive stimulus-response chains. This mechanism can therefore be seen as the neural basis of volition, the ability of humans to decide for or against a certain course of action (Haggard, 2008).

The following set of empirical studies aims to gain further insight into these control processes by measuring changes to brain activity in situations that feature impairments to cognitive control, resulting in the frequently observed phenomenon of performance errors.

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Through the analysis of event-related potentials (ERPs) preceding and following errors, I aim to investigate the complex interplay of control subprocesses and in how far cognitive control can serve to adjust neural processing to improve subsequent performance. I intend to demonstrate in detail how investigations based on such *error precursors* form a methodological approach that is able to answer questions on cognitive control that cannot be answered by means of conventional analyses.

## Cognitive control

First attempts to determine the concept of cognitive control started, when (mostly) conscious controlled processes were differentiated from automated ones (Pribram, Miller, & Galanter, 1960; Shiffrin & Schneider, 1977). Key features of this controlled processing were described as being slow, capacity-limited, and modifiable. The classical Stroop task (Stroop, 1935) may serve as a suitable example for this. Here, the comparably slow, controlled process of color naming can be subject to strong interference from the much faster, automatic process of word reading. This results in slower response times and far more performance errors in incongruent trials, in which the word meaning and its font color differ. Since then, a vast number of psychological and neuroscientific studies have extended our knowledge on cognitive control (for reviews, see Botvinick et al., 2001; Kiesel et al., 2010; Miller, 2001; Posner et al., 2004; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004) and it is possible to provide a more detailed picture of the subject. Today, automaticity and control are regarded not as an exclusionary dichotomy but as a continuum and the concept of cognitive control is seen as a large set of potentially context-specific top-down processes that support other processing and share certain features. They include representations of task goals that are used as signals to guide further processing and to repel interference from distracting events and processes. Furthermore, they can be updated to better fit to the needs of changing

environments (Cohen, 2017). The main constraint of controlled processing, its apparent limitation of capacity, is currently thought to be better explained by domain-specific predispositions towards cross-talk between processes that share overlapping pathways than by limitations to the system of cognitive control itself (Cohen, 2017; Cohen, Servan-Schreiber, & McClelland, 1992).

Braver et al. (Braver, 2012; Braver, Gray, & Gregory C. Burgess, 2007) presented a framework that brings together two important aspects of cognitive control that are also at the core of this thesis. They distinguish *proactive control*, the anticipatory maintenance of goal-relevant information, and *reactive control*, stimulus-driven goal-reactivation after conflictual and unexpected events (see Table 1). Both types of cognitive control are predominantly located in the prefrontal cortex (PFC), although particularly reactive control also affects other brain regions by means of adjustments after cognitive conflict.

**Table 1.** Distinctions between Proactive and Reactive Control

	<b>Proactive Control</b>	<b>Reactive Control</b>
<b>Computational Properties</b>	Future-oriented, early selection, preparatory attention	Past-oriented, late correction, interference resolution
<b>Information Processing</b>	Strong goal-relevant focus, global control effects	Increased goal-irrelevant processing, item-specific control
<b>Temporal Dynamics</b>	Sustained, activation prior to imperative stimulus	Transient, activation after imperative stimulus
<b>Neural Substrates</b>	Lateral PFC, midbrain DA (phasic activity)	ACC, lateral PFC (transient response), MTL, others

*Note.* From Braver et al., 2007, p. 81. ACC = anterior cingulate cortex; DA = dopamine; MTL = medial temporal lobe; PFC = prefrontal cortex.



According to the authors, the distinctive feature of proactive control is the active maintenance of context representations, that is, information about task-relevant aspects that are intended to bias response selection in favor of the current task. This context information is subsequently able to influence domains such as perception, attention, memory, and emotion (Braver et al., 2007). In contrast to proactive control, reactive control is engaged only in cases of increased cognitive conflict or erroneous behavior, in an “if need be” manner. These corrective mechanisms are active only temporarily and decay quickly.

Braver et al. (Braver, 2012; Braver et al., 2007) argue that such a two-component system of control processes is necessary and superior to more parsimonious models of cognitive control, because proactive and reactive control each have their individual costs and benefits, which results in a tradeoff that requires constant balancing of the degrees that both components contribute in a particular situation.

### **Proactive control: task preparation**

Among the many cognitive processes that are part of the cognitive control system, processes of task preparation have gained particular research interest. A common method to investigate these processes is the task switching paradigm, in which participants work on one speeded choice response task at a time out of a pool of two or more tasks (Allport, Styles, & Hsieh, 1994; Jersild, 1927; Iring Koch, 2003; Meiran, 1996; Monsell, Sumner, & Waters, 2003; Rogers & Monsell, 1995; Spector & Biederman, 2016; for reviews, see Kiesel et al., 2010; I. Koch, Gade, Schuch, & Philipp, 2010; Monsell, 2003; Vandierendonck, Liefoghe, & Verbruggen, 2010). The tasks vary in an alternating or random way, creating *task repetitions* (AA) and *task switches* (AB). A robust finding in this paradigm is that switch costs – slower responses and higher error rates in task switches – are reduced with longer intervals between the trials (Koch, 2003; Monsell et al., 2003; Rogers & Monsell, 1995). And, in

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variants of this paradigm in which a cue indicates the upcoming task, also with longer cue-stimulus intervals (Arrington & Logan, 2004; Hoffmann, Kiesel, & Sebold, 2003; Logan & Bundesen, 2003; Meiran, Chorev, & Sapir, 2000). There are two major theoretical views on what forms the basis of these switch costs and their reduction with longer intervals between the tasks. According to Allport et al. (1994) and subsequent papers (e.g. Allport & Wylie, 1999; Meuter & Allport, 1999; Wendt & Kiesel, 2008; Wylie & Allport, 2000), *inertia* of task sets causes interference with subsequent tasks when the previous task set is still active to some degree in working memory. Nonetheless, not all switch-cost related effects can be attributed to such interference and decay processes. This is why other authors suggest some form of *advance reconfiguration* of the upcoming task set, the sum of all mental representations and processes involved in executing a certain task, as the underlying process of at least a part of the observed task-switching costs (Logan & Gordon, 2001; Meiran, 1996; Monsell & Mizon, 2006; Rogers & Monsell, 1995).

The exact nature of this reconfiguration, however, is subject to dispute. In the classic paper by Rogers & Monsell (1995), task-set reconfiguration is viewed as an additional processing stage that is added only to task switch trials, whereas it is unnecessary and thus absent in repetitions. To be able to explain the existence of residual switch costs, i.e. switch costs despite very long preparation intervals, two-stage models assume that this reconfiguration process is split in a pre-stimulus part and a post-stimulus part (Mayr & Kliegl, 2000, 2003; Meiran, 2000; Rogers & Monsell, 1995; Rubinstein, Meyer, & Evans, 2001). Prior to the onset of the stimulus, preparation consists of shifting goals or biasing now task-relevant stimuli. After the stimulus has been displayed, a second stage is necessary in which rules that link valid responses to the current task are activated and the possible responses are weighted with regard to their expected correctness. In contrast, some authors explain residual switch costs through eventually one single preparation stage that simply fails to be executed successfully in certain trials (De Jong, 2000; Nieuwenhuis & Monsell, 2002). Only in such

trials with failed advance preparation, post-stimulus preparation occurs, which finally leads to the observed residual switch costs in averaged response times. Nonetheless, some other studies suggest that switch-specific preparation may play only a subordinate role. For example, increasing the ability to prepare for tasks leads to faster responses also on repetition trials (Dreisbach, Haider, & Kluwe, 2002; Koch, 2001; Koch & Allport, 2006), which means that some kind of task-updating must also occur in these trials. Moreover, variants of the cued task-switching paradigm in which a 2:1 cue-task mapping is implemented (two cues refer to one task, two cues to the other) showed that a considerable proportion of the switch costs actually emerges due to switching the cue, not the task (Logan & Bundesen, 2003; Mayr & Kliegl, 2000, 2003). They conclude that preparation in task switching paradigms rests largely on a combination of two stages that manifest in both switch and repetition trials: first, the cue is to be encoded and second, currently relevant stimulus-response mappings need to be retrieved from long-term memory.

One step towards a more distinct analysis of preparatory processes are approaches that include psychophysiological measures. Particularly ERPs provide a means for a systematic identification and separation of cognitive processes due to their remarkable temporal resolution (Kappenman & Luck, 2012; Steven J. Luck, 2005). Consequently, it is not surprising that there is a multitude of ERP studies that investigated preparatory brain activity in task-switching paradigms. Most robustly, such studies find a posterior positivity in task-switches compared to task repetitions (Astle, Jackson, & Swainson, 2008a; Goffaux, Phillips, Sinai, & Pushkar, 2008; Jost, Mayr, & Rösler, 2008; Karayanidis et al., 2009; Kieffaber & Hetrick, 2005; Lavric, Mizon, & Monsell, 2008; Miniussi, Marzi, & Nobre, 2005; Nicholson, Karayanidis, Bumak, Poboka, & Michie, 2006; Nicholson, Karayanidis, Davies, & Michie, 2006). This *switch positivity* occurs for many different types of cues, stimulus sets and response sets (for reviews, see Karayanidis et al., 2010; Karayanidis & Jamadar, 2014), predicts response times in general, and its amplitude is negatively correlated with behavioral

switch costs (Karayanidis et al., 2009; Karayanidis, Provost, Brown, Paton, & Heathcote, 2011; Karayanidis, Whitson, Heathcote, & Michie, 2011; Lavric et al., 2008; Wang, Ding, & Kluger, 2015). Nonetheless, subsequent studies were able to demonstrate that the switch positivity in fact consists of several subcomponents. For example, including single-task blocks (AAAAAA) in the experimental design and comparing the associated all-repetition trials with conventional (mixed-)repetitions allows for a differentiation of the switch positivity and a slightly more centro-parietal and slightly earlier *mixing positivity*. This substantiates accounts proposing that indeed two separate mechanisms underlie switch-independent cue encoding and switch-specific task set reconfiguration (Goffaux et al., 2008; Jost et al., 2008; Karayanidis, Whitson, et al., 2011; Nicholson, Karayanidis, Poboka, Heathcote, & Michie, 2005). Furthermore, studies have identified other preparatory processes with distinct functional significance, such as an early frontal modulation prior to the posterior positivity that is supposed to reflect an early stage of initiation of the subsequent task-set reconfiguration (Astle et al., 2008a; Brass, Ullsperger, Knoesche, von Cramon, & Phillips, 2005; Rushworth, Passingham, & Nobre, 2005). Additionally, a stimulus-preceding negativity is reported to represent inhibitory processes that suppress the conflicting response set (Astle et al., 2008a; Astle, Jackson, & Swainson, 2008b; Brunia, van Boxtel, & Böcker, 2012; Karayanidis, Provost, et al., 2011; van Boxtel & Böcker, 2004; Walter et al., 1964). Taken together, a complex picture of preparatory processes emerges that encompasses a multitude of distinguishable control processes in task preparation.

However, all these studies share a potentially profound limitation. Based on a comparison of task repetitions and switches and the associated response times and error rates, they seek to make specific statements about whether certain cognitive control processes are causally linked to the reconfiguration of task sets. In other words, they assume to address the *effectiveness* of task-set reconfiguration, that is, whether or not individual processes produce the desired outcome of successfully (re)activating the currently relevant task set. In fact,

however, this prevalent approach is unsuitable to differentiate effectiveness from *efficiency*. It is unclear if findings on task-set reconfiguration so far truly address processes that are indeed *required* for successful reconfiguration or rather reflect processes that merely support task preparation and are thus linked to an *optimization* of reconfiguration.

Independently of this last issue, the complexity of preparatory control processes is even more drastic in cases of a concurrent execution of two or more tasks. Such multitasking situations are commonly investigated in dual-tasking experiments, most notably by means of the psychological refractory period (PRP) paradigm. Here, two choice response tasks are separated by a variable stimulus onset asynchrony (SOA) and abundance of studies found slower responses to Task 2 (T2) with shorter SOAs, the PRP effect, whereas Task 1 (T1) is unaffected by the SOA (Bertelson, 1966; Telford, 1931). This seemingly delayed execution of T2 is commonly attributed to a *cognitive bottleneck* during the response selection stage (Pashler, 1994a; Pashler & Johnston, 1989). Response selection of T2 can only start as soon as this stage has been completed for T1. As a result, shorter SOAs exhibit a cognitive slack right before the response selection stage, which in turn causes increased response times for this task. In contrast, the *capacity sharing* view (Kahneman, 1973; McLeod, 1977; Tombu & Jolicœur, 2002, 2003, 2005) suggests that parallel processing of both tasks is possible in all stages. Due to limited resources that have to be shared between the tasks, however, processing of T2 is slowed down in short SOAs. A third class of theories on dual-tasking assumes that while parallel processing is possible in principle, serial completion of certain stages is less resource-consuming and thus offers benefits for a fast execution of the tasks (Lehle & Hübner, 2009; Lehle, Steinhauser, & Hübner, 2009; Meyer & Kieras, 1997). Following this *strategic prioritization* account, cognitive control assigns different roles to the two tasks in advance and treats them in specific ways with regard to, as Meyer & Kieras (1997) phrase it, an expected immediate (T1) or deferred (T2) execution. This view highlights the importance

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of task preparation on this effect and is in line with findings by De Jong (1995), which suggest that both subtasks are prepared in advance, differently with regard to whether they are scheduled for execution as T1 and T2. Beyond that, evidence from task order switches in cued PRP paradigms suggests that aspects of both subtasks in the PRP paradigm are merged into a superordinate *dual-task set* that is prepared in addition to the two individual task sets of the subtasks (Hirsch, Nolden, & Koch, 2017; Luria & Meiran, 2003). Nonetheless, neural evidence for such an interaction of task-set preparation on different hierarchical levels in dual-tasking is scarce so far. And again, nor are there studies that feature the necessary experimental approach to thoroughly address the above mentioned separation of effectiveness vs. efficiency. Distinguishing whether the examined processes are *necessary prerequisites* for successful scheduling of subtasks in the PRP paradigm or whether these processes merely *support performance* through optimization is hardly investigable by focusing only on response times.

### **Reactive control: adaptive task post-processing**

On executing a task, a cascade of monitoring processes – mostly located in the posterior medial frontal cortex – is triggered that intends to evaluate the outcome of the respective actions in order to improve subsequent behavior (pMFC; Donoso, Collins, & Koechlin, 2014; Koechlin & Summerfield, 2007; Miller, 2001). As part of the complex of cognitive control processes, this *performance monitoring system* facilitates goal-directed behavior through initiating alterations to cognitive processes – and subsequently behavior – in situations with unexpected, unfavorable outcomes. This is particularly the case in performance errors, which is why the research field of error processing offers a fruitful window into analyzing cognitive control.

Performance errors elicit changes to both behavior and psychophysiology. Most frequently, an increase in response times after errors is reported, the so-called *post-error slowing* (PES; for a review, see Danielmeier & Ullsperger, 2011). However, the exact nature of PES is up to dispute. Some argue that it is a mere byproduct of the distraction and interference that is caused by the error, representing an orienting response to this comparably rare event (Notebaert et al., 2009). Others see PES as an adaptive, goal-directed attempt to prevent the occurrence of further errors (Carter & van Veen, 2007; Gehring & Fencsik, 2001; Ridderinkhof et al., 2004). Likewise, findings on post-error changes to accuracy are inconsistent. Whereas many studies find a *post-error decrease of accuracy* (PEDA; e.g., Fiehler, Ullsperger, & Von Cramon, 2005; Hajcak & Simons, 2008; Rabbitt & Rodgers, 1977), others report an *increase of accuracy* after errors (PEIA; e.g., Danielmeier, Eichele, Forstmann, Tittgemeyer, & Ullsperger, 2011; Maier, Yeung, & Steinhauser, 2011; Marco-Pallarés, Camara, Münte, & Rodríguez-Fornells, 2008). In fact, recent evidence suggests that errors elicit both adaptive and non-adaptive processes that interact and add up to the observed PES and, depending on the paradigm and the relative proportion of adaptive adjustments, either PEDA or PEIA (Purcell & Kiani, 2016; M. Steinhauser, Ernst, & Ibal, 2016).

With regard to the psychophysiological level, ERPs such as the error-related negativity (Ne/ERN; Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991; Gehring, Goss, & Coles, 1993) and the error positivity (Pe; Falkenstein et al., 1991; Hajcak, McDonald, & Simons, 2003; for a review, see Overbeek, Nieuwenhuis, & Ridderinkhof, 2005) were found to be reflecting aspects of this performance monitoring system. Originally thought to represent an error detection mechanism itself (Gehring et al., 1993), the Ne/ERN is today considered to be either a neural correlate of response conflict (Yeung, Botvinick, & Cohen, 2004) or of the prediction error in reinforcement-learning theories (Holroyd & Coles, 2002). Peaking over frontocentral electrodes, this ERP component emerges already up to 50 ms before response button press and obtains its maximum amplitude around 100 ms after the response (Gehring,

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Liu, Orr, & Carp, 2011). The Pe, on the other hand, peaks around 300-500 ms over parietal electrodes and was found to be connected to processes of error awareness (Gehring et al., 2011). M. Steinhauser and Yeung (2010) showed that the Pe, in contrast to the Ne/ERN, mirrors the accumulation of evidence for the occurrence of an error over time.

Whereas some studies report correlations of PES and the Ne/ERN but not the Pe (Debener et al., 2005; Gehring et al., 1993; Holroyd, Yeung, Coles, & Cohen, 2005), others find links between PES and the Pe, but not the Ne/ERN (Hajcak et al., 2003; Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001). These seemingly contradictory results may well be explained by the findings (see above) that PES is but the final outcome of a series of adaptive and non-adaptive adjustment processes and thus is only indirectly linked to the pMFC performance monitoring system (Danielmeier et al., 2011; Danielmeier & Ullsperger, 2011; King, Korb, von Cramon, & Ullsperger, 2010). Hence, studies that correlate the amplitude of the Ne/ERN or the Pe with the amount of PES are able to provide evidence for adaptive neural adjustments after errors only to a very limited degree. A study by Maier, M. Steinhauser, and Yeung (2011) addresses this issue with a more sophisticated approach. The authors compare two types of errors, errors due to speed pressure and errors caused by insufficient selective attention. Only the latter type of error should be followed by adjustments to selective attention. Indeed, only this error type elicited such adjustments on the behavioral level and the amplitude of the Ne/ERN was found to predict the degree of adjustments.

Neural evidence for adaptive post-error adjustments that go beyond correlates of the performance monitoring system itself (i.e., the Ne/ERN or PE, see Debener et al., 2005; Gehring et al., 1993; Holroyd et al., 2005; Maier et al., 2011) and directly address task-related processes is likewise reported in a small number of studies. Nonetheless, given that M. Steinhauser et al. (2017; see also Schiffler, Bengtsson, & Lundqvist, 2017) found adaptive adjustments to be task-specific, goal-directed adjustments to such lower-level processes are of particular interest. As an example, in a functional magnetic resonance imaging (fMRI) study,



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King et al. (2010) found that activity in brain areas representing task-irrelevant features of the stimulus (stimulus location: sensorimotor cortex) was suppressed after errors, whereas activity in task-relevant parts of the brain (face gender: fusiform face area) was increased. Likewise, Danielmeier et al. (2011) report increased activity in task-relevant perceptual brain areas and decreased activity in areas that represent the task-irrelevant perception of distractor stimuli. These examples show that in addition to distracting, unfavorable consequences, performance errors can indeed elicit neural adjustments in order to prevent the occurrence of further errors in task-specific processes. Hence, such adaptive adjustments are a core part of the complex system of cognitive control processes, enabling humans to find back to expedient and goal-directed behavior.

With respect to their experimental approach, King et al. (2010), Maier et al. (2011), and Danielmeier (2011) differ significantly from previous studies. They specifically include considerations about the error causes into their interpretation of post-error adjustments. As a result, they can examine such adjustments as to whether they strive to mend error-causing deviations in neural activity preceding the error and thus can truly be considered as being goal-directed, adaptive adjustments. Error-precursing brain activity serves as a necessary baseline here, which any neural changes after the errors have to be compared to. These considerations bear striking resemblance to the distinction of effective and efficient task preparation elaborated above. Without an inclusion of error causes as task-specific baselines, also investigation of reactive control processes runs the risk of not being able to thoroughly identify the true nature of post-error adjustments in a specific task environment – that is, if they are goal-directed adaptations or mere byproducts of error-related interference. For this reason, the following section seeks to outline how the analysis of *error precursors* may contribute to a more exact investigation of effective versus efficient processes of cognitive control and why this approach was chosen as the methodological framework of this thesis.

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## Error precursors

On the neural level, performance errors are not only preceded by the onset of the Ne/ERN, which emerges from about 50 ms prior to the erroneous response button press. A number of studies have shown that neural deviations from normal, functional patterns foreshadow errors far earlier, up to several trials in advance (H. Eichele, Juvodden, Ullsperger, & Eichele, 2010; Eichele et al., 2008; Ruiz, Strübing, Jabusch, & Altenmüller, 2011; Shou, Dasari, & Ding, 2015; M. Steinhauser et al., 2012). Such *error precursors* have largely been investigated to discover origins and causes of decreasing performance on the neural level. One important cause of errors appears to be lapses of attention, which are mirrored by increased alpha activity (Mazaheri, Nieuwenhuis, Van Dijk, & Jensen, 2009; O’Connell et al., 2009) and a reduced task-related deactivation of the default-mode network (Weissman, Roberts, Visscher, & Woldorff, 2006). But also the performance monitoring system itself can be a cause for errors, as seen in an error-preceding positivity with similar topography and time course as the Ne/ERN (Ridderinkhof, Nieuwenhuis, & Bashore, 2003). It is argued that this positivity reflects occasional failures of the performance monitoring system to compensate for subthreshold incorrect response tendencies, thus creating interference that can lead to an actual error in the subsequent trial. Likewise, H. Eichele et al. (2010) and M. Steinhauser et al. (2012) found performance errors to emerge because of maladaptations in conflict monitoring over several trials, which can – in certain task environments – lead to error-prone states that favor speed over accuracy.

However, unveiling the origins of performance errors is not the main aim of the following studies. Rather, error precursors are utilized as a *methodological approach* to investigate questions from the research on cognitive control that would not be answerable to an equally thorough degree by means of conventional analyses. Most cognitive control studies examine how different experimental conditions such as stimulus-response (SR) compatible vs.

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incompatible trials (e.g., Kornblum, Hasbroucq, & Osman, 1990), low vs. high working memory load (e.g., de Fockert & Lavie, 2001), or task repetitions vs. switches (e.g., Rogers & Monsell, 1995) affect, most importantly, response times and ERP components. Originally rooted in the additive factors logic (Donders, 1868; Sternberg, 1969), it is commonly assumed that manipulations in such conditions give, by way of increased processing time, insight into the impact of certain processing stages or individual subprocesses on the overall execution of the task (see also Anderson, Zhang, Borst, & Walsh, 2016). While this predominant approach is appropriate for many research questions, on closer examination it becomes evident that it is not possible to thoroughly distinguish if individual processes of cognitive control serve to improve or optimize performance, or if they are essential prerequisites for successful task execution. To specifically address this question, performance errors need to be considered because only they represent occurrences of a complete failure of task execution. Only this condition allows for an explicit separation of the impact of control processes on how efficient vs. how effective tasks are executed.

To illustrate this approach, in Studies 1 and 2, error precursors are used as markers for specific cognitive processes. By contrasting brain activity preceding correct trials from activity preceding specific types of errors, it is possible to identify and isolate those preparatory processes that lead to the respective errors. This approach constitutes an elegant and promising way to disentangle the complexity of task preparation and to assess which processes are effectively necessary for successful task-set reconfiguration. In Study 3, deviating brain activity prior to performance errors is used as a baseline for deciding whether post-error adjustments are adaptive or non-adaptive. Only by taking into consideration the cause of the error by means of analysis of error precursors, post-error changes to brain activity can be classified with regard to adaptivity in the sense of a mechanism that seeks to mend dysfunctional processes in order to reinstate goal-directed behavior.

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## Multivariate pattern analysis

A major disadvantage of common ERP analysis is its comparably bad signal-to-noise ratio (Steven J. Luck & Kappenman, 2012). Particularly in conditions with small trial numbers, e.g., in error trials, random noise can be far larger than the effects to be investigated (Gehring et al., 2011). A promising way to drastically improve signal-to-noise ratio in EEG data is multivariate pattern analysis (MVPA). This technique is more common in fMRI studies (for reviews, see Mahmoudi, Takerkart, Regragui, Boussaoud, & Brovelli, 2012; Norman, Polyn, Detre, & Haxby, 2006), but recent studies have also implemented it for MEG and EEG studies (e.g., Bode, 2015; Parra et al., 2002; M. Steinhauser & Yeung, 2010; Stokes, Wolff, & Spaak, 2015; Tucciarelli, Turella, Oosterhof, Weisz, & Lingnau, 2015). Conventional ERP analysis relies on EEG data of different conditions that are averaged over trials and participants and then analyzed at single electrodes or electrode clusters. Contrastingly, MVPA is based on training a classifier, i.e., computing a weight vector over the whole set of electrodes, which discriminates optimally between two base conditions, for example by means of logistic regression or support vector machines (Blankertz, Lemm, Treder, Haufe, & Müller, 2011; Bode, 2015; Lemm, Blankertz, Dickhaus, & Müller, 2011; Parra, Spence, Gerson, & Sajda, 2005; Pereira & Botvinick, 2011). This weight vector serves as a filter that extracts only that brain activity from the EEG data set that constitutes the difference between the two base conditions. Importantly, an individual weight vector is computed for every participant, thus taking into account interindividual anatomical differences.

This approach can be used to extract more robust measures for various kinds of cognitive progresses and associated ERP components, such as the ERN/Ne and Pe (e.g., M. Steinhauser & Yeung, 2010), the P300 (e.g., Ernst et al., 2017), motor components (e.g., Parra et al., 2002), and visual attention (e.g., Fahrenfort, Grubert, Olivers, & Eimer, 2016). One key

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feature of MVPA is that the data set for training the classifier does not necessarily have to be the same as the *prediction data set* of the actual analysis (in fact, identity of training and prediction data sets requires cross-validation to prevent overfitting). This allows, on the one hand, that discriminating weight vectors can be trained on large datasets, e.g., correct trials, and then be applied to smaller datasets, e.g. errors – thus enhancing signal-to-noise ratio in conditions with few trials even more (see Study 3). On the other hand, this enables analyses that extract brain activity representing specific cognitive processes in order to investigate to what degree these processes are involved in other conditions (see Study 1, which extracts switch-specific preparatory and compares this in two different types of errors). MVPA is highly suitable for the analysis of error precursors due to its enhancement of the signal-to-noise ratio, through which it increases the likeliness to isolate error precursors although commonly there are only few error trials per subject. At the same time, this technique requires large base effects for training the classifier and not all experimental designs feature such a distinct ERP contrast in the first place (see Study 2, which exhibits ERP effects in correct trials that were too small to successfully train an MVPA classifier for subsequent analysis of error trials).

## Outline of subsequent studies

The following three studies aim to provide further insight into the nature of cognitive control processes, all by means of utilizing neural activity prior to performance errors. As outlined above, these error precursors provide a promising methodological approach for examining proactive and reactive control processes and to distinguish processes that are effectively necessary for task execution from processes that support efficiency. The starting point of this investigation will form the question of how well individual preparatory processes are separable and in how far error precursors may help to find out about those processes’

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exact functional roles within the complex of task preparation. Subsequently, I want to examine to what degree established findings about preparatory processes are applicable to more complex situations. In a dual-tasking paradigm, two tasks potentially compete for preparatory resources and cognitive control needs to establish an environment that facilitates successful execution of both tasks. Finally, I aim to investigate the relationship of reactive control and specific error causes. My goal is to provide evidence for reactive control processes that are able to mend specific maladaptive pre-error cognition that caused the error in the first place.

*Study 1* implements a cued task-switching paradigm with bivalent response mapping. Although only one task has to be executed per trial, stimuli for both tasks are presented, which leads to occasional confusions with regard to the currently relevant task. These *task errors* are contrasted with *response errors*, in which the correct task is executed but an incorrect response for this task is selected. In addition to task switches and task repetitions, the paradigm also features single-task blocks with all-repeat trials. This allows for an MVPA-based extraction of two distinct processes of proactive control – switch-specific and general preparatory activity. These two subcomponents of task preparation are subsequently investigated with regard to their relative contribution to the two error types. To this aim, neural precursors of task errors are compared to the baseline of response errors. This approach allows to find out if in fact switch-specific preparation, the reactivation of the currently relevant task set, or general preparation, the cue-driven updating of the task set from long-term memory, lies at the root of such task confusions and is thus the more impactful factor for successful task-set reconfiguration.

Following this first attempt to separate preparatory processes and their significance for successful task execution, *Study 2* aims to extend this approach to more complex situations as they are more common in real life. To this aim, a PRP paradigm with cued task order was chosen. This enables, on the one hand, analysis of neural correlates of task preparation as

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commonly done in task-switching paradigms, and, on the other hand, depicts the potentially more complex relationships of preparatory processes due to the increased number of processing levels as is the case in dual-tasking. Specifically, dual-tasking may comprise task preparation on the individual subtask level (De Jong, 1995) as well as a superordinate task-set level that encompasses the dual-task as a whole, with information about the task order and task prioritization (Hirsch et al., 2017; Luria & Meiran, 2003). Consequently, in addition to analyzing neural correlates of the preparation of task-order switches (superordinate level), I utilize distinct error precursors of Task-1 errors and Task-2 errors to provide evidence for the question whether and how both subtasks are prepared individually prior to the onset of Task 1. Identity or distinctiveness of these error precursors and their relationship to superordinate task preparation contributes to understanding if subtasks are prioritized in advance with regard to their immediateness within the dual-task trial.

Study 3 finally focusses on reactive control processes. Here, error precursors are utilized as an important prerequisite for answering the question on the adaptivity of post-error adjustments in visual search: changes to neural correlates of selective attention after errors can only be considered part of reactive control if they are deployed in order to mend dysfunctional deviations that caused the error. The paradigm chosen for this study is a two-stage visual search task in which a target stimulus first has to be located within a set of distractors and, second, needs to be classified with respect to its visual features. Due to the lateralization of the target, it is possible to obtain specific neural correlates of these two stages of the deployment of selective attention. As a result, error causes can be distinguished based on deviations in these ERP components. These error precursors can then be related to post-error changes of brain activity. If the post-error changes occur for the same component as the error cause and in opposite direction to the original error-causing deviation, this would be direct evidence for an adaptive adjustment to selective attention, i.e. a reactive control process in this domain.

## **Study 1: General and switch-specific preparation as distinct error sources in variable and stable task environments**

By Robert Steinhauser and Marco Steinhauser

### **Abstract**

Despite common agreement on the fact that tasks benefit from advance preparation, the nature of this preparation is up to debate. In a cued task-switching paradigm, we investigated the impact of two subcomponents of preparation, switch-specific preparatory activity and general preparatory activity in event-related potentials, on task-set reconfiguration. To this end, we analyzed deviations of these forms of preparation in task confusions, in which participants erroneously executed the currently irrelevant task. We found impairments in general preparation to be a main source of task confusions in the variable task environment of mixed-task blocks, whereas switch-specific preparation was uninvolved here. However, this latter component was a source of task confusions in the far more stable environment of single-task blocks, in contrast to general preparatory activity. Our results highlight the distinct functional significance of these two components of task preparation and show that control processes can be maladaptive in certain contexts. They support accounts that suggest cue encoding and memory retrieval as the main driving force behind switch costs and switch-specific processes serving as a subordinate addition to this.

This paper is currently under review at *NeuroImage*.



## Study 2: Preparatory brain activity in dual-tasking

By Robert Steinhauser and Marco Steinhauser

### Abstract

Task preparation in dual-tasking is more complex than preparation for single tasks and involves additional factors such as task prioritization. Utilizing event-related potentials, we sought to disentangle preparatory processes involving preparation on the subtask level and the superordinate dual-task level. Participants worked on a psychological refractory period paradigm in which two temporally overlapping tasks have to be completed in a specified order. Whereas dual-task-related preparation was measured by comparing task-order switches and repetitions, subtask preparation was isolated through error precursors for the individual subtasks. We found that a switch-related posterior positivity was linked to the preparation of the superordinate dual-task set. In contrast, an early frontal modulation and a stimulus-preceding negativity were markers of subtask preparation of Task 1 and Task 2, respectively. Our study provides neural evidence for a hierarchical system of control processes in dual-tasking and confirms assumptions from earlier behavioral and computational studies on strategic task prioritization.

This paper is currently under review at *Neuropsychologia*.

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## Study 3: Neural signatures of adaptive post-error adjustments in visual search

By Robert Steinhauser, Martin E. Maier, and Marco Steinhauser

### Abstract

Errors in speeded choice tasks can lead to post-error adjustments both on the behavioral and on the neural level. There is an ongoing debate whether such adjustments result from adaptive processes that serve to optimize performance or whether they reflect interference from error monitoring or attentional orientation. The present study aimed at identifying adaptive adjustments in a two-stage visual search task, in which participants had to select and subsequently identify a target stimulus presented to the left or right visual hemifield. Target selection and identification can be measured by two distinct event-related potentials, the N2pc and the SPCN. Using a decoder analysis based on multivariate pattern analysis, we were able to isolate the processing stages related to error sources and post-error adjustments. Whereas errors were linked to deviations in the N2pc and the SPCN, only for the N2pc we identified a post-error adjustment, which exhibits key features of source-specific adaptivity. While errors were associated with an increased N2pc, post-error adjustments consisted in an N2pc decrease. We interpret this as an adaptive adjustment of target selection to prevent errors due to disproportionate processing of the task-irrelevant target location. Our study thus provides evidence for adaptive post-error adjustments in visual search.

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## General discussion

### Error precursors as a window to cognitive control

All three studies of this thesis utilized neural precursors of performance errors to gain insight into cognitive control processes. My overarching endeavor was to investigate how this methodological approach can be used for a more thorough identification of control processes and to distinguish control processes that are required for successful task execution from processes that support its optimization. In Study 1 and Study 2, error precursors prior to the onset of the imperative stimulus made it possible to distinguish and identify the functional impact of specific preparatory processes. In Study 3, error precursors after stimulus onset – deviations in two stages of selective attention that lead to two distinct types of errors – were analyzed and related to post-error adjustments to provide evidence for adaptivity in reactive control processes.

Both types of error precursors proved to be a fruitful tool for extracting specific components of cognitive control. Contrasting brain activity in cases of functional, successful task execution, i.e. correct trials, with activity in specific types of performance errors turns out to complement conventional ways of investigating cognitive control, such as varying time intervals or task difficulties. Different from the prolongation of task execution that becomes evident in increased response times, errors represent a different quality of failed task execution. Consequently, errors constitute a situation that allows for the investigation of processes that are truly required for successful task execution, whereas response time measures cannot distinguish between indispensable control processes and those that support efficient processing in an ancillary way. In this regard, Studies 1 and 2 succeeded in identifying specific processes – general preparatory activity and those stages of task preparation that are mirrored by the early frontal modulation (EFM) and the stimulus-preceding negativity (SPN) – whose impairments lead to failed task execution in task-

switching and dual-tasking, respectively. In contrast, deviations in the posterior positivity, which is commonly reported to be the most distinct preparatory ERP effect in task-switching studies (Astle et al., 2008a; Goffaux et al., 2008; Jost et al., 2008; Karayanidis et al., 2009; Kieffaber & Hetrick, 2005; Lavric et al., 2008; Miniussi et al., 2005; Nicholson, Karayanidis, Bumak, et al., 2006; Nicholson, Karayanidis, Davies, et al., 2006), preceded performance errors only in one particular condition of Study 1 – when other, more effective subcomponents of proactive control were factored out. This underlines that control processes that are related to decisions and an efficient selection of responses are not necessarily causal prerequisites for these (see also Katz, Yates, Pillow, & Huk, 2016).

In addition to this fundamental dissociation of control processes as efficiency-supporting or effectively necessary components of successful task execution, by utilizing error precursors it is possible to elaborate layers of functional significance that are not accessible in other ways. For example, in previous studies, the EFM and PSN as preparatory ERP components in task-switching were conventionally analyzed by contrasting task switches and repetitions (Karayanidis et al., 2010; Karayanidis, Provost, et al., 2011). Error-precursor driven analysis in Study 2, however, allowed for an extraction of these components without the conventional repetition-switch contrast. As a result, the significance of the EFM and PSN on subtask preparation in dual-tasking could be demonstrated, although this aspect of preparation proved to be independent of task switches and would hence be unobservable in the conventional contrast.

Likewise, contrasting correct from erroneous trials in Study 3 yielded two distinct error sources that could be related to specific stages within the time course of selective attention in visual search. These differences extend previous knowledge on the functional significance of the N2pc and the sustained posterior contralateral negativity (SPCN), which have so far been investigated with respect to manipulations to stimuli and task demands (Eimer, 2014a, 2014b, Mazza et al., 2009b, 2007). Interestingly, the two error precursors

behaved differently with regard to stimulus-response (SR) compatibility – increased N2pc was an error source only in SR compatible trials, whereas decreased SPCN was an error source independent of SR compatibility. This observation was an essential prerequisite for being able to thoroughly separate the two error sources and to consolidate our findings on the N2pc with models on the interaction of task-relevant and –irrelevant dimensions on SR compatibility (Kornblum et al., 1990): it provides direct neural evidence for the account that only in SR incompatible trials, rash evaluation of the task-irrelevant target location leads to a premature activation of the corresponding response and consequently raises the likeliness of performance errors.

Taken together, although the occurrence of performance errors is not directly susceptible to experimental manipulation, error precursors constitute an elegant and fruitful way to extract specific cognitive processes and investigate in detail their functional significance, particularly with regard to their causal role for successful task execution. Being matched with particular behavioral outcomes, i.e. specific types of errors, error precursors serve as powerful markers for the time course of cognitive control and have the potential for furthering our insight into which control processes are causally linked to successful task execution and which serve optimizing purposes.

### **The interplay of preparatory processes**

Study 1 and Study 2 of this thesis have focused on proactive control, preparatory processes that facilitate the successful execution of one or more tasks. Extending the findings of previous studies (Karayanidis et al., 2010; Karayanidis, Provost, et al., 2011; Mansfield et al., 2012), Study 1 was not only able to separate a switch-specific and a general form of task preparation in the task-switching paradigm – both by means of conventional ERP analysis and MVPA. I could also elaborate on their distinctive participation in the emergence of task

confusions. In contrast to traditional views of switch-specific preparation being the main driving force in this paradigm (Rogers & Monsell, 1995) but in line with more recent findings (Altmann, 2004a; Altmann & Gray, 2008), deficits in general task preparation were shown to precede task confusions in blocks with random presentation of the two tasks. In contrast, the switch-specific subcomponent played no significant role for the emergence of task confusions here. In single-task blocks with a constant repetition of the same task, however, encoding of the cue is not necessary. Correspondingly, general preparatory activity was independent from the emergence of task confusions. The exciting fact that task confusions were also observed in this far less challenging task environment can be explained by increased switch-specific preparatory activity in such task confusions. Possibly due to mind wandering or attentional lapses (Weissman et al., 2006), aspects of this subcomponent of task preparation – though not necessary in single-task blocks – may have triggered the switch to the other, inappropriate task. In sum, I could show that the interplay of preparatory processes in task switching is a delicate fabric that can be a source of performance errors if the fine-tuning of relative weighting between the subcomponents happens to be impaired.

Similarly, my findings on task preparation in dual-tasking (Study 2) draw a complex picture of preparatory processes in situations where the execution of several tasks has to be coordinated. First, I could show that task preparation in dual-tasking occurs on more than one level: the posterior switch-related positivity varied with regard to task-order switches in a way that resulted in a more pronounced positivity in order switches. As such order switches feature a repetition on the subtask level (Task 2 of trial N-1 is the same as Task 1 in trial N), this shows that this ERP component indeed refers to the superordinate task-order level in this paradigm. In line with this, the posterior positivity remained unaltered with respect performance errors on the subtask level – in contrast to two other ERP components, the EFM and the SPN, which were both found to be neural precursors of performance errors in Task 1 and Task 2, respectively. This finding of position-specific preparation of the subtasks is

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pivotal to understanding how the execution of two task is organized in human cognition. It is direct neural evidence for earlier assumptions from behavioral (De Jong, 1995) and computational (Meyer & Kieras, 1997) studies that suppose a multi-level mode of control in task preparation. This mode of control assigns different priorities to the two tasks and accordingly allocates resources differently for immediate (Task 1) and deferred (Task 2) execution. In fact, the time courses and topographies of the error precursors match those of ERP components in task-switching studies that suggest the neural basis of this task scheduling as a combination of two processes (Karayanidis, Provost, et al., 2011; Mansfield et al., 2012). Whereas reconfiguration of the task set of Task 1 is initiated for immediate execution, the response set for Task 2 is temporarily suppressed for reduced interference until after the execution of Task 1.

In conclusion, my findings from Study 1 and Study 2 show that proactive control rests upon a multipart conjunction of separate preparatory processes with distinct functional significance. Well-balanced interaction of these processes is required for the successful execution of cognitively demanding tasks. Otherwise, performance errors can arise from discrepancies in these mechanisms.

### **Causes and consequences of errors**

Processes of proactive control need to be flexible enough to be able to adapt to changing situations and requirements. For this reason and to optimize performance, the balancing of control processes, which are in parts complementary and competing, is subject to constant variation (Botvinick et al., 2001; Braver, 2012; Braver et al., 2007). However, this flexibility can result in occasional maladaptive changes to control processes and subsequently in unfavorable characteristics of neural circuits that may lead to performance errors. Study 1 of this thesis highlighted this phenomenon when increased switch-specific preparatory

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activity caused task confusions in experimental blocks with constantly repeated tasks. Similarly, in the dual-task setting of Study 2, errors emerged when preparatory activity was not distributed well with regard to the within-trial position of the respective subtask, resulting, for example, in Task 2 errors, if the corresponding task set was not kept in working memory for deferred execution sufficiently.

The reactive control processes elicited by the performance monitoring system in turn can be error sources by themselves. Jentzsch and Dudschig (2009) suggested that error monitoring is dependent on limited resources. As a result, resource allocation in the case of errors creates interference and decreased performance in subsequent trials. Similarly, Notebaert (2009) argues that errors as rare events elicit an orienting response, which causes interference and likewise increases the likelihood for further errors after the original one. More recent evidence suggests that indeed beneficial, adaptive adjustments and unfavorable changes due to interference occur at the same time and in most cases balance each other (Purcell & Kiani, 2016; M. Steinhauser et al., 2016). In this regard, the results of Study 3 confirm how imperative it is to include knowledge of prevailing error sources in any considerations about the adaptivity of post-error adjustments. The decreased post-error target localization as found in this study could easily be mistaken for generally decreased sensory activity as reported by Van der Borght et al. (2016). However, because this post-error reduction opposes the increase that was found to be an error source, and, additionally, this post-error reduction occurs predominantly in SR incompatible trials, one can confidently regard them as an adaptive mechanism to suppress task-irrelevant features in order to favor task-relevant ones.

These examples illustrate how delicate the system of proactive and reactive control needs to balance its many subcomponents and processes to avoid becoming part of a vicious circle that results in performance errors due to gradually worsening maladaptive adjustments.



Its largely accurate performance in both experimental settings and the daily life, however, show that this precise adjustment are well established in most situations.

## **Multivariate pattern analysis and EEG**

By utilizing MVPA-based surrogates instead of raw grand averaged ERP components, Study 1 and Study 3 deviated largely from conventional EEG analysis. Instead of averaging voltage differences at individual electrodes, subject-specific classifiers were computed that aggregate the combined activity of all 64 electrodes (Parra et al., 2002, 2005). These classifiers output the likeliness of a trial to belong to one of several distinct conditions, whose optimal difference constituted the core of the training algorithm. Through this, it is – in theory – possible to extract any kind of cognitive process that can be represented as the contrast between two conditions. In practice, this technique is dependent on a considerable size of the effect, e.g. a large amplitude of the respective difference wave, and a comparably large number of trials in the training data set. Study 2 did not meet these prerequisites because the preparatory ERP effects in the dual-tasking environment proved to be too small for successful training of a classifier. For this reason, conventional ERP analysis had to be applied in this case. However, if the prerequisites are met, MVPA results in more robust measures for the underlying components that take into account, first, not only single electrodes (or electrode clusters) but the whole scalp topography and, second, inter-individual differences in brain anatomy.

Considering the comparison of task errors and response errors in Study 1, it becomes evident why MVPA is superior to conventional ERP analysis in this case. Raw ERP grand averages of the two error types show no differences with regard to the mixing positivity or switch positivity. MVPA-based classifier outputs, on the other hand, reveal distinct differences with regard to switch-specific and general preparatory activity due to increased

sensitivity of this method. Equally, in Study 3, raw ERP waves are subject to large amounts of noise due to the limited number of error trials and are unable to yield significant differences between correct and erroneous trials. In contrast, classifier outputs again allowed for a detailed analysis of error sources and post-error adjustments.

Both studies took advantage of MVPA's ability to train classifiers on one data set or one pair of conditions and use the resulting weight vectors on a different set. In Study 1, training was conducted on correct all-repeat trials vs. correct mixed-repeat trials and on correct mixed-repeat trials vs. correct switch trials in order to extract general and switch-specific preparatory activity, respectively. The study's main analysis was subsequently conducted on task errors and response errors, thus filtering both types of errors for preparatory activity only. In Study 3, classifiers were trained on correct trials with left-hemifield targets vs. correct trials with right-hemifield targets. This is based on the conventional approach of identifying ERP components of selective attention by subtracting contralateral from ipsilateral posterior electrodes (e.g., PO7 minus PO8), which yields the N2pc and SPCN (Eimer, 2014a; Steven J. Luck, 2012; Mazza et al., 2009b). Correspondingly, MVPA-based contrasting of left-hemifield and right-hemifield trials yields a *robust N2pc* and *robust SPCN*, which resemble the ERP measures both in time courses and topographies but again take into account inter-individual difference and the whole electrode set. These classifiers are subsequently used successfully in the main analysis of Study 3, first, to differentiate correct and erroneous trials in order to extract error sources, and, second, to identify post-error adjustments by contrasting pre-error trials and post-error trials.

The results of both studies confirm that MVPA proves to be a valuable extension for EEG analysis. Its versatility allows for various applications in different contexts and with different approaches (for examples, see Bode, 2015; Mansfield et al., 2012; Parra et al., 2005; M. Steinhauser & Yeung, 2010). Nonetheless, conventional ERP analysis will also be

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necessary in the future, if the sizes of the underlying effects are too small for classifier training, as was the case in Study 2.

## Conclusion

This doctoral thesis aimed at gaining further insight into the nature and interplay of cognitive control processes. To achieve this, I conducted three EEG studies that focused on proactive control in a task-switching paradigm (Study 1), in dual-tasking (Study 2), and on reactive control in a visual-search task (Study 3). The results of these studies unveiled several novel interrelationships between processes of cognitive control.

First I could show that two distinct preparatory processes, general and switch-specific preparation, are relevant for successful task execution in task-switching paradigms. However, task confusions, likely one of the most severe forms of failed preparation in such a scenario, emerge from impaired general preparation, whereas flaws in switch-specific preparation, originally thought to be the most profound component of task preparation in task-switching (Rogers & Monsell, 1995), proved to be irrelevant in this regard. Nonetheless, switch-specific preparatory brain activity was found to be a relevant error source in a variant of this paradigm in which the same task was to be repeated without interference by the other task, highlighting this subprocess's potential role in initiating a sudden switch towards a different task-set. In the more complex environment of dual-tasking, task preparation presents itself as a multi-level system. Cognitive control processes are implemented for each subtask as well as for the superordinate dual-task as a distinct entity. Moreover, I found subtasks to be prepared in a position-specific manner, supporting accounts of advance prioritization and scheduling of subtasks in dual-tasking (Lehle & Hübner, 2009; Lehle et al., 2009; Meyer & Kieras, 1997). Finally, I investigated the relationship of error sources and post-error adjustments in visual selective attention. I found a post-error reduction of target localization to be an adaptive

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adjustment in order to confine an opposing trend of overly intense target localization preceding and causing certain errors. Observations on the exact time course of this adjustment and its occurrence only on stimulus-response incompatible trials – same as the error source – add further support for interpreting these results as a form of reactive control.

The findings that constitute my doctoral thesis provide a basis for further investigation on the nature and functional significance of specific control processes, both in proactive and reactive control. All studies showed that well-established knowledge on the nature of control processes may need to be reconsidered when taking into account more fine-grained differentiation of subcomponents, more complex environments, or with more detailed knowledge about events and neural activity that precede the examined one. Importantly, I could show that error precursors constitute a methodological approach that – different from conventional analysis of, e.g., response times – is able to more thoroughly dissociate efficiency-related optimizing processes from control processes that are effectively necessary for successful task execution. In this regard, more research is required to increase our insight into the exact characteristics, the constraints, and the interactions of cognitive control processes, their neural correlates, and their causal relationship to successful, goal-directed behavior.

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## Authors' contributions

Table: Contributions of the authors to the most important production steps of each study. The order of names in each cell represents the magnitude of the contribution.

Study	Idea/ conception	Planning/ conduction	Data analysis	Writing
Steinhauser R., & Steinhauser, M. (submitted). General and switch-specific preparation as distinct error sources in variable and stable task environments.	RS, MS	RS	RS	RS, MS
Steinhauser R., & Steinhauser, M. (submitted). Preparatory brain activity in dual-tasking.	RS, MS	RS	RS	RS, MS
Steinhauser, R., Maier, M. E., & Steinhauser, M. (2017). Neural signatures of adaptive post-error adjustments in visual search. <i>NeuroImage</i> , 150, 270–278.	RS, MS	RS	RS	RS, MS, MM

Abbreviations: MS = Marco Steinhauser, RS = Robert Steinhauser, MM = Martin E. Maier

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## Acknowledgements

My expedition into the intriguing world of cognitive neuroscience started on a very hot and sunny day in July 2013, when Prof. Dr. Marco Steinhauser approached me with a surprising offer to work for him. At that time, I had no idea about the weird EEG science stuff he did and I asked myself if this were truly something I would enjoy doing. Several years later, I have become immensely enthusiastic about this field of research and Marco has played a big role in this process. Having met dozens of PhD students over the last year, I have learned how extremely important it is to have a competent, dedicated, motivating, and kind supervisor on the road towards a successful doctorate. Marco epitomizes these attributes more than any PhD student could wish for and saw to it that these past 3½ years became such an intellectually as well as personally rewarding experience. Not only with regard to his scientific work but also in terms of his leadership style and his approach to supporting one's mentees, he has been a role model for my (hopefully) many future days in scientific research.

Marco's job offer is very likely to be rooted in the immense support that I have always received from my boss (2010-2013), mentor (since I got to know her), colleague (2014-2015) and, most importantly, dear friend Prof. Dr. Kathrin Maier. She was the one that told me I simply *had* to do a PhD back when I had no idea that this career path was in any way realistically feasible for myself. She was the one who provided me with profound methods knowledge, well-considered advice on important decisions, and – not least – a beautiful flat in the center of Eichstätt. And, although she has climbed the ladder so fast that she has ended up with her own professorship in Munich after far too little time, she is the one who is always there for Clara and me – for coffee and chat just as well as for some counsel and sushi in Munich.

As stressful, frustrating, and annoying the composition of a doctoral thesis is sometimes, as important is it to have that special someone that you can resort to when you

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feel unfortunate and incompetent. When this someone not only willingly listens to your lamentations but also truly understands your grievance about p-values, topographies, and reviewers, you know that you have found someone *very* special. Stopping work to enjoy a relaxing walk in the Hofgarten, spending time out on our balcony during a thunderstorm, watching some weird TV documentary until we fall asleep on the couch: I could not imagine these most rewarding times without her. It is more than luck that I have found my Clara – not only as my central pillar during the last three years but also in hopefully many, many years to come.

Whatever question I had as a child on how something would work or what the reason for a particular phenomenon was, Mama would always guide me to use our family's encyclopedia. Initially, she would help me to read and understand those little paragraphs. Later, I had systematically learned that I could extend my knowledge immensely by making an effort to investigate a topic myself. Likewise, countless times I discussed and also disputed smaller technical and bigger philosophical questions with my Papa – not always did we agree in opinion but at all times I was able to enhance my logical reasoning and argumentation skills. I am pretty sure that my occasional thirst for knowledge is deeply rooted in those days, and am more than grateful to my parents for their placid yet ever supporting way of accompanying my academic growth.

They say that those times are gone, when scientists did their science in solitude on top of an ivory tower. And they are right: a genial and supporting workgroup is an important factor to fruitful research. I was lucky enough to become part of the gang that now consists of Clara, Franz, Francesco, Ben, Martin, Johanna, Petra, Miriam, Alodie, and Eva. Not only did we discuss indispensable empirical findings and theoretical accounts on the family relations in *Game of Thrones*. We also had shorter and longer chats on how this or that EEG analysis method could be implemented or how unusual task-switching findings might be interpreted. We shared ideas, scripts, papers, anger at reviewers, astonishment about students, chocolate

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(I received more than I gave, I have to admit), student assistants, lunch money, and a lot more.

What a boring time if this were any different.

Many thanks also to the co-evaluator of my PhD thesis, Dr. Søren Andersen. I am glad that this distinguished EEG expert agreed to assess my work, not only because Clara and I will join his lab in Aberdeen, Scotland for an eight-weeks methods workshop in spring 2018 but also because on numerous occasions I have learned about his sophisticated and elegant way of utilizing advanced methodological approaches in neuroscientific research. Additionally, conference rumour has it that besides his superior knowledge on SSVEPs, he is also superior to certain professors on other virtual battlefields...

Empirical studies need a lot of data collection. I was very lucky to be able to rely on a competent team of student assistants, bachelor's degree candidates, and state exam candidates that spent many hours in our EEG lab to recruit participants, plug in electrodes, and record the so eagerly awaited psychophysiological data. I can hardly imagine how much more challenging it would have been to complete this thesis, were it not for them to help me with this crucial work.

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