Business as Unusual: Conflict and Error Processing in Children and Adults

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This cumulative dissertation includes an umbrella paper and the following studies:

Study 1:

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Study 2:

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Study 3:

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Study 4:

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Umbrella Paper

Business as Unusual: Conflict and Error Processing in Children and Adults

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Abstract

Adjusting information processing flexibly to changing task demands and detecting self-generated errors are prerequisites for goal-directed behavior and critical abilities for living an autonomous life. This dissertation presents empirical work on the effects of cognitive conflicts and errors on subsequent task performance and episodic memory. Two studies investigated the temporal and developmental trajectories of performance slowing after detecting cognitive conflicts and errors. Conflicts and errors were experimentally induced by occasional incongruent trials requiring the inhibition of a prepotent response tendency leading to increased error rates and slower responses. The findings revealed reduced variability of response times from eight years to adulthood. More specifically, conflict and error related slowing decreased with age, suggesting more fine-tuned cognitive control adjustments with development. Two other studies showed that cognitive conflicts also affect long-term memory in adults. The underlying cognitive mechanisms are discussed in terms of interacting processes loading cognitive control needed for selective encoding. Avenues for future research examining memory consequences of conflicts in children are outlined. Investigating age-related qualitative changes in the functional connection between cognitive control and encoding processes could further our understanding of the driving forces for developmental progression.

Content

1. Introduction

When everything runs smoothly, detecting regularities in the environment promotes learning and automation of repetitive activities (e.g., driving home on a quiet country road). In this “business as usual” scenario, automatic information processing runs without much attention and without loading limited cognitive resources (Schneider & Shiffrin, 1977). However, sometimes unexpected events happen, and therefore it is indispensable to detect *ir*regularities in the environment (e.g., a cat crossing the road). In this “business as *un*usual” scenario, controlled information processing promotes flexible and goal-oriented behavior (Gratton et al., 2018; Schneider & Shiffrin, 1977). Although children are well able to pursue a goal (e.g., heading home after school), they still have difficulties inhibiting irrelevant actions in the face of distraction (e.g., petting a cat that crossed their way home; Diamond, 2013; Rothbart et al., 2006). As a consequence, children often act impulsively and commit errors of not being able to wait (e.g., chasing a cat across the street without waiting for the green light; Neuenschwander & Blair, 2017). Thus, it appears that, without the discipline to stay on task when pursuing a long-term goal, no one would ever finish a long, time-consuming task such as writing a dissertation. Yet, people do, and strange as it may sound, some write a dissertation about this very ability.

Goal-directed behavior means selectively processing information according to one’s goals (i.e., focusing on task-relevant information and ignoring task-irrelevant information). A prerequisite for goal-directed behavior is the ability to recognize unusual situations in which automated action sequences do not lead to goal achievement. Cognitive conflicts represent such situations as they involve conflicting information associated with different responses. Monitoring denotes a set of processes that signal the occurrence of cognitive conflicts requiring an upregulation of cognitive control, enabling goal-oriented, selective information processing

(Botvinick et al., 2001; Yeung et al., 2004). Cognitive control promotes flexible and controlled behavior and involves inhibiting dominant responses, switching between tasks, and updating content in working memory. All these functions are subsumed under the term "executive functions" (Anderson, 2002; Diamond, 2013; Miyake et al., 2000).

Sometimes either the detection of conflict or the implementation of cognitive control fails, and an error occurs. In the case of error detection, cognitive control can prevent further errors by pausing and inhibiting erroneous response tendencies, recalling the task to be solved, and updating content in working memory. Thus, metacognitive monitoring of one’s thinking, including conflict and error detection, is inextricably linked with executive functions (Roebers, 2017). Children make significant progress during their school years by learning to assess their performance accurately and recognizing self-generated mistakes (Bayard et al., 2021; Blair & Diamond, 2008; Chevalier & Blaye, 2016; Latzman et al., 2010; Neuenschwander et al., 2013; Roebers, 2017; Roebers et al., 2012, 2014; Roebers & Spiess, 2017). Thus, the efficient coupling between monitoring and appropriate cognitive control adjustments seems to be a major force behind developmental progression.

Having introduced the main concepts, I will proceed with describing the cognitive conflict paradigms and immediate and subsequent effects of conflict on task performance (i.e., congruency effect and post-conflict slowing). Next, I describe the effects of errors on subsequent task performance (i.e., post-error slowing and post-error accuracy changes). I will point out that children do also show these effects. To account for age-related changes in these effects, I review major process theories and relevant developmental theories. In doing so, I focused on the following two questions: *What are the underlying processes involved in conflict and error processing? How do these processes develop from school age into adulthood?*

In the second part, I present two studies investigating behavioral adjustments after conflicts and errors in children and adults. Relating to the reviewed theories, I evaluate their contribution to understanding the development of conflict and error processing. In the third part, I extend the gained knowledge to a new research line and present two studies examining the long-term memory consequences of conflict in adults. Bridging these research lines, I will speculate about possible developmental changes in the relationship between cognitive control and encoding processes. I will end with a general discussion of the four studies by integrating the findings to highlight developmental changes in the interplay of different cognitive processes and their effects on behavior.

1.1 Conflict processing

For the investigation of cognitive conflict processing, different paradigms can be used to induce conflicts experimentally. Here I describe three prominent cognitive conflict tasks (Simon, Stroop, and flanker). In all three tasks, incongruent trials activate two concurrent stimulus-response mappings leading to conflicting response tendencies (Braem et al., 2019; Egner, 2007).

In the **Simon task**, stimuli of two different colors are presented either to the left or the right of a central fixation cross (Lu & Proctor, 1995; Simon & Small, 1969). Participants have to categorize the stimuli according to the color by pressing the corresponding button with their left or right hand. The irrelevant stimulus dimension (spatial location: left vs. right) triggers a response tendency that is either congruent or incongruent with the response to the relevant dimension (stimulus color mapped to left hand vs. right hand response).

In the classical **Stroop task**, words for colors (red, blue, green, and yellow) are presented either in the same color ink or a different color ink (Stroop, 1935). In a child-friendly version adapted for illiterate participants (Archibald & Kerns, 1999), fruits and vegetables are displayed in their real color or a different, unrealistic color. Participants have to identify the word’s ink color or the fruit’s real color. The irrelevant stimulus dimension (semantic meaning of the word/printed color of the fruit) triggers a response tendency that is either congruent or incongruent with the response to the relevant dimension (ink color/real color).

In the **flanker task** (Eriksen & Eriksen, 1974; McDermott et al., 2007), a central target stimulus is presented either among identical or different flanking stimuli. Participants have to identify the target. The irrelevant stimuli (flankers) trigger a response tendency that is either congruent or incongruent with the response to the relevant stimulus (target).

Although the conflict's exact source varies, all conflicts are associated with longer response times and more errors (Braem et al., 2019; Egner, 2007; Eriksen & Eriksen, 1974; Simon & Small, 1969; Stroop, 1935). These performance costs are termed **congruency effects** and reflect behavioral consequences of conflicts. Conflict processing can have an even longer-lasting impact on performance, as evidenced by **post-conflict slowing** across several subsequent (non-conflict) trials (Rey-Mermet & Meier, 2017).

Already 5-7-year-old children are able to detect cognitive conflicts and modulate their behavior accordingly as evidenced by congruency effects in the Simon, Stroop, and flanker tasks and long-lasting post-conflict slowing (Ambrosi et al., 2016; Grundy & Keyvani Chahi, 2017; Smulders et al., 2018). Although young children already show the classical conflict effects reported in the adult literature, they do not necessarily engage in the same processes as adults. Considering the multifaceted construct of executive functions and the distinct developmental trajectories of its component processes promotes the idea of age-related differences in the engagement of distinct processes underlying conflict effects (Anderson, 2002; Diamond, 2013;

Egner, 2007; Grundy & Keyvani Chahi, 2017; Smulders et al., 2018). Before discussing relevant theories, I describe the behavioral effects associated with error processing.

1.2 Error processing

Despite the effort to respond as accurately as possible, errors occur, and their detection has consequences on subsequent performance. Although actions aimed at correcting the error are fast, response times on subsequent trials are slowed (Rabbitt, 1966; Rabbitt & Phillips, 1967). This so-called **post-error slowing** effect emerges more likely after aware than unaware errors (Chang et al., 2014; Nieuwenhuis et al., 2001; Wessel et al., 2011). Post-error slowing is largest with shorter response-stimulus intervals (Compton et al., 2017; Jentzsch & Dudschig, 2009), when accuracy is emphasized over speed (Czernochowski, 2014), and in conditions of low error frequency and in highly-accurate individuals (Houtman et al., 2012; Notebaert et al., 2009; Steinborn et al., 2012).

Contrary observations of post-error accuracy changes spawned a vigorous debate about the functionality of post-error slowing and the underlying processes (Danielmeier & Ullsperger, 2011). **Post-error accuracy *increase*** is usually evident after aware errors and with relatively long response-stimulus intervals, while a **post-error accuracy *decrease*** is occasionally evident with shorter intervals and in conditions of overall low accuracy (Buzzell et al., 2017; Compton et al., 2017; Hester et al., 2007; Houtman et al., 2012; Jentzsch & Dudschig, 2009; Marco-Pallarés et al., 2008; Van der Borght et al., 2016). Interference from task-irrelevant stimulus dimensions is reduced after error processing, which should benefit performance (King et al., 2010; Ridderinkhof, 2002; Ridderinkhof et al., 2002). The performance benefit of improved interference resolution contradicts findings of post-error accuracy decrease. As will be explored later, the contradicting effects may reflect variations in the expression of a number of processes acting on different timescales.

Already preschool children detect committed errors and adjust their performance as indicated by substantial **post-error slowing** (Brewer & Smith, 1989; Fairweather, 1978; Gupta et al., 2009; Jones et al., 2003; Smulders et al., 2016). Brewer and Smith (1989) examined reaction times on ten trials before and after an error in a broad age range (5-23-year-olds). Participants responded increasingly faster before an error with the fastest reaction times observed on error trials, after which they slowed down markedly. Reaction time differences between trials (i.e., reaction time variability) decreased with age, reflecting a trend towards smoother and more fine-tuned reaction time adjustments across development. More recent studies of the same age range also found an age-related decrease in post-error slowing (Carrasco, Harbin, et al., 2013; Carrasco, Hong, et al., 2013; Gupta et al., 2009; Schachar et al., 2004; Smulders et al., 2016). However, other studies found no age-related changes or even an age-related increase in post-error slowing (Davies et al., 2004; Hogan et al., 2005; Ladouceur et al., 2007; Masina et al., 2018; Overbye et al., 2019; Santesso et al., 2006; Santesso & Segalowitz, 2008; van de Laar et al., 2011; Wiersema et al., 2007). As will be explored later, the contradicting empirical findings can be reconciled by considering that different processes acting on different timescales follow distinct developmental trajectories.

1.3 Process theories

Conflict-monitoring theory is an influential theory of conflict and error processing that posits a monitoring system implemented in the anterior cingulate cortex that detects cognitive conflicts or errors and sends a signal to the dorsolateral prefrontal cortex, which in turn adjusts cognitive control (Botvinick et al., 2001). The up-regulation of cognitive control is implemented by modulating the balance between speed and correctness (i.e., speed-accuracy tradeoff) in a sense that more weight is given to correctness than speed. Thus, the detection of a cognitive conflict leads to an increase in cognitive control, resulting in an attentional bias toward task-relevant information processing while task-irrelevant information processing is reduced (Carter & van Veen, 2007; Veen & Carter, 2006). This attentional bias leads to less interference from incongruent stimulus dimensions. According to this account, cognitive control supports interference resolution and leads to slowed performance after conflicts and errors.

Threshold theories complement the conflict-monitoring theory as they specify the implementation of the speed-accuracy tradeoff. According to these theories, modulations of the speed-accuracy tradeoff are implemented by modulations of sensory thresholds and motor thresholds, which lead to delayed sensory information processing and selective inhibition of prepotent motor tendencies (Crump & Logan, 2013; Laming, 1979; Ridderinkhof, 2002). Changes in the sensory threshold are associated with activity changes in task-specific sensory cortex areas (Danielmeier et al., 2011; King et al., 2010). Changes in the motor threshold are associated with activity changes in the prefrontal cortex and motor cortex (Marco-Pallarés et al., 2008; Ridderinkhof et al., 2004). These changes occur on a trial-by-trial basis after cognitive conflicts and errors and are supplemented by long-term strategic adjustments that are sensitive to the frequency of conflicts and errors and reflect increased caution (Dutilh et al., 2012; Ridderinkhof, 2002). As a result, it takes longer to gather sensory information sufficient for a motor response to be initiated, which translates into slower and more correct responses (Hester et al., 2007; Van der Borght et al., 2016).

As mentioned earlier, errors do not necessarily lead to better performance on subsequent trials (Houtman et al., 2012; Houtman & Notebaert, 2013; Notebaert et al., 2009). Especially young children are prone to post-error decreases in accuracy, while adults are better able to keep accuracy levels constant (Czernochowski, 2014). According to the **orienting account**, an error represents a rare event that attracts attention for a certain time and subsequently leads to performance losses (Notebaert et al., 2009). During this time, information is processed under divided attention, or no information is processed at all until attention is returned to the task. This **attentional bottleneck** is associated with slower but not necessarily more correct responses (Jentzsch & Dudschig, 2009). In contrast to the conflict monitoring and threshold theories, which assume a *selective* inhibition of irrelevant stimulus dimensions, the bottleneck is *not* selective. Rather, all information processing is impaired after a rare event. Critically, the bottleneck is transient and can be overcome by increasing the time between trials (Buzzell et al., 2017; Jentzsch & Dudschig, 2009).

Given the critical role that time plays in information processing, introducing a time component could bridge different accounts and foster a synergistic conflict and error processing theory explaining more empirical findings than each account on its own (Danielmeier & Ullsperger, 2011; Verguts & Notebaert, 2008, 2009; Wessel, 2018). Specifically, a **timing component** is needed to explain why accuracy after errors decreases with short and increases with longer inter-trial intervals. Wessel (2018) proposed that errors trigger a cascade of processes acting on different timescales. The first set of processes start immediately after error detection and are short-lived, while the second set of processes exert longer-lasting effects on performance. The first set of processes involves unspecific inhibition of information processing and attentional reorienting toward the source of the error (cf. attentional bottleneck and orienting accounts). These processes start immediately after error detection and impair information processing leading to lower accuracy. The second set of processes starts later and involves cognitive control processes improving interference resolution leading to higher accuracy (cf. conflict-monitoring and threshold adjustment accounts).

Critically, both sets of processes are associated with longer response times but for different reasons. The first set of processes slows performance because of generally diminished information processing. In contrast, the second set of processes slows performance because of strategic changes in the speed-accuracy tradeoff. Considering the time course of different processes underlying post-error slowing may also reconcile inconsistent empirical findings of age differences in post-error slowing (Smulders et al., 2016). Thus, Studies 1 and 2 tested the hypothesis of distinct temporal and developmental trajectories of different processes underlying post-conflict slowing and post-error slowing. Before elaborating this, I would like to introduce relevant developmental theories.

1.4 Developmental theories

Performance on cognitive conflict tasks improves considerably from childhood into adulthood, reflecting faster processing speed with age and better control of interference with age (Davidson et al., 2006; Erb & Marcovitch, 2018; Kail, 1991, 2000; Oeri et al., 2018; Śmigasiewicz et al., 2020; Smulders et al., 2018). Interference control involves the **inhibition** of "internal or external competing information to protect working memory or to focus attention on goal-relevant information" (Nigg, 2017, p. 363). The ability to inhibit a prepotent response in the face of conflict emerges between 3 and 4 years (Jones et al., 2003). After this age, the congruency effect decreases, suggesting improving inhibitory control with age (Davidson et al., 2006; Ridderinkhof et al., 1999; Ridderinkhof & van der Molen, 1995; Rueda et al., 2004; Smulders et al., 2018). Thus, age-related improvements in cognitive conflict tasks are related to children's increasing ability to inhibit task-irrelevant mental representations and prepotent response tendencies, enabling selective attention for task-relevant information and goal-oriented behavior (Diamond, 2013; Ridderinkhof & van der Molen, 1995).

Theories of **maturing cognitive control** propose that age-related differences in processing speed, response inhibition, and flexible behavioral adjustments after conflicts and errors reflect the protracted maturation of brain areas associated with executive functions. Improvements in executive functions are associated with maturational changes in brain structure (i.e., myelination and pruning) and strengthened connections between the conflict/error signaling anterior cingulate cortex and regions of the prefrontal cortex responsible for cognitive control implementation (Crone & Steinbeis, 2017; Hämmerer et al., 2014; Jonkman, 2006; Luna et al., 2004, 2010; Luna & Sweeney, 2004; Rubia, 2013; Rueda et al., 2004; Velanova et al., 2008). Given the immature functional connection between the anterior cingulate cortex and the dorsolateral prefrontal cortex, most age-related differences are expected in flexibly translating monitoring outcomes (i.e., detection of conflict and errors) into actions (i.e., cognitive control adjustments). Thus, age-related improvements in flexible behavior reflect more optimal coordination of cognitive control based on internally generated signals of increased cognitive control demands.

One theory of cognitive control development suggests three key **developmental transitions** toward more flexible behavior (Munakata et al., 2012). The first transition describes children's developing ability to apply cognitive control in response to environmental cues signaling the need to overcome habits. For example, while 3-year-old children perseverate a habitual task, 4-year-olds successfully switch tasks when asked to perform another task (Diamond et al., 2005; Zelazo et al., 1996). The second transition represents the shift from reactive to proactive cognitive control mode as cognitive resources increase. For example, while

5-year-old children preferably recruit cognitive control reactively, as needed momentarily, 10-year-olds recruit cognitive control proactively, whenever advance preparation is possible (Chevalier et al., 2015). The third transition describes the shift from reliance on environmental to internal signals as children become more self-directed. For example, although 4-year-olds successfully switch tasks when explicitly instructed about the new rule, they will not do well when asked to apply another rule without explicit instructions until seven years of age (Smidts et al., 2004). An even stronger reliance on internal signals is required by behavioral adjustments based on self-detected errors. Consequently, post-error behavioral adjustments reflect the ability to act adaptively based on the internal error signal generated by the monitoring system.

The overarching idea of these developmental transitions is that cognitive control development involves qualitative changes in the use and **coordination of different control strategies** toward more optimal control engagement with age (Chevalier, 2015a, 2015b; Chevalier et al., 2015). For the second transition, for example, this means that 6-year-olds do not simply replace reactive control with proactive control. Rather, they learn how to flexibly engage either form of control depending on task demands (Chevalier, 2015b). As proactive control relies on more cognitive resources, it is economically better to engage reactive control for easy tasks and to shift to proactive control only when the task becomes more difficult (Braver, 2012). Optimal executive functioning thus entails increasing control when demands increase but also releasing control when demands decrease. The ability to flexibly shift between control modes may thus underlie performance improvements in conflict tasks from childhood to adulthood. With age, the coordination of the control repertoire – or meta-control – becomes more optimal. Ultimately, the development of flexible and successful cognitive self-regulation reflects the increasingly efficient coupling between metacognition and executive functions (Roebers, 2017).

2. Effects of cognitive conflicts and errors on task performance in children and adults

The previous chapter gave an overview of the effects of conflicts and errors on performance (i.e., congruency effect, post-conflict slowing, post-error slowing, and post-error accuracy changes). Process theories that account for different aspects of these effects have been presented. As an interim summary, what can be noted about the underlying processes is that multiple cognitive control processes give rise to different aspects of the effects. Specifically, the detection of conflicts and errors temporarily disengages attention from the task leading to slower and more erroneous responses. Subsequently, cognitive control processes take over. Attention is directed toward task-relevant information reducing interference from task-irrelevant information. Ultimately, cognitive control promotes goal-oriented behavior leading to slower and more accurate responses. Age-related improvements in cognitive conflict tasks and the reviewed developmental theories suggest that cognitive control develops substantially from childhood to adulthood, as attentional control, interference resolution, and inhibition improve with age (Anderson, 2002; Diamond, 2013). However, it is not yet clear how the dynamics of the involved processes change with age. Two studies addressed this question by tracking behavioral adjustments after conflicts and errors on a trial-by-trial basis. In the following, I will shortly summarize these two studies that are also appended to this paper (Appendix B).

2.1. Study 1

The first study compared the temporal trajectories of post-conflict slowing and post-error slowing in 9-13-year-old children and young adults. Cognitive conflict was induced by occasional incongruent trials interspersed among congruent trials in the Simon task. Response times were measured on four post-conflict and four post-error trials and were compared to response times in a pure congruent baseline block with no conflict and only a few errors (on average less than one error in 24 trials). The difference to the baseline block thus represents post-conflict slowing and post-error slowing. The difference between post-conflict slowing and post-error slowing represents slowing exclusively attributable to the error (i.e., pure post-error slowing) since conflict related slowing is subtracted. The strengths of this study are the experimental induction of errors by infrequent conflicts (only every 5th trial was incongruent) and the assessment of slowing across multiple trials in the same task.

Results showed that children responded more slowly and variably than adults. Children's coarser response time adjustments in the block with occasional conflicts is in line with previous studies and the theory of increasing ability to inhibit interference and self-regulate (Brewer & Smith, 1989; Davidson et al., 2006; Diamond, 2013; Jonkman, 2006; Kail, 1991, 2000). Specifically, the coarser response time adjustments were expressed as stronger congruency effects and stronger slowing after conflicts and errors. Infrequent conflicts seem to disrupt children's "business as usual" mode more strongly than adult's. Since errors occurred even less frequently (cf. Fig. 2 of the attached paper showing the error rate distribution), errors acted as an even stronger disruption. This was reflected in a stronger slowing on the first trial after an error, over and above conflict-induced slowing. Error-induced slowing peaked on the first trial *after* the error, while conflict-induced slowing peaked *on* the conflict trial (cf. Fig. 3 of the attached paper showing the slowing trajectories). Of course, the error can only be detected after committing the error. Thus, error-induced slowing must be displaced for one trial. Apart from this displacement and the generally stronger error-induced slowdown, the trajectories were similar.

The similarities in slowing trajectories suggest that conflicts and errors trigger the same processes but displaced in time. Depending on when the conflict or error is detected, the monitoring system triggers a cascade of processes (Botvinick et al., 2001; Wessel, 2018).

Naturally, the cascade starts earlier for conflicts than for errors. The first processes starting immediately after conflict/error detection involve motor and sensory inhibition and a brief but strong attentional orientation toward the source of conflict or error (Notebaert et al., 2009; Ridderinkhof, 2002). The second set of processes reflect less strong but longer-lasting control adaptations, including a more cautious response style and shifts in the speed-accuracy tradeoff, improving information processing efficiency (Botvinick et al., 2001; Ridderinkhof et al., 2004).

Proportionally, children slowed down more on the first trial after an error than on subsequent trials, whereas adults showed less variation over the four trials. That is, age-related differences in post-error slowing were most pronounced on the first trial. This indicates that children had a pronounced inhibitory and orientation response but then showed a comparatively weaker increase in cognitive control, suggesting a qualitative shift in the underlying processes' proportional weights with age. Thus, conflict and error related slowing involve at least two processes; a first process that is transient and dissipates with time and a second, longer-lasting process that gains in weight with age (Erb et al., 2017; Erb & Marcovitch, 2018, 2019; Jentzsch & Dudschig, 2009; Smulders et al., 2016; Steinhauser et al., 2017). Accordingly, younger children should show an even stronger orientation response, whereas they should show even less control adaptation on subsequent trials. The second study followed up on this hypothesis.

2.2. Study 2

The second Study extended the first Study by examining a broader age and task range. Participants were from four age groups (8-, 10-, 12-year-olds, and young adults) and solved the Simon, Stroop, and flanker tasks. All tasks had the same task structure as in Study 1. The main aim of this paper was to test the developmental hypothesis that the early orienting response after errors decreases with age, while strategic cognitive control adjustments increase with age.

Indeed, across all tasks, we found an age-related decrease in slowing on the first post-error trial, while adults showed more persistent slowing on subsequent trials. The younger age groups changed response speed more dramatically, as evidenced by larger slowing on the first post-error trial with a steeper decrease in slowing on the second trial. This pattern suggests more fine-tuned cognitive control adjustments with age and is in line with theories of protracted cognitive control development (Brewer & Smith, 1989; Chevalier, 2015b; Diamond, 2013; Luna et al., 2010; Thaqi & Roebers, 2020).

In all tasks, the congruency effect on response times decreased with age. Surprisingly, in the flanker task, however, the congruency effect on accuracy increased with age, suggesting that this task may have been more challenging for adults. However, they did not show stronger post-error slowing than children. Although this is consistent with the overall pattern of less exaggerated response time adjustments in adults, we nevertheless wanted to test whether the age effect on post-error slowing would persist after controlling for error rates. Therefore, we calculated a covariance analysis in Study 1. For this dissertation, however, I wanted to complement this analysis with another approach. I calculated the median error number in each task and split the participants into groups of highly accurate and less accurate individuals (see Fig. 1 & 2). Based on previous work, I expected larger post-error slowing for highly accurate individuals compared to less accurate individuals (Houtman et al., 2012; Steinborn et al., 2012).

To test this hypothesis, I extended the analysis of variance reported in the manuscript by including the factor *median split*. Table 1 and Figure 1 present the results of the first sample that solved the Stroop and Simon tasks. Table 2 and Figure 2 present the results of the second sample that solved the Stroop and flanker tasks. Most importantly, the originally reported interaction between age group and trial was significant in all four analyses and was not modulated by the factor median split (i.e., no 3-way-interaction, cf. Tables 1 & 2). A significant main effect of the median split emerged only in the first sample. Indeed, the effect went in the expected direction, with a stronger post-error slowing in highly accurate individuals. This effect was especially prominent on the first trial of the Simon task, as evidenced by an interaction between median split and trial (cf. Table 1). This is in line with the orienting account of post-error slowing, suggesting that infrequent events trigger an orienting response on the first post-error trial (Houtman et al., 2012; Notebaert et al., 2009). Highly accurate individuals experience errors as infrequent events. Thus they slow down more strongly than lower-performing individuals who make more frequent errors. This effect was most pronounced on the first trial (cf. Fig. 1 & 2), highlighting the transient nature of the orienting response.

2.3. Discussion

Error is naturally correlated with conflict, as most errors happen on conflict trials (Verguts et al., 2011). We used this feature to induce errors experimentally. The first study showed a similar time course of conflict and error induced slowing when the timing of conflict and error detection is considered. Both elicit most slowing immediately after detection. In the case of a correct response, the conflict was detected in time and allowed timely inhibition of prepotent responses and reduced sensory interference from irrelevant stimulus dimensions. In the case of an incorrect response, however, the conflict was not detected in time. Consequently, inhibition failed, and conflict processing was postponed leading to exaggerated slowing on the first trial after an error. In this study, children showed generally stronger slowing than adults reflecting the protracted inhibitory control development (Davidson et al., 2006; Diamond, 2013).

The second study confirmed and extended the findings of the first study. Robust post-error slowing was found across three cognitive conflict tasks (Simon, Stroop, and flanker), and robust age effects were found between four age groups (8-, 10-, and 12-year-olds, and adults). Specifically, slowing on the first trial decreased with age, while on subsequent trials, adults showed more persistent slowing than children. This pattern suggests that the orienting response on the first post-error trial decreases with age and strategic threshold adjustments on subsequent trials increase with age (Botvinick et al., 2001; Czernochowski, 2014; Notebaert et al., 2009; Ridderinkhof & van der Molen, 1995).

The changing age effect across trials could explain why some studies using relatively long inter-trial intervals of over 1000 ms found no age effects or even an age-related decrease in post-error slowing (Davies et al., 2004; Overbye et al., 2019; Santesso et al., 2006; Santesso & Segalowitz, 2008; Smulders et al., 2016). Based on the notion that the underlying processes are sensitive to time, we used relatively short inter-trial intervals of only 250 ms and tracked the dynamics of the underlying processes across trials (Compton et al., 2017; Jentzsch & Dudschig, 2009; Smulders et al., 2016). With this method, we found evidence for age-related qualitative changes in the contribution of different processes to performance adjustments (Chevalier et al., 2013). In conclusion, better inhibitory control and more fine-tuned cognitive control adjustments with age promote more balanced trial-by-trial performance adjustments with age (Brewer & Smith, 1989; Ridderinkhof et al., 1999; Ridderinkhof & van der Molen, 1995).

3. Effects of cognitive conflicts on memory in adults

Another kind of conflict is induced by **task switching**. Conflict is especially high with bivalent stimuli as they have attributes that are relevant for both tasks, thus activating competing task-sets (Allport et al., 1994; Meier et al., 2009; Rey-Mermet & Meier, 2012; Woodward et al., 2003). Task-set reconfiguration leads to **switch costs** on performance, characterized as slower and more erroneous responses on switch than repeat trials (Koch, 2003; Monsell, 2003; Rogers

& Monsell, 1995). A new line of research showed also switch costs on **memory**, characterized as impaired memory for stimuli presented on switch trials (Brito et al., 2016; Muhmenthaler & Meier, 2019a, 2019b; Reynolds et al., 2004; Richter & Yeung, 2012, 2015).

The principle of the combined task switching and memory paradigm is to present trial unique stimuli in a study phase and to test subsequent memory for stimuli presented on switch versus repeat trials. Richter and Yeung (2012) presented picture-word compounds in the study phase consisting of a cued task switching paradigm. Participants switched between classifying the picture as human-made versus natural and classifying the word as an abstract versus concrete noun. Thus, switch trials involved shifting attention to the task-relevant target and away from the previously relevant but now irrelevant distractor. The results of the subsequent recognition test revealed that target memory was impaired while distractor memory was even better on switch than repeat trials. This suggests that task switching does not reduce a general encoding capacity but the capacity to *selectively* encode task-relevant targets (Richter & Yeung, 2012, 2015). Thus, task switching reduces memory selectivity and not memory in general.

Based on this selective memory effect, Richter and Yeung (2015) rejected an interpretation of task-set reconfiguration processes consuming cognitive resources shared with encoding processes because such a resource sharing account would predict reduced memory not only for targets but also for distractors. Instead, they proposed that reduced top-down control on switch trials reduces selective processing. They reasoned that giving participants more time between tasks would support the application of top-down control and would therefore increase selective processing. Indeed, they found higher memory selectivity for longer cue-to-stimulus intervals and interpreted this as evidence for their top-down control account. However, other manipulations of top-down control (i.e., voluntary task switching and monetary incentives) did not modulate memory selectivity in the expected direction (Arrington & Logan, 2005; Braun & Arrington, 2018; Richter & Yeung, 2015). Instead of rejecting their top-down control account, Richter and Yeung relativized the effectiveness of their manipulations by stating that "the present findings converge with other evidence questioning the idea that voluntary task switching provides a relatively pure and direct measure of top-down control" (p. 1143).

The circularity of Richter and Yeung's (2015) arguments concerning the influence of top-down control on memory selectivity and the presented data question the validity of their account. Thus, we followed up on the resource sharing account – but with a little twist. Instead of conceptualizing resource limitations in the sense of limited amount of information that can be stored, resource limitations can be seen as limitations to cognitive control resources needed for selective information processing (Lavie, 2010; Lavie & De Fockert, 2005; Liefooghe et al., 2008). Accordingly, task-set reconfiguration processes compete with encoding processes for limited cognitive control resources (Barrouillet et al., 2004, 2007; Lavie, 2010). Thus, we ascribed the memory selectivity effect to cognitive control resources shared between task-set reconfiguration processes and encoding processes (instead of a shared storage capacity affecting memory in general). Specifically, we hypothesized that increasing cognitive load at stimulus presentation would impair selective encoding and consequently reduce memory selectivity.

To test this hypothesis, we conducted two studies using Richter and Yeung's (2012, 2015) paradigm with different manipulations of selective attention. Study 3 manipulated selective attention by varying the time for advance task preparation and stimulus presentation duration. Study 4 manipulated selective attention by physiologically altering the activity of relevant brain areas. In the following, I will shortly summarize these two studies that are also appended to this paper (Appendix B).

3.1. Study 3

A conflict between two concurring task-sets increases the need for cognitive control. When enough preparation time is given, the required task-set is activated in advance, facilitating selective target processing (Richter & Yeung, 2015). However, when preparation time is short, task-set reconfiguration occurs during stimulus presentation, loading cognitive control resources needed for selective target processing. Based on this rationale, we predicted that shorter preparation times would reduce selective encoding of targets and result in reduced memory selectivity. Preparation time was operationalized by varying the cue-to-stimulus interval in the cued task switching paradigm, and the response-to-stimulus interval in the alternating runs task switching paradigm (cf. Rogers & Monsell, 1995).

A further manipulation was the stimulus presentation duration. Stimuli were presented either for 500 ms or until response of the participant. When stimuli are presented only for a limited amount of time, cognitive control is running to capacity because the stimuli representations need to be held actively in working memory in order to solve the task (Cattapan-Ludewig et al., 2005). However, when stimuli are presented until response, working memory is less engaged, sparing cognitive control resources for selective encoding. We hypothesized that the higher cognitive load associated with short stimulus presentation durations would result in less selective target encoding and lower memory selectivity for stimuli presented only shortly than for stimuli presented until response. Five experiments tested these hypotheses for the cued task switching paradigm and the alternating runs paradigm.

We replicated the finding that task switching reduces memory selectivity in all experiments. As hypothesized, shorter preparation times and shorter stimulus presentation duration reduced memory selectivity. The effect of stimulus presentation duration was most pronounced on switch trials, suggesting that holding stimuli representations active in working memory while concurrently reconfiguring task-sets multiply their detrimental effects on selective encoding. Critically, preparation time did not interact with task switching but with paradigm. Short preparation times reduced memory selectivity in the cued task switching paradigm but not in the alternating runs paradigm, suggesting that task-set cuing is critical for preparation effects on memory. These results are in line with the time-based resource-sharing model, according to which task switching loads working memory and critically, concurrent processes compete for limited cognitive control resources while sequential processes do not interfere (Barrouillet et al., 2004, 2007; Liefooghe et al., 2008). In conclusion, cognitive load reduces selective attention and consequently hurts memory selectivity.

3.2. Study 4

To test the hypothesis that task switching reduces selective attention for target encoding, we modulated neuronal activation of brain areas associated with selective attention to find a corresponding effect on memory. Functional neuroimaging studies showed an association between the activation of the dorsolateral parietal cortex and selective attention, while the ventrolateral parietal cortex is primarily active when attention is broadened (Corbetta et al., 2008; Corbetta & Shulman, 2002; Shomstein, 2012). Thus, we reasoned that enhancing neuronal activation in the dorsal attentional network would increase selective attention toward targets leading to better memory for those stimuli. In contrast, enhancing neuronal activation in the ventral attentional network should decrease selective attention toward targets and decrease memory for those stimuli. To test this, we combined Richter and Yeung’s (2012, 2015) paradigm with a physiological intervention that was previously successful in modulating memory (Jacobson et al., 2012).

In Jacobson et al.’s (2012) study, participants were instructed to memorize word lists during a study phase and were informed that their recognition memory would be assessed in a test phase. In the study phase, participants received oppositional transcranial direct current stimulation (tDCS) over parietal substrates of attention. Subsequent recognition memory was better for the stimulation condition that targeted an increase in selective attention than the condition that targeted a decrease in selective attention. In our study, the study phase consisted of a task switching procedure with picture-word pairs as stimuli (cf. Richter & Yeung, 2012). Participants switched between categorizing the picture or the word in alternating task order. After the study phase and a filled retention interval of approximately 20 minutes, a surprise recognition memory test of the previously presented pictures and words followed.

In the study phase, the same tDCS protocol was applied as in Jacobson et al.’s study (2012). One electrode was placed over the posterior dorsolateral parietal cortex targeting the dorsal attentional network. The other electrode was placed over the posterior ventrolateral parietal cortex targeting the ventral attentional network. Participants were randomly assigned to one of three stimulation conditions: Dorsal-Anodal, Ventral-Anodal, and Sham. In the Dorsal-Anodal stimulation condition, participants received anodal stimulation over the substrate of the dorsal attentional network and cathodal stimulation over the substrate of the ventral attentional network. As anodal stimulation increases, whereas cathodal stimulation decreases neuronal activity in the underlying brain structures, this stimulation setup should *increase* selective attention (Jacobson et al., 2012). In the Ventral-Anodal condition, electrode placement was reversed to *decrease* selective attention. The Sham stimulation condition was a control condition in which no current was applied.

The results revealed reduced selective memory for target stimuli from switch trials, replicating previous research (Richter & Yeung, 2012, 2015). However, there was no effect of stimulation. Although this was surprising insofar as we used the exact stimulation protocol that was already successful in modulating memory (Jacobson et al., 2012), our results align with other studies finding no effect of tDCS (Savic, Cazzoli, et al., 2017; Savic, Müri, et al., 2017). Because tDCS interacts with the brain activity elicited by a specific task (Leite et al., 2011), differences in the tasks best explain the inconsistent results. The explicit memory task in Jacobson et al.'s study poses fewer demands on executive functions than the task switching procedure in our study. This is supported by participants reporting that the task was cognitively demanding. Thus, we reasoned that our task taxed more prefrontal executive functions interfering with the parietal stimulation.

3.3. Discussion

In two studies, we confirmed that task switching reduces memory selectivity in adults, suggesting that the task-set reconfiguration process involved in task switching loads cognitive control resources that are no longer available for selective encoding. We reasoned that the mechanism underlying this effect is based on selective attention, which is reduced under cognitive load (Lavie, 2005; Lavie et al., 2004). Study 3 supports the selective attention hypothesis, as several manipulations of selective attention had independent and interactive effects on memory selectivity. In line with a time-based resource-sharing model, we found that processes loading cognitive control concurrently have a more detrimental impact on memory selectivity than processes loading cognitive control sequentially (Barrouillet et al., 2007). Thus, cumulated cognitive load at stimulus presentation reduces selective attention and selective memory.

Although tDCS modulation of selective attention was not successful in modulating memory, this must not be seen as evidence against the selective attention hypothesis. A large body of neuroimaging studies suggests that activation in ventral and dorsal parietal brain areas is associated with behavioral indicators of selective attention and subsequent memory effects (Corbetta et al., 2008; Corbetta & Shulman, 2002; Hutchinson et al., 2009; Shomstein, 2012; Uncapher & Wagner, 2009). Thus, the nonsignificant effect rather represents the general difficulty of finding reliable tDCS effects on memory, as tDCS exerts its influence only under specific conditions (Galli et al., 2019). In conclusion, we questioned the effectiveness of the specific tDCS protocol combined with the specific paradigm instead of questioning the association between parietally implemented selective attention and selective memory.

4. General discussion

Study 1 investigated the effects of cognitive conflicts and errors in children and young adults. Study 2 investigated the developmental trajectory of the time-course of post-error slowing in more detail by comparing children of different ages and adults. These studies used the Simon, Stroop, and flanker tasks to induce cognitive conflict by occasionally presenting incongruent trials. Selectively attending to task-relevant stimulus dimensions and inhibiting responding to task-irrelevant dimensions are critical abilities for good performance on these tasks. As indicated by stronger congruency effects, children's performance suffered more from conflict than adult's. When confronted with conflicts and errors, children changed their response speed more drastically than adults. In conclusion, the age-related decrease in the congruency effect and response time variability may reflect the protracted development of attentional and inhibitory control from childhood to adulthood (Brewer & Smith, 1989; Davidson et al., 2006; Diamond, 2013; Ridderinkhof et al., 1999; Ridderinkhof & van der Molen, 1995).

Studies 3 and 4 investigated the impact of cognitive conflict on adults' memory. These studies used task switching paradigms to induce cognitive conflict by concurring task-sets. Resolving this conflict involves task-set reconfiguration. This process is associated with increased load on cognitive control, impairing selective attention to task-relevant information (Barrouillet et al., 2007; Lavie, 2010; Liefooghe et al., 2008). Impaired selective attention during stimulus processing results in less selective memories for task-relevant stimuli (Muhmenthaler & Meier, 2019a, 2019b; Richter & Yeung, 2012, 2015). Critically, Study 3 showed that processes consuming cognitive control resources at the same time (i.e., task-set reconfiguration + holding a stimulus representation in working memory) cumulate their detrimental effects on memory selectivity. That is, cognitive load reduces selective attention and selective memories. Study 4 aimed to strengthen this conclusion by showing a corresponding memory effect of a physiological intervention targeting parietal substrates of selective attention. However, the specific tDCS protocol was not effective in modulating selective attention or memory (Galli et al., 2019). Activity in prefrontal areas may have compensated for tDCS-induced changes in parietal areas. In the following, I elaborate on this idea by providing an outlook for future research.

4.1. Outlook

The presented research raises new questions, as for example: *Could prefrontal tDCS be more effective in modulating selective attention in task switching? Do children also show task switching costs on memory? What are the memory consequences of errors?* In the following, I describe two ongoing studies addressing the first two questions and discuss directions for future research addressing the third question.

Could prefrontal tDCS be more effective in modulating selective attention in task switching?

It could be that frontal areas of the brain associated with executive functions compensated the tDCS-induced activity modulation in parietal regions. A recent meta-analysis suggests that the stimulation protocol we used may not be effective in modulating executive functions (Imburgio & Orr, 2018). Placing the active electrode over the lateral prefrontal cortex and the reference electrode extracranially would be more suitable for modulating executive functions (Imburgio & Orr, 2018; Strobach et al., 2016; Strobach & Antonenko, 2017). To follow-up on this, we designed a study with a tDCS protocol targeting prefrontal executive functions. By changing the stimulation location and keeping the task constant, we hope to disentangle the interaction between task-induced brain activation and tDCS stimulation. With anodal stimulation of the prefrontal cortex, we expect to increase task switching performance (i.e., fewer errors and faster response times) and memory selectivity. This study is still in the data collection phase.

Do children also show task switching costs on memory?

Task switching induces interference from the previously relevant task, and overcoming this interference involves task-set reconfiguration processes leading to switch costs on performance and memory (Monsell, 2003; Muhmenthaler & Meier, 2019a, 2019b; Rogers & Monsell, 1995). We have preliminary data of a study where 8-13-year-old children and young adults switched between two picture categorization tasks (cf. Muhmenthaler & Meier, 2019a, Exp. 2). Participants had to categorize pictures of animals and objects as bigger or smaller than a soccer ball or as living or non-living. As all stimuli could be categorized according to both tasks, the stimuli are potentially relevant for both tasks, turning them into bivalent stimuli. The method and results are presented in Appendix A.

Children showed similar switch costs on performance as adults indicating stable switch costs across age (Crone et al., 2006; Davidson et al., 2006; Reimers & Maylor, 2005). For adults, we replicated the detrimental effect of task switching on target memory (Muhmenthaler & Meier, 2019a). However, children did not show a corresponding switch cost on memory. This is somewhat surprising, as one would assume that task switching is more difficult for children than adults. Consequently, an even stronger switch cost on memory would be expected. However, this was clearly not the case as the Bayes Factors indicated more evidence for the null hypothesis (i.e., no difference in memory for stimuli presented on repeat vs. switch trials).

As working memory develops earlier than inhibitory control, children's working memory capacity may actually be at adults' level, explaining why all age groups had similar switch costs on performance (Davidson et al., 2006). Because the literature is lacking comparable research, it is more difficult to explain the missing memory effect in children. It could be that conflict processing and encoding are functionally less connected in children than in adults. However, this is only speculative, and more research is needed to understand why children did not show switch costs on memory. For example, presenting task-irrelevant distractors could indeed impact children's memory selectivity (in contrast to general memory capacity), as most age effects are found on inhibitory control (Crone et al., 2006; Diamond, 2013; Diamond et al., 2005; Ridderinkhof et al., 1999). This hypothesis has yet to be tested.

What are the memory consequences of errors?

Another question is how errors affect memory. Especially in view of its relevance for learning, it is surprising how little research is done on this topic. A very recent study addressed this question by investigating adults' memory for post-error stimuli (Decker et al., 2020). Participants categorized trial-unique images as living versus non-living (Exp. 1) or natural versus human-made (Exp. 2). After a short delay, participants performed a surprise recognition memory task. Memory was impaired for stimuli presented on the first post-error trial, and this correlated with the extent of post-error slowing. This is in line with our finding of a large slowing effect on the first post-error trial, probably reflecting a strong orienting response involving delayed sensory information processing (Laming, 1979; Notebaert et al., 2009). Critically, memory impairment was only transient, as memory performance was restored to baseline levels on the second and third post-error trials (Decker et al., 2020). This aligns with our findings of reduced slowing on later post-error trials. As cognitive control takes over on these trials, selective attention and sensory processing may return to baseline levels contributing to restored memory encoding.

Building a bridge to our post-error slowing research offers new hypotheses about age differences in post-error memory. As Studies 1 and 2 showed, children slowed more strongly than adults, and this difference was most pronounced on the first post-error trial. Thus, I suspect that post-error memory would be impaired more strongly in children than adults. However, as we did not find any task switching effects on children’s memory, the post-error memory effect may also depend on age-related qualitative changes in the functional connection between task-related (or error-related) processing and encoding. For example, qualitative differences in episodic memory formation have been reported in the context of infantile amnesia, which refers to the inability to recall personal information from infancy and early childhood (West & Bauer, 1999). This phenomenon was attributed to fundamental transitions in children’s thinking around the age of four years (Bruce et al., 2000). Qualitative changes in information processing (e.g., language use) may thus explain why adults are not able to consciously recall memories that were stored before the age of four years. Unfortunately, changes in memory formation later in development are largely understudied. Our findings of developmental differences in conflict and error processing and the distinct effects on memory in children and adults suggest that there may be qualitative differences in encoding mechanisms between children and adults. This is an interesting avenue for future research.

4.2. Conclusion

Incongruent information and changing task demands represent cognitive conflicts. To keep performance at a constant level, it is crucial to detect such situations on time as they require a change from automatic to more controlled information processing (Botvinick et al., 2001; Schneider & Shiffrin, 1977). Failing to increase cognitive control before response execution likely leads to errors, which can be seen as a conflict between the given (incorrect) and the required (correct) response signaling an even stronger need for behavioral adjustments. The present dissertation addressed the development of cognitive control by presenting two studies investigating age-related differences in behavioral adjustments after conflicts and errors. The results revealed a developmental pattern consistent with notions of increasingly fine-tuned cognitive control adjustments with age (Brewer & Smith, 1989).

This dissertation also addressed longer-term consequences of conflicts by presenting two studies investigating the impact of cognitive load on memory. Both studies showed that the conflict associated with task switching impaired memory for task-relevant stimuli and improved memory for task-irrelevant stimuli (Muhmenthaler & Meier, 2019a, 2019b; Richter & Yeung, 2012, 2015). This effect of reduced memory selectivity was attributed to the concurrent load imposed by task-set reconfiguration processes diverting cognitive control resources needed for selective encoding (Barrouillet et al., 2007; Lavie, 2010). Future research investigating the effect of conflicts and errors on children’s memory may further elucidate qualitative age-related changes in the functional connection between executive functions and encoding.

In conclusion, goal-directed behavior involves detecting irregularities in the environment and adjusting information processing accordingly. As children grow older, they transition from relying solely on automatized behavior based on regularities in the environment (i.e., congruent information) to self-guided individuals who flexibly adapt behavior to ever-changing environments, occasionally also involving the resolution of incongruent information or self-generated mistakes. “Business as unusual” disrupts children’s information processing more than adults’, as evidenced by children’s stronger reactions to conflicts and errors. With increasingly fine-tuned cognitive control adjustments with age, performance becomes more stable across time, allowing selective information processing and promoting the effective pursuit of long-term goals. Increasingly coordinated cognitive control is thus a driving force for developmental progression.

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Tables and Figures

Table 1

Results of the 4 x 2 x 4 (Age group x Median split x Trial) ANOVA on post-error slowing in the Stroop and Simon tasks

Effect	Stroop					Simon				
	df_{Num}	df_{Den}	F	p	η^2_p	df_{Num}	df_{Den}	F	p	η^2_p
Age group	3.00	116.00	7.35	<.001	.16	3.00	143.00	5.07	.002	.10
Median split	1.00	116.00	4.22	.042	.04	1.00	143.00	11.21	.001	.07
Age group x Median split	3.00	116.00	0.42	.742	.01	3.00	143.00	0.56	.640	.01
Trial	2.52	292.32	40.49	<.001	.26	1.62	232.17	52.80	<.001	.27
Age group x Trial	7.56	292.32	2.13	.036	.05	4.87	232.17	3.55	.004	.07
Median split x Trial	2.52	292.32	0.09	.947	<.01	1.62	232.17	8.82	.001	.06
Age group x Median split x Trial	7.56	292.32	0.26	.973	<.01	4.87	232.17	1.82	.112	.04

Note. df_{Num} indicates degrees of freedom numerator. df_{Den} indicates degrees of freedom denominator. Degrees of freedom and p-values of effects, including the factor trial, incorporate the Greenhouse-Geisser correction. η^2_p indicates partial eta-squared.

Table 2

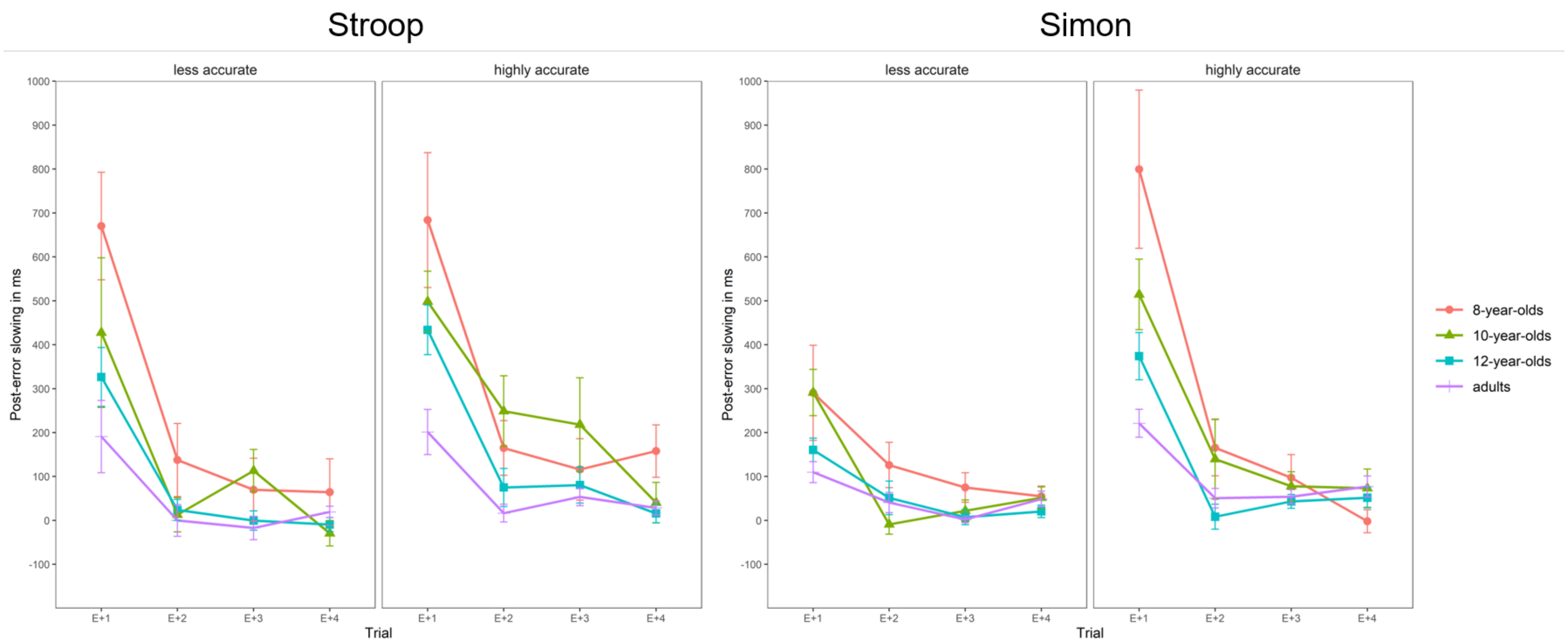
Results of the 4 x 2 x 4 (Age group x Median split x Trial) ANOVA on post-error slowing in the Stroop and flanker tasks

Effect	Stroop					Flanker				
	df_{Num}	df_{Den}	F	p	η^2_p	df_{Num}	df_{Den}	F	p	η^2_p
Age group	3.00	91.00	3.86	.012	.11	3.00	107.00	2.58	.057	.07
Median split	1.00	91.00	0.14	.712	.01	1.00	107.00	1.87	.174	.02
Age group x Median split	3.00	91.00	1.65	.183	.05	3.00	107.00	2.48	.065	.06
Trial	2.37	215.87	24.99	<.001	.22	1.63	174.11	17.80	<.001	.14
Age group x Trial	7.12	215.87	3.23	.003	.10	4.88	174.11	4.04	.002	.10
Median split x Trial	2.37	215.87	0.21	.847	<.01	1.63	174.11	0.42	.614	<.01
Age group x Median split x Trial	7.12	215.87	0.63	.733	.02	4.88	174.11	1.14	.339	.03

Note. df_{Num} indicates degrees of freedom numerator. df_{Den} indicates degrees of freedom denominator. Degrees of freedom and p-values of effects, including the factor trial, incorporate the Greenhouse-Geisser correction. η^2_p indicates partial eta-squared.

Figure 1

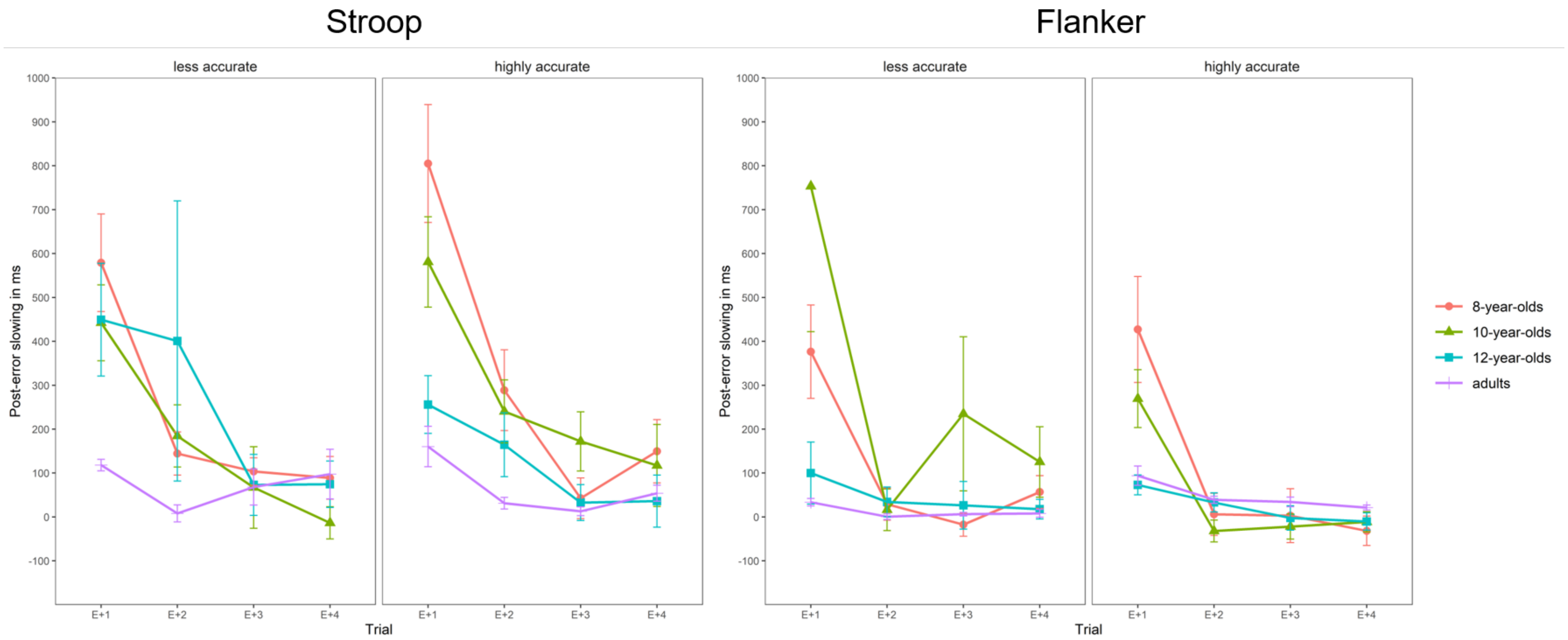
Trajectories of post-error slowing in the Stroop and Simon tasks separately for less and highly accurate participants



Note. Groups of less accurate and highly accurate participants were formed by a median split based on the number of errors. The group of less accurate participants involved participants with more than 2 errors for the Stroop task and more than 5 errors for the Simon task. Error bars show standard errors.

Figure 2

Trajectories of post-error slowing in the Stroop and flanker tasks separately for less and highly accurate participants



Note. Groups of less accurate and highly accurate participants were formed by a median split based on the number of errors. The group of less accurate participants involved participants with more than 3 errors for the Stroop task and more than 6 errors for the flanker task. Error bars show standard errors.

Appendix A

The method and preliminary results of a study assessing memory consequences of task switching in children and adults are described. The stimuli and procedure were adapted from a previous study (Muhmenthaler & Meier, 2019, Exp. 2). Children of three age groups and young adults performed an alternating runs task switching procedure. Recognition memory for the stimuli presented on switch and repeat trials was assessed in a first recognition test immediately after task switching and in a delayed recognition test after one week.

Method

Participants

We obtained data of 39 8-year-olds, 37 10-year-olds, 28 12-year-olds, and 28 young adults. After data screening, we excluded three 8-year-olds and four 10-year-olds due to high error rates (over 30 %), and four 8-year-olds, two 10-year-olds, and two 12-year-olds due to a strong response bias in the recognition test (i.e., negative values when calculating hits minus false alarms). Table 1 presents the demographic characteristics of the final sample.

Table 1

Demographic characteristics

Age group	M_{Age}	SD_{Age}	Age range	Female/Male	n
8-year-olds	8.2	0.5	7.0 – 8.9	15/17	32
10-year-olds	10.2	0.4	9.5 – 11.2	17/14	31
12-year-olds	12.3	0.4	11.7 – 13.2	13/13	26
Young adults	23.0	3.5	19.8 – 37.3	23/ 5	28

Material

The stimuli consisted of 212 colored photographs drawn from four categories: animals and common objects that are bigger or smaller than a soccer ball. Twenty of these stimuli were used for practice trials and warm-up trials in the task switching phase. The remaining 192 stimuli were divided into 16 separate lists of 12 pictures. These lists were counterbalanced across participants with regards to the assignment to repeat versus switch trials, size versus animacy task, old versus new item, and immediate versus delayed test.

Procedure

All participants went through the same procedure. Children were tested individually in a room in their school, and adults were tested individually in a laboratory at the university. In the task switching phase, participants were instructed to categorize the stimuli as quickly and correctly as possible according to two tasks. In the size task, participants had to categorize the stimuli as bigger or smaller than a soccer ball. In the animacy task, participants had to categorize the stimuli as living or non-living. Participants were instructed to press the b-key when an object was bigger or living and the n-key when the object was smaller or non-living. The stimuli were presented until response, and the next stimulus appeared after a response-to-stimulus interval of 200 ms.

Participants practiced the size task and the animacy task separately in two practice blocks of four trials. Both tasks together were practiced in a third mixed task block of eight trials. Participants were instructed to perform the size task if it appeared in the upper half of the screen and to perform the animacy task if it appeared in the lower half of the screen. The stimuli appeared in clockwise order in the upper left, upper right, lower right, and lower left corners of the screen. Thus, the tasks alternated in an AABB order. After the three practice blocks, started the experimental block consisting of four warm-up trials discarded from analyses and 96 experimental trials.

After the task switching phase, participants performed an unrelated filler task for five to seven minutes before coming to the first recognition test. Participants were asked to indicate whether they had seen a stimulus already during the task switching phase or not. They were instructed to press the b-key for “old” stimuli and the n-key for “new” stimuli. The stimuli were presented until response, and the next stimulus appeared after a response-to-stimulus interval of 100 ms. After one week, the investigators returned to the schools, and the adult participants returned to the laboratory for the second session. The procedure of the delayed recognition test was the same as in the first session. One half of the stimuli were old (presented in the task switching phase), and the other half new (never seen before).

Design

Task switching performance was investigated in a 2x4 mixed design involving the within-subject factor transition (repeat vs. switch) and the between-subjects factor age group (8-year-olds vs. 10-year-olds vs. 12-year-olds vs. adults). Memory performance was investigated in a 2x4x2 mixed design involving the factors transition, age group, and the within-subject factor retention interval (immediate vs. delayed).

Results

Analyses of variance (ANOVAs) were conducted for task switching and memory performance. For significance tests, an alpha level of .05 was set. Effect sizes are expressed as Cohen’s d or η_p^2. As traditional significance tests do not allow interpreting nonsignificant results, we also provide Bayes Factors (BF_{01}) representing evidence for the null hypothesis over the alternative hypothesis (Dienes, 2014; Wagenmakers et al., 2018). For example, $BF_{01} = 3$ means that the data are three times more likely under the null hypothesis than the alternative hypothesis.

Task switching performance

For each participant, the mean accuracy rates and median[1] response times on correct trials were computed for repeat and switch trials. Table 2 provides descriptive statistics for task switching performance.

Table 2

Task switching performance

Age group	M_{Acc}		SE_{Acc}		M_{RT}		SE_{RT}	
	repeat	switch	repeat	switch	repeat	switch	repeat	switch
8-year-olds	.852	.830	.018	.017	1552	2307	119	234
10-year-olds	.881	.850	.018	.016	1316	1989	58	134
12-year-olds	.939	.912	.016	.017	1056	1686	40	83
Young adults	.975	.955	.005	.006	782	1196	33	36

Note. *ACC* indicates the proportion of correct responses. *RT* indicates response times in ms.

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[1] We preferred the median over the mean because the median is less susceptible to outliers. However, the same analysis on mean response times did not change the results.

The 2x4 ANOVA on accuracy revealed significant main effects for transition, *F*(1, 113) = 27.22, $p < .001$, $\eta_p^2 = .19$, and age group *F*(3, 113) = 15.45, $p < .001$, $\eta_p^2 = .29$, but no interaction, *F*(3, 113) = 0.27, $p = .849$, $\eta_p^2 < .01$. Two sided post-hoc Tukey t-tests indicated that 8-year-olds did not differ significantly from 10-year-olds, *t*(113) = -1.25, $p = .597$, but differed significantly from 12-year-olds, *t*(113) = -4.11, $p < .001$, and adults, *t*(113) = -6.15, $p < .001$. Similarly, 10-year-olds differed significantly from 12-year-olds, *t*(113) = -2.90, $p = .023$, and adults, *t*(113) = -4.89, $p < .001$. Finally, 12-year-olds did not differ significantly from adults, *t*(113) = -1.85, $p = .255$.

The same ANOVA on response times revealed the same pattern of significant main effects for transition, *F*(1, 113) = 155.99, $p < .001$, $\eta_p^2 = .58$, and age group, *F*(3, 113) = 13.59, $p < .001$, $\eta_p^2 = .27$, but no interaction, *F*(3, 113) = 2.17, $p = .095$, $\eta_p^2 = .05$. Two sided post-hoc Tukey t-tests indicated that 8-year-olds did not differ significantly from 10-year-olds, *t*(113) = 1.85, $p = .254$, but differed significantly from 12-year-olds, *t*(113) =3.56, $p = .003$, and adults, *t*(113) =6.12, $p < .001$. In contrast, 10-year-olds did not differ significantly from 12-year-olds, *t*(113) = 1.78, $p = .287$, but differed significantly from adults, *t*(113) =4.29, $p < .001$. Finally, 12-year-olds did not differ significantly from adults, *t*(113) = 2.36, $p = .090$.

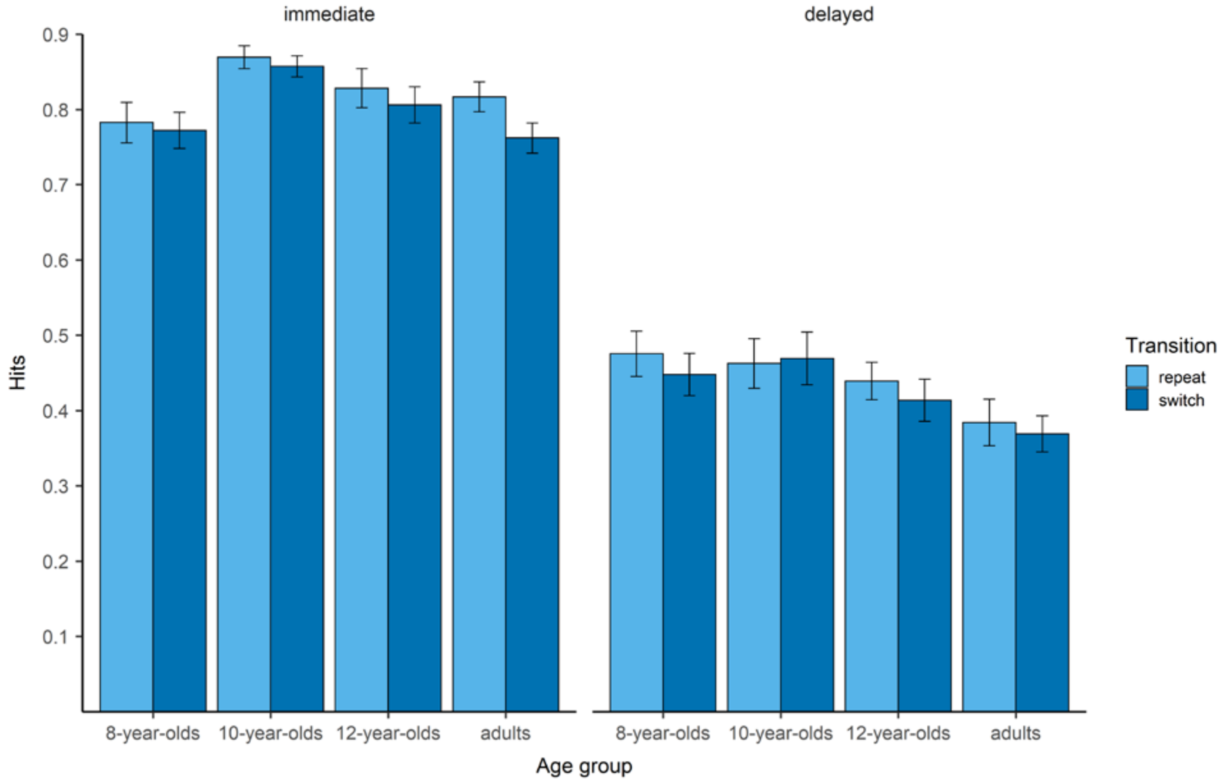
Memory performance

Before coming to our main analysis, we first tested whether false alarm rates were comparable between age groups. A 2 x 4 ANOVA on false alarm rates revealed fewer false alarms in the immediate (*M* = 0.11, *SE* = .01) than in the delayed recognition test (*M* = .17, *SE* = .01), as indicated by a significant main effect of retention interval, *F*(1, 113) = 32.53, $p < .001$, $\eta_p^2 = .22$. False alarm rates did not vary significantly between age groups, *F*(3, 113) = 1.43, $p = .238$, $\eta_p^2 = .04$. The interaction was not significant, *F*(3, 113) = 0.63, $p = .596$, $\eta_p^2 = .02$.

Figure 1 depicts the proportion of hits as a function of transition, age group, and retention interval. The critical 2x4x2 ANOVA on hit rates revealed significant effects for transition, $F(1, 113) = 6.96$, $p = .010$, $\eta_p^2 = .06$, age group, $F(3, 113) = 3.15$, $p = .028$, $\eta_p^2 = .08$, and retention interval, $F(1, 113) = 683.91$, $p < .001$, $\eta_p^2 = .86$. The interactions were not significant. Interactions between transition and retention interval, transition and age group, and retention and age group were not significant, $F(1, 113) = 0.40$, $p = .528$, $\eta_p^2 < .01$, $F(3, 113) = 0.79$, $p = .503$, $\eta_p^2 = .02$, and $F(3, 113) = 2.38$, $p = .073$, $\eta_p^2 = .06$, respectively, and neither was the three-way interaction, $F(3, 113) = 0.68$, $p = .567$, $\eta_p^2 = .02$.

Figure 1

Proportion of hits in the immediate and delayed recognition tests.



Note. Error bars represent the standard error of the mean.

For theoretical reasons we further examined the expected switch costs on recognition performance in each age group separately. We conducted separate two sided t-tests for each age group and separately for the immediate and the delayed tests. In the immediate test, memory for stimuli of repeat versus switch trials did not differ significantly in the child age groups: 8-year-olds, $t(31) = 0.45$, $p = .659$, $d = 0.08$, $BF_{01} = 4.83$; 10-year-olds, $t(30) = 0.78$, $p = .444$, $d = 0.14$, $BF_{01} = 3.96$, and 12-year-olds, $t(25) = 1.20$, $p = .241$, $d = 0.24$, $BF_{01} = 2.53$. This was also true for the delayed test: 8-year-olds, $t(31) = 1.21$, $p = .235$, $d = 0.21$, $BF_{01} = 2.71$, 10-year-olds, $t(30) = -0.35$, $p = 725.$, $d = -0.06$, $BF_{01} = 4.92$, and 12-year-olds, $t(25) = 0.87$, $p = .393$, $d = 0.17$, $BF_{01} = 3.43$. Critically, and replicating previous research, adults recognized significantly more stimuli from repeat trials in the immediate test, $t(27) = 3.19$, $p = .004$, $d = 0.60$. This effect was not significant anymore in the delayed test, $t(27) = 0.61$, $p = .546$, $d = 0.12$, $BF_{01} = 4.20$.

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Appendix B

The following pages contain the four studies referenced in this paper.

Study 1:

Dubravac, M., Roebers, C. M., & Meier, B. (2020). Different temporal dynamics after conflicts and errors in children and adults. *PLOS ONE*, *15*(8), e0238221. https://doi.org/10.1371/journal.pone.0238221

Study 2:

Dubravac, M., Roebers, C. M., & Meier, B. (to be submitted). Age-related qualitative differences in post-error cognitive control adjustments. *The Abstract has been submitted to a special issue on development of self-regulation, cognitive control, and executive function, appearing in the journal Developmental Science*

Study 3:

Dubravac, M., & Meier, B. (in revision). Cognitive load at encoding hurts memory selectivity. *Submitted to the Journal of Experimental Psychology: Learning, Memory, and Cognition*.

Study 4:

Dubravac, M., & Meier, B. (2021). Stimulating the parietal cortex by transcranial direct current stimulation (tDCS): No effects on attention and memory. *AIMS Neuroscience*, *8*(1), 33–46. https://doi.org/10.3934/Neuroscience.2021002

PLOS ONE

RESEARCH ARTICLE

Different temporal dynamics after conflicts and errors in children and adults

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Abstract

After perceiving cognitive conflicts or errors, children as well as adults adjust their performance in terms of reaction time slowing on subsequent actions, resulting in the so called post-conflict slowing and post-error slowing, respectively. The development of these phenomena has been studied separately and with different methods yielding inconsistent findings. We aimed to assess the temporal dynamics of these two slowing phenomena within a single behavioral task. To do so, 9-13-year-old children and young adults performed a Simon task in which every fifth trial was incongruent and thus induced cognitive conflict and, frequently, also errors. We compared the reaction times on four trials following a conflict or an error. Both age groups slowed down after conflicts and did so even more strongly after errors. Disproportionally high reaction times on the first post-error trial were followed by a steady flattening of the slowing. Generally, children slowed down more than adults. In addition to highlighting the phenomenal and developmental robustness of post-conflict and post-error slowing these findings strongly suggest increasingly efficient performance adjustment through fine-tuning of cognitive control in the course of development.

Citation: Dubravac M, Roebers CM, Meier B (2020) Different temporal dynamics after conflicts and errors in children and adults. PLoS ONE 15(8): e0238221. https://doi.org/10.1371/journal.pone.0238221

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Data Availability Statement: Raw as well as processed data files and the Rscript including detailed description of the data preparation and data analysis steps are available at Mendeley Data public repository: http://dx.doi.org/10.17632/z8bd48s9ds.1.

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Introduction

Experiences shape our behavior and behavior shapes our experiences. If we experience a difficult task, we generally slow down performance to avoid errors. In laboratory studies, difficulty is induced by cognitive conflicts where an automatic prepotent response has to be inhibited to avoid errors. When experiencing conflicts or errors, adults as well as children slow down performance [1–10]. The ability to adjust our behavior flexibly is critical for achieving our goals and is thought to be a driving force for cognitive development in adolescence [11,12]. Understanding the time course of adjustment processes after experiencing conflicts and errors may elucidate fine-grained cognitive development throughout adolescence. Thus, we investigated the temporal dynamics of performance adjustments after experiencing increased task difficulty induced by occasional cognitive conflicts and errors in preadolescent children and young adults.

One often used experimental task to induce cognitive conflict is the Simon task [6,13,14]. In a variant of this task, colored stimuli appear on the left or right hand side of a screen. Participants are asked to respond to the color of the stimuli (task-relevant dimension) by pressing the corresponding left or right key as fast and accurately as possible while ignoring the location of the stimulus (task-irrelevant dimension). On congruent trials, the task-irrelevant location and the task-relevant color point to the same response. On incongruent trials, however, the task-irrelevant location and the task-relevant color point to different responses. Incongruent trials, thus, induce a response conflict. The costs of this cognitive conflict is reflected in the congruency effect which is characterized by slower reaction times and higher error rates on incongruent compared to congruent trials [15]. Incongruent trials have also longer-lasting effects on performance as evidenced by the **post-conflict slowing** effect [1,2,5]. Similarly, errors also lead to subsequent performance adjustments as evidenced by the **post-error slowing** effect [16].

One prominent framework to account for performance adjustments is the *conflict monitoring theory* [17]. According to this theory, incongruent trials simultaneously activate two conflicting response alternatives leading to response conflict. Detection of response conflict increases cognitive control on the next trial, which leads to increased focusing on the task-relevant stimulus dimension. This increased task-focusing then leads to reduced interference from the task-irrelevant stimulus dimension on the subsequent incongruent trial [6,7,18–21]. It also leads to increased reaction times on several trials after experiencing the conflict, that is, post-conflict slowing [1]. According to the conflict monitoring theory, the detection of a committed error is associated with high levels of conflict as for a short moment both the correct and incorrect responses are co-activated leading to cognitive conflict and subsequent slowing [17,22].

The generalizability of the conflict monitoring theory has been challenged by studies suggesting a dissociation between post-conflict and post-error control adjustments. For example, post-error slowing generalized over task-sets while post-conflict adaptation was task-specific [4,23]. Moreover, different event-related potentials were found for post-error and post-conflict slowing [24]. However, more recent studies suggest that the task-specificity of post-conflict slowing changes across the course of a task [1], and that task-unspecific post-error slowing dissipates quickly while task-specific post-error slowing persists [25,26]. Moreover, evidence for the involvement of two processes with different developmental trajectories is found for post-conflict slowing, as well as post-error slowing [8,27–29]. However, so far, no study has compared the time-courses and developmental trajectories of the two slowing phenomena directly. The aim of the present study was to fill this gap by examining the reaction times on four trials after conflicts and errors in children and adults. Before coming to our own study, we briefly review studies that examined the time-course of post-conflict slowing or post-error slowing in children and/or in adults.

Post-conflict slowing has been investigated by inducing occasional conflict trials (i.e., incongruent trial in the Simon task) and measuring reaction times on subsequent non-conflict trials. The increase in reaction times relative to a block involving only non-conflict trials represents post-conflict slowing [30]. Presenting adult participants incongruent trials on every fifth trial, post-conflict slowing was found on all four subsequent trials [1]. A related study showed even longer lasting post-conflict slowing by presenting incongruent stimuli on six trials evenly interspersed among 120 trials resulting in 19 post-conflict trials [2]. In this study, adults showed post-conflict slowing for up to twelve trials [2]. This method has also been used to investigate post-conflict slowing in children. Monolingual children showed post-conflict slowing for up to twelve trials while bilingual children showed post-conflict slowing only for up to two trials, suggesting faster disengagement of attention by bilingual children [5]. Assuming that adults are faster in regulating attention control compared to children, we hypothesized that children would show stronger and longer lasting post-conflict slowing.

Post-error slowing has been measured by comparing reaction times on post-error trials to either correct trials [9,10,25,31,32], post-correct trials [33–37] or pre-error trials [26,38]. A recent study compared the different measures [39]. Most important for the present study, post-error slowing was found consistently in children as well as in adults. For example, in one study reaction times were examined on ten trials before and after an error in several age groups from five-year-olds to young adults [9]. Participants responded increasingly faster before an error with the fastest reaction times observed on the error trials, after which they slowed down markedly. Reaction time differences between trials decreased with age reflecting a trend towards smoother and more fine-tuned reaction time adjustments across development. A more recent study examined reaction times around errors in the Simon task and corroborated the finding of faster reaction times on pre-error and error trials and stronger post-error slowing in younger compared to older children [40]. In line, other studies also found a decrease in post-error slowing with age [10,31,32,41]. Based on these findings, we assumed stronger and longer lasting post-error slowing in children than adults.

In the present study, children and adult participants completed a Simon task in which every fifth trial was incongruent. We were especially interested in comparing the time courses of post-conflict slowing and post-error slowing. Due to the experimental set up, with every fifth trial being an incongruent trial, errors were provoked experimentally. This method allows for a differentiated investigation of performance slowing for up to four subsequent trials [42]. Post-conflict slowing was measured by subtracting individual reaction times in a pure congruent block from reaction times on the four trials immediately following a *correct* response to an incongruent trial. Aiming to compare the time-courses, post-error slowing was measured correspondingly; reaction times in a pure congruent block were subtracted from reaction times on the four trials immediately following an *erroneous* response to an incongruent trial. Thus, the main analysis focused on congruent trials following correct and incorrect incongruent trials, respectively.

We expected that error specific slowing would add up to conflict related slowing. The difference represents slowing uniquely attributable to the error. Thus, we hypothesized stronger post-error slowing compared to post-conflict slowing. We also hypothesized that the time courses of post-conflict and post-error slowing would be comparable across age groups. Although young children already have the ability to inhibit responses and thus modulate cognitive control [6] further development is taking place during late childhood as older children show more fine-tuned performance adjustments [9,31]. During the maturation of the prefrontal cortex supported by synaptic pruning and myelination adolescents further develop their inhibitory skills and fine-tune performance adjustment skills [12,43–46]. As inhibition and resistance to interference as well as deliberate strategy use develop substantially through childhood and until adulthood, and based on previous findings reported above, we expected stronger slowing in children than adults.

Method

Participants

We recruited 65 children from schools of the German speaking part of Switzerland and 75 adults via advertisements on the university's billboard or posted in a local online news portal. Based on our piloting studies, we assumed more exclusions in the adult sample and thus we recruited more adults than children. After data screening, we excluded twelve adult participants because they did not commit any error on the critical incongruent trials intended to elicit errors. We excluded two children because they responded incorrectly on the critical post-error trials as well. The final sample consisted of 63 children aged between 9 and 12 years (*M* = 11, *SD* = 1, 32 males) and 63 adults aged between 18 and 33 years (*M* = 23, *SD* = 3, 13 males).

The study was approved by the ethics committee of the University of Bern. Prior to testing the participants, we obtained written informed consent of the adult participants and children's parents. Children received a small present for their participation, psychology students received credits and external participants were financially compensated.

Design

The study design consisted of the between-subject factor *age group* (child vs. adult) and three within-subject factors; *congruency* (congruent vs. incongruent trials), *slowing type* (post-conflict vs. post-error), and position of the current *trial* (t+1, t+2, t+3, t+4, with t referring to an incongruent trial). Accuracy and reaction times were measured on every trial and provided the basis for computing post-conflict and post-error slowing.

Materials

The Simon task was adopted from Roebers and Kauer (2009) [13]. The stimuli were yellow and blue starfish, which appeared on the left or right side of a laptop screen (Fig 1). The stimuli were presented in two blocks with a fixed block order, which was not repeated. The first, purely congruent block comprised 24 trials, in which 12 yellow and 12 blue starfish appeared in random order always on the congruent response side. The second, mixed block comprised a total 124 trials, of which the first four trials were congruent warm-up trials. The remaining 120 experimental trials in the mixed block comprised 96 congruent trials and 24 incongruent trials. On incongruent trials, the starfish appeared on the incongruent response side. The incongruent trials were determined randomly with replacement and were evenly interspersed among the 96 congruent trials, occurring on every fifth trial [42].

Procedure

The procedure was the same for children and adults. Participants were tested individually. They were seated in front of a laptop computer at approximately arm length distance to the keyboard, on which the response had to be given by pressing either the left mouse button with the left index finger for a yellow starfish or the right mouse button with the right index finger for a blue starfish. Each trial consisted of a fixation cross for 250 ms (= response-stimulus interval) in the middle of the screen, followed by a yellow or blue starfish which appeared either on the left or right side and stayed on screen until response. Participants were asked to respond as accurately and fast as possible. The procedure is depicted in Fig 1.

To ensure that the task was clear to the participants the examiner showed two congruent example trials before the congruent practice block and two incongruent example trials before the mixed practice block. The practice blocks consisted of four practice trials. In the case of more than two errors, the experiment automatically returned to the start of the practice block and the examiner explained the task again (this happened in three cases altogether). After a successful practice run, the respective experimental block started. The mixed block was preceded by four congruent warm up trials not included in the analysis.

The reasons for presenting a pure congruent block before the mixed block were a) to induce a congruency training (i.e., to establish a response tendency to the side of the stimulus) aimed at increasing error rates on incongruent trials in the following mixed block, b) to be able to compute post-conflict slowing by comparing the reaction times on congruent trials between blocks, and c) to have a baseline for speed-differences between children and adults [2]. The pure congruent block consisted of 24 congruent trials, while the mixed block consisted of 24 incongruent trials evenly interspersed among 96 congruent trials. We were mainly interested in the four congruent trials following incongruent trials. Collapsing these four trials to one

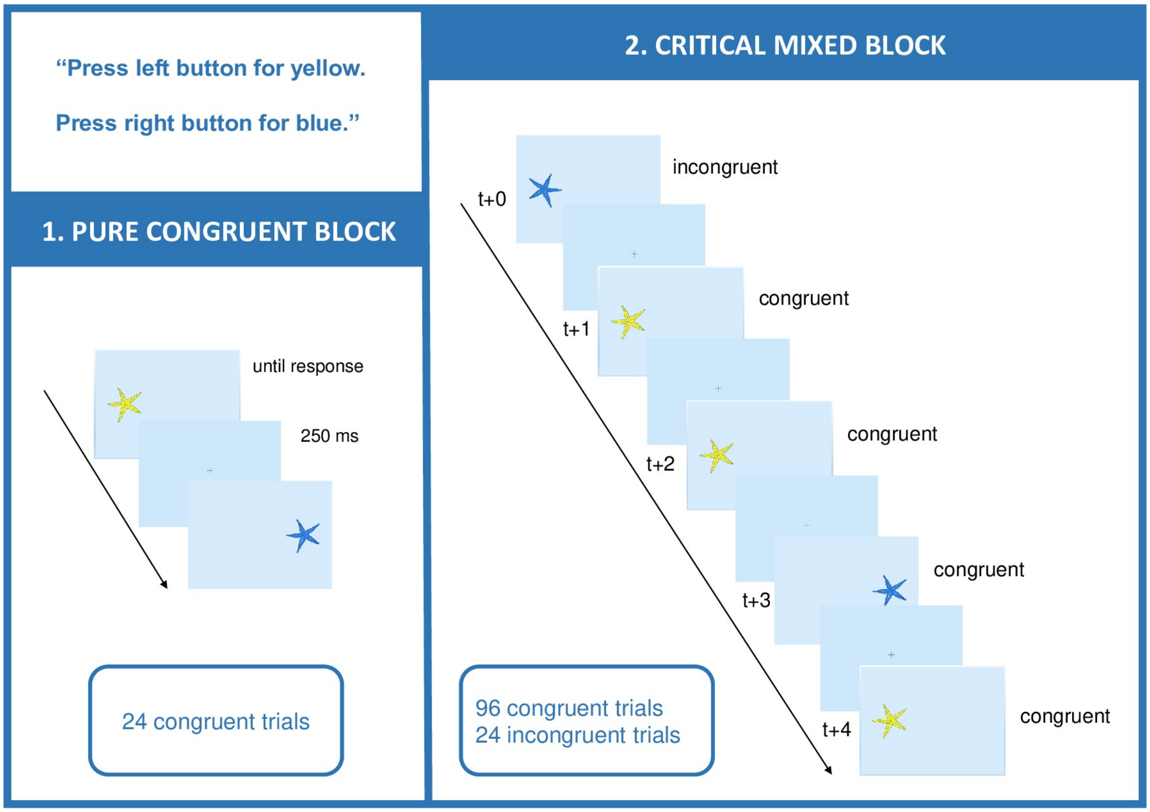

Fig 1. Schematic representation of the procedure with congruent and incongruent trial examples. Procedure; Depending on whether the response on trial t+0 was correct or incorrect, the subsequent trials (t+1, t+2, t+3, t+4) were considered as post-conflict or post-error trials, respectively.

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event results in 24 incidents of performance adjustments after conflicts and errors (120/ 5 = 24). This in turn can be related to the 24 incidents of congruent trials in the shorter congruent block. With this trial number and block order we successfully created a short, convenient, and child-friendly task inducing a maximal error rate on incongruent trials. While piloting the task, we aimed at a 20% error rate. We reached this goal with the presented method, although the error rate was slightly lower in the present sample (i.e., 17.15%).

Data preparation and analysis

For every participant, mean accuracy rates and median reaction times in ms were computed. Compared to the mean, the median is less susceptible to outliers. We preferred to keep as many trials as possible in the analysis and thus we used the median. However, conclusions do not change after conducting the analyses with the mean. Because we were interested in the reaction times on *correctly* answered congruent trials after incorrectly answered incongruent trials, we had to exclude participants who did not provide values in those cells. That is, we excluded participants either who did not commit any errors on incongruent trials or who committed further errors on the congruent trials after an error on an incongruent trial.

The pure congruent block served as a baseline for the mixed block which comprised the critical incongruent (conflict) and congruent (non-conflict) trials. As a manipulation check, we analyzed the congruency effect to confirm that the incongruent trials indeed induced cognitive conflict in both age groups. The main analysis applied to reaction times on four congruent trials as a function of the correctness of the response on the previous incongruent trial. We excluded incorrect responses on congruent trials and discarded the following trials as well (thus excluding double errors). This yielded a total of 1907 post-error trials and 9511 post-conflict trials, that is, on average, 69 post-conflict and 19 post-error observations per child, and 82 post-conflict and 11 post-error observations per adult.

In order to control for speed differences, we computed post-conflict and post-error slowing by subtracting individual median correct reaction times in the pure congruent block from the four trials following incongruent trials in the mixed block. A significant difference from zero thus represents conflict and error related slowing (as it is compared to a block without conflict and with very little errors). This is a standard analytical approach used to investigate post-conflict slowing[1,2,5,30]. For comparability reasons, we computed post-error slowing the same way. To compare our findings to other studies of post-error slowing, however, we additionally calculated post-error slowing as the difference between post-error and post-correct reaction times. This measure represents pure post-error slowing because conflict related slowing is subtracted.

We performed analyses of variance (ANOVA) on accuracy rates, reaction times and difference scores representing slowing. For significance tests, an alpha level of .05 was set. As Mauchly's test of sphericity was significant for the factor trial, corrected Greenhouse-Geisser values are reported.

Results

Descriptive statistics

Tables 1 and 2 give a descriptive overview of the data. Participants performed well on the congruent trials of the pure block with accuracy rates at ceiling. Critical for assessing post-error slowing in the mixed block, accuracy was below 85% on incongruent trials while accuracy was relatively high on congruent trials. Fig 2 shows the distribution of errors on incongruent trials among children and adults. Not surprisingly, children made more errors than adults. The even distribution of errors among participants suggests that the error rate is not driven by outliers.

Congruency effect

To test for the expected congruency effect (longer reaction times and lower accuracy rates on incongruent trials compared to congruent trials), we conducted a 2x2 ANOVA on accuracy rates and correct reaction times from the mixed block with the between-subjects variable age group (children vs. adults) and the within-subject variable congruency (congruent vs. incongruent). See Table 1 for descriptive statistics.

Accuracy rates. The expected main effect of congruency was significant, indicating that participants responded more accurately on congruent than incongruent trials, $F(1, 124) = 364.42$, $p < .001$, $\eta_p^2 = .75$. The highly significant main effect of age group indicated that children committed more errors than adults, $F(1, 124) = 32.90$, $p < .001$, $\eta_p^2 = .21$. The interaction between congruency and age group was significant, $F(1, 124) = 22.07$, $p < .001$, $\eta_p^2 = .15$, suggesting a stronger congruency effect for children than for adults. Paired t-tests indicated that the difference between congruent and incongruent trials was significant for children, $t(62) = 14.902$, $p < .001$, as well as for adults, $t(62) = 11.943$, $p < .001$. However, a significant Welch two sample t-test indicated that the difference was indeed larger for children ($M = .190$, $SE = .013$) than for adults ($M = .115$, $SE = .010$), $t(115.34) = 4.698$, $p < .001$.

Reaction times. The expected main effect of congruency was significant, indicating that participants responded faster on congruent than incongruent trials, $F(1, 124) = 420.60$, $p <$

Table 1. Reaction times and accuracy for pure and mixed blocks.

		Pure block	Mixed block	
Measure	**Age group**	**Congruent**	**Congruent**	**Incongruent**
RT	Children	388 (9)	598 (10)	733 (15)
	Adults	315 (7)	432 (9)	519 (11)
Accuracy	Children	0.987 (0.003)	0.970 (0.005)	0.779 (0.015)
	Adults	0.999 (0.001)	0.994 (0.001)	0.878 (0.010)

RT = mean of the correct median reaction times in ms, accuracy = mean proportion of correct responses. Standard errors of the means are in parentheses.

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.001, $\eta_p^2 = .77$. The highly significant main effect of age group indicated that children responded slower than adults, $F(1, 124) = 152.24$, $p < .001$, $\eta_p^2 = .55$. The interaction between congruency and age was significant, $F(1, 124) = 19.65$, $p < .001$, $\eta_p^2 = .14$, suggesting a stronger congruency effect for children than for adults. Paired t-tests indicated that the difference between congruent and incongruent trials was significant for children, $t(62) = 14.685$, $p < .001$, as well as for adults, $t(62) = 15.221$, $p < .001$. However, a significant Welch two sample t-test indicated that the difference was indeed larger for children ($M = 135$, $SE = 9$) than for adults ($M = 87$, $SE = 6$), $t(103.71) = 4.433$, $p < .001$.

Pure post-error slowing

As shown in Table 2, pure post-error slowing was computed by subtracting reaction times on trials after correct responses from reaction times on trials after incorrect responses on incongruent trials. T-tests indicated that the difference scores were significantly different from 0 on every trial, confirming a post-error slowing effect for both age groups. An ANOVA with age group (children vs. adults) as between subjects variable and trial (t+1, t+2, t+3, t+4) as a within-subjects variable revealed no main effect of age group, $F(1, 124) = 0.84$, $p = .361$, $\eta_p^2 < .01$, and no interaction with trial, $F(1.64, 202.87) = 0.44$, $p = .603$, $\eta_p^2 < .01$. The main effect of trial, however, was highly significant, $F(1.64, 202.87) = 48.07$, $p < .001$, $\eta_p^2 = .28$, suggesting a decline of post-error slowing over the course of the four trials. Bonferroni adjusted post-hoc t-tests revealed that the differences between the first trial and all other trials were significant, all p's $< .001$. The difference between the second and third trial was also significant, $p = .05$, while the other comparisons were not significant, $p > .26$.

Table 2. Reaction times in the mixed block.

Age group	Trial type (T)	T+0	T+1	T+2	T+3	T+4
Children	Correct conflict	735 (16)	624 (13)	577 (11)	540 (9)	536 (10)
	Incorrect conflict	485 (13)	874 (32)	645 (21)	560 (12)	591 (15)
	Pure post-error slowing	-250 (14)	249 (29)	68 (18)	20 (10)	56 (13)
Adults	Correct conflict	518 (11)	450 (10)	429 (10)	403 (9)	406 (9)
	Incorrect conflict	355 (13)	667 (40)	482 (19)	436 (13)	446 (15)
	Pure post-error slowing	-163 (11)	218 (33)	52 (16)	33 (10)	40 (11)

Values represent the mean of median reaction times in ms. Standard errors are in parentheses. "T+0" is the incongruent trial and "T+1", "T+2", "T+3", "T+4" denote the following four congruent trials. Please note that the values are not exactly the same as in Table 1 (cf. "incongruent trial in the mixed block" in Table 1 vs. "correct conflict on T+0" in Table 2), due to the exclusion of correct incongruent trials that were preceded by an error. The difference between "correct conflict" and "incorrect conflict" represents "pure post-error slowing" (shaded).

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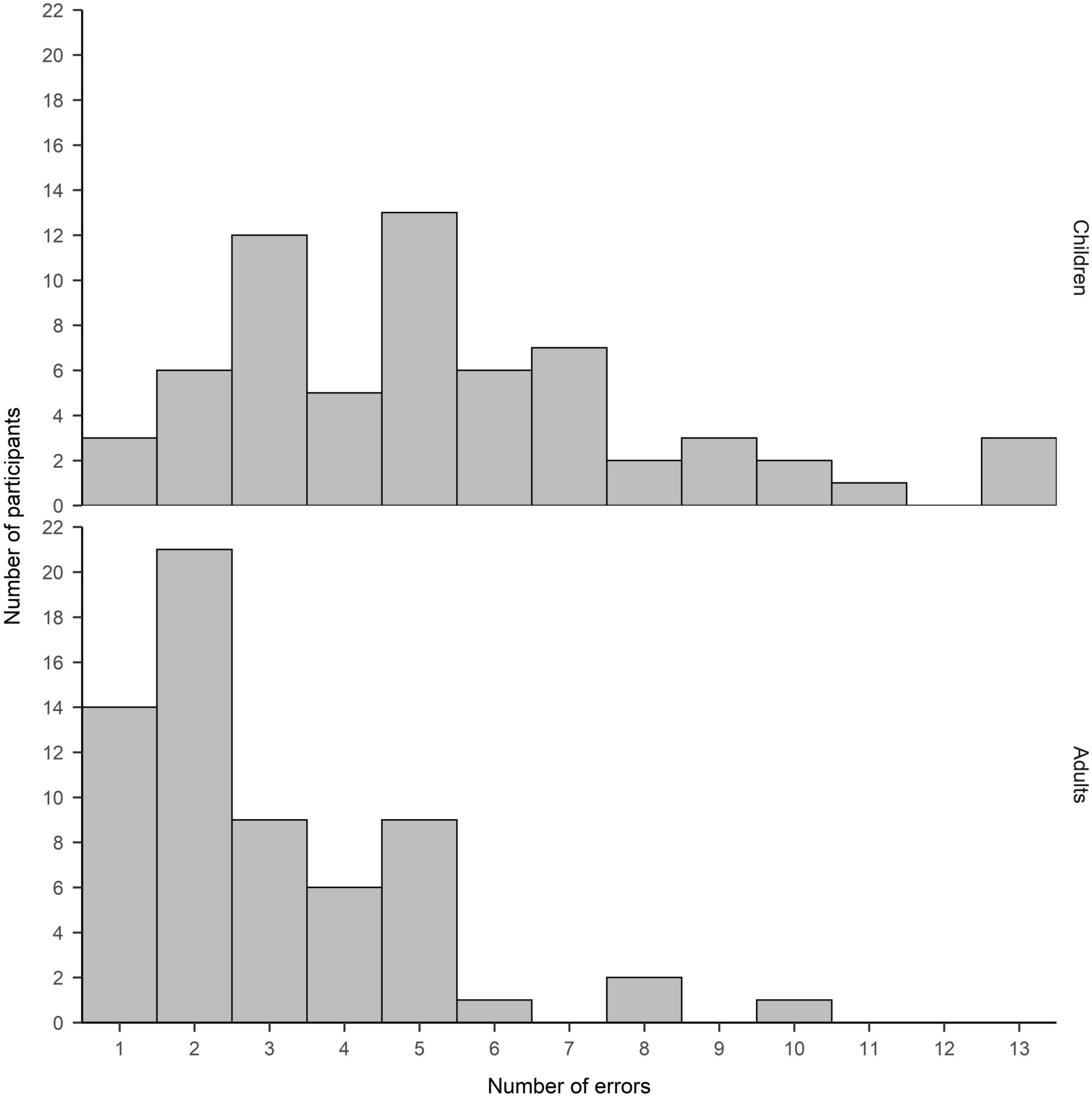

Fig 2. Distribution of error rates on incongruent trials among participants.

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Because lower error rates are sometimes associated with more pronounced post-error slowing [47], a possibly stronger post-error slowing effect in children may have been disguised by the fact that children had higher error rates, thus reducing post-error slowing. To account for different error rates in the age groups, we conducted an ANCOVA including the covariate "accuracy on incongruent trials". The main effect of age group was indeed significant, $F(1, 123) = 4.46$, $p = .037$, $\eta_p^2 = .04$, suggesting stronger slowing in children. The main effect of trial was still significant, $F(1.69, 207.93) = 5.42$, $p = .008$, $\eta_p^2 = .28$, suggesting a decrease in post-error slowing with time. The interaction between age group and trial was also significant, $F(1.69, 207.93) = 3.59$, $p = .036$, $\eta_p^2 = .03$. The main effect of accuracy rate was also significant, $F(1, 123) = 8.34$, $p = .005$, $\eta_p^2 = .06$, as well as the interaction with trial, $F(1.69, 207.93) = 10.36$, $p < .001$, $\eta_p^2 = .08$, suggesting that the accuracy rate affects not only the strength of the effect but also the longevity. However, because the accuracy rate variable is not independent from our main variable age group, the interpretations drawn by this ANCOVA need to be viewed with caution.

Post-conflict slowing versus post-error slowing

We calculated post-conflict and post-error slowing by subtracting the individual baseline reaction times (pure congruent block) from the reaction times on four congruent trials after correct and incorrect incongruent trials in the mixed block (see Fig 3 for the resulting difference scores and the trajectory over the four trials). The deviation from zero thus represents the amount of slowing due to the inducement of cognitive conflict and errors. We tested for every trial and separately for adults and children whether slowing was significantly greater than zero. The t-tests indicated significant slowing on every trial, all p's $< .001$. To examine post-conflict and post-error slowing, we conducted our main ANOVA with age group (children vs. adults) as a between-subjects variable, and slowing type (post-conflict vs. post-error) and trial (t+1, t+2, t+3, t+4) as within-subjects variables. Fig 3 depicts the time courses of post-conflict and post-error slowing. Please note that the incongruent trial (t+0) is presented in Fig 3 for completeness reasons and was not included in the analysis.

Children performed slower than adults ($M = 205$, $SE = 7$ vs. $M = 138$, $SE = 7$) as indicated by a significant main effect of age group, $F(1, 124) = 27.68$, $p < .001$, $\eta_p^2 = .18$. Both age groups performed slower after errors ($M = 221$, $SE = 9$ vs. $M = 122$, $SE = 3$), as indicated by a significant main effect of slowing type, $F(1, 124) = 174.28$, $p < .001$, $\eta_p^2 = .58$. Reaction times decreased from the first ($M = 282$, $SE = 15$) to the second ($M = 156$, $SE = 7$), and to the third ($M = 117$, $SE = 5$) post trial, with reaction times increasing towards the fourth trial ($M = 131$, $SE = 6$), as indicated by a significant main effect of trial, $F(1.62, 201.21) = 103.47$, $p < .001$, $\eta_p^2 = .45$. Pairwise comparisons with the Bonferroni correction for multiple comparisons indicated significant decreases in slowing from t+1 to t+3, all p's $< .001$, but an insignificant increase from t+3 to t+4, $p = .144$.

The interaction between age group and slowing type was not significant, $F(1, 124) = 0.03$, $p = .858$, $\eta_p^2 < .01$, suggesting comparable reaction time adjustments after conflicts and errors for both age groups. However, the interaction between age group and trial was significant, $F(1.62, 201.21) = 3.36$, $p = .047$, $\eta_p^2 = .03$, suggesting age related differences in the time course of reaction time adjustments. Although children had stronger slowing on every trial, the difference was largest on t+1 ($M = 107$, $SE = 27$) compared to the other trials t+2 ($M = 64$, $SE = 15$), t+3 ($M = 47$, $SE = 12$), and t+4 ($M = 53$, $SE = 14$). Furthermore, the interaction between slowing type and trial was highly significant, $F(1.57, 194.63) = 49.54$, $p < .001$, $\eta_p^2 = .29$, suggesting a different time course for reaction time adjustments after conflicts and errors. Although post-error slowing was stronger than post-conflict slowing on every trial, all p's $< .001$, the difference on the first trial was significantly largest compared to all other trials, all p's $< .001$. The other trial comparisons of the difference between post-conflict and post-error slowing were

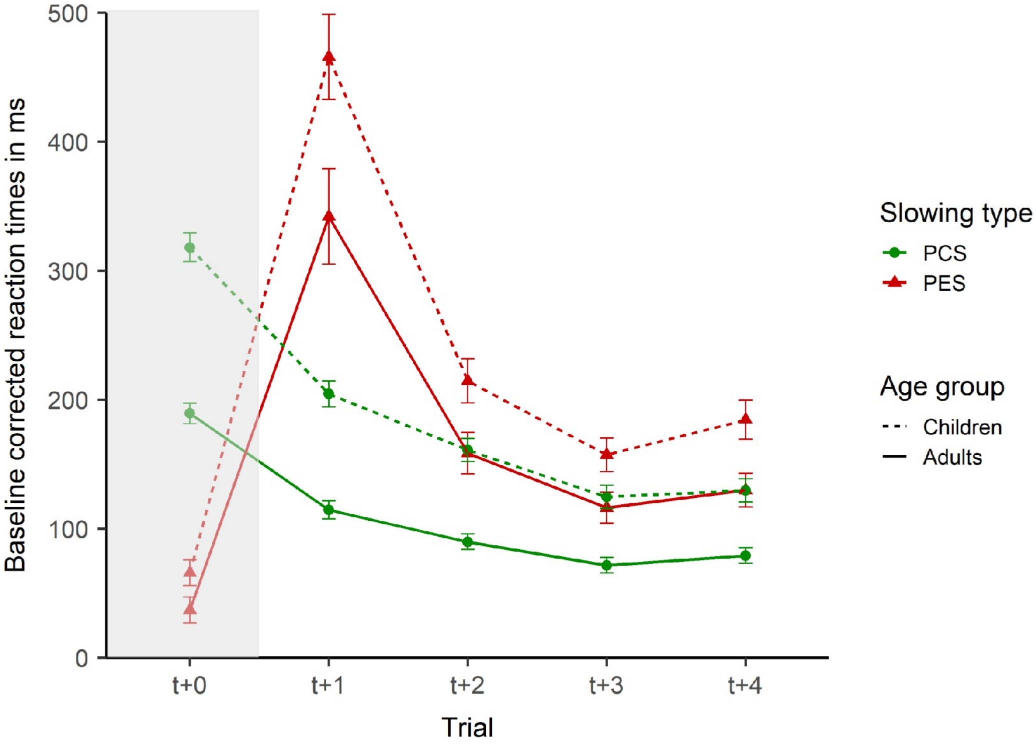

Fig 3. Post-Conflict slowing and post-error slowing. Baseline corrected reaction times of children (dotted line) and adults (solid line) on incongruent trials (t+0) and the following correct congruent trials (t+1, t+2, t+3, t+4). The slowing type depends on the correctness of trial t+0. Post-Conflict Slowing (PCS; green line, circles) follows a correct response and Post-Error Slowing (PES; red lines, triangles) follows an incorrect response. Error bars represent standard errors of the mean.

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not significant, all p's $> .053$. The three-way interaction was not significant, $F(1.57, 194.63) = 0.65$, $p = .486$, $\eta_p^2 < .01$.

Discussion

The present study compared the time course of adjustments following cognitive conflict and errors. Preadolescent children and young adults performed a Simon task, in which every fifth trial was incongruent. These incongruent trials were designed to experimentally provoke conflict and errors. Reaction times were examined on the subsequent four congruent trials as a function of whether the response on the previous incongruent trial was correct (post-conflict) or incorrect (post-error). Compared to a baseline block consisting of only congruent trials, both age groups showed substantial slowing for several trials after conflicts and errors. This long-lasting slowing effects are in line with previous studies investigating post-conflict slowing or post-error slowing [2,5,8,9]. For the first time, the two slowing phenomena were compared directly by using the same analytical approach. Results indicated that both age groups showed stronger post-error than post-conflict slowing. The difference in slowing represents the pure post-error slowing effect and suggests that participants noticed the error and adjusted performance [48,49]. The additional slowing after an error was most pronounced on the first trial. According to the conflict monitoring theory, this finding suggests that participants experienced an additional response conflict between the correct and incorrect response [17]. Apart from this delayed conflict detection, the time-course was comparable to post-conflict slowing. As the age effect (i.e., stronger slowing in children) was also comparable between the two slowing phenomena, we suggest that post-conflict slowing and post-error slowing share underlying processes.

Overall, children slowed down more strongly than adults. Due to the baseline correction, this slowing does not solely reflect slower information processing [50]. It rather reflects more monitoring costs and/or coarser performance adjustments after conflicts and errors [8,9]. More slowing has been shown to emerge in conditions of higher control demands [51,52]. As the higher error rates and stronger congruency effects indicate, the mixed block was indeed more demanding for the children than for the adults. The relative higher cognitive load may have led to more monitoring for the expected conflict trials and thus more slowing. Assuming an involvement of an affective component in conflict and error monitoring, the higher cognitive load may elicit a stronger affective response in children leading to stronger slowing [53,54]. On the other hand, less developed performance adjustment skills would lead to stronger after-effects of responding (correctly or incorrectly) to a conflict trial [55]. Thus, we suspect that more monitoring costs as well as less developed performance adjustment skills contributed to the performance differences between children and adults. With better adjustment skills there is less need to engage in costly monitoring.

The larger post-conflict slowing effect in children is consistent with findings showing reduced interference with age and is in line with the theory of increasing ability to inhibit interference and to self-regulate [45,46,56]. A recent study suggests that congruent trials affect sequential control adaptation by relaxing cognitive control [57]. It may be that the stronger post-conflict slowing in children is not only due to slower performance adaptations after conflicting incongruent trials, but it may also be that children are slower in relaxing cognitive control after encountering congruent trials. We investigated post-conflict slowing on four subsequent congruent trials and on all four trials post-conflict slowing was stronger in children than in adults. It is an open debate whether this longevity of the age effect is due to stronger and longer lasting disturbance from conflicts or whether it is due to children's slower relaxation of cognitive control in the face of congruent trials.

The quasi-experimental nature of the research on post-error slowing raised debates on methodological, empirical and theoretical grounds. For example, it has been found that the inter-trial interval affects the magnitude of post-error slowing, with shorter intervals typically leading to larger slowing effects [8,16,25,58–60]. Some studies report reduced post-error slowing with age, in line with the theory of improving cognitive control [9,10,31,32,41]. However, the findings are mixed [8]. Some studies did not find any age related change [33,35,37,61] and others found even an age-correlated increase in post-error slowing [36]. Differences in error rates between age groups may obscure true age effects. As highly accurate individuals exhibit largest post-error slowing [47] and adults are typically more accurate than children, adult's post-error slowing is relatively increased compared to children's. Furthermore, the traditional measure of post-error slowing compares mean reaction times for post-correct and post-error trials. This aggregated measure may not be sensitive to differences in fine-grained performance adjustments across trials [9,40]. Our results support this interpretation by showing the expected decrease in slowing with age using the method inspired by research on post-conflict slowing while the traditional measure of post-error slowing yielded no significant age differences. However, when controlling for error rates by means of a covariance analysis we found the expected age effect even with this method.

Accounts of strategic monitoring and adjustment of performance assume increased response caution and increased cognitive control after errors and predict that post-error slowing is accompanied by a reduction of interference and accuracy increase. This is exactly what some studies using relatively long inter-trial intervals found [34,62–64]. However, other studies using a relatively short inter-trial interval found a post-error accuracy decrease [65,66].

These studies support the orienting account of post-error slowing which assumes that an automatic orienting response to the error and away from the current task is responsible for decreased post-error performance [67]. Studies varying the inter-trial interval found that timing is critical for the emergence and direction of post-error changes in performance [25,58]. Thus, the two accounts are not mutually exclusive [16]. Rather, their combination may explain more empirical findings.

The present results are best explained with two-process theories. According to Wessel's *adaptive orienting theory of error processing* errors first invoke processes inhibiting ongoing behavior and orienting attention toward the source of the error after which more controlled error-specific processes adjust the existing task set [68]. As response inhibition is not fully matured in preadolescent children this may explain the stronger slowing in children compared to adults [45]. Thus, our results support inhibition accounts of post-error slowing [69,70]. While responses are inhibited the error captures attention because it is an unexpected event and thus this account may also apply to occasional incongruent trials [67]. Orienting attention to the error leads to a co-activation of the given incorrect response and the required correct response. We propose that errors induce response conflict on the first subsequent trial. This assumption is supported by the result of very fast reaction times on error trials and very slow reaction times immediately after the error. In other words, errors are followed by a cognitive conflict triggered by the realization of the incompatibility of the given incorrect response and the required correct response. The incompatibility of the two responses induces response conflict similar to the response conflict induced by incongruent trials [17,22].

The advantage of the presented method is the possibility to compare post-conflict slowing and post-error slowing with the same analytical approach. However, there are also drawbacks to this method. One limitation is the relatively low trial number. In experimental cognitive research a lot of trials are used to increase power. Especially in research on post-error slowing a lot of trials are needed to ensure enough post-error trials. However, in developmental research lengthy tasks are not suitable as children's motivation and attention declines over a longer period of repetitive trials. Thus, we aimed to come up with a task that was short enough to engage and keep children focused on the task while at the same time ensuring that the task elicits enough errors in adults. We opted for a shorter task and compensated for the loss in power with a relatively large sample size [71]. However, the problem of differing error rates in children and adults is not solved. As the error rate is found to influence post-error slowing [47], future studies could match children and adults on error rates. Another limitation related to the shortness of the task is the fixed block order. By presenting the pure congruent block first, we aimed at increasing the congruency effect and thus increasing the error rate on incongruent trials. Including more blocks and balancing block order is another direction for future studies.

Taken together, occasional incongruent trials in the Simon task elicit cognitive conflicts leading to slower and more error-prone responses on this incongruent trials. Performance on the subsequent congruent trials is slowed and even more so if an error happened. We propose the same processes underlying post-conflict and post-error slowing just displaced in time. A first inhibitory process hinders fast and inappropriate responses and a second process regulates the speed-accuracy trade-off by an upregulation of cognitive control [9,17,28]. Successful response inhibition leads to a correct response after which the consequences of the speed-accuracy regulation are still observable as longer reaction times (post-conflict slowing). If, however, response inhibition fails on an incongruent trial, it is likely that an error occurs. This error is characterized by fast reaction times and entails a delayed, yet strong response inhibition leading to post-error slowing [69,70]. Both slowing phenomena last for several trials reflecting the upregulation of cognitive control [17].

In conclusion, we propose that the same processes underlie post-error slowing and post-conflict slowing but they are displaced in time (cf. Fig 3). The effect of the first process dissipates quickly while the second process has longer lasting effects. Previous research on conflict-slowing and post-error slowing suggest that the first process is age invariant but time sensitive, while the second process is sensitive to age but not to time [8,25–29]. Further studies are needed to explain in detail how conflict and error processing are supposed to differ functionally and anatomically if the timing of the involved processes is taken into account [4,23,24,72,73]. The presented method allows differentiating between different processes experimentally and investigating cognitive development in more detail.

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Formal analysis: Mirela Dubravac.

Funding acquisition: Claudia M. Roebers, Beat Meier.

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Visualization: Mirela Dubravac.

Writing – original draft: Mirela Dubravac.

Writing – review & editing: Mirela Dubravac, Claudia M. Roebers, Beat Meier.

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Age-related qualitative differences in post-error cognitive control adjustments

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Abstract

Metacognitive performance monitoring is crucial for flexible adaptation to changing demands. Detecting an error signals the need for increased cognitive control and behavioral adjustments. Considerable development in monitoring and cognitive control is evidenced by lower error rates and faster response times in multi-trial executive function tasks with age. Besides these quantitative changes, we were interested in whether qualitative changes in balancing accuracy and speed contribute to developmental progression during elementary school years. We conducted two studies investigating the temporal and developmental trajectories of post-error slowing in three prominent cognitive conflict tasks (Stroop, Simon, and flanker). We instructed children (8-, 10-, and 12-year-old) and adults to respond as fast and as accurately as possible and measured their response times on trials after correct and incorrect responses to a cognitive conflict. Results revealed that all age groups had longer response times on post-error versus post-correct trials, reflecting post-error slowing. Critically, slowing on the first post-error trial declined with age, suggesting an age-related reduction in the orienting response toward errors. On subsequent trials, however, this age effect reversed. Children showed sporadic slowing while adults showed persistent slowing across trials, suggesting that adults engaged in more sustained cognitive control adaptations after errors. This pattern suggests an age-related change from a relatively strong orienting response to more balanced cognitive control adaptations. This change may reflect the transition from reactive to proactive cognitive control modes from childhood to adulthood. Besides this robust developmental pattern, we observed differences between tasks probably due to different cognitive control demands.

Keywords: cognitive control, post-error slowing, cognitive conflict, Stroop task, Simon task, flanker task, cognitive development.

Age-related qualitative differences in post-error cognitive control adjustments

Executive functions refer to a diverse set of processes involved in the regulation of goal-oriented behavior. Already young children show executive functioning as they switch between different tasks, inhibit inappropriate actions, and adjust behavior flexibly to changing demands. However, much development is still taking place during childhood, as evidenced by striking differences between children's and adults' performance on executive function tasks (Davidson et al., 2006; Ridderinkhof & van der Molen, 1995). Usually, children need more time to respond and commit more errors than adults. The developmental trajectory of these quantitative performance improvements depends on the demands that a specific task poses on different aspects of executive functioning, complicating the understanding of emerging "executive control" (Anderson, 2002; Davidson et al., 2006; Diamond, 2013). Thus, the question arises of how children achieve to orchestrate different cognitive processes to work in concert for optimal performance. Recent theoretical advances point to qualitative changes in the coordination of performance monitoring and cognitive control as a driving force for developmental progression (Chevalier, 2015; Hämmerer et al., 2014; Roebers, 2017). Adopting a fine-grained approach to the study of developing executive functioning, the present study investigated the developmental trajectories of processes involved in monitoring and adjusting response times on a trial-by-trial basis.

Trial-by-trial adjustments are already evident in young children as they show longer response times after cognitive conflicts (Ambrosi et al., 2016; Grundy & Keyvani Chahi, 2017; Smulders et al., 2018). Similarly, detecting self-generated errors leads also to longer response times on subsequent trials (Brewer & Smith, 1989; Danielmeier & Ullsperger, 2011; Dubravac et al., 2020; Fairweather, 1978; Gupta et al., 2009; Jones et al., 2003; King et al., 2010; McDermott et al., 2007; Schroder et al., 2020; Smulders et al., 2016; Thaqi & Roebers, 2020). Post-error slowing has been attributed to motor inhibition (Marco-Pallarés et al., 2008; Ridderinkhof, 2002), inhibition of irrelevant information (King et al., 2010), delayed processing of sensory information (Buzzell et al., 2017; Laming, 1979), attentional orienting toward the source of the error (Notebaert et al., 2009), and cognitive control adjustments following error detection (Botvinick et al., 2001). These accounts are complementary, as motor inhibition facilitates attentional orientation toward the error delaying information processing and thus gaining time for the implementation of cognitive control processes, such as response threshold adjustments (Danielmeier & Ullsperger, 2011; Wessel, 2018). That is, error detection triggers different processes that operate at different time scales and may follow distinct developmental trajectories (Compton et al., 2017; Dubravac et al., 2020; Dudschig & Jentzsch, 2009; Jentzsch & Dudschig, 2009; Van der Borght et al., 2016).

Brewer and Smith (1989) were among the first to investigate developmental changes in post-error response times across multiple trials. Participants of a wide age range (5-15 years and adults) performed a simple choice response time task. The examination of correct and error response times for error-to-error sequences varying from 2 to 16 trials revealed more fine-tuned adjustments with age as variability in response times decreased (Brewer & Smith, 1989). More recent studies confirmed the age-related decrease in response time variability surrounding errors and, particularly, post-error slowing (Dubravac et al., 2020; Gupta et al., 2009; Smulders et al., 2016; Thaqi & Roebers, 2020). The decrease in post-error slowing between 7- and 8-year-old children and between 9- and 10-year-old children was related to the development of inhibitory control in this age range (Gupta et al., 2009). This suggests that developing inhibitory control may promote smoother response time adjustments after errors.

The age range between eight years and young adulthood represents a transition period associated with qualitative changes in cognitive control (Chevalier et al., 2013, 2015; Chevalier & Blaye, 2016; Munakata et al., 2012). Children transition from relying predominantly on environmental cues signaling increased cognitive control demands to relying on self-generated error detection signals originating from internal performance monitoring. Furthermore, children become more and more efficient in coordinating different cognitive control modes (i.e., reactive and proactive) according to moment-to-moment variations in task demands and metacognitive performance monitoring outcomes (Chevalier, 2015; Chevalier et al., 2015; Chevalier & Blaye, 2016; Czernochowski, 2014; Roebers, 2017). Considering differences in the developmental trajectories of distinct components of executive functions, as inhibitory control or cognitive flexibility (Anderson, 2002; Davidson et al., 2006; Diamond, 2013), the age range between eight years and adulthood is an interesting period for investigating qualitative changes in post-error response time adjustments.

Building on previous work, we set up two studies investigating developmental and temporal trajectories of post-error slowing in three different executive function tasks (Simon, Stroop, and flanker). The first study compared the Stroop and Simon tasks. The second study compared the Stroop and flanker tasks. Participants of four age groups (8-, 10-, 12-year-olds, and young adults) took part in either one of the two studies. The samples differed between studies, and the Stroop task was administered in both samples to have an internal replication that helps to disentangle true differences between tasks from sampling effects. All three tasks elicit cognitive conflict on incongruent trials, where irrelevant stimulus dimensions (in the Stroop and Simon tasks) or irrelevant distractors (in the flanker task) trigger a prepotent but incorrect response that has to be inhibited to respond correctly. In contrast, congruent trials involve no conflict as the relevant and irrelevant stimulus dimensions and distractors call for the same response. Incongruent trials are thus expected to increase error rates and response times relative to congruent trials (i.e., congruency effect). We expected substantial congruency effects in all tasks and an age-related decrease in the congruency effect as inhibitory control improves with age (Ridderinkhof & van der Molen, 1995).

To increase the likelihood of errors, we presented incongruent trials only occasionally. This decision was based on empirical evidence indicating that the congruency effect increases with a decreasing frequency of incongruent trials (Gratton et al., 1992; Stürmer et al., 2002). We exploited this effect to induce errors on incongruent trials experimentally. Incongruent trials were occasionally interspersed among congruent trials. With every 5th trial being an incongruent trial, response times on four subsequent congruent trials were measured as a function of the correctness of the incongruent trial. By subtracting response times following correct conflict trials from response times following incorrect conflict trials, conflict related slowing was subtracted from conflict + error related slowing. The difference thus represents pure post-error slowing. We expected substantial slowing after errors in all age groups and tasks. However, the extent and persistence of slowing may vary between age groups.

Previous studies indicated an age-related decrease in response time variability, and in line with the theory of developing cognitive control (Brewer & Smith, 1989; Davidson et al., 2006; Diamond, 2013), we predicted an age-related decrease in post-error slowing. With respect to the time course of post-error slowing, we hypothesized that slowing would decrease across trials. The strongest slowing is expected on the first post-error trial reflecting short-lived attentional distraction (Notebaert et al., 2009). Less pronounced but persistent slowing across subsequent trials, in contrast, would indicate strategic cognitive control adjustments in the sense of increased caution implemented by elevated response thresholds (Botvinick et al., 2001; Dutilh et al., 2012). By measuring slowing on four post-error trials, we aimed to track the dynamics of these component processes underlying post-error slowing.

The main aim of the present study was to identify age differences in the component processes underlying post-error slowing. Based on theories assuming increasing attentional control and response inhibition and more optimal coordination of cognitive control with age (Anderson, 2002; Chevalier, 2015; Diamond, 2013; Luna et al., 2010; Luna & Sweeney, 2004), we hypothesized that the time course of post-error slowing would vary as a function of age. This would be evident in an interaction between age group and post-error trial. Specifically, we hypothesized that the younger age groups would have more difficulties inhibiting attentional distraction from an error resulting in a strong attentional orienting response toward the error on the first post-error trial. With increasing attentional control, slowing on the first post-error trial should decrease with age. As slowing on subsequent trials reflects more strategic cognitive control adjustments, we expected this kind of slowing in adults and to a lesser degree in children.

Method

Participants

The children were recruited from local schools, and the young adults were undergraduate psychology students. The ethics committee of the local University approved the studies. Prior to testing the participants, we obtained written informed consent of the adult participants and children's parents. Children received a small present for their participation, and adults received credits.

Task structure and design

In the Stroop task, the color of fruits and vegetables either matched their color in the real-world (congruent) or was an unrealistic color (incongruent), and the task was to indicate the real-world color. In the Simon task, participants had to indicate the color of a starfish by pressing a button either with their right or left hand. The presentation side of the starfish was either congruent with the required response side (i.e., left side presentation + left hand response) or was incongruent (i.e., left side presentation + right hand response). In the flanker task, a central target fish was presented among distracting fish that faced either in the same (congruent) or different (incongruent) direction, and the task was to respond according to the side the central fish was facing. All tasks comprised a pure congruent block and a critical mixed block. The mixed block comprised 24 incongruent trials evenly interspersed among 96 congruent trials (Meier et al., 2009; Woodward et al., 2003). Every fifth trial was thus incongruent. We were mainly interested in the four congruent trials following incongruent trials. Thus, the study design consisted of the between-subjects factor age group (8-, 10-, and 12-year-old children and adults) and the within-subject factor trial (T+1, T+2, T+3, T+4, with T referring to an incongruent trial). Accuracy and response times were measured on every trial. Depending on whether the response on trial T+0 was correct or incorrect, the subsequent trials (T+1, T+2, T+3, T+4) were considered as post-correct or post-error trials, respectively. Subtracting the response times on post-correct trials from post-error trials gives the main dependent variable post-error slowing. Figure 1 gives an overview of the three tasks.

Data preparation and analysis

For every participant and each condition, mean accuracy rates and median response times in ms were computed. Because we were interested in the response times on correctly answered congruent trials after incorrectly answered incongruent trials, we had to exclude participants with missing data in those cells. That is, we excluded participants either who did not commit any error on incongruent trials or who committed further errors on the congruent trials each time after an error on an incongruent trial. The numbers of excluded participants are listed in the "participants" sections.

As a manipulation check, we analyzed the congruency effect in the mixed block of each task. The main analysis applied to response times on four congruent trials as a function of the correctness of the response on the previous incongruent trial. We excluded incorrect responses on congruent trials and discarded the following trials as well (thus excluding double errors). First, we tested the hypothesis of slower responses after errors for each age group separately by conducting one-sided paired t-tests comparing post-error response times to post-correct response times on each of the four trials. This gave us a first impression of the persistence of the post-error slowing effect for each age group. Next, we created the main dependent variable *post-error slowing* by subtracting post-correct response times from post-error response times. This difference score was subjected to an analysis of variance (ANOVA) with the within-subject factor trial (T+1, T+2, T+3, T+4) and the between-subject factor age group (8-year-olds, 10-year-olds, 12-year-olds, and adults). For significance tests, an alpha level of .05 was set. Where appropriate, corrected Greenhouse-Geisser values are reported. Effect sizes are expressed as η_p^2. Post-hoc t-tests were two-sided.

Study 1

Participants

We recruited 44 8-year-olds, 46 10-year-olds, 52 12-year-olds, and 40 young adults. Due to technical problems, we did not obtain Stroop task data from one 8-year-old, five 10-year-olds, and three 12-year-olds. After data screening, we applied the following task-wise exclusion criteria. We excluded participants who did not commit any error on the critical incongruent trials intended to elicit errors (Stroop task: nine 8-year-olds, seven 10-year-olds, eleven 12-year-olds, and 17 adults; Simon task: three 8-year-olds, six 10-year-olds, six 12-year-olds, and five adults). We also excluded participants with an accuracy rate under 50% (Stroop task: one 8-year-old; Simon task: two 10-year olds, one 12-year-old, and one adult). This is important because low accuracy rates indicate that they probably did not understand the task, and then they would not be aware of their errors. As error rates influence post-error slowing (Steinborn et al., 2012), we further excluded participants with error rates higher than two times the standard deviation (Stroop task: one 8-year-old, one 10-year-old, two 12-year-olds; Simon task: two 8-year-olds, one 10-year-old, and two 12-year-olds). This resulted in a more homogenous sample and allowed comparisons across participants, tasks, and groups. Finally, because we included only correct trials in the analysis of post-error response times, participants who committed errors on post-error trials (i.e., double errors) were also excluded as they did not provide values in those critical cells (Stroop task: no one; Simon task: one 12-year-old and one adult). Table 1 presents the demographic characteristics of the final sample.

Material

The Stroop task was adapted from Archibald & Kerns (1999). The stimuli were colored quadrants and drawings of salad, strawberry, plum, and banana appearing in the middle of a tablet screen. Below were quadrants displayed in red, green, blue, and yellow. The Simon task was the same as in a previous study (reference withheld for blinding purposes). The stimuli were yellow and blue starfish appearing on the left or right side of a laptop screen. Stimuli are presented in Figure 1.

Procedure

The procedure was the same for children and adults. Participants were tested individually and completed first the Stroop task on a tablet and then the Simon task on a laptop computer. The tablet and laptop were placed at approximately arm length distance, and the response was given by pressing on the touch screen of the tablet (Stroop task) or by pressing on either the left or right mouse button of the laptop (Simon task). Participants were asked to respond as accurately and as fast as possible.

Stroop task

The Stroop task consisted of three blocks with a fixed block order, which was not repeated. The first block comprised 12 trials, the second block 24 trials, and the third block 120 trials. In the first block, colored quadrants were presented in the middle of the screen, and participants had to choose the corresponding color from four alternatives presented below the probe color quadrant. They gave the response by pressing directly on the touchscreen on the color quadrant. In the second, purely congruent block, fruits were presented in the congruent color (i.e., typical color of the fruit). Participants had to choose the corresponding color from four alternatives presented below the probe color fruit. The third block was the critical mixed block, in which fruits were either presented in the congruent color or in one of the three incongruent colors (i.e., not a typical color of the fruit). Participants had to press on the color that is typical for the probe fruit (i.e., yellow for banana). On 96 trials, the color was congruent, and on 24 trials, the color was incongruent. The incongruent trials were determined randomly with replacement and were evenly interspersed among the 96 congruent trials, occurring on every fifth trial. Each trial started with a fixation cross for 250 ms (= response-stimulus interval) in the middle of the screen, followed by the probe stimulus (i.e., colored quadrant in the first block or fruit in the second and third blocks) which stayed on screen until response. To ensure that the task was clear to the participants, four practice trials were included before the critical third block. In the case of more than two errors, the examiner explained the task again, and another four practice trials were presented. After a successful practice run, the mixed block started. The mixed block was preceded by four congruent warm-up trials not included in the analysis.

Simon task

The Simon task consisted of two blocks with a fixed block order, which was not repeated. The first block comprised 24 trials, and the second block 120 trials. Participants responded by pressing on the left or right mouse button of the laptop keyboard. For yellow starfish, participants had to press the left mouse button with the left index finger. For blue starfish, participants had to press the right mouse button with the right index finger. In the first, purely congruent block, 12 yellow and 12 blue starfish appeared in random order always on the congruent response side. The second block was the critical mixed block, in which the starfish were either presented on the congruent or incongruent side. The 24 incongruent trials were determined randomly with replacement and were evenly interspersed among the 96 congruent trials, occurring on every fifth trial. Each trial consisted of a fixation cross for 250 ms (= response-stimulus interval) in the middle of the screen, followed by a yellow or blue starfish, which appeared either on the left or right side and stayed on screen until response. To ensure that the task was clear to the participants, the examiner showed two congruent example trials before the congruent practice block and two incongruent example trials before the mixed practice block. The practice blocks consisted of four practice trials. In the case of more than two errors in the practice block, the examiner explained the task again, and another four practice trials were presented. After a successful practice run, the respective block started. The mixed block was preceded by four congruent warm-up trials not included in the analysis.

Results

Stroop task

Figure 2 depicts the distribution of error rates, and Figure 3 depicts mean response times for congruent and incongruent trials. To test the expected **congruency effect** of lower accuracy rates and higher response times on incongruent compared to congruent trials in all four age groups, we conducted two separate 2x4 mixed ANOVAs with trial type and age group as factors. The ANOVA on **accuracy** revealed a main effect of trial type, *F*(1, 120) = 356.80, $p < .001$, $\eta_p^2 = .75$, but no main effect of age group, *F*(3, 120) = 1.93, $p = .128$, $\eta_p^2 = .05$, and no interaction, *F*(3, 120) = 1.00, $p = .396$, $\eta_p^2 = .02$. The lower accuracy rates on incongruent trials (*M* = 91.6%, *SE* = 0.4%) compared to congruent trials (*M* = 99.6%, *SE* = 0.1%) indicates that the manipulation of inducing errors by incongruent trials was successful. The ANOVA on **response times** revealed a main effect of trial type, *F*(1, 120) = 1017.98, $p < .001$, $\eta_p^2 = .89$, and a main effect of age group, *F*(3, 120) = 66.86, $p < .001$, $\eta_p^2 = .63$. The interaction was significant, *F*(3, 120) = 22.33, $p < .001$, $\eta_p^2 = .36$, indicating a decrease in the congruency effect with age (cf. Fig. 3).

Table 2 shows response times on correct and incorrect incongruent trials (T+0). More relevantly, Table 2 also shows the post-correct and post-error response times on the subsequent trials (T+1, T+2, T+3, and T+4). On T+1, participants of all age groups responded slower on post-error trials than post-correct trials (*p*s < .001). On T+2, however, slowing was significant in children (*p*s < .05) but not in adults ($p = .223$). On T+3, slowing was again significant in all age groups (*p*s < .05). On T+4, slowing was significant in 8-year-olds and adults (*p*s < .05), but not in 10-year-olds and 12-year-olds (*p*s > .285).

Post-error slowing was calculated by subtracting post-correct response times from post-error response times on T+1, T+2, T+3, and T+4. This difference score was then subjected to a 4x4 mixed ANOVA with the factors age group and trial. The main effect of age group was significant, *F*(3, 120) = 8.80, $p < .001$, $\eta_p^2 = .18$, as well as the main effect of trial, *F*(2.53, 303.40) = 52.58, $p < .001$, $\eta_p^2 = .30$. The interaction was also significant, *F*(7.59, 303.40) = 2.89, $p = .005$, $\eta_p^2 = .07$. To resolve the interaction, we compared the age groups on each trial. Separate one-way ANOVAs revealed a significant main effect of age group on the first post-error trial, *F*(3, 120) = 7.37, $p < .001$, $\eta_p^2 = .16$, as well as on the second post-error trial, *F*(3, 120) = 2.87, $p = .039$, $\eta_p^2 = .07$, but not on the third and fourth trials, *F*(3, 120) = 1.84, $p = .144$, $\eta_p^2 = .04$, and *F*(3, 120) = 2.35, $p = .075$, $\eta_p^2 = .06$, respectively. Comparing the age groups on the first and second post-error trials revealed an age-related decrease in post-error slowing. Figure 4 depicts the trajectories of post-error slowing.

Simon task

Figure 5 depicts the distribution of error rates, and Figure 6 depicts mean response times for congruent and incongruent trials. To test the expected **congruency effect**, we conducted two separate 2x4 mixed ANOVAs with the factors trial type and age group. The ANOVA on **accuracy** revealed a main effect of trial type, *F*(1, 147) = 278.39, *p* < .001, η_p^2 = .65, but no main effect of age group, *F*(3, 147) = 1.96, *p* = .122, η_p^2 = .04, η_p^2 = .05, and no interaction, *F*(3, 147) = 0.58, *p* = .630, η_p^2 = .01. This is consistent with the results of the Stroop task. The lower accuracy rates on incongruent trials (*M* = 85.1 %, *SE* = 0.8%) compared to congruent trials (*M* = 98.0%, *SE* = 0.2%) indicates that the manipulation of inducing errors by incongruent trials was successful. The ANOVA on **response times** revealed again a main effect of trial type, *F*(1, 147) = 604.96, *p* < .001, η_p^2 = .80, and a main effect of age group, *F*(3, 147) = 121.04, *p* < .001, η_p^2 = .71. Also consistent with the results of the Stroop task, the interaction was significant, *F*(3, 147) = 17.14, *p* < .001, η_p^2 = .26, indicating a decreasing congruency effect with age (cf. Fig. 6).

Table 2 shows response times on correct and incorrect incongruent trials (T+0). More relevantly, Table 2 also shows the post-correct and post-error response times on the subsequent trials (T+1, T+2, T+3, and T+4). On T+1, participants of all age groups responded slower on post-error trials than post-correct trials (*p*s < .001). On T+2, however, slowing was significant only in 8-year-olds and adults (*p*s < .05), but not in 10-year-olds and 12-year-olds (*p*s > .09). On T+3, slowing was again significant in all age groups (*p*s < .05). On T+4, slowing was significant in all older age groups (*p*s < .05) but not in 8-year-olds (*p* = .096).

Post-error slowing was calculated by subtracting post-correct response times from post-error response times on T+1, T+2, T+3, and T+4. This difference score was subjected to a 4x4 mixed ANOVA with the factors age group and trial. The main effect of age group was significant, *F*(3, 147) = 4.80, *p* =

.003, η_p^2 = .09, as well as the main effect of trial, $F(1.58, 231.86) = 64.03$, $p < .001$, η_p^2 = .30. The interaction was also significant, $F(4.73, 231.86) = 3.88$, $p = .003$, η_p^2 = .07. To resolve the interaction, we compared the age groups on each trial. Separate one-way ANOVAs revealed a significant main effect of age group on the first post-error trial, $F(3, 147) = 5.18$, $p = .002$, η_p^2 = .10, but not on the following trials, $F(3, 147) = 2.37$, $p = .073$, η_p^2 = .05, $F(3, 147) = 1.44$, $p = .233$, η_p^2 = .03, and $F(3, 147) = 1.24$, $p = .297$, η_p^2 = .02, respectively. Comparing the age groups on the first post-error trial revealed an age-related decrease in post-error slowing. Figure 7 depicts the trajectories of post-error slowing.

Discussion

Participants of four age groups (8-, 10-, 12-year-old children, and young adults) performed the Stroop and Simon tasks with the instruction to respond as fast and accurately as possible. In both tasks, incongruent trials elicited a cognitive conflict resulting in a congruency effect of more errors and higher response times on incongruent trials. The interaction between congruency and age group on response times indicated a relatively gradual decrease in the congruency effect across age groups. This is in line with our hypothesis of an age-related decrease in the congruency effect.

Post-error slowing was measured as the difference in response times on four trials following an error versus a correct response. As predicted, reliable slowing was found in both tasks. The extent of slowing on the first post-error trial ranged between 200 and 700 ms. As hypothesized, post-error slowing decreased with age. Age-related differences were most pronounced on the first post-error trial, with a relatively continuous decrease from 8 years to young adulthood. In line with our hypothesis of decreasing post-error slowing across trials, the extent of slowing decreased sharply from the first to the second trial, more so for the younger age groups. This was reflected in an interaction between age group and trial, confirming our hypothesis of age-related differences in the time courses of post-error slowing.

While age effects were still evident on the second post-error trial in the Stroop task, this was not the case for the Simon task. Compared to adults, children showed a steeper decrease in slowing from the first to the second trial, abolishing the age effect on the second trial in the Simon task. This finding suggests that age-related differences in the time course of post-error slowing vary across tasks. Before discussing task differences, we first present Study 2, where different participants performed the same Stroop task and a flanker task. Replicating the Stroop task results and extending the results to the flanker task will provide a better basis for discussing task-related differences in developmental and temporal trajectories of post-error slowing.

Study 2

In the second study, we aimed to replicate the Stroop task results and extend the findings to the flanker task. In this task, a target stimulus is flanked by similar stimuli, and cognitive conflict is induced by having the target and flankers pointing to different responses. It could be argued that the flanker task is more a perceptual conflict task than a cognitive conflict task. We were interested in whether the sort of conflict would change the temporal and developmental pattern of post-error slowing.

Participants

For the second study, we recruited new participants. We recruited 55 8-year-olds, 39 10-year-olds, 29 12-year-olds, and 32 young adults. Due to technical problems, we did not obtain Stroop task data from three 8-year-olds, one 10-year-old, and two adults. After data screening, we applied the following task-wise exclusion criteria. We excluded participants who did not commit any error on the critical incongruent trials intended to elicit errors (Stroop task: eleven 8-year-olds, eleven 10-year-olds, eight 12-year-olds, and nine adults; flanker task: eight 8-year-olds, ten 10-year-olds, eight 12-year-olds, and three adults). We also excluded participants with an accuracy rate under 50% (Stroop task: no one; flanker task: one 8-year-old and one adult). This is important because low accuracy rates indicate that they probably did not understand the task, and then they would not be aware of their errors. As error rates influence post-error slowing (Steinborn et al., 2012), we further excluded participants with error rates higher than two times the standard deviation (Stroop task: six 8-year-olds, and two 10-year-olds; flanker task: five 8-year-olds, and one 10-year-old). This resulted in a more homogenous sample and allowed comparisons across participants, tasks, and groups. Finally, because we included only correct trials in the analysis of post-error response times, participants who committed errors on post-error trials (i.e., double errors) were also excluded as they did not provide values in those critical cells (Stroop task: three 12-year-olds; flanker task: one 10-year-old and two 12-year-olds). Table 3 presents the demographic characteristics of the final sample.

Material

The Stroop task was the same as in Study 1. The flanker task was adapted from previous studies (references withheld). The stimuli were red fish on blue background facing the left or right side presented on a tablet screen. Example stimuli are presented in Figure 1.

Procedure

The procedure was the same for children and adults. Participants were tested individually and completed the Stroop task on a tablet and then the flanker task on the same tablet with external response buttons connected to it. The tablets were placed at approximately arm length distance, and the response was given by pressing on the touch screen of the tablet (Stroop task) or by pressing on either the left or right response button (flanker task). Participants were instructed to respond as accurately and fast as possible.

Stroop task

Please see Study 1 for a detailed description of this task.

Flanker task

The flanker task consisted of two blocks with a fixed block order, which was not repeated. The first block comprised 24 trials, and the second block 120 trials. Seven fish were presented horizontally.

Beneath the central fish, at the bottom of the screen, was a shell (see Fig. 1). In the first block, participants responded to the side the fish were facing by pressing the left or right response button. For left-facing fish, participants had to press the left button with the left hand. For the right-facing fish, participants had to press the right button with the right hand. In this purely congruent block, all seven fish were facing the same side. The fish faced 12 times left and 12 times right in random order. The second block was the critical mixed block, in which the central fish (target) sometimes did not face the same side as the other six fish (flankers). These trials were considered incongruent trials. The 24 incongruent trials were determined randomly with replacement and were evenly interspersed among the 96 congruent trials, occurring on every fifth trial. Each trial started with a fixation cross for 250 ms (= response-stimulus interval) in the middle of the screen, followed by six flankers and the target with a delay of 80 ms. The full array (target and flanker fish) stayed on screen until response. To ensure that the task was clear to participants, the examiner showed two congruent example trials before the congruent practice block. The congruent and mixed practice blocks consisted of four practice trials. In the case of more than two errors, the examiner explained the task again, and another four practice trials were presented. After successful practice, the respective block started. The mixed block was preceded by four congruent warm-up trials not included in the analysis.

Results

Stroop task

Figure 8 depicts the distribution of error rates, and Figure 9 depicts mean response times for congruent and incongruent trials. To test the expected **congruency effect** of lower accuracy rates and higher response times on incongruent compared to congruent trials in all four age groups, we conducted two separate 2x4 mixed ANOVAs with trial type and age group as factors. The ANOVA on **accuracy** revealed a main effect of trial type, $F(1, 95) = 239.09$, $p < .001$, $\eta_p^2 = .72$. In contrast to Study 1, the main effect of age group was significant, $F(3, 95) = 3.65$, $p = .015$, $\eta_p^2 = .10$, as well as the interaction, $F(3, 95) =$

2.87, *p* = .040, η_p^2 = .08. The lower accuracy rates on incongruent trials (*M* = 89.9%, *SE* = 0.6%) compared to congruent trials (*M* = 99.6%, *SE* = 0.1%) indicates that the manipulation of inducing errors by incongruent trials was successful. Separate t-tests indicated that this was true for each age group (all *p*'s < .001). However, the accuracy difference between congruent and incongruent trials (i.e., congruency effect) decreased with age. The accuracy differences between congruent and incongruent trials in percent points were: 11.8 in 8-year-olds, 9.4 in 10-year-olds, 8.2 in 12-year-olds, and 7.6 in adults. The ANOVA on **response times** revealed again a main effect of trial type, *F*(1, 95) = 785.93, *p* < .001, η_p^2 = .89, as well as a main effect of age group, *F*(3, 95) = 55.50, *p* < .001, η_p^2 = .64. In line with Study 1, the interaction was significant, *F*(3, 95) = 28.14, *p* < .001, η_p^2 = .47, indicating a decrease in the congruency effect with age (cf. Fig. 9).

Table 4 shows response times on correct and incorrect incongruent trials (T+0). More relevantly, Table 4 also shows the post-correct and post-error response times on the subsequent trials (T+1, T+2, T+3, and T+4). On T+1, participants of all age groups responded slower on post-error trials than post-correct trials (*p*s < .001). On T+2, slowing was again significant in all age groups (*p*s < .05). On T+3, slowing was significant in the two youngest age groups and in adults (*p*s < .05), but not in 12-year-olds (*p* = .110). On T+4, slowing was significant in 8-year-olds and adults (*p*s < .05), but not in 10-year-olds and 12-year-olds (*p*s > .125).

Post-error slowing was calculated by subtracting post-correct response times from post-error response times on T+1, T+2, T+3, and T+4. This difference score was subjected to a 4x4 mixed ANOVA with the factors age group and trial. The main effect of age group was significant, *F*(3, 95) = 7.05, *p* < .001, η_p^2 = .18, as well as the main effect of trial, *F*(2.38, 225.87) = 36.54, *p* < .001, η_p^2 = .28. In line with Study 1, the interaction was also significant, *F*(7.13, 225.87) = 4.24, *p* < .001, η_p^2 = .12. To resolve the interaction, we compared the age groups on each trial. Separate one-way ANOVAs revealed a significant main effect of age group on the first post-error trial, *F*(3, 95) = 9.56, *p* < .001, η_p^2 = .23, but not on the second, third and fourth trials, $F(3, 95) = 2.40$, $p = .073$, $\eta_p^2 = .07$, $F(3, 95) = 1.93$, $p = .129$, $\eta_p^2 = .06$, and $F(3, 95) = 0.45$, $p = .717$, $\eta_p^2 = .01$, respectively. Comparing the age groups on the first post-error trial revealed an age-related decrease in post-error slowing. Figure 10 depicts the trajectories of post-error slowing.

Flanker task

Figure 11 depicts the distribution of error rates, and Figure 12 depicts mean response times for congruent and incongruent trials. To test the expected **congruency effect**, we conducted two separate 2x4 mixed ANOVAs with the factors trial type and age group. The ANOVA on **accuracy** revealed a main effect of trial type, $F(1, 111) = 159.34$, $p < .001$, $\eta_p^2 = .59$, but no main effect of age group, $F(3, 111) = 1.87$, $p = .139$, $\eta_p^2 = .05$, $\eta_p^2 = .05$. The interaction was significant, $F(3, 111) = 12.89$, $p < .001$, $\eta_p^2 = .26$. The lower accuracy rates on incongruent trials (*M* = 86.0 %, *SE* = 0.9%) compared to congruent trials (*M* = 96.8%, *SE* = 0.3%) indicates that the manipulation of inducing errors by incongruent trials was successful. The accuracy differences between congruent and incongruent trials in percent points were: 7.0 in 8-year-olds, 7.2 in 10-year-olds, 10.7 in 12-year-olds, and 19.9 in adults. Separate t-tests indicated that this was true for each age group (all *p*'s < .001). In contrast to the results of the Stroop task, the congruency effect on accuracy *increased* with age. This was due to both an age-related decrease in accuracy on congruent trials and a relative increase on incongruent trials. Accuracy rates for congruent trials were as follows: 8-year-olds (*M* = 94.9%, *SE* = 0.5%), 10-year-olds (*M* = 95.3%, *SE* = 0.7%), 12-year-olds (*M* = 98.6%, *SE* = 0.5%), and adults (*M* = 99.6%, *SE* = 0.2%). Accuracy rates for incongruent trials were as follows: 8-year-olds (*M* = 87.9%, *SE* = 1.2%), 10-year-olds (*M* = 88.1%, *SE* = 1.8%), 12-year-olds (*M* = 87.9%, *SE* = 1.4%), and adults (*M* = 79.8%, *SE* = 2.4%). The ANOVA on **response times** revealed a main effect of trial type, $F(1, 111) = 183.21$, $p < .001$, $\eta_p^2 = .62$, and a main effect of age group, $F(3, 111) = 64.73$, $p < .001$, $\eta_p^2 = .64$. Consistent with all our previous results, the interaction was also significant, $F(3, 111) = 3.80$, $p = .012$, $\eta_p^2 = .09$, indicating a decrease in the congruency effect with age (cf. Fig. 12).

Table 4 shows response times on correct and incorrect incongruent trials (T+0). More relevantly, Table 4 also shows the post-correct and post-error response times on the subsequent trials (T+1, T+2, T+3, and T+4). On T+1, participants of all age groups responded slower on post-error trials than post-correct trials (*p*s < .05). On T+2, however, slowing was only significant in 12-year-olds and adults (*p*s < .05), but not in the two younger age groups (*p*s > .275). On T+3, slowing was only significant in adults (*p* = .002), but not in children (*p*s > .128). Similarly, on T+4, slowing was only significant in adults (*p* < .001) but not children (*p*s > .102).

Post-error slowing was calculated by subtracting post-correct response times from post-error response times on T+1, T+2, T+3, and T+4. This difference score was subjected to a 4x4 mixed ANOVA with the factors age group and trial. The main effect of age group was only marginally significant, *F*(3, 111) = 2.56, *p* = .058, η_p^2 = .06. The main effect of trial and the interaction, however, were highly significant, *F*(1.62, 179.62) = 21.44, *p* < .001, η_p^2 = .16, and *F*(4.85, 179.62) = 4.46, *p* < .001, η_p^2 = .11, respectively. To resolve the interaction, we compared the age groups on each trial. Separate one-way ANOVAs revealed a significant main effect of age group on the first post-error trial, *F*(3, 111) = 4.75, *p* = .004, η_p^2 = .11, but not on the following trials, *F*(3, 111) = 0.45, *p* = .715, η_p^2 = .01, *F*(3, 111) = 1.05, *p* = .372, η_p^2 = .03, and *F*(3, 111) = 0.69, *p* = .560, η_p^2 = .02, respectively. Comparing the age groups on the first post-error trial revealed an age-related decrease in post-error slowing. Figure 13 depicts the trajectories of post-error slowing.

Discussion

In line with Study 1, we found a congruency effect of lower accuracy rates and higher response times on incongruent trials in both tasks. Complementing Study 1, the interaction between congruency and age group was not only significant for response times but also for accuracy rates. Critically, the age effect on congruency went in the expected direction for response times and accuracy rates in the Stroop task. However, in the flanker task, the expected age-related decrease emerged for response times, while an unexpected age-related *increase* emerged for accuracy. While accuracy rates on congruent trials slightly increased with age, accuracy rates on incongruent trials decreased dramatically. Adult's accuracy rates were almost ten percent points lower than children's accuracy rates. The distribution of error rates (see Fig. 11) suggests that outliers did not drive this effect. In fact, the error distribution in the flanker task was even more balanced than in the other tasks. Thus, it is safe to conclude that the flanker task was more difficult for adults than for children.

It seems that younger participants were better at focusing on the central fish and ignoring the incongruent flanking fish. This age pattern contrasts with the assumption of better inhibitory control with age (Davidson et al., 2006; Diamond, 2013; Luna & Sweeney, 2004). Speculating that inhibitory control plays a minor role in this task, the transition from analytic to holistic perceptual processing may explain these counterintuitive results. Analytic processing refers to perceiving specific and individual features of a visual array separately. In contrast, holistic processing refers to perceiving the individual features and their spatial relations as an integrated whole. In one study, a perceptual matching task was used to assess the degree to which children and adults perceive faces analytically versus holistically (Joseph et al., 2015). The authors manipulated the similarity of features and spatial relations and assessed participants' response times when discriminating pairs of faces and houses. They found that younger children (6-8 years) showed analytical processing, older children (9-11 years) showed an intermediate pattern, while adults showed holistic processing (Joseph et al., 2015). In the flanker task, holistic processing of the whole array of fish increases the conflict, while analytical processing allows focusing more on the task-relevant, central fish. Different preferences in processing style may thus lead to differences in performance.

Proceeding to the discussion of post-error slowing, the results were in line with Study 1 as reliable post-error slowing emerged in both tasks. The extent and time course of post-error slowing were comparable across tasks. As hypothesized, post-error slowing decreased with age. As in Study 1, age-related differences were most pronounced on the first post-error trial, with a relatively continuous decrease from 8 years to young adulthood in the Stroop task. In contrast, the flanker task yielded a discontinuous pattern of age-related differences of slowing on the first post-error trial. The two younger age groups (8- and 10-year-olds) showed stronger slowing than the two older age groups (12-year-olds and adults).

On subsequent trials, post-error slowing decreased, and so did the age effect in both tasks. This is in line with our hypotheses and the results of the Simon task of Study 1. However, in the Stroop task of Study 1, the age effect was still significant on the second trial and vanished afterward. Although the differing results of the two Stroop tasks may be a sampling effect, it is interesting to note that the age effect on the second trial in the Stroop task of Study 1 was similar to the discontinuous age effect on the first trial in the flanker task of Study 2. The age-related difference was found between the two younger age groups and the two older age groups, suggesting a developmental gap between 10 and 12 years.

General Discussion

We consistently found age effects on the congruency effect and post-error slowing across three prominent cognitive conflict tasks. In all tasks, the congruency effect on response times decreased with age, in line with previous research (Davidson et al., 2006; Erb & Marcovitch, 2019; Ridderinkhof & van der Molen, 1995). All tasks produced robust post-error slowing in all age groups. In line with previous research, slowing on the first post-error trial decreased from childhood to adulthood (Brewer & Smith, 1989; Carrasco, Harbin, et al., 2013; Carrasco, Hong, et al., 2013; Fairweather, 1978; Gupta et al., 2009; Schachar et al., 2004; Smulders et al., 2016). Generally, the younger age groups changed response speed more dramatically, as evidenced by larger slowing on the first post-error trial with a steeper decrease in slowing on the second trial. This pattern suggests more fine-tuned behavioral adjustments with age and reflects improving cognitive control from childhood to adulthood (Brewer & Smith, 1989; Diamond, 2013; Luna et al., 2010).

Post-error slowing was strongest in the Stroop task. Compared to the Simon and flanker tasks, the Stroop task elicited the lowest error rates. As post-error slowing is found to be strongest with low error rates, the differences in error rates between tasks could explain the stronger post-error slowing in the Stroop task (Notebaert et al., 2009; Steinborn et al., 2012). Apart from this difference in the extent of post-error slowing, the three tasks elicited similar time courses of post-error slowing. In line with other's studies, we found a general decrease in post-error slowing across trials (Compton et al., 2017; Dubravac et al., 2020; Jentzsch & Dudschig, 2009; Smulders et al., 2016). This generalized pattern across tasks indicates that the different cognitive conflicts elicited response-speed errors, leading to task unspecific slowing (Damaso et al., 2020; Forster & Cho, 2014). Thus, while the persistence of post-error slowing was similar across tasks, the extent varied due to different error rates, reflecting the impact of cognitive control demand on post-error slowing (Regev & Meiran, 2014).

According to the orienting account of post-error slowing (Notebaert et al., 2009), infrequent events trigger an orienting response whereby attention is directed towards the infrequent event (i.e., error), resulting in performance slowing on the subsequent trial (i.e., post-error slowing). Thus, children's stronger slowing on the first post-error trial likely reflects a stronger orienting response in children as they have more difficulties inhibiting the automatic attention orientation toward the error. This is in accordance with theories of developing inhibitory control (Davidson et al., 2006; Jonkman, 2006; Luna & Sweeney, 2004; Velanova et al., 2008; Williams et al., 1999). On subsequent trials, adults showed relatively persistent slowing possibly reflecting more fundamental cognitive control adjustments (Botvinick et al., 2001). In contrast, children showed only sporadic slowing on later trials, reflecting their difficulties with coordinating different cognitive control strategies, especially when it comes to proactive engagement of cognitive control (Chevalier et al., 2013, 2015). Together, our results suggest that the different processes underlying post-error slowing follow distinct developmental trajectories. The short-lived orienting response immediately after the error is more pronounced in children than in adults, while longer-lasting and more sophisticated cognitive control adjustments take over on subsequent trials (Botvinick et al., 2001; Notebaert et al., 2009; Wessel, 2018).

In conclusion, the present study presents evidence for qualitative developmental changes in post-error slowing across the Stroop, Simon, and flanker tasks. On the first post-error trial slowing decreased with age. This age effect diminished on the following trials suggesting exaggerated behavioral adjustments in children. In contrast to the short-lived post-error slowing in children, adults showed relatively persistent slowing across four post-error trials. Behavioral adjustments after errors become more fine-tuned with age, characterizing qualitative aspects of cognitive control development from 8 years to adulthood. The diminishing age effect across trials and the sensitivity to error rates highlight the importance of methodological considerations when investigating post-error slowing from a developmental perspective.

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Tables

Table 1

Study 1: Demographic characteristics of the sample

Age group	Stroop task					Simon task				
	M_{Age}	SD_{Age}	Age range	Female /Male	n	M_{Age}	SD_{Age}	Age range	Female /Male	n
8-year-olds	8.4	0.4	7.8-8.9	10/22	32	8.4	0.4	7.8-9.0	14/25	39
10-year-olds	10.1	0.4	9.4-10.9	13/20	33	10.1	0.4	9.4-10.9	16/21	37
12-year-olds	12	0.4	11.2-13	16/20	36	12	0.4	11.2-13.0	19/23	42
adults	23	3.6	19.5-34.9	17/6	23	22.9	3.2	19.5-34.9	28/5	33

Table 2

Study 1: Response times

Age group	Trial type	T+0		T+1		T+2		T+3		T+4	
		M	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Stroop task											
8-year-olds	correct	1514	43	1082	38	1010	38	974	33	943	35
	error	1127	56	1759	109	1161	68	1067	65	1054	56
10-year-olds	correct	1276	33	886	24	827	20	804	15	789	18
	error	1032	51	1363	68	1004	64	991	80	808	37
12-year-olds	correct	1093	37	749	21	720	18	704	17	708	19
	error	833	33	1135	49	772	34	749	34	713	25
adults	correct	804	16	586	10	581	9	576	9	570	10
	error	649	32	786	45	594	20	617	17	597	14
Simon task											
8-year-olds	correct	965	29	835	26	748	24	725	20	712	22
	error	629	29	1399	122	896	46	812	38	736	27
10-year-olds	correct	786	15	684	16	614	18	592	16	578	14
	error	513	34	1084	59	677	52	642	31	640	32
12-year-olds	correct	638	14	557	12	532	13	496	11	505	12
	error	435	15	840	40	559	24	524	16	544	19
adults	correct	501	10	425	8	391	9	388	8	376	9
	error	340	11	626	30	440	25	432	17	448	26

Note. Values represent response times in ms on incongruent conflict trials (T+0) and subsequent correct congruent trials (T+1, T+2, T+3, and T+4) as a function of age group and trial type (correctness on T+0).

Table 3

Study 2: Demographic characteristics of the sample

Age group	Stroop task					Flanker task				
	M_{Age}	SD_{Age}	Age range	Female /Male	n	M_{Age}	SD_{Age}	Age range	Female /Male	n
8-year-olds	8.1	0.5	7.0 – 8.9	19/16	35	8.1	0.5	7.0 – 8.8	17/24	41
10-year-olds	10.2	0.3	9.9 – 10.7	14/11	25	10.2	0.3	9.5 – 10.9	13/14	27
12-year-olds	12.3	0.4	11.7 – 13.1	11/7	18	12.3	0.5	11.7 – 13.2	8/11	19
adults	23	3.6	19.8 – 37.3	17/4	21	23.1	3.4	19.8 – 37.3	23/5	28

Table 4

Study 2: Response times

Age group	Trial type	T+0		T+1		T+2		T+3		T+4	
		M	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
						Stroop					
8-year-olds	correct	1587	53	1126	52	965	29	968	28	971	34
	error	1156	63	1821	95	1184	62	1040	42	1091	65
10-year-olds	correct	1376	48	952	37	883	34	872	28	852	31
	error	1152	76	1494	88	1107	60	1015	63	933	74
12-year-olds	correct	1071	32	722	27	702	19	692	16	686	21
	error	851	60	1032	56	933	103	736	34	733	38
adults	correct	807	20	586	10	584	11	566	9	552	7
	error	645	37	741	45	612	17	587	13	612	22
						Flanker task					
8-year-olds	correct	877	32	779	28	666	20	734	24	656	20
	error	592	58	1180	88	684	31	726	31	670	26
10-year-olds	correct	795	44	691	35	616	30	616	27	579	22
	error	544	94	1193	170	607	32	718	98	634	46
12-year-olds	correct	570	9	489	13	454	10	473	11	445	13
	error	346	13	568	24	487	19	477	25	440	16
adults	correct	468	5	361	6	346	6	355	6	339	7
	error	321	6	436	19	372	9	381	9	356	8

Note. Values represent response times in ms on incongruent conflict trials (T+0) and subsequent correct congruent trials (T+1, T+2, T+3, and T+4) as a function of age group and trial type (correctness on T+0).

Figures

Figure 1

Schematic depiction of the three tasks

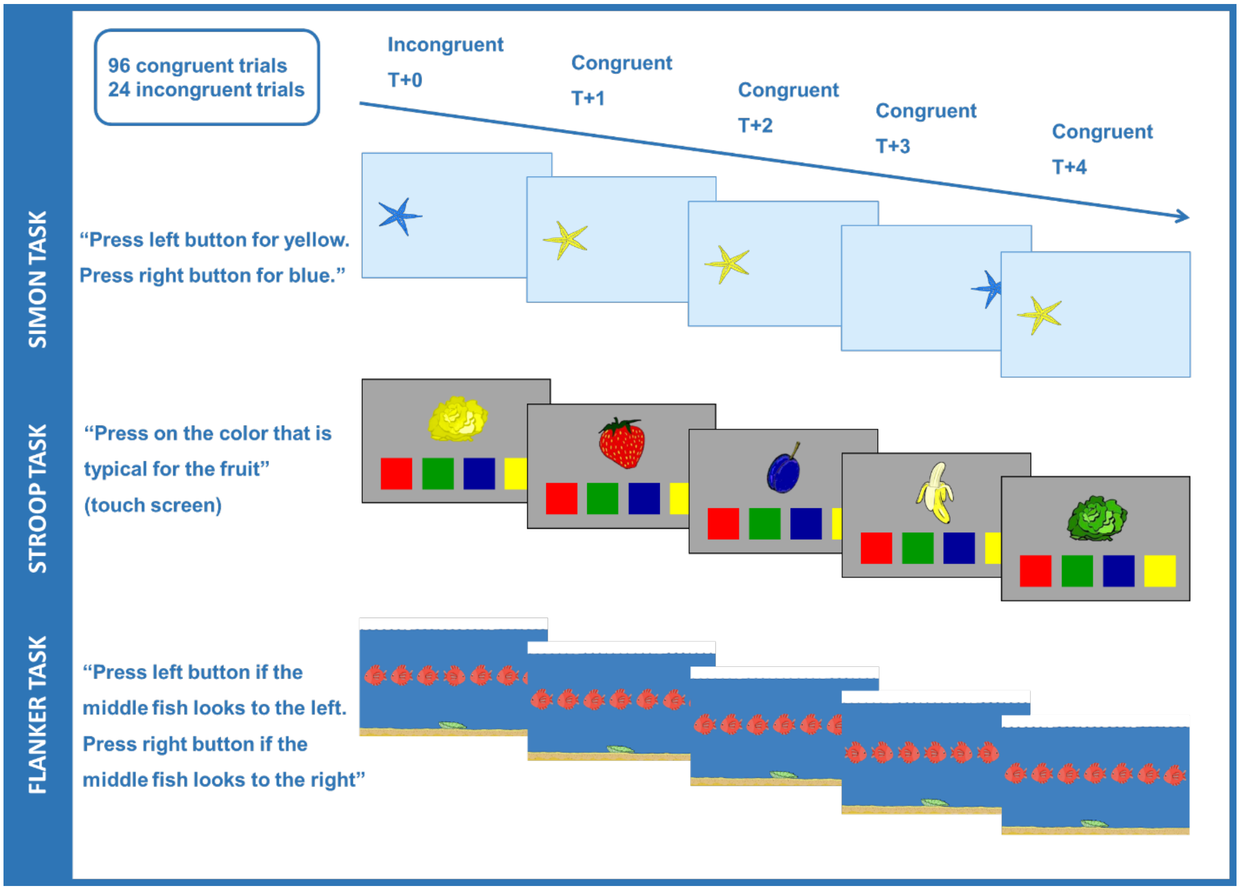


Figure 2

Study 1: Distribution of error rates in the Stroop task

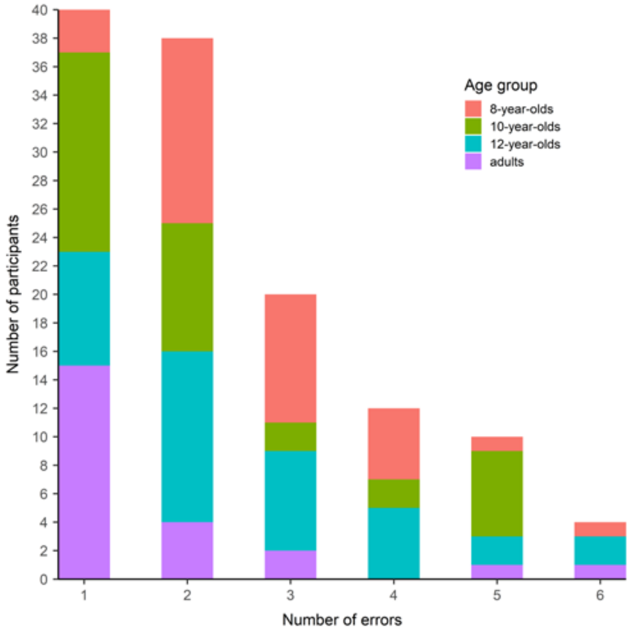
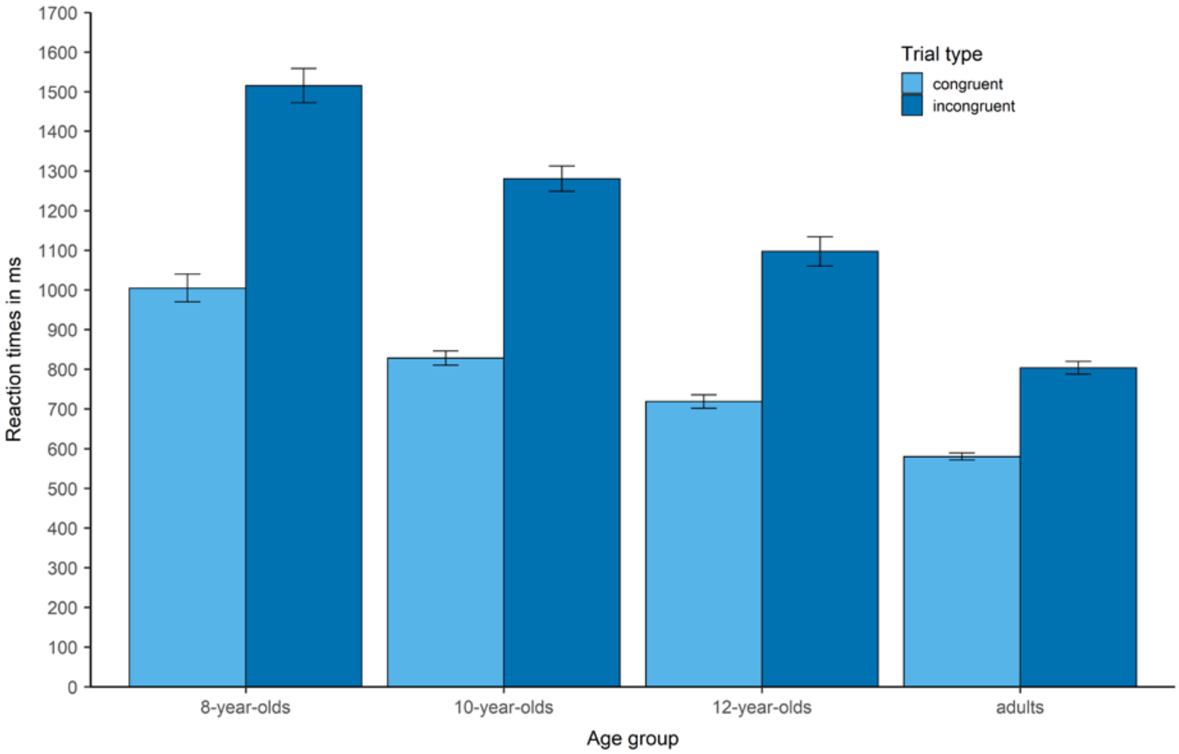


Figure 3

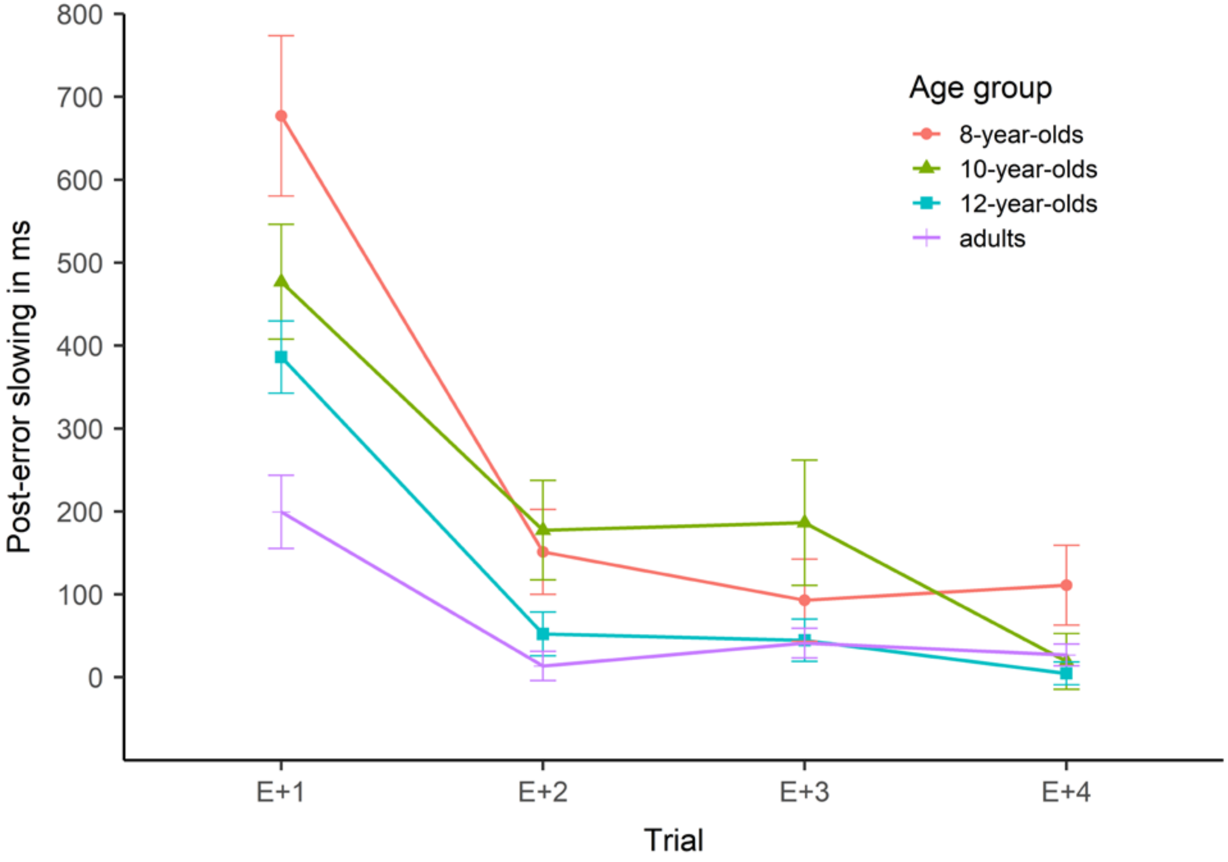
Study 1: Congruency effect in the Stroop task



Note. Depicted are mean response times on correct congruent and correct incongruent trials per age group. Error bars show standard errors.

Figure 4

Study 1: Trajectories of post-error slowing in the Stroop task



Note. Error bars show standard errors

Figure 5

Study 1: Distribution of error rates in the Simon task

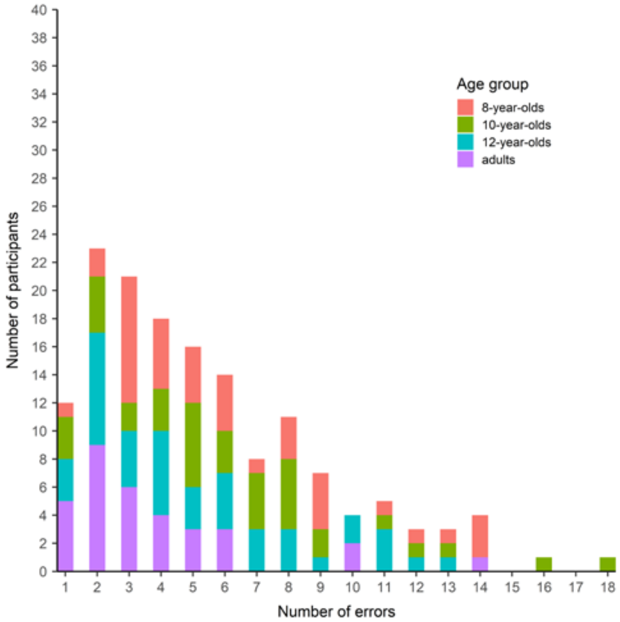
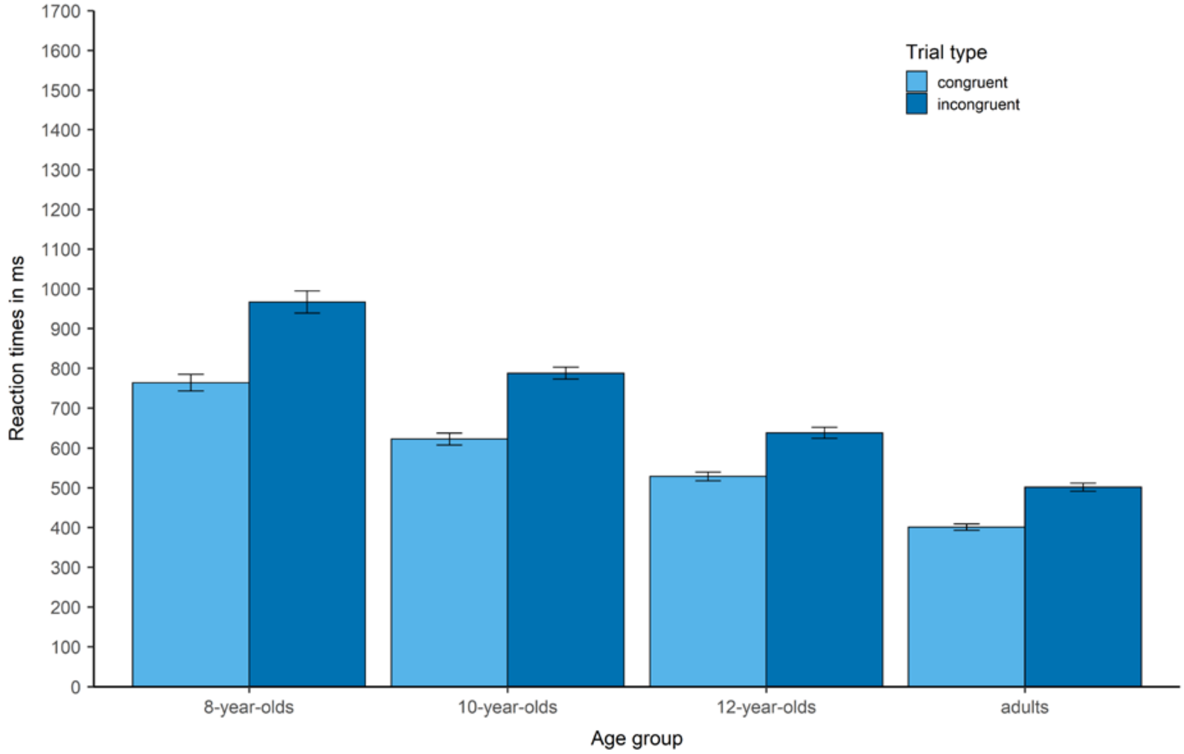


Figure 6

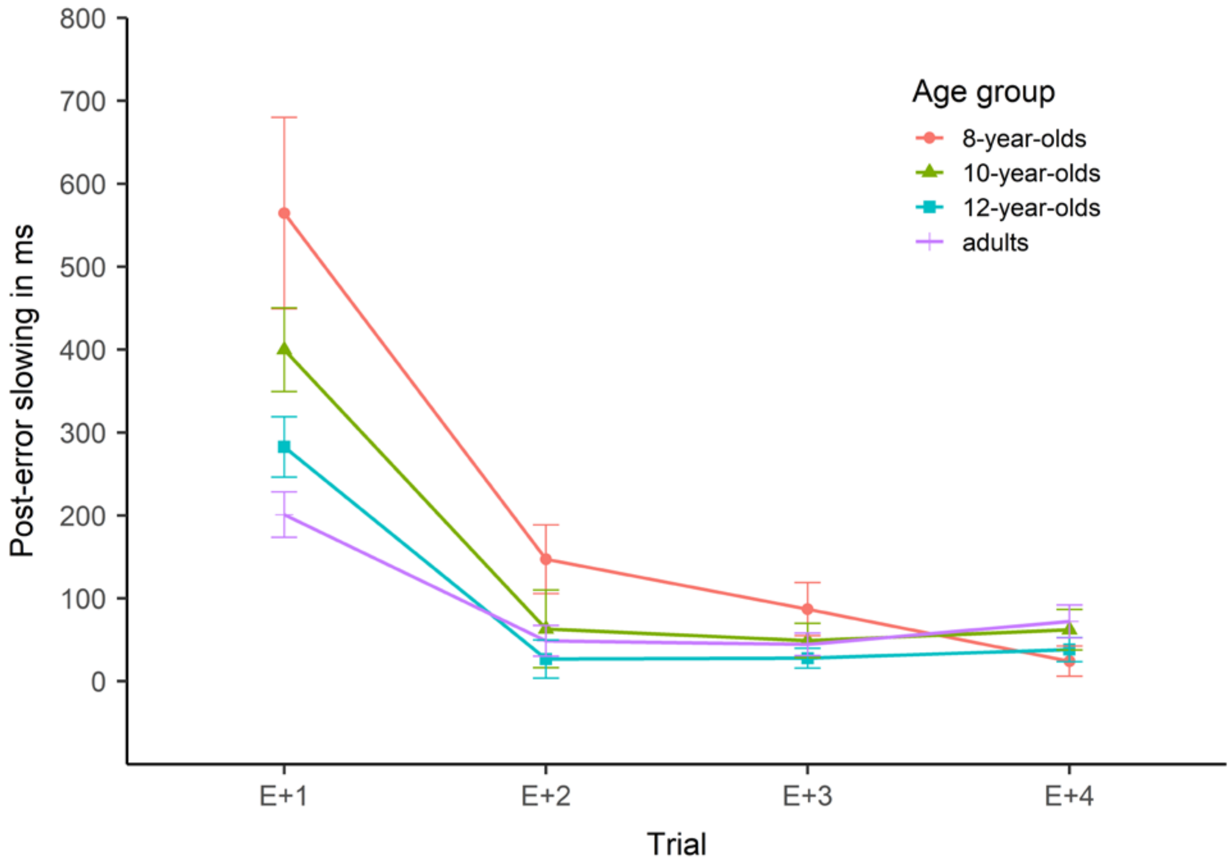
Study 1: Congruency effect in the Simon task



Note. Depicted are mean response times on correct congruent and correct incongruent trials per age group. Error bars show standard errors.

Figure 7

Study 1: Trajectories of post-error slowing in the Simon task



Note. Error bars show standard errors

Figure 8

Study 2: Distribution of error rates in the Stroop task

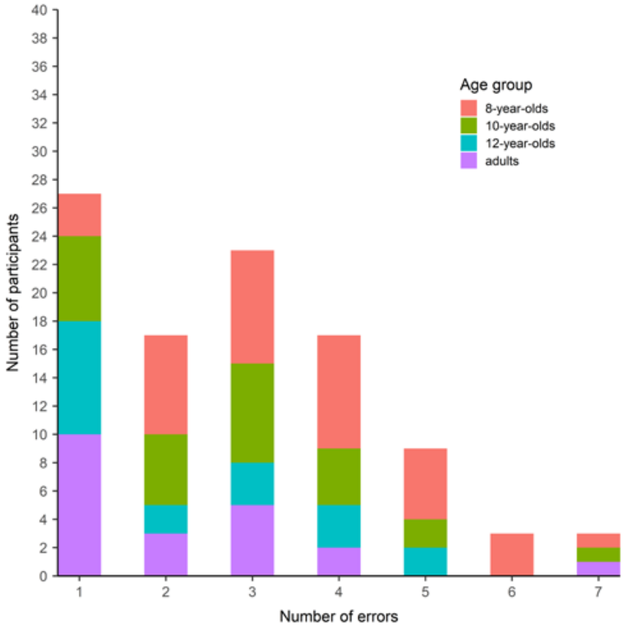
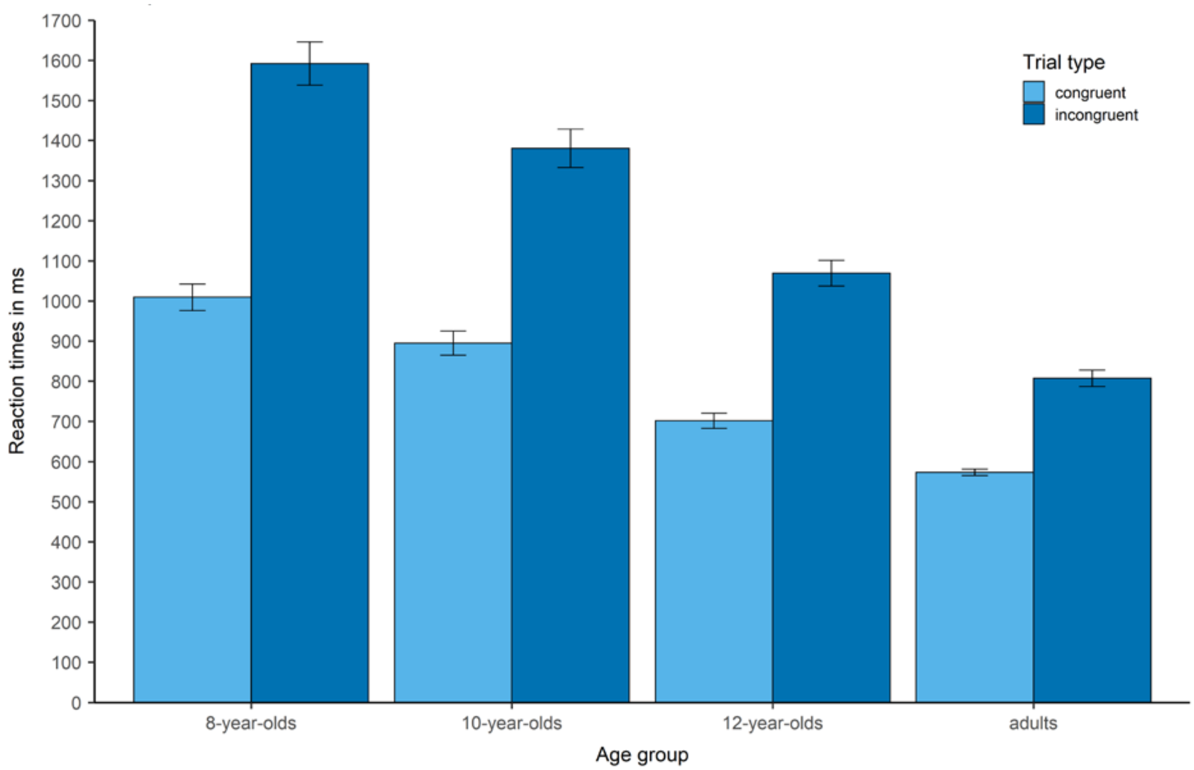


Figure 9

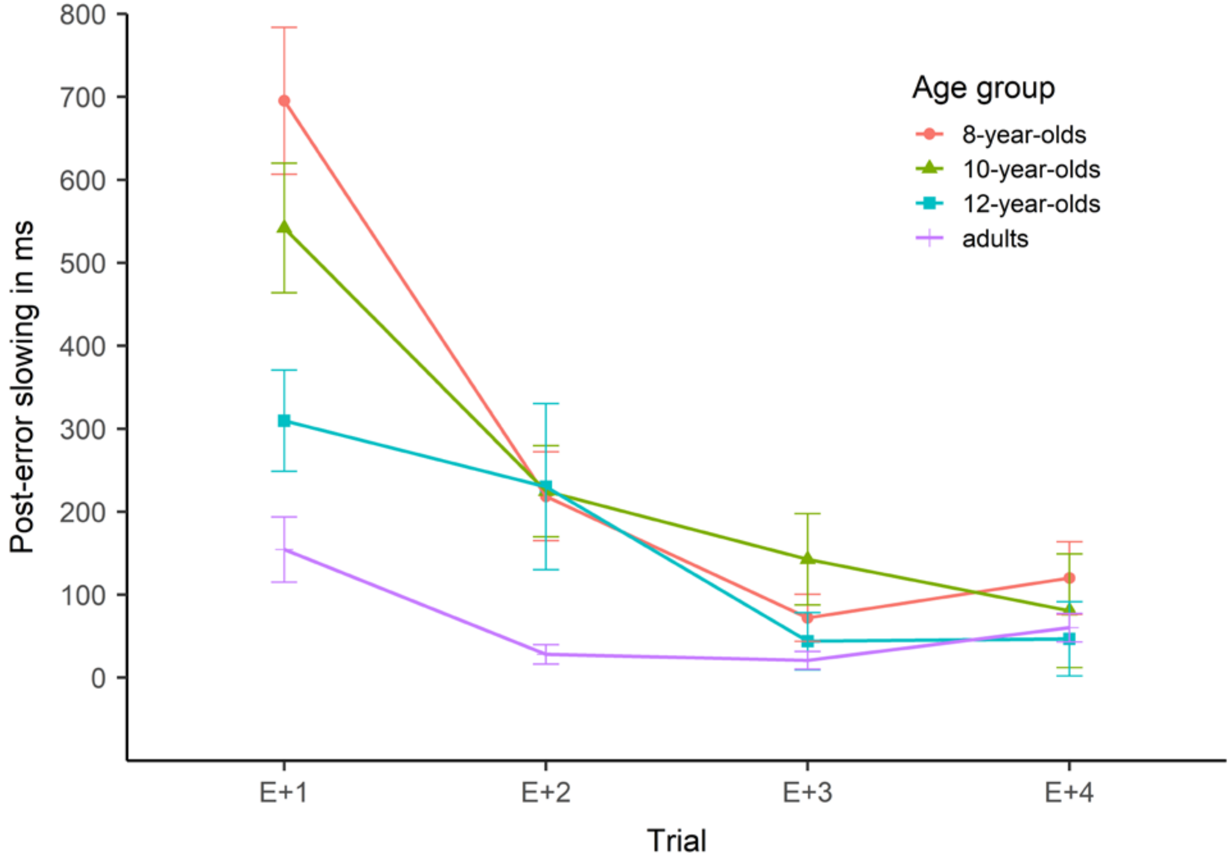
Study 2: Congruency effect in the Stroop task



Note. Depicted are mean response times on correct congruent and correct incongruent trials per age group. Error bars show standard errors.

Figure 10

Study 2: Trajectories of post-error slowing in the Stroop task



Note. Error bars show standard errors

Figure 11

Study 2: Distribution of error rates in the flanker task

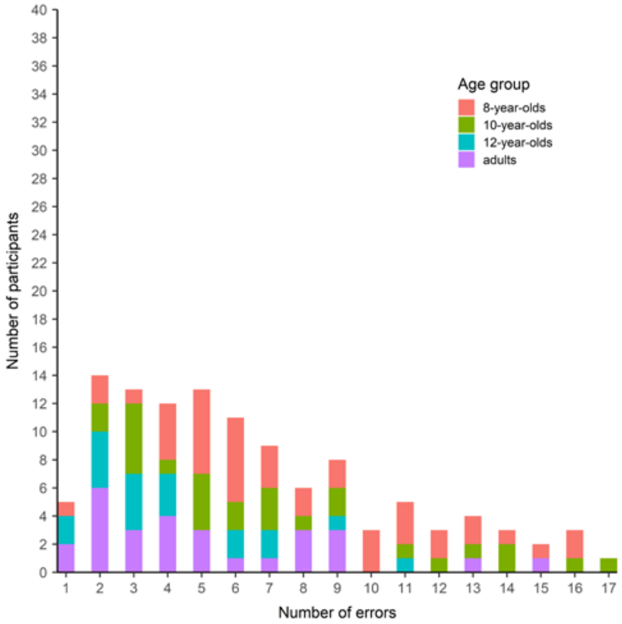
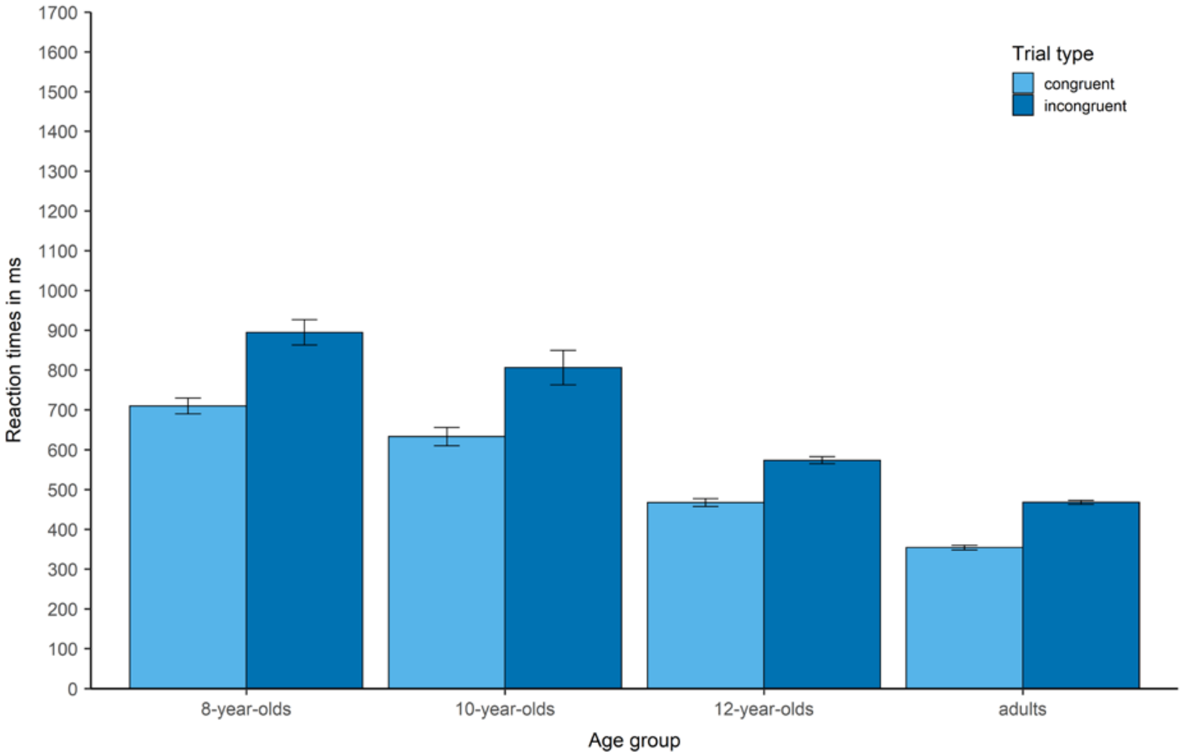


Figure 12

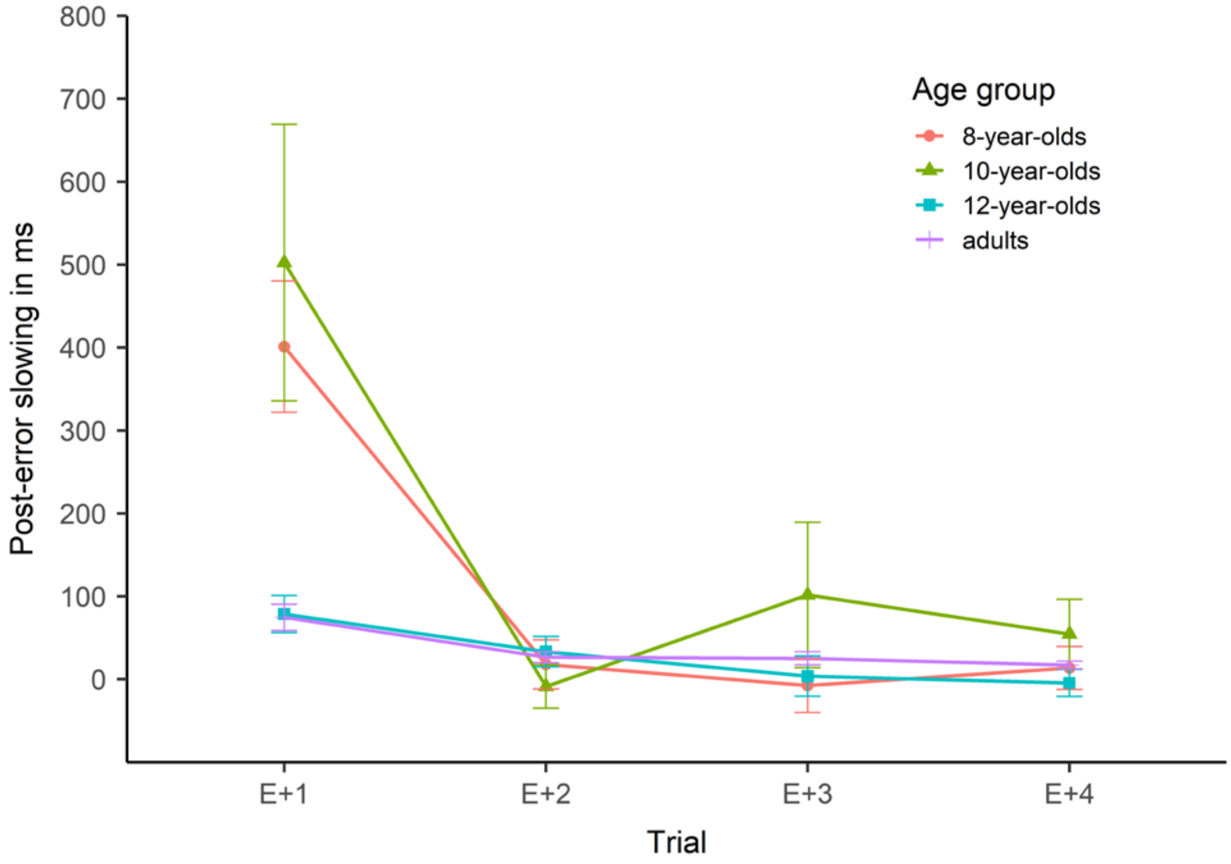
Study 2: Congruency effect in the flanker task



Note. Depicted are mean response times on correct congruent and correct incongruent trials per age group. Error bars show standard errors.

Figure 13

Study 2: Trajectories of post-error slowing in the flanker task



Note. Error bars show standard errors

Cognitive Load at Encoding Hurts Memory Selectivity

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Abstract

People remember more task-relevant information than task-irrelevant information, and this difference can be conceptualized as memory selectivity. Selectively attending and remembering relevant information is a key ability for goal-directed behavior and is thus critical for leading an autonomous life. In the present study, we tested the influence of cognitive load on memory selectivity. Specifically, we investigated the effects of task switching, stimulus presentation duration, and preparation time during incidental learning in five experiments (N = 351). For the study phase, we used two established task switching paradigms (cued and alternating runs). Participants were presented with picture-word pairs on which they performed one of two classification tasks. Depending on the task, participants had to attend to the picture or to the word. In a subsequent surprise recognition test, we assessed how well they remembered the targets and distractors. After one day or one week, a second recognition test assessed the longevity of the effects. Results showed that task switches (vs. task repetitions), short (vs. until response) stimulus duration, and short (vs. long) preparation time reduced memory selectivity. The effect of preparation time was significant only in cued task switching but not in the alternating runs paradigm, highlighting the importance of advance cues for preparation effects on memory. With longer retention intervals, the effects washed out. In conclusion, higher cognitive load leads to lower selective attention and consequently to lower memory selectivity. The present study provides links between theories of attention, cognitive control, and memory.

Keywords: Memory, attention, cognitive control, task switching, cognitive load

Cognitive Load at Encoding Hurts Memory Selectivity

Memory and attention are inextricably linked (Chun & Johnson, 2011; Chun & Turk-Browne, 2007; Logan, 2002). Previous experiences guide attention allocation, and attention, in turn, controls the contents of working memory and long-term memory. While pursuing our goals, we switch between different tasks many times a day and shield the current task-set by directing our attention selectively towards task-relevant information. This results in better memory for relevant over irrelevant information, that is, memory selectivity (Richter & Yeung, 2012, 2015, 2016). Richter and Yeung (2012) discussed their results in the context of the load theory of selective attention (Lavie, 2005) and resource-sharing accounts (Liefooghe et al., 2008). As task switching affected only the identity, not the amount, of information encoded into long-term memory, task switching does not reduce general encoding resources (Richter & Yeung, 2012). Rather, task switching reduces the selectivity of encoding. This suggests that task switching and selective encoding share cognitive control resources. To test this interpretation, we assessed the interactive effects of different cognitive load manipulations.

The **load theory of selective attention** combines early and late selection processes in a hybrid model for attention and distinguishes between perceptual and cognitive load (Lavie, 2000, 2005, 2010). Perceptual processing has capacity limits and operates automatically (Lavie, 1995). When perceptual load is low, task-irrelevant distractors are automatically processed. When perceptual load is high, however, the processing capacity is exhausted by the processing of task-relevant targets, and thus distractors are not processed. Several studies support this theory by showing that various manipulations of perceptual load in a target task affect the processing of distractors (Brand-D’Abrescia & Lavie, 2007; Forster & Lavie, 2008; Lavie, 1995; Lavie et al., 2003; Lavie & Cox, 1997). Further studies showed that perceptual load reduced subsequent distractor memory (Jenkins et al., 2005; Lavie et al., 2009). In other words, perceptual load *enhances* selective encoding.

When perceptual load is low, a second, higher-order control mechanism that actively inhibits attention to irrelevant distractors comes into play (Lavie, 2000). The efficiency of this control mechanism depends on the *cognitive* load associated with the target task (Lavie et al., 2004). When cognitive load is low, there is enough cognitive control capacity to inhibit distractor interference. When cognitive load is high, however, control functions are already absorbed by the target task, and thus there is not enough capacity to inhibit distractor interference. Switching between different tasks and actively maintaining contents in working memory require cognitive control functions (Lavie, 2010). Supporting studies showed that cognitive load increased distractor interference (Lavie et al., 2004; Lavie & De Fockert, 2005). Although not explicitly framed within this theory, later studies found that cognitive load associated with task switching and response inhibition reduced target memory and enhanced distractor memory (Chiu & Egner, 2015a, 2015b, 2016; Muhmenthaler & Meier, 2019a, 2019b; Reynolds et al., 2004; Richter & Yeung, 2012, 2015). In other words, **cognitive load *impairs* selective encoding**.

According to the “time-based resource-sharing model”, cognitive load results from concurrent attention demanding activities competing for limited cognitive control resources (Barrouillet et al., 2004, 2007). For example, task switching loads cognitive control because it involves an attention demanding and time consuming task-set reconfiguration process diverting attentional resources from selective stimulus processing (Liefooghe et al., 2008; Vandierendonck et al., 2010). Accordingly, we operationalized cognitive load as a function of the proportion of time during which concurrent cognitive processing captures attention (cf. Barrouillet et al., 2007). Processes that load cognitive control concurrently should therefore divert attentional resources needed for selective encoding. Specifically, we tested the independent and interactive effects of task switching, stimulus presentation duration, and the time for advance task preparation on subsequent memory selectivity. Presenting task-relevant stimuli only for a short amount of time increases cognitive load because the stimuli need to be actively maintained in working memory. In contrast, preponing task-related processes, however, alleviates cognitive load through the sequencing of cognitive operations. Before introducing our own study, we briefly review similar studies that held the perceptual load low (thus allowing for distractor processing) and varied the cognitive load by using a task switching paradigm to investigate the influence on memory.

As task switching loads cognitive control, selective attention is impaired on switch compared to repeat trials (Lavie, 2010; Liefooghe et al., 2008). The impaired selective attention on switch trials is mirrored in lower memory for to-be-attended target stimuli presented on switch compared to repeat trials (Muhmenthaler & Meier, 2019a; Reynolds et al., 2004). Moreover, task switching has an opposite effect on to-be-ignored distractor stimuli. For example, Richter and Yeung (2012) used a **cued task switching paradigm** with picture-word compounds as stimuli to investigate subsequent memory for the pictures and words. Depending on the cue signaling the task to be performed (picture vs. word classification), participants either attended to the picture or the word. Task switching impaired recognition memory for targets but actually improved memory for distractors. This finding suggests that task switching impairs selective attention at encoding resulting in lower memory selectivity at retrieval. A follow-up study replicated the **switch cost on memory selectivity** and investigated the impact of preparation time, voluntary task switching, and motivation (Richter & Yeung, 2015). Most relevant for the present study, a shorter (vs. longer) cue-to-stimulus interval reduced memory selectivity. This finding suggests that limiting the time for advance task preparation loads cognitive control at the time of stimulus presentation, which impairs selective encoding resulting in lower memory selectivity.

The cost of task switching on memory selectivity is also evident in predictable task switches. Muhmenthaler and Meier (2019a) presented participants pictures of animals and objects on which they had to perform two classification tasks in **alternating runs**. In a subsequent recognition test, participants recognized more pictures from repeat than switch trials, and this effect was larger for bivalent (i.e., relevant for two tasks) than univalent (i.e., relevant for only one task) stimuli (Muhmenthaler & Meier, 2019a). A follow-up study confirmed the finding of switch costs in the alternating runs task switching paradigm with words and a free recall memory test (Muhmenthaler & Meier, 2019b). The findings suggest that task switching impairs encoding of task-relevant information by withdrawing attention from target encoding in order to enable operations on the task level. Due to the lack of an exogenous cue signaling the upcoming task, the alternating runs paradigm requires keeping track of the task sequence, which may pose a further cognitive load.

In contrast to the cued task switching paradigm, the role of task preparation has not been investigated in the alternating runs paradigm, and one goal of the present study was to fill this gap. As an exogenous task cue triggers top-down preparation processes that activate the appropriate task-set in advance, we suggest that a short cue-to-stimulus interval impairs selective encoding because the preparation processes are not yet completed at stimulus presentation (Koch, 2003; Koch & Allport, 2006; Meiran, 1996; Monsell, 2003; Rubin & Koch, 2006). In other words, if preparation time is too short, selective encoding is impaired. In the alternating runs paradigm, however, there is no exogenous cue triggering preparatory processes, questioning an effect of the response-to-stimulus interval on encoding. Furthermore, the studies of Richter and Yeung (2012, 2015) and Muhmenthaler and Meier (2019a, 2019b) differ in respect of stimulus presentation duration, which may also affect selective encoding. A shorter stimulus presentation duration can pose cognitive load because a stimulus representation needs to be actively maintained in working memory, which is not the case if the stimulus is presented until response.

The Present Study

We present five experiments in which we investigated the interactive effects of different cognitive load manipulations on subsequent memory selectivity. Specifically, we manipulated task switching, preparation time, and stimulus presentation duration. We used the same stimulus materials and tasks in both the cued and the alternating runs task switching paradigms in order to compare the effects across paradigms. Further, we were interested in whether the effects would change with longer retention intervals. Therefore, we also included retention intervals of one day and one week. As the stimuli are encoded in the context of increased cognitive load (i.e., on switch trials), it could be that consolidation strengthens the stimulus-context-association. After one day, the effect on memory selectivity may become even stronger. Alternatively, the memory selectivity effect may wash-out after a longer retention interval. In addition, we used the remember/know procedure to assess the contribution of recollection and familiarity to recognition memory performance (Dubravac & Meier, 2021; Gardiner & Java, 1991; Meier et al., 2013; Muhmenthaler & Meier, 2019a; Tulving, 1985; Yonelinas, 2002). Typically, the proportion of remember-responses to know-responses declines with longer retention intervals indicating a weakening of the memory traces over time (Meier et al., 2013; Yonelinas, 2002). Experiment 1 tested whether recollection would contribute to the switch related reduction of target memory (Muhmenthaler & Meier, 2019a). Conversely, we predicted that familiarity would contribute to the switch related increase in distractor memory.

As cognitive load impairs selective attention (Lavie, 2010), we suggest that cognitive load at encoding determines what is later remembered (i.e., memory selectivity). According to the time-based resource-sharing model, cognitive load results from concurrent activities that compete for limited cognitive control resources (Barrouillet et al., 2004, 2007). As processes required for selective encoding and processes required for task switching (e.g., task-set reconfiguration) compete for limited cognitive control resources (Liefooghe et al., 2008; Vandierendonck et al., 2010), we hypothesized that **task switching impairs selective encoding** (Richter & Yeung, 2012, 2015). As task preparation is a time consuming process that also relies on cognitive control resources (Kiesel et al., 2010), we hypothesized that a **short preparation time impairs selective encoding** (Richter & Yeung, 2015). As the stimulus representation needs to be actively maintained in working memory while solving a task (i.e., picture/word categorization), we hypothesized that a **short stimulus presentation duration impairs selective encoding** (Cattapan-Ludewig et al., 2005).

Specifically, we predicted that task switching (vs. task repetition), short (vs. long) preparation time, and short (vs. until response) stimulus presentation duration reduce subsequent memory selectivity. These predictions are derived from the “shared resource hypothesis” whereby cognitive load at encoding diverts cognitive control resources shared by encoding processes (Chiu & Egner, 2015b; Rissman et al., 2009). Increased cognitive load should therefore reduce selective attention and selective encoding. The main question concerns possible interactions between the manipulations of cognitive load. The time-based resource-sharing model would predict interacting effects when the manipulations draw concurrently on the same resources and independent effects when the manipulations draw asynchronously on the same resources. As advance task preparation consumes most resources *before* stimulus presentation, an interaction with task switching or stimulus presentation duration is not expected. However, an interaction between task switching and stimulus presentation duration is expected because these manipulations consume resources concurrently *during* stimulus presentation.

To anticipate the main results, all experiments replicated the basic finding that task switching reduces memory selectivity (Dubravac & Meier, 2021; Richter & Yeung, 2012, 2015). Targets were remembered worse when they appeared on switch compared to repeat trials. Distractors, however, were better remembered when they appeared on switch compared to repeat trials. Experiment 1 further showed that a longer retention interval of one week reduced memory selectivity and that the effect of task switching vanished with time. These findings were consistent across experiments. Experiments 2-5 showed that a short stimulus duration reduced memory selectivity mainly for switch trials. In contrast, preparation time did not interact with task switching but with paradigm. Preparation time affected memory selectivity only in the cued task switching paradigm (Exp. 2 & 3), and not in the alternating runs paradigm (Exp. 4 & 5). An additional “meta”-analysis across Experiments 2-5 confirmed the effect of paradigm. Together, our results suggest that cognitive load at encoding hurts memory selectivity at retrieval.

General Method

Table 1 (left part) gives an overview of the five experiments. The experiments involved two phases; a study phase and a subsequent test phase. The study phase consisted of a task switching procedure using either the cued task switching paradigm (Fig. 1) or the alternating runs paradigm (Fig. 2). The test phase consisted of an immediate and a delayed surprise recognition test.

Participants

In a power analysis, we computed the sample size as a function of effect sizes (η^2_p) reported by Richter and Yeung (2015), a significance level of 0.05, and 0.90 as power level. For the interaction between task switching and attention ($\eta^2_p = 0.788$), we calculated a sample size of seven participants. For the interaction between preparation time and attention ($\eta^2_p = 0.409$), we calculated a sample size of 18 participants. To account for between-subjects variables, we recruited 20 participants per condition. Table 1 (right part) presents the demographic characteristics of the sample of each experiment. Participants were recruited and tested by undergraduate students. All participants gave written consent. The local ethics committee of the University of Bern approved the study.

Stimuli

We adopted the stimuli from Richter and Yeung (2012). The set consisted of 288 words and 288 pictures. The words (originally from Poldrack et al., 1999) were abstract and concrete nouns translated into German and one to four syllables long. The pictures were monochrome photographs of natural and human-made objects on a black background (Hemera Photo Objects, Hull, Quebec, Canada). Words were printed in brown Arial font and superimposed over the pictures. Pictures and words were paired pseudo randomly to ensure an equal number of the four category combinations (abstract noun + human-made object, abstract noun + natural object, concrete noun + human-made object, concrete noun + natural object). The picture-word associations were held constant. The pairs were counterbalanced across participants. The stimuli were presented using E-prime 2.0 software (Psychology Software Tools, Inc., Pittsburgh, PA, USA).

Procedure

Study Phase

Participants were tested individually. They were seated in front of a laptop screen at approximately arm length distance to the keyboard. They were instructed to categorize pictures as human-made or natural objects and words as abstract or concrete nouns as fast and correctly as possible. Participants gave their responses by keypress with their left middle and index fingers for the word task (x-key for abstract and c-key for concrete nouns) and the right middle and index fingers for the picture task (n-key for natural and m-key for human-made objects).

The study phase consisted of 192 experimental trials comprising two thirds of the words and pictures. The other third was reserved for the test phase. Participants practiced the task in 20 trials. The practice block repeated until the participant reached a minimum of 80% correct answers. After ensuring participant’s comprehension of the task, the experimental block started with four warm-up trials that were discarded from analysis. In total, the study phase lasted for approximately 10 minutes. Participants were not informed about the test phase and therefore were not instructed to memorize the items presented during task switching. In the following sections, we describe the trial sequences separately for the cued and alternating runs task switching paradigms.

Cued Task Switching. A colored frame around the picture-word pair cued the task (cf. Richter & Yeung, 2015). A brown frame cued the word task and a grey frame cued the picture task. Cue presentation lasted until participant’s response. With this procedure, task order was not predictable. Depending on the preparation time condition, the **cue-to-stimulus interval (CSI)** was either 150 or 1200 ms. Depending on the **stimulus presentation duration condition**, the stimuli lasted either for 500 ms (Fig. 1 upper panel) or until response (Fig. 1 lower panel). After the response and an inter-trial-interval of 500 ms followed the next cue starting a new trial. The two tasks alternated in a pseudorandom order.

Alternating Runs. The position of the picture-word pair on the screen cued the task (cf. Dubravac & Meier, 2021; Muhmenthaler & Meier, 2019a, Exp. 2; Rogers & Monsell, 1995). If the pair appeared in the upper half of the screen, participants had to solve the picture task, and if it appeared in the lower half, they had to solve the word task. Participants were informed that the stimuli would appear successively in adjacent quadrants, in continuous, clockwise rotation: top left, top right, bottom right, bottom left, top left, and so on. As the tasks alternated every second trial, task order was predictable. The predictable task order was emphasized, and participants were asked to use this information to prepare for the upcoming task. Depending on the preparation time condition, the **response-to-stimulus interval (RSI)** was either 150 or 1200 ms (cf. Rogers & Monsell, 1995; Steenbergen, Sellaro, Hommel, & Colzato, 2015). Depending on the **stimulus presentation duration condition**, the stimuli lasted either for 500 ms (Fig. 2 upper panel) or until response (Fig. 2 lower panel).

Test Phase

Participants were instructed to identify *all* the items of the study phase in a forced-choice recognition test. They were asked to press the b-key for old and the n-key for new items. The stimulus was presented in the middle of the screen until a key was pressed. After every “old” response a remember/know judgment was assessed (cf. Dubravac & Meier, 2021; Meier et al., 2013; Muhmenthaler & Meier, 2019a; Tulving, 1985). Participants had to press “1” if they were sure they remembered the item (recollection) and “2” if they had a feeling of knowing (familiarity). Words and pictures were tested in separate blocks. Two short practice blocks with four trials each, were administered before the experimental blocks. To attenuate the picture-superiority-effect (Standing, 1973), the word block was always administered before the picture block.

All participants completed the first test phase immediately after the study phase. Because at least three minutes elapsed between the end of the study phase and the start of the first experimental block of the test phase (with instructions and practice blocks in between), we were sure not to be measuring short-term memory. We administered two recognition tests. During the first test phase (immediate recognition test), one half of the old items (96 pictures and 96 words) were presented randomly intermixed with 48 new pictures and 48 new words. During the second test phase (delayed recognition test), the other half of the old items were presented randomly intermixed with 48 other new items. The assignment of old and new items to one of the two test phases was counterbalanced across participants. We chose a 2:1 ratio of old and new items in the test phase because only one half of the old items were attended during the encoding phase (targets) and the other half was not attended (distractors). A 1:1 ratio of old and new items could lead to response bias (cf. Richter & Yeung, 2012; 2015). Time of day effects were minimized by testing the participants at roughly the same time across sessions. After completion of the final test phase, participants were debriefed, thanked and dismissed.

Analyses

To assess recognition memory performance, we computed the mean proportion of correctly recognized old items (hits) per participant and separately for target and distractor stimuli. As it was not possible to assign the false alarm rates to the experimental conditions, we used hit rates to assess memory performance (cf. Muhmenthaler & Meier, 2019a). To assess task switching performance, we computed mean accuracy rates and median reaction times of correctly answered switch and repeat trials per participant. The results of the study phase are reported in the supplemental material.

The design varied slightly across experiments. The full design is specified in the "design" section of the respective experiment. In a first step, we performed analyses of variance (ANOVA) on recognition memory performance, remember-responses, and know-responses (results are presented in Tables 2-6). In a second step, we computed the memory selectivity score by subtracting the hit rate of the distractors from the hit rate of the targets. More hits for targets and fewer hits for distractors means that selectively more targets over distractors are remembered. The bigger the difference between targets and distractors, the higher the score, and the higher the score, the higher memory selectivity (cf. Richter & Yeung, 2012). Thus, for example, an interaction between transition (switch vs. repeat trial) and attention (target vs. distractor) on absolute recognition performance would be reflected in a main effect of transition on memory selectivity.

An alpha level of .05 was used for all statistical tests. Effect sizes are expressed as η_p^2. Reported t-tests were two-sided. For better interpretability of the results, we also conducted Bayesian ANOVAs. In a first step, we used Morey and Rouder's "BayesFactor" package for R to compute the Bayes factor (BF) for each effect as evidence against null (R Core Team, 2020; Rouder et al., 2012). In a second step, we used the "bayestestR" package to compute the Bayes factor of inclusion ($\mathrm{BF}_{\mathrm{incl}}$) as evidence for a model including a particular effect (Makowski et al., 2019). For every main effect or interaction, models including the particular effect were compared to equivalent models stripped of the effect. These calculations were performed on UBELIX (http://www.id.unibe.ch/hpc), the HPC cluster at the University of Bern. For Bayesian t-tests, the alternative hypothesis of a true difference between two means is compared against the null hypothesis (no difference). When comparing two means, we thus report Bayes factors (BF_{10}) indicating how much more likely the data are under the alternative hypothesis. A BF_{10} above 1 favors the alternative hypothesis, while a BF_{10} below 1 favors the null hypothesis. The higher the BF_{10}, the more evidence is found for the alternative hypothesis (Wagenmakers et al., 2018).

Experiment 1

The aims of Experiment 1 were to extend the findings of Richter and Yeung (2012, 2015) to a longer retention interval and to assess the contribution of recollection and familiarity to the effects of attention modulation during task switching on subsequent memory (cf. Muhmenthaler & Meier, 2019a). Preparation time (150 ms cue-to-stimulus interval) and stimulus presentation duration (500 ms) were held constant in a cued task switching procedure (Fig. 1). The first recognition test followed immediately after the study phase and the second test followed after one week.

The first goal of Experiment 1 was to replicate the basic finding of lower memory selectivity for switch compared to repeat trials (Richter & Yeung, 2012, 2015). This would be evident in an interaction between attention and transition. The second goal was to examine further the contribution of recollection and familiarity to this effect. Based on a previous study, we expected that the memory benefit for targets from repeat trials would be mainly expressed in remember-responses (Muhmenthaler & Meier, 2019a). Assuming that on switch trials attention is directed towards distractors unintentionally, we predicted that the memory benefit for distractors from switch trials would be mainly expressed in know-responses. As recollection is more prone to long-term forgetting than familiarity, we further hypothesized that the proportion of remember-responses to know-responses would decline with a longer retention interval due to a reduction in remember-responses (Meier et al., 2013; Yonelinas, 2002). The third goal was to investigate the role of retention interval on memory selectivity. A change in memory selectivity would be evident in an interaction between attention and retention interval. As the memory benefit for targets is mainly expressed in remember-responses and remember-responses decline with a longer retention interval (Meier et al., 2013), we should find a decline in memory selectivity with a longer retention interval.

Design and Participants

The design consisted of the within-subject factors *attention* (target vs. distractor), *transition* (switch vs. repeat trial), and *retention interval* (immediate vs. delayed test). After data screening, we excluded data of one participant with an error rate > 30% in the study phase (cf. Muhmenthaler & Meier, 2019a, 2019b). The final sample consisted of 39 participants (see right part of Table 1 for demographic characteristics of the sample).

Results and Discussion

Overall, recognition performance was higher in the immediate test ($M = .521$, $SE = .019$) than in the delayed test ($M = .333$, $SE = .029$), $t(38) = 7.92$, $p < .001$, $\mathrm{BF}_{10} > 100$. The false alarm rate was slightly lower in the immediate test ($M = .194$, $SE = .021$) than in the delayed test ($M = .247$, $SE = .031$), $t(38) = 2.28$, $p = .028$, $\mathrm{BF}_{10} = 1.72$. Table 2 presents the results of three separate 2x2x2 ANOVAs on hit rates for overall recognition, recollection-based recognition (remember-responses), and familiarity-based recognition (know-responses). Figure 3 depicts recognition memory performance and the proportion of remember-responses and know-responses for each condition.

As shown in Table 2, the main effects of attention and retention interval were significant in all three analyses with BFs indicating strong support for these effects. The main effect of transition, however, was only significant for remember-responses with a BF favoring the null hypothesis. The main effect of attention represents the memory benefit for attended, task-relevant targets over unattended, task-irrelevant distractors and replicates previous research (Richter & Yeung, 2012, 2015, 2016). The main effect of retention interval represents forgetting over one week. The stronger effect of retention interval for remember-responses than for know-responses confirms that recollection is more prone to forgetting than familiarity (Gardiner & Java, 1991; Meier et al., 2013; Yonelinas, 2002). The significant interaction between attention and transition is in line with previous studies and represents the effect of task switching on memory selectivity: Switching tasks reduces memory selectivity (Dubravac & Meier, 2021; Richter & Yeung, 2012, 2015). The BFs indicate stronger support for a recollection based effect. The interaction between retention interval and attention was also significant in all three analyses. However, the BFs indicate stronger support for a recollection based effect. The weaker effect for know-responses is probably related to the weaker susceptibility to attention manipulations and forgetting (Yonelinas, 2002). Due to a significant three-way interaction (see Table 2), we conducted follow-up ANOVAs separately for the immediate and delayed tests.

Immediate Test

Participants recognized more targets (M = .694, SE = .021) than distractors (M = .348, SE = .024) and gave more remember-responses to old targets (M = .498, SE = .026) than old distractors (M = .165, SE = .023). This main effect of attention was significant for overall recognition performance, $F(1, 38) = 241.49$, $p < .001$, $\eta_p^2 = .86$, $\text{BF}_{\text{incl}} > 100$, as well as for recollection, $F(1, 38) = 285.78$, $p < .001$, $\eta_p^2 = .88$, $\text{BF}_{\text{incl}} > 100$, but not for familiarity $F(1, 38) = 0.79$, $p = .380$, $\eta_p^2 = .02$, $\text{BF}_{\text{incl}} = 0.32$. The main effect of transition was not significant for recognition performance, $F(1, 38) = 0.54$, $p = .469$, $\eta_p^2 = .01$, $\text{BF}_{\text{incl}} = 0.18$. This was probably because remember-responses and know-responses rendered opposing effects. On the one hand, participants gave less remember-responses to old items from switch trials (*M* = .321, *SE* = .024) than from repeat trials (*M* = .342, *SE* = .022), *F*(1, 38) = 6.30, *p* = .016, η_p^2 = .14, BF_{incl} = 0.49. On the other hand, participants gave more know-responses to old items from switch trials (*M* = .203, *SE* = .013) than from repeat trials (*M* = .176, *SE* = .012), *F*(1, 38) = 11.00, *p* = .002, η_p^2 = .22, BF_{incl} = 1.76. However, the BFs were very low and support an interpretation that there is no difference between switch and repeat trials. Together, this pattern of results suggests that task switching has no overall effect on memory. Thus, task switching does not affect general encoding capacities. Rather, task switching affects the *selectivity* of memories. This is further supported by the highly significant interaction between attention and transition for overall recognition performance, *F*(1, 38) = 29.88, *p* < .001, η_p^2 = .44, BF_{incl} > 100. This interaction was based on recollection because the pattern was mirrored in a highly significant interaction for remember-responses, *F*(1, 38) = 22.24, *p* < .001, η_p^2 = .37, BF_{incl} = 20.95, but not for know-responses, *F*(1, 38) = 3.29, *p* = .077, η_p^2 = .08, BF_{incl} = 0.69. Participants recognized less targets of switch (*M* = .666, *SE* = .022) than repeat trials (*M* = .723, *SE* = .023), *t*(38) = -3.59, *p* < .001, BF_{10} = 32.40, but more distractors of switch (*M* = .382, *SE* = .024) than repeat trials (*M* = .314, *SE* = .024), *t*(38) = 6.07, *p* < .001, BF_{10} > 100. Participants' remember-responses indicated that they remembered less targets from switch (*M* = .465, *SE* = .028) than repeat trials (*M* = .530, *SE* = .026), *t*(38) = -4.55, *p* < .001, BF_{10} > 100, but slightly more distractors from switch (*M* = .177, *SE* = .024) than repeat trials (*M* = .153, *SE* = .024), *t*(38) = 2.23, *p* = .032, BF_{10} = 1.55.

Delayed Test

After one week, the main effect of attention remained significant for overall recognition performance, *F*(1, 38) = 50.33, *p* < .001, η_p^2 = .57, BF_{incl} > 100, remember-responses, *F*(1, 38) = 35.20, *p* < .001, η_p^2 = .48, BF_{incl} > 100, and know-responses, *F*(1, 38) = 22.15, *p* < .001, η_p^2 = .37,

$\mathrm{BF_{incl}} > 100$. This pattern suggests that after one week, participants still recognized more targets (M = .384, SE = .030) than distractors (M = .282, SE = .031) and that this effect was driven by both, recollection and familiarity. Neither the main effect of transition nor the interaction were significant for overall recognition performance, $F(1, 38) = 2.63$, $p = .113$, $\eta_p^2 = .06$, $\mathrm{BF_{incl}} = 0.35$, and $F(1, 38) = 2.16$, $p = .150$, $\eta_p^2 = .05$, $\mathrm{BF_{incl}} = 0.51$, respectively. The same applied to remember-responses, $F(1, 38) = 1.59$, $p = .215$, $\eta_p^2 = .04$, $\mathrm{BF_{incl}} = 0.33$, and $F(1, 38) = 0.80$, $p = .376$, $\eta_p^2 = .02$, $\mathrm{BF_{incl}} = 0.29$, respectively, as well as for know-responses, $F(1, 38) = 1.24$, $p = .273$, $\eta_p^2 = .03$, $\mathrm{BF_{incl}} = 0.21$, and $F(1, 38) = 1.52$, $p = .226$, $\eta_p^2 = .04$, $\mathrm{BF_{incl}} = 0.38$, respectively.

To summarize, Experiment 1 replicated the finding of Richter and Yeung (2012) that task switching reduces memory selectivity (cf. Dubravac & Meier, 2021; Richter & Yeung, 2015). The effect was mainly driven by recollection (cf. Muhmenthaler & Meier, 2019a) and vanished after one week. Our findings are consistent with the idea that the cognitive load associated with task switching reduces memory selectivity. Thus, beyond the well documented task switching costs on immediate performance (as evidenced by longer reaction times and higher error rates on switch compared to repeat trials, see Monsell, 2003), there is also a task switching cost for memory selectivity. This suggests that task-set reconfiguration draws on limited cognitive control resources shared with selective encoding.

In Experiment 1, preparation time and stimulus presentation duration were held constant. In the task switching literature, preparation (operationalized as preparation time or task predictability) is found to reduce switch costs but the effect is not specific to switch trials, as preparation improves performance on both switch and repeat trials (Kiesel et al., 2010). This raises the question whether varying preparation time and the stimulus presentation duration may modulate memory selectivity. Moreover, we were interested whether preparation time and stimulus presentation duration interact with task switching. Based on the time-based resource-sharing model (Barrouillet et al., 2004, 2007) we predicted task switching to interact with stimulus presentation duration but not with preparation time, as preparation takes place *before* stimulus presentation and thus the manipulation of preparation time is asynchronous to the other two manipulations while task-set reconfiguration and working-memory maintenance take place concurrently. This was tested in the following experiments.

Experiment 2

In Experiment 2, we further investigated the impact of cognitive load at encoding on subsequent memory. We extended Experiment 1 by introducing two new manipulations of cognitive load; preparation time and stimulus presentation duration. As in Experiment 1, a cued task switching procedure was used in the study phase (Fig. 1). Preparation time was varied by using a cue-to-stimulus interval (CSI) of 150 or 1200 ms. Stimulus duration was varied by presenting stimuli either for 500 ms or until response of the participants. The first recognition test followed immediately after the study phase and the second test followed after one day. In Experiment 1, the cost of task switching for memory selectivity vanished after one week. It could be that we would still find a switch cost on memory selectivity after a shorter interval. Thus, we shortened the retention interval for the delayed test from one week to one day.

On task switching trials, load is increased compared to task repetition trials because the task-set reconfiguration process is cognitively demanding (Liefooghe et al., 2008). With a shorter CSI advance task preparation is limited and cognitive load is increased at stimulus presentation compared to a longer CSI when task related processes (e.g., task-set reconfiguration) are completed before stimulus presentation (Barrouillet et al., 2004, 2007; Koch, 2003; Liefooghe et al., 2008). As switch trials require a reconfiguration of the task-set and repeat trials do not, the effect of CSI may be more pronounced on switch than repeat trials. This would be evident in an interaction between transition type and CSI. However, a time-based resource-sharing model (Barrouillet et al., 2004, 2007) would predict otherwise. As preparation and task-set reconfiguration act on different time scales the processes do not compete for limited resources and thus no interaction is expected. When the stimuli are presented for a short time, cognitive load is also increased because a representation of the picture and word needs to be kept in working memory while this is not the case when the stimuli are presented until response. Here too, we explored the possibility of an interaction between stimulus duration and transition type expressed as a multiplication of load on switch trials. Here, the time-based resource-sharing model (Barrouillet et al., 2004, 2007) would predict an interaction as task-set reconfiguration and stimulus maintenance take place concurrently and thus compete for limited cognitive control resources. As cognitive load impairs selective attention (Lavie et al., 2004), we hypothesized that cognitive load impairs target encoding and enhances distractor encoding (i.e., impairs selective encoding). Together, task switching (vs. task repetition), short (vs. long) CSI, and short (vs. until response) stimulus duration should reduce memory selectivity.

Design and Participants

The design consisted of the within-subject factors *attention* (target vs. distractor), *transition* (switch vs. repeat trial), and *retention interval* (immediate vs. delayed test), as well as the between-subjects factors *CSI* (150 vs. 1200 ms) and *stimulus duration* (500 ms vs. until response). Participants were randomly assigned to the four between-subjects conditions (1 = 150ms-CSI and 500ms-stimulus-duration, 2 = 150ms-CSI and until-response-stimulus-duration, 3 = 1200ms-CSI and 500ms-stimulus-duration, 4 = 1200ms-CSI and until-response-stimulus-duration). After data screening, we excluded data of two participants (of conditions 2 and 3) with error rates > 30% in the study phase (cf. Muhmenthaler & Meier, 2019a, 2019b). Data of one participant (of condition 1) was excluded from the remember/know analyses because she occasionally pressed key “3” instead of “1” or “2” for the remember/know judgments. The final sample consisted of 78 participants (see right part of Table 1 for demographic characteristics of the sample).

Results and Discussion

Overall recognition performance was higher in the immediate test (*M* = .533, *SE* = .012) than in the delayed test (*M* = .416, *SE* = .014), *t*(77) = 13.14, *p* < .001, BF_{10} > 100. The false alarm rates were lower in the immediate recognition test (*M* = .182, *SE* = .011), compared to the delayed recognition test (*M* = .209, *SE* = .013), *t*(77) = 2.63, *p* = .010, BF_{10} = 3.07. For completeness reasons, results of the remember-know analyses are provided in tables but will not be discussed in detail hereafter. Table 3 presents the results of the 2x2x2x2x2 ANOVAs on hit rates for overall recognition, recollection based recognition (remember-responses), and familiarity based recognition (know-responses). Consistent with Experiment 1, the interaction between attention and transition was significant. The interactions between attention and CSI and between attention and stimulus duration were also significant (at least for overall recognition performance). Because retention interval modulated several effects (see Table 3), we analyzed the immediate and delayed tests separately. To further enhance comprehensibility, we collapsed the interactions with attention by using memory selectivity as the dependent variable. To this end, we computed the memory selectivity score by subtracting the hits of the distractors from the hits of the targets. This allowed us to analyze the effects of transition, CSI, and stimulus duration on memory selectivity in a 2x2x2 mixed ANOVA separately for the immediate and delayed tests. We report and discuss these results in the following sections. Results are depicted in Figure 4.

Immediate Test

Memory selectivity was lower for items from switch (*M* = .370, *SE* = .017) than repeat trials (*M* = .462, *SE* = .015). This effect of transition was highly significant, *F*(1, 74) = 36.42, $p <$ .001, η_p^2 = .33, $\text{BF}_{\text{incl}} > 100$, and is in line with Experiment 1 and previous studies (Richter & Yeung, 2012, 2015). The main effect of CSI was significant, *F*(1, 74) = 9.92, *p* = .002, η_p^2 = .12, BF_{incl} = 16.09. Participants in the 150ms-CSI condition had lower memory selectivity scores (*M* = .374, *SE* = .019) than participants in the 1200ms-CSI condition (*M* = .459, *SE* = .019), suggesting that a shorter CSI impairs selective encoding. This is consistent with the results of Richter and Yeung (2015). The effect of stimulus duration failed to reach significance, *F*(1, 74) = 3.73, *p* = .057, η_p^2 = .05, BF_{incl} = 1.39. Numerically, the effect of stimulus duration goes in the expected direction: Participants in the 500ms-stimulus-duration condition had lower memory selectivity scores (*M* = .389, *SE* = .023) than participants in the until-response-stimulus-duration condition (*M* = .443, *SE* = .016). The interactions were not significant, all *F*'s < 1.75, *p*'s > .190.

Delayed Test

After one day, the main effect of transition was still significant, *F*(1, 74) = 8.91, *p* = .004, η_p^2 = .11, BF_{incl} = 9.57. Memory selectivity was lower for items from switch (*M* = .253, *SE* = .015) than repeat trials (*M* = .296, *SE* = .015). The main effect of CSI was not significant anymore, *F*(1, 74) = 2.27, *p* = .136, η_p^2 = .03, BF_{incl} = 0.70. The main effect of stimulus duration emerged indeed significant in the delayed test, *F*(1, 74) = 4.71, *p* = .033, η_p^2 = .06, BF_{incl} = 1.97. Consistent with the immediate test, participants in the 500ms-stimulus-duration condition had lower memory selectivity scores (*M* = .247, *SE* = .019) than participants in the until-response-stimulus-duration condition (*M* = .302, *SE* = .016). The interactions were not significant, all *F*'s < 1.07, *p*'s > .305.

To summarize, task switching (vs. task repetition), short (vs. long) CSI, and short (vs. until response) stimulus duration at encoding reduced subsequent memory selectivity. Thus, the higher cognitive load in these conditions impairs selective encoding. The effects on memory selectivity are driven mainly by recollection. Testing memory one day after encoding (vs. testing immediately after encoding) reduced memory selectivity, suggesting that with longer retention intervals the attentional priority given to targets at encoding loses its weight. In contrast to Experiment 1, where the switch cost on memory selectivity vanished after one week, the effect was still significant in Experiment 2 with a shorter retention interval of one day. The novel elements of Experiment 2 were the assessments of the effects of CSI and stimulus presentation duration after consolidation. After one day, the effect of CSI vanished but the effect of stimulus presentation duration increased. Experiment 3 tested how the effects of CSI and stimulus presentation duration would be affected by an even longer retention interval of one week.

Experiment 3

One aim of Experiment 3 was to replicate the effects of task switching, preparation time, and stimulus presentation duration on memory selectivity found in the immediate recognition test in Experiment 2. A further aim was to extend the findings of the second recognition test to a longer retention interval and assess the impact of CSI and stimulus presentation duration after one week.

Design and Participants

The design consisted of the within-subject factors *attention* (target vs. distractor), *transition* (switch vs. repeat trial), and *retention interval* (immediate vs. delayed test), as well as the between-subjects factors *CSI* (150 vs. 1200 ms) and *stimulus duration* (500 ms vs. until response). Participants were randomly assigned to the four between-subjects conditions (1 = 150ms-CSI and 500ms-stimulus-duration, 2 = 150ms-CSI and until-response-stimulus duration, 3 = 1200ms-CSI and 500ms-stimulus-duration, 4 = 1200ms-CSI and until-response-stimulus-duration). After data screening, we excluded data of three participants (one of condition 1, two of condition 3) with error rates > 30% in the study phase (cf. Muhmenthaler & Meier, 2019a, 2019b). Data of one participant (in condition 2) was excluded from the remember/know analyses because she occasionally pressed key “3” instead of “1” or “2” for the remember/know judgments. The final sample consisted of 77 participants (see right part of Table 1 for demographic characteristics of the sample).

Results and Discussion

Overall recognition performance was higher in the immediate test (M = .503, SE = .013) than in the delayed test (M = .324, SE = .014), $t(76) = 13.96$, $p < .001$, $BF_{10} > 100$. The false alarm rates were lower in the immediate recognition test (M = .151, SE = .009), compared to the delayed recognition test (M = .216, SE = .012), $t(76) = 6.26$, $p < .001$, $BF_{10} > 100$. Table 4 presents the results of the 2x2x2x2x2 ANOVAs on hit rates for overall recognition, recollection based recognition (remember-responses), and familiarity based recognition (know-responses). As retention interval was again involved in several interactions, we conducted separate 2x2x2 mixed ANOVAs of memory selectivity for the immediate and delayed tests. Results are depicted in Figure 5.

Immediate Test

Memory selectivity was lower for items from switch (M = .379, SE = .016) than repeat trials (M = .472, SE = .017). This main effect of transition was highly significant, $F(1, 73)$ =

40.61, $p < .001$, $\eta_p^2 = .36$, $\mathrm{BF}_{\mathrm{incl}} > 100$, and is in line with Experiments 1 and 2, and previous studies (Richter & Yeung, 2012, 2015). The main effect of CSI was significant, $F(1, 73) = 9.97$, $p = .002$, $\eta_p^2 = .12$, $\mathrm{BF}_{\mathrm{incl}} = 11.98$. Participants in the 150ms-CSI condition had lower memory selectivity scores ($M = .385$, $SE = .020$) than participants in the 1200ms-CSI condition ($M = .467$, $SE = .018$). This is in line with Experiment 2 and suggests that shorter CSI impairs selective encoding (cf. Richter & Yeung, 2015). Consistent with Experiment 2, stimulus duration modulated memory selectivity. While stimulus duration had no significant main effect on memory selectivity, $F(1, 73) = 0.30$, $p = .585$, $\eta_p^2 < .01$, $\mathrm{BF}_{\mathrm{incl}} = 0.30$, the interaction with transition emerged highly significant, $F(1, 73) = 13.15$, $p < .001$, $\eta_p^2 = .15$, $\mathrm{BF}_{\mathrm{incl}} = 56.49$. For repeat trials the difference between the 500ms-stimulus-duration condition ($M = .491$, $SE = .025$) and the until-response-stimulus-duration condition ($M = .454$, $SE = .022$) was not significant, $t(75) = 1.12$, $p = .265$, $\mathrm{BF}_{10} = 0.41$. For switch trials, however, the effect of stimulus duration went in the same direction as in Experiment 2; lower memory selectivity in the 500ms-stimulus-duration condition ($M = .343$, $SE = .021$), compared to the until-response-stimulus-duration condition ($M = .413$, $SE = .022$), $t(75) = -2.28$, $p = .025$, $\mathrm{BF}_{10} = 2.15$. This pattern of results suggests that a short stimulus duration reduces memory selectivity in conditions of heightened cognitive load (i.e., switch trials). The interaction between stimulus duration and CSI missed significance, $F(1, 73) = 3.48$, $p = .066$, $\eta_p^2 = .05$, $\mathrm{BF}_{\mathrm{incl}} = 1.28$. All other interactions were also not significant, all F's < 0.46, p's $> .498$.

Delayed Test

After one week, no effect was significant anymore, all F's < 1.45, p's $> .232$. This suggests that the effects found on immediate recognition wash out with time. Compared to Experiment 2, where we still found a small effect after one day, the effect vanished with a one-week retention interval. To summarize, Experiment 3 replicated the finding that cognitive load at encoding reduces memory selectivity at retrieval. These effects were based mainly on recollection. Task switching and short CSI reliably reduced memory selectivity while short stimulus duration reduced memory selectivity only when the stimuli were presented on switch trials. We conclude that stimulus presentation duration affects selective encoding mostly on switch trials because the task-set reconfiguration process involved in task switching concurrently increases demands for shared cognitive control resources. In Experiments 4 and 5, we extended these findings to the alternating runs task switching paradigm.

Experiment 4

The aim of Experiment 4 was to extend the findings of Experiment 2 to the alternating runs task switching paradigm (Fig. 2). Preparation time was varied by using a response-to-stimulus interval (RSI) of 150 or 1200 ms. Stimulus duration was varied by presenting stimuli either for 500 ms or until response of the participants. The first recognition test followed immediately after the study phase and the second test followed after one day. Based on previous studies with this paradigm (Muhmenthaler & Meier, 2019a, 2019b) and based on the reliable effects in Experiments 1-3 we expected that task switching (vs. task repetition) would reduce memory selectivity. Moreover, we tested whether the task switching paradigm modulates the effects of preparation time and stimulus presentation duration on memory selectivity.

Design and Participants

The design consisted of the within-subject factors *attention* (target vs. distractor), *transition* (switch vs. repeat trial), and *retention interval* (immediate vs. delayed test) and the between-subjects factors *RSI* (150 vs. 1200 ms) and *stimulus duration* (500 ms vs. until response). Participants were randomly assigned to the four between-subjects conditions (1 =

150ms-RSI and 500ms-stimulus-duration, 2 = 150ms-RSI and until-response-stimulus-duration, 3 = 1200ms-RSI and 500ms-stimulus-duration, 4 = 1200ms-RSI and until-response-stimulus-duration). After data screening, we excluded data of two participants (of condition 3) with error rates > 30% in the study phase (cf. Muhmenthaler & Meier, 2019a, 2019b). Data of two male participants (of the conditions 2 and 4) and two female participants (of the conditions 1 and 2) were excluded from the remember/know analyses because they occasionally pressed key "3" instead of "1" or "2" for the remember/know judgments. One participant did not finish the second recognition test due to technical problems close to the end. Thus, recognition data of two stimuli are missing for this participant. The final sample consisted of 78 participants (see right part of Table 1 for demographic characteristics of the sample).

Results and Discussion

Overall recognition performance was higher in the immediate test (M = .544, SE = .013) than in the delayed test (M = .415, SE = .017), $t(77) = 13.83$, $p < .001$, $BF_{10} > 100$. The false alarm rates were lower in the immediate recognition test (M = .193, SE = .013), compared to the delayed recognition test (M = .225, SE = .015), $t(77) = 3.48$ and $p < .001$, $BF_{10} = 28.92$. Table 5 presents the results of the 2x2x2x2x2 ANOVA on hit rates for recognition and separately for remember-responses and know-responses. Consistent with our hypothesis and the results of Experiments 2 and 3, the interaction between attention and transition was significant, suggesting robust task switching costs for memory selectivity. The significant interaction between attention and stimulus duration was also consistent with the cued task switching Experiment 2. However, in contrast to Experiments 2 and 3, the interaction between attention and RSI was not significant.

As in Experiments 2 and 3, we computed the memory selectivity score by subtracting the hits of the distractors from the hits of the targets and analyzed the effects of transition, RSI, and stimulus duration in a 2x2x2 mixed ANOVA separately for the immediate and delayed recognition tests. Results are depicted in Figure 6.

Immediate Test

Memory selectivity was lower for items from switch (*M* = .384, *SE* = .015) than repeat trials (*M* = .459, *SE* = .014). This main effect of transition was highly significant, $F(1, 74) = 24.36$, $p < .001$, $\eta_p^2 = .25$, $\mathrm{BF}_{\mathrm{incl}} > 100$, and is in line with our previous experiments as well as other studies (Richter & Yeung, 2012, 2015). The main effect of RSI was not significant, $F(1, 74) = 0.55$, $p = .462$, $\eta_p^2 < .01$, $\mathrm{BF}_{\mathrm{incl}} = 0.29$, indicating that in contrast to experiments with a cued task switching paradigm (Exp. 2 and 3; Richter & Yeung, 2015, Exp. 1), varying preparation time in the alternating runs paradigm does not modulate memory selectivity. The main effect of stimulus duration was highly significant, $F(1, 74) = 14.10$, $p < .001$, $\eta_p^2 = .16$, $\mathrm{BF}_{\mathrm{incl}} = 63.82$. Consistent with Experiments 2 and 3, memory selectivity was lower in the 500ms-stimulus-duration condition (*M* = .380, *SE* = .016) than in the until-response-stimulus-duration condition (*M* = .461, *SE* = .015), suggesting that shorter stimulus duration impairs selective encoding. The effect of stimulus duration was qualified by an interaction with transition, $F(1, 74) = 4.38$, $p = .040$, $\eta_p^2 = .06$, $\mathrm{BF}_{\mathrm{incl}} = 1.49$. Consistent with Experiment 3, the effect of stimulus duration was only significant for switch, $t(76) = -4.26$, $p < .001$, $\mathrm{BF}_{10} > 100$, but not repeat trials, $t(76) = -1.82$, $p = .073$, $\mathrm{BF}_{10} = 0.97$, suggesting that stimulus duration affects selective encoding mostly on switch trials, when cognitive load is already high. Other interactions were not significant, all *F*’s < 1.73, *p*’s > .192.

Delayed Test

After one day, the main effects of transition, $F(1, 74) = 11.67$, $p = .001$, $\eta_p^2 = .14$, $\mathrm{BF}_{\mathrm{incl}} = 38.77$, and stimulus duration, $F(1, 74) = 4.38$, $p = .040$, $\eta_p^2 = .06$, $\mathrm{BF}_{\mathrm{incl}} = 1.69$, were still significant, consistent with the results in the delayed test of Experiment 2. Memory selectivity was lower for items from switch (*M* = .235, *SE* = .013) than repeat trials (*M* = .288, *SE* = .013). Participants in the 500ms-stimulus-duration condition had lower memory selectivity scores (*M* = .238, *SE* = .012) than participants in the until-response-stimulus-duration condition (*M* = .283, *SE* = .017). No other effects were significant, all *F*'s < 0.76, *p*'s > .386.

To summarize, Experiment 4 confirms and extends the finding that task switching reduces memory selectivity (cf. Exp. 2 and 3; Richter & Yeung, 2012; 2015). Previous studies with the alternating runs paradigm showed a task switching cost for target memory and a task switching benefit for distractor memory (Dubravac & Meier, 2021; Muhmenthaler & Meier, 2019a, 2019b). Thus, even if task switches are predictable they nevertheless impair selective encoding. In line with Experiments 2 and 3, presenting the stimuli for only 500 ms (vs. until response) reduced memory selectivity. Opposed to Experiments 2 and 3, RSI had no effect on memory selectivity. The effects of task switching and stimulus presentation duration on memory selectivity were based mainly on recollection.

Experiment 5

The aims of Experiment 5 were to extend the findings of Experiment 4 to a longer retention interval of one week. Moreover, it allows a comparison to Experiment 3, in which a cued task switching procedure was used. The first recognition test followed immediately after the study phase and the second test followed after one week. This extended retention interval should lead to a stronger decrease in memory selectivity. Based on our findings in Experiment 4, we hypothesized that task switching and short stimulus duration – but not short RSI – would reduce memory selectivity.

Design and Participants

The design consisted of the within-subject factors *attention* (target vs. distractor), *transition* (switch vs. repeat trial), and *retention interval* (immediate vs. delayed test) and the between-subjects factors *RSI* (150 vs. 1200 ms) and *stimulus duration* (500 ms vs. until response). Participants were randomly assigned to the four between-subjects conditions (1 = 150ms-RSI and 500ms-stimulus-duration, 2 = 150ms-RSI and until-response-stimulus-duration, 3 = 1200ms-RSI and 500ms-stimulus-duration, 4 = 1200ms-RSI and until-response-stimulus-duration). After data screening, we excluded data of one participant (of condition 2) with an error rate > 30% in the study phase (cf. Muhmenthaler & Meier, 2019a, 2019b). Data of three female participants (of conditions 1, 2, and 3) and one male participant (of condition 1) were excluded from the remember/know analyses because they occasionally pressed key “3” or “4” instead of “1” or “2” for the remember/know judgments. The final sample consisted of 79 participants (see right part of Table 1 for demographic characteristics of the sample).

Results and Discussion

Overall recognition performance was higher in the immediate test (M = .546, SE = .012) than in the delayed test (M = .375, SE = .013), $t(78) = 14.34$, $p < .001$, $BF_{10} > 100$. The false alarm rates were lower in the immediate recognition test (M = .201, SE = .012), compared to the delayed recognition test (M = .273, SE= .011), $t(78) = 6.42$, $p < .001$, $BF_{10} > 100$. Table 6 presents the results of the 2x2x2x2x2 ANOVA on hit rates for recognition and separately for remember-responses and know-responses. As in Experiments 2, 3 and 4, we computed the memory selectivity score by subtracting the hits of the distractors from the hits of the targets and analyzed the effects of transition, RSI, and stimulus duration in a 2x2x2 mixed ANOVA separately for the immediate and delayed recognition tests. Results are depicted in Figure 7.

Immediate Test

Memory selectivity was lower for items from switch (*M* = .378, *SE* = .014) than repeat trials (*M* = .449, *SE* = .014). This main effect of transition was highly significant, *F*(1, 75) = 22.05, *p* < .001, η_p^2 = .23, $\mathrm{BF}_{\mathrm{incl}}$ > 100, and is in line with all our previous experiments as well as other studies (Richter & Yeung, 2012, 2015). As in Experiment 4, the main effect of RSI was not significant, *F*(1, 75) = 0.56, *p* = .456, η_p^2 = .01, $\mathrm{BF}_{\mathrm{incl}}$ = 0.31. Consistent with Experiments 2-4, participants in the 500ms-stimulus-duration condition had numerically lower memory selectivity scores (*M* = .395, *SE* = .017) than participants in the until-response-stimulus-duration condition (*M* = .432, *SE* = .016), *F*(1, 75) = 2.46, *p* = .121, η_p^2 = .03, $\mathrm{BF}_{\mathrm{incl}}$ = 0.84. The interaction between stimulus duration and transition was not significant, *F*(1, 75) = 1.95, *p* = .166, η_p^2 = .03, $\mathrm{BF}_{\mathrm{incl}}$ = 0.51, however, for the sake of comparability, we nevertheless calculated two-sided independent t-tests. Consistent with Experiments 2-4, the effect of stimulus duration was significant for switch trials, *t*(77) = -2.11, *p* = .038, BF_{10} = 1.57, but not for repeat trials, *t*(77) = -0.59, *p* = .555, BF_{10} = 0.27. Other interactions were not significant, all *F*’s < 0.71, *p*’s > .402.

Delayed Test

After one week, the main effect of transition was not significant anymore, *F*(1, 75) = 1.14, *p* = .290, η_p^2 = .01, $\mathrm{BF}_{\mathrm{incl}}$ = 0.28. However, transition was involved in an interaction with RSI, *F*(1, 75) = 4.27, *p* = .042, η_p^2 = .05, $\mathrm{BF}_{\mathrm{incl}}$ = 1.69. The switch cost on memory selectivity was significant for participants in the 150ms-RSI condition, *t*(38) = -2.28, *p* = .029, BF_{10} = 1.71, but not for participants in the 1200ms-RSI condition, *t*(39) = 0.70, *p* = .490, BF_{10} = 0.21. Other main effects and interactions were not significant, all *F*’s < 2.15, *p*’s > .147.

To summarize, task switching again reduced memory selectivity and this effect was driven mainly by recollection. This is in line with all our previous experiments as well as other studies (Richter & Yeung, 2012, 2015). Consistent with Experiments 2-4, short (vs. until response) stimulus presentation duration also reduced memory selectivity especially on switch trials when cognitive load was high. Consistent with Experiment 4, RSI did not affect memory selectivity. The effect of preparation time was consistently found in cued task switching paradigms (Exp. 2 and 3; Richter & Yeung, 2015) while it was absent in the alternating runs paradigm (Exp. 4 and 5). In order to follow up on this null finding, we conducted a "meta"-analysis across the immediate test results of Experiments 2-5 including the factor paradigm. Collapsing the data of Experiment 2 and Experiment 3 (cued task switching, immediate test condition) and collapsing the data of Experiment 4 and Experiment 5 (alternating runs, immediate test condition) increases power and thus allows for a stronger test of paradigm specific effects of preparation time.

«Meta»-analysis of Experiments 2-5

The cued task switching paradigm and the alternating runs paradigm yielded differing results regarding the influence of preparation time on memory selectivity. To follow up on the effect of paradigm, we reanalyzed memory selectivity across Experiments 2-5. Data of the immediate tests of Experiments 2 and 3 were collapsed to one paradigm condition (cued) and the immediate tests of Experiments 4 and 5 were collapsed to another paradigm condition (alternating). A mixed 2 (*paradigm*: cued vs. alternating) x 2 (*preparation time*: short vs. long) x 2 (*stimulus duration*: 500 ms vs. until response) x 2 (*transition*: switch vs. repeat trial) ANOVA was conducted. As expected, the main effects of transition, $F(1, 304) = 117.84$, $p < .001$, $\eta_p^2 = .28$, $BF_{incl} > 100$, preparation time, $F(1, 304) = 11.80$, $p < .001$, $\eta_p^2 = .04$, $BF_{incl} = 18.81$, and stimulus duration, $F(1, 304) = 14.18$, $p < .001$, $\eta_p^2 = .04$, $BF_{incl} > 100$, were highly significant. The main effect of paradigm was not significant, $F(1, 304) = 0.09$, $p = .760$, $\eta_p^2 < .01$, $BF_{incl} =$

0.15. However, in line with the results of the individual experiments, paradigm interacted significantly with preparation time, $F(1, 304) = 11.16$, $p < .001$, $\eta_p^2 = .04$, $\mathrm{BF}_{\mathrm{incl}} = 27.16$. Also, the previously reported interaction between stimulus duration and transition was confirmed, $F(1, 304) = 8.75$, $p = .003$, $\eta_p^2 = .03$, $\mathrm{BF}_{\mathrm{incl}} = 8.67$. The interaction between preparation time and transition did not reach significance, and the Bayesian ANOVA indicates anecdotal evidence for the null hypothesis, $F(1, 304) = 3.51$, $p = .062$, $\eta_p^2 = .01$, $\mathrm{BF}_{\mathrm{incl}} = 0.63$. The three-way interaction between paradigm, preparation time, and stimulus duration did not reach significance, and the Bayesian ANOVA indicates only anecdotal evidence for this effect, $F(1, 304) = 3.72$, $p = .055$, $\eta_p^2 = .01$, $\mathrm{BF}_{\mathrm{incl}} = 1.53$. All other interactions were far from significance, all F's < 1.60, all p's > .207. To resolve the interaction between paradigm and preparation time, we conducted separate 2x2x2 mixed ANOVAs for the two paradigms.

For cued task switching, the main effects of transition, $F(1, 151) = 72.47$, $p < .001$, $\eta_p^2 = .32$, $\mathrm{BF}_{\mathrm{incl}} > 100$, and preparation time, $F(1, 151) = 20.07$, $p < .001$, $\eta_p^2 = .12$, $\mathrm{BF}_{\mathrm{incl}} > 100$, were significant. The main effect of stimulus duration did not reach significance, $F(1, 151) = 3.20$, $p = .076$, $\eta_p^2 = .02$, $\mathrm{BF}_{\mathrm{incl}} = 0.85$. The interaction between preparation time and stimulus duration did not reach significance $F(1, 151) = 3.32$, $p = .071$, $\eta_p^2 = .02$, $\mathrm{BF}_{\mathrm{incl}} = 0.97$. The interaction between stimulus duration and transition did also not reach significance, $F(1, 151) = 3.02$, $p = .084$, $\eta_p^2 = .02$, $\mathrm{BF}_{\mathrm{incl}} = 0.68$. Other interactions were also not significant, all F's < 1.90, all p's > .171. For alternating runs, the main effects of transition, $F(1, 153) = 46.61$, $p < .001$, $\eta_p^2 = .23$, $\mathrm{BF}_{\mathrm{incl}} > 100$, and stimulus duration, $F(1, 153) = 13.55$, $p < .001$, $\eta_p^2 = .08$, $\mathrm{BF}_{\mathrm{incl}} = 75.82$, were significant. The main effect of preparation time, however, was not significant, $F(1, 153) = 0.01$, $p = .942$, $\eta_p^2 < .01$, $\mathrm{BF}_{\mathrm{incl}} = 0.20$. The interaction between transition and stimulus duration was significant, *F*(1, 153) = 6.00, *p* = .015, η_p^2 = .04, BF_{incl} = 2.89. All other interactions were not significant, all *F*'s < 1.61, all *p*'s > .206.

These results are in line with the separate analyses and confirm our previous finding that memory selectivity is reduced with shorter preparation times in the cued but not in the alternating runs task switching paradigm, suggesting that the effect of preparation time depends on the particular task switching procedure. The differences between the cued task switching and the alternating runs procedures are cue type and task predictability. It remains an avenue for future research to determine whether cue type, task predictability, or both represent the critical differences between paradigms.

General Discussion

The load theory of attention states that cognitive load impairs selective attention (Lavie, 2000, 2005, 2010). In the present study, we tested the hypothesis that impairing selective attention through cognitive load would impair selective encoding and subsequently reduce memory selectivity. In five experiments, we showed participants pictures and words in the context of a task switching procedure and tested their memory in a subsequent recognition test. In the cued task switching paradigm, a colored frame cued the required task. In the alternating runs paradigm, the stimulus position on the screen cued the required task. Conceptualizing cognitive load as a function of time during which concurrent attention demanding activities compete for limited cognitive control resources (Barrouillet et al., 2004, 2007), we manipulated selective attention through task switching, preparation time, and stimulus presentation duration, and investigated the impact on memory.

In each of the five experiments, participants recognized more task-relevant targets than task-irrelevant distractors. In line with previous research, our results showed that targets encountered under high selective encoding conditions were better remembered than targets under low selective encoding conditions, while for distractors it was the other way round (Richter & Yeung, 2012, 2015, 2016). The effects on targets were mostly based on recollection (cf. Muhmenthaler & Meier, 2019a), while the effects on distractors were mostly based on familiarity. With longer retention intervals of one day and one week, not only memory performance diminished but also memory selectivity, that is, the relative advantage of targets over distractors. This effect was accompanied by a relative decline in recollection and a relative increase in familiarity with time (Yonelinas, 2002). Task switching, preparation time, and stimulus presentation duration had opposing effects on targets and distractors suggesting that they rather affected the selectivity of memories than memory in general. Next, we discuss the effects of task switching, preparation time, and stimulus presentation duration on memory selectivity.

Across all experiments, we consistently showed that **task switching** reduces memory selectivity. This switch cost on memory selectivity is in line with previous research using either the cued task switching paradigm or the alternating runs task switching paradigm (Richter & Yeung, 2012, 2015; see also Muhmenthaler & Meier, 2019a, 2019b; Reynolds et al., 2004; Brito et al., 2016; Chiu & Egner, 2016; Dubravac & Meier 2021). As task switching is associated with increased cognitive load (Lavie, 2010), switch trials impair target encoding and enhance distractor encoding.

In Experiments 2-5, we showed that short (vs. until response) **stimulus presentation duration** reduced memory selectivity, especially for switch trials. Participants saw the stimuli either for 500 ms or until response. In the 500 ms condition, participants had to maintain the stimuli in working memory and simultaneously classify the targets according to the task requirements. The higher working memory load in this condition impairs selective attention and facilitates thus distractor intrusions (Cattapan-Ludewig et al., 2005; Lavie, 2010; Lavie et al., 2004). Ultimately, short stimulus presentation duration leads to lower memory selectivity. This effect was especially pronounced for switch trials, suggesting that stimulus presentation duration affects memory selectivity mostly in conditions when cognitive load is already high (Liefooghe et al., 2008). Task switching and short stimulus presentation duration thus seem to draw concurrently on the same limited cognitive control resources (i.e., working memory capacity) shared by encoding processes.

In Experiments 2-5, we further tested the effect of **preparation time** on memory selectivity. Short (vs. long) preparation time led to lower memory selectivity in Experiments 2 and 3 with the cued task switching paradigm but not in Experiments 4 and 5 with the alternating runs paradigm. A “meta”-analysis across Experiments 2-5 confirmed that the specific task switching paradigm mediated the impact of preparation time on memory selectivity. In the alternating runs procedure, the cue (stimulus position on screen) and the stimulus were presented *simultaneously* and the response-to-stimulus interval (RSI) was varied. In the cued task switching procedure, however, the cue (colored frame) was presented *before* stimulus presentation and the cue-to-stimulus interval (CSI) was varied. Our results with the cued task switching procedure are in line with a related study by Richter and Yeung (2015, Exp. 1), who kept RSI constant while varying CSI. We propose that a short CSI impairs selective encoding because the advance cue triggers time consuming preparation processes loading cognitive control at stimulus presentation. In the alternating runs paradigm, however, there is no advance cue triggering preparation processes. Thus, varying RSI rather affects passive task-set decay than active preparation. Advance cuing, thus seems critical for preparation time effects on memory selectivity. Identifying the exact reasons for this difference between paradigms is an avenue for future research.

The importance of cues for an effect of preparation time converges with the finding that the brain activity elicited by a cue just before stimulus onset predicts whether the item will be recollected in a subsequent memory test (Otten et al., 2006, 2010; Padovani et al., 2013). Critically, this subsequent memory effect was found for switch as well as repeat trials (Otten et al., 2010). This is in line with our finding that CSI affected memory selectivity but did not interact with task switching. Instead, preparation time affected cognitive load at stimulus presentation on switch as well as repeat trials. However, stimulus presentation duration interacted with task switching, as the effect on memory selectivity emerged mostly on switch trials, when cognitive load was increased. Moreover, extrinsic motivation, operationalized as monetary incentives, is found to abolish the effect of task switching on memory selectivity (Richter & Yeung, 2015, Exp. 3). However, this interaction was only significant when data of an outlier was removed. More research is needed to elucidate under which conditions task switching interacts with other attention manipulations. The time-based resource-sharing model (Barrouillet et al., 2004, 2007) would predict interactions when cognitive load is increased concurrently but not sequentially.

Assuming that the number of processes per time unit is limited (e.g., updating working memory and keeping track of task order), concurrent processes exceeding this limit accumulate cognitive load and reduce selective encoding at stimulus presentation. This account explains also the finding that voluntary (vs. instructed) task switching reduces memory selectivity (Richter & Yeung, 2015). Richter and Yeung (2015) asked participants to indicate the cued task (instructed task switching condition) or to indicate which task they chose (voluntary task switching condition). In the voluntary task switching condition, participants were instructed to try to choose the task randomly and to try to perform roughly equal numbers of trials of each task as well as of task switches and repetitions (Richter & Yeung, 2015, Exp. 2). Updating the number of trials of each task and keeping track of task order load working memory and cognitive control (Arrington & Logan, 2004, 2005; Demanet et al., 2010). If these processes exceed the RSI, then cognitive load will be increased at stimulus presentation and selective encoding will be impaired resulting in reduced memory selectivity.

The load theory of attention proposes that perceptual load reduces selective attention (Lavie, 2010). Although studies already showed that perceptual load reduced subsequent distractor memory (Jenkins et al., 2005; Lavie et al., 2009), finding a contrary effect on target memory is a further direction for future research. The task switching paradigms are suitable to investigate the effect of perceptual load on memory. Manipulating the salience and timing of target and distractor presentation would further our understanding of the dynamics of bottom-up and top-down cognitive control and its influence on encoding (Theeuwes, 2010; Theeuwes et al., 2000). To determine the most effective conditions for encoding, more research is needed on the effects and interactions of perceptual and cognitive load on memory.

Conclusion

Cognitive load during study affects selective attention and long-term memory. Our findings suggest that the load theory of attention (Lavie, 2010) can be applied to the memory domain and contributes to the comprehension of the interaction between attention and memory (Chun & Johnson, 2011; Chun & Turk-Browne, 2007; Logan, 2002). A higher cognitive load impairs cognitive control capacities needed for directing attention selectively to targets and inhibiting distractor interference. With a lower cognitive load, however, cognitive control supports selective attention and selective encoding of targets, which is reflected in a later memory benefit for targets over distractors. Cognitive load cumulates when cognitive processes concurrently engage working memory resources manifesting in further decrements in memory selectivity. The memory selectivity effect is driven mainly by recollection, suggesting a more elaborate encoding of target events in conditions of increased selective attention. That is, selective attention leads to selective memories.

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Table 1

Overview of the Experiments and Characteristics of the Sample

	Manipulations				Sample		
Exp.	Task Cue	Preparation Time	Stimulus Duration	Retention interval	*N*	Men/ Women	Mean age (*SD*)
1	Advance cue	150 ms CSI	500 ms	immediate/after 1 week	39	20/19	23 (3)
2	Advance cue	150/1200 ms CSI	500 ms/until response	immediate/after 1 day	78	30/48	26 (7)
3	Advance cue	150/1200 ms CSI	500 ms/until response	immediate/after 1 week	77	13/64	21 (3)
4	Stimulus position	150/1200 ms RSI	500 ms/until response	immediate/after 1 day	78	26/52	22 (4)
5	Stimulus position	150/1200 ms RSI	500 ms/until response	immediate/after 1 week	79	30/49	23 (4)

Note. In cued task switching experiments (Exp. 1-3), the task was cued by a colored frame before stimulus onset. In alternating runs task switching experiments (Exp. 4&5), the task was cued by the position of the stimulus on the screen.

CSI = cue-to-stimulus interval

RSI = response-to-stimulus interval

Table 2

Results of Experiment 1

Experiment 1	Recognition				Remember				Know			
Effect	$F(1,38)$	p	η^2_p	BF_{incl}	$F(1,38)$	p	η^2_p	BF_{incl}	$F(1,38)$	p	η^2_p	BF_{incl}
Attention	178.98	<.001	.82	>100	316.23	<.001	.89	>100	11.57	.002	.23	>100
Transition	0.41	.527	.01	0.12	8.87	.005	.19	0.30	3.08	.087	.07	0.20
Retention interval	62.68	<.001	.62	>100	148.68	<.001	.80	>100	6.32	.016	.14	>100
Attention x Transition	**25.25**	**<.001**	**.40**	13.66	**20.47**	**<.001**	**.35**	3.51	**4.40**	**.043**	**.10**	0.54
Attention x Retention interval	**212.50**	**<.001**	**.85**	>100	**212.67**	**<.001**	**.85**	>100	**8.42**	**.006**	**.18**	8.33
Transition x Retention interval	3.97	.054	.09	0.27	1.89	.178	.05	0.19	12.74	.001	.25	0.87
Attention x Transition x Retention interval	**10.61**	**.002**	**.22**	0.88	**15.93**	**<.001**	**.30**	6.00	**0.38**	**.541**	**.01**	0.33

Note. Mean proportion of hits was analyzed by means of a 2 (attention: target vs. distractor) x 2 (transition: switch vs. repeat trial) x 2 (retention interval: immediate vs. delayed test) repeated measures analysis of variance (ANOVA). The immediate test took place immediately after the incidental study phase. The delayed test took place after one week. The same ANOVA was conducted for remember-responses and for know-responses. Effects of interest are printed in bold. η^2_p indicates partial eta-squared. BF_{incl} represents the Bayes factor for a model including the effect in question compared to matched models excluding the effect.

Table 3

Results of Experiment 2

Experiment 2	Recognition				Remember				Know			
Effect	*F*(1,74)	*p*	η^2_p	BF_{incl}	*F*(1,73)	*p*	η^2_p	BF_{incl}	*F*(1,73)	*p*	η^2_p	BF_{incl}
CSI	0.22	.644	<.01	0.28	0.97	.328	.01	0.41	0.58	.448	.01	0.32
Stimulus duration	1.44	.234	.02	0.46	0.17	.680	<.01	0.32	1.10	.297	.01	0.43
Attention	951.36	<.001	.93	>100	561.38	<.001	.88	>100	31.66	<.001	.30	>100
Transition	0.06	.806	<.01	0.04	0.20	.659	<.01	0.09	0.37	.547	<.01	0.09
Retention interval	177.42	<.001	.71	>100	434.43	<.001	.86	>100	51.86	<.001	.42	>100
CSI x Stimulus duration	0.14	.707	<.01	0.34	0.03	.857	<.01	0.35	0.61	.438	.01	0.42
CSI x Attention	**7.28**	**.009**	**.09**	>100	**7.97**	**.006**	**.10**	>100	**0.39**	**.534**	**.01**	0.18
Stimulus duration x Attention	**5.49**	**.022**	**.07**	97.70	**2.04**	**.157**	**.03**	2.28	**0.95**	**.333**	**.01**	0.30
CSI x Transition	3.08	.084	.04	0.26	0.57	.455	.01	0.16	1.14	.290	.02	0.18
Stimulus duration x Transition	0.27	.608	<.01	0.13	2.57	.113	.03	0.20	0.95	.333	.01	0.16
CSI x Retention interval	4.94	.029	.06	4.58	1.57	.214	.02	0.34	1.30	.258	.02	0.39
Stimulus duration x Retention interval	0.32	.573	<.01	0.15	3.81	.055	.05	1.68	2.05	.157	.03	0.86

Attention x Transition	**38.68**	**<.001**	**.34**	>100	**20.57**	**<.001**	**.22**	41.33	**6.67**	**.012**	**.08**	0.50
Attention x Retention interval	**127.03**	**<.001**	**.63**	>100	**350.05**	**<.001**	**.83**	>100	**50.57**	**<.001**	**.41**	>100
Transition x Retention interval	0.11	.740	<.01	0.12	0.41	.523	.01	0.14	0.19	.668	<.01	0.13
CSI x Stimulus duration x Attention	0.98	.327	.01	0.52	0.48	.488	.01	0.35	0.07	.789	<.01	0.18
CSI x Stimulus duration x Transition	1.41	.239	.02	0.20	0.70	.406	.01	0.23	0.41	.523	.01	0.18
CSI x Stimulus duration x Retention interval	0.01	.904	<.01	0.26	0.11	.740	<.01	0.19	0.04	.833	<.01	0.20
CSI x Attention x Transition	1.90	.173	.02	0.33	1.42	.237	.02	0.22	0.31	.580	<.01	0.17
Stimulus duration x Attention x Transition	0.07	.788	<.01	0.17	0.06	.804	<.01	0.20	0.17	.677	<.01	0.18
CSI x Attention x Retention interval	3.40	.069	.04	0.74	1.33	.252	.02	0.25	0.93	.338	.01	0.27
Stimulus duration x Attention x Retention interval	0.01	.920	<.01	0.17	0.42	.520	.01	0.18	0.38	.542	.01	0.19
CSI x Transition x Retention interval	0.59	.444	.01	0.22	0.10	.758	<.01	0.14	0.53	.468	.01	0.21
Stimulus duration x Transition x Retention interval	0.45	.505	.01	0.19	1.17	.284	.02	0.21	0.23	.636	<.01	0.19
Attention x Transition x Retention interval	**6.07**	**.016**	**.08**	0.85	**7.54**	**.008**	**.09**	0.51	**0.14**	**.706**	**<.01**	0.21
CSI x Stimulus duration x Attention x Transition	0.16	.695	<.01	0.21	1.25	.268	.02	0.35	1.94	.168	.03	0.25
CSI x Stimulus duration x Attention x Retention interval	0.08	.784	<.01	0.27	1.73	.193	.02	0.63	2.20	.143	.03	0.77

CSI x Stimulus duration x Transition x Retention interval	0.28	.597	<.01	0.23	0.20	.657	<.01	0.22	0.12	.731	<.01	0.16
CSI x Attention x Transition x Retention interval	0.27	.602	<.01	0.25	1.01	.318	.01	0.22	0.05	.828	<.01	0.25
Stimulus duration x Attention x Transition x Retention interval	1.56	.215	.02	0.27	1.01	.318	.01	0.15	5.30	.024	.07	0.85
CSI x Stimulus duration x Attention x Transition x Retention interval	0.01	.939	<.01	0.07	< 0.01	.982	<.01	0.82	< 0.01	.980	<.01	0.31

Note. Mean proportion of hits was analyzed by means of a 2 (cue-to-stimulus interval [CSI]: 150 vs. 1200 ms) x 2 (stimulus duration: 500 ms vs. until response) x 2 (attention: target vs. distractor) x 2 (transition: switch vs. repeat trial) x 2 (retention interval: immediate vs. delayed test) analysis of variance (ANOVA). The immediate test took place immediately after the incidental study phase. The delayed test took place after one day. The same ANOVA was conducted for remember-responses and for know-responses. Effects of interest are printed in bold. η^2_p indicates partial eta-squared. BF_{incl} represents the Bayes factor for a model including a specific effect compared to matched models excluding the effect.

Table 4

Results of Experiment 3

Experiment 3	Recognition				Remember				Know			
Effect	$F(1,73)$	p	η^2_p	$\mathrm{BF}_{\mathrm{incl}}$	$F(1,72)$	p	η^2_p	$\mathrm{BF}_{\mathrm{incl}}$	$F(1,72)$	p	η^2_p	$\mathrm{BF}_{\mathrm{incl}}$
CSI	0.21	.644	<.01	0.25	6.42	.013	.08	3.70	3.79	.055	.05	1.28
Stimulus duration	0.29	.589	<.01	0.30	0.64	.427	.01	0.28	<0.01	.962	<.01	0.29
Attention	1028.95	<.001	.93	>100	748.43	<.001	.91	>100	61.58	<.001	.46	>100
Transition	0.02	.899	<.01	0.10	0.27	.602	<.01	0.09	0.24	.625	<.01	0.10
Retention interval	193.28	<.001	.73	>100	442.63	<.001	.86	>100	43.51	<.001	.38	>100
CSI x Stimulus duration	1.20	.278	.02	0.92	0.09	.761	<.01	0.32	1.10	.299	.01	0.57
CSI x Attention	**6.83**	**.011**	**.09**	12.62	**11.83**	**.001**	**.14**	>100	0.72	.398	.01	0.20
Stimulus duration x Attention	**0.50**	**.480**	**.01**	0.46	**0.56**	**.456**	**.01**	0.19	0.02	.887	<.01	0.12
CSI x Transition	0.16	.694	<.01	0.10	0.53	.468	.01	0.13	0.72	.400	.01	0.13
Stimulus duration x Transition	3.27	.075	.04	0.21	3.59	.062	.05	0.18	1.27	.264	.02	0.18
CSI x Retention interval	1.05	.309	.01	1.00	1.55	.218	.02	0.95	0.02	.887	<.01	0.13
Stimulus duration x Retention interval	1.77	.187	.02	1.73	3.77	.056	.05	18.18	0.24	.629	<.01	0.15

Attention x Transition	**28.76**	**<.001**	**.28**	26.16	**28.35**	**<.001**	**.28**	16.89	0.80	.375	.01	0.17
Attention x Retention interval	**390.60**	**<.001**	**.84**	>100	**508.60**	**<.001**	**.88**	>100	29.89	<.001	.29	>100
Transition x Retention interval	0.07	.794	<.01	0.11	2.04	.157	.03	0.17	1.23	.271	.02	0.19
CSI x Stimulus duration x Attention	2.23	.140	.03	0.21	0.38	.541	.01	0.25	1.28	.261	.02	0.33
CSI x Stimulus duration x Transition	0.66	.418	.01	0.21	0.02	.893	<.01	0.14	2.02	.159	.03	0.30
CSI x Stimulus duration x Retention interval	0.16	.691	<.01	0.11	0.02	.894	<.01	0.18	0.14	.711	<.01	0.21
CSI x Attention x Transition	0.02	.875	<.01	0.17	0.50	.480	.01	0.19	0.20	.656	<.01	0.21
Stimulus duration x Attention x Transition	11.40	.001	.14	1.37	5.76	.019	.07	0.46	2.60	.111	.03	0.36
CSI x Attention x Retention interval	7.15	.009	.09	1.11	6.83	.011	.09	6.44	0.03	.862	<.01	0.17
Stimulus duration x Attention x Retention interval	0.02	.902	<.01	0.07	0.53	.468	.01	0.25	0.67	.416	.01	0.21
CSI x Transition x Retention interval	0.09	.760	<.01	0.18	2.52	.116	.03	0.29	1.04	.311	.01	0.26
Stimulus duration x Transition x Retention interval	<0.01	.979	<.01	0.19	0.41	.525	.01	0.19	0.28	.598	<.01	0.16
Attention x Transition x Retention interval	**15.09**	**<.001**	**.17**	4.36	**9.69**	**.003**	**.12**	0.87	2.47	.120	.03	0.47
CSI x Stimulus duration x Attention x Transition	1.26	.265	.02	0.28	1.53	.220	.02	0.25	<0.01	.991	<.01	0.28
CSI x Stimulus duration x Attention x Retention interval	2.71	.104	.04	0.77	1.14	.288	.02	0.46	0.54	.463	.01	0.25

CSI x Stimulus duration x Transition x Retention interval	0.55	.462	.01	0.27	0.64	.427	.01	0.27	<0.01	.974	<.01	0.30
CSI x Attention x Transition x Retention interval	1.14	.290	.02	0.26	0.15	.701	<.01	0.23	0.64	.427	.01	0.38
Stimulus duration x Attention x Transition x Retention interval	3.69	.059	.05	0.52	3.56	.063	.05	0.47	0.29	.592	<.01	0.32
CSI x Stimulus duration x Attention x Transition x Retention interval	0.35	.558	<.01	0.41	0.05	.827	<.01	0.18	0.72	.397	.01	0.18

Note. Mean proportion of hits was analyzed by means of a 2 (cue-to-stimulus interval [CSI]: 150 vs. 1200 ms) x 2 (stimulus duration: 500 ms vs. until response) x 2 (attention: target vs. distractor) x 2 (transition: switch vs. repeat trial) x 2 (retention interval: immediate vs. delayed test) analysis of variance (ANOVA). The immediate test took place immediately after the incidental study phase. The delayed test took place after one week. The same ANOVA was conducted for remember-responses and for know-responses. Effects of interest are printed in bold. η^2_p indicates partial eta-squared. BF_{incl} represents the Bayes factor for a model including a specific effect compared to matched models excluding the effect.

Table 5

Results of Experiment 4

Experiment 4	Recognition				Remember				Know			
Effect	*F*(1,74)	*p*	η^2_p	BF$_{incl}$	*F*(1,70)	*p*	η^2_p	BF$_{incl}$	*F*(1,70)	*p*	η^2_p	BF$_{incl}$
RSI	1.63	.206	.02	0.67	1.58	.213	.02	0.68	0.01	.905	<.01	0.27
Stimulus duration	0.23	.637	<.01	0.35	0.01	.909	<.01	0.34	0.70	.405	.01	0.39
Attention	1247.15	<.001	.94	>100	801.20	<.001	.92	>100	32.65	<.001	.32	>100
Transition	0.57	.454	.01	0.11	6.14	.016	.08	0.27	7.14	.009	.09	0.77
Retention interval	194.75	<.001	.72	>100	334.99	<.001	.83	>100	46.04	<.001	.40	>100
RSI x Stimulus duration	1.00	.320	.01	0.58	2.69	.105	.04	0.90	0.42	.518	.01	0.44
RSI x Attention	**< 0.01**	**.972**	**<.01**	0.13	**0.60**	**.442**	**.01**	0.25	**0.83**	**.366**	**.01**	0.30
Stimulus duration x Attention	**10.70**	**.002**	**.13**	>100	**3.10**	**.083**	**.04**	3.95	**2.02**	**.160**	**.03**	0.97
RSI x Transition	0.27	.603	<.01	0.16	4.95	.029	.07	0.31	0.71	.402	.01	0.72
Stimulus duration x Transition	0.01	.934	<.01	0.12	0.02	.890	<.01	0.12	0.03	.870	<.01	0.09
RSI x Retention interval	4.04	.048	.05	4.63	1.14	.289	.02	0.47	0.70	.406	.01	0.23
Stimulus duration x Retention interval	0.11	.746	<.01	0.15	0.14	.714	<.01	0.16	0.04	.834	<.01	0.13

Attention x Transition	**29.32**	**<.001**	**.28**	>100	**31.14**	**<.001**	**.31**	>100	**2.54**	**.116**	**.04**	0.56
Attention x Retention interval	**286.89**	**<.001**	**.79**	>100	**514.26**	**<.001**	**.88**	>100	**52.20**	**<.001**	**.43**	>100
Transition x Retention interval	3.72	.058	.05	0.34	3.18	.079	.04	0.26	0.63	.432	.01	0.11
RSI x Stimulus duration x Attention	0.19	.663	<.01	0.21	4.72	.033	.06	31.78	4.83	.031	.06	41.62
RSI x Stimulus duration x Transition	1.11	.295	.01	0.25	0.40	.529	.01	0.17	2.78	.100	.04	0.29
RSI x Stimulus duration x Retention interval	0.75	.390	.01	0.26	1.21	.275	.02	0.61	6.10	.016	.08	43.66
RSI x Attention x Transition	1.50	.224	.02	0.33	6.46	.013	.08	0.96	0.56	.457	.01	0.01
Stimulus duration x Attention x Transition	3.68	.059	.05	0.75	4.13	.046	.06	0.47	0.13	.717	<.01	0.15
RSI x Attention x Retention interval	3.23	.076	.04	0.33	0.21	.645	<.01	0.19	0.64	.425	.01	0.10
Stimulus duration x Attention x Retention interval	4.19	.044	.05	0.39	6.41	.014	.08	1.03	0.28	.600	<.01	0.08
RSI x Transition x Retention interval	3.00	.087	.04	0.44	1.72	.194	.02	0.21	0.61	.439	.01	0.20
Stimulus duration x Transition x Retention interval	0.04	.850	<.01	0.17	0.92	.340	.01	0.25	1.56	.215	.02	0.27
Attention x Transition x Retention interval	**1.47**	**.229**	**.02**	0.27	**1.22**	**.272**	**.02**	0.17	**0.01**	**.931**	**<.01**	0.18
RSI x Stimulus duration x Attention x Transition	0.09	.771	<.01	0.21	1.81	.182	.03	0.36	1.18	.280	.02	0.43
RSI x Stimulus duration x Attention x Retention interval	3.33	.072	.04	0.44	0.01	.924	<.01	0.28	2.32	.132	.03	0.57

RSI x Stimulus duration x Transition x Retention interval	0.04	.840	<.01	0.31	0.63	.431	.01	0.24	0.21	.651	<.01	0.27
RSI x Attention x Transition x Retention interval	0.03	.863	<.01	0.17	1.56	.216	.02	0.41	0.82	.368	.01	0.62
Stimulus duration x Attention x Transition x Retention interval	0.95	.333	.01	0.33	4.66	.034	.06	0.50	0.57	.452	.01	0.24
RSI x Stimulus duration x Attention x Transition x Retention interval	2.96	.090	.04	2.69	2.86	.095	.04	2.94	0.24	.627	<.01	0.32

Note. Mean proportion of hits was analyzed by means of a 2 (response-to-stimulus interval [RSI]: 150 vs. 1200 ms) x 2 (stimulus duration: 500 ms vs. until response) x 2 (attention: target vs. distractor) x 2 (transition: switch vs. repeat trial) x 2 (retention interval: immediate vs. delayed test) repeated measures analysis of variance (ANOVA). The immediate test took place immediately after the incidental study phase. The delayed test took place after one day. The same ANOVA was conducted for remember-responses and for know-responses. Effects of interest are printed in bold. η^2_p indicates partial eta-squared. BF_{incl} represents the Bayes factor for a model including a specific effect compared to matched models excluding the effect.

Table 6

Results of Experiment 5

Experiment 5	Recognition				Remember				Know			
Effect	*F*(1,75)	*p*	η^2_p	BF_{incl}	*F*(1,71)	*p*	η^2_p	BF_{incl}	*F*(1,71)	*p*	η^2_p	BF_{incl}
RSI	3.01	.087	.04	0.89	0.06	.810	<.01	0.25	3.53	.064	.05	1.26
Stimulus duration	0.31	.580	<.01	0.28	0.31	.580	<.01	0.27	<0.01	>.999	<.01	0.28
Attention	1019.98	<.001	.93	>100	950.23	<.001	.93	>100	16.38	<.001	.19	>100
Transition	0.57	.451	.01	0.10	0.19	.666	<.01	0.09	0.07	.790	<.01	0.09
Retention interval	200.18	<.001	.73	>100	442.24	<.001	.86	>100	76.98	<.001	.52	>100
RSI x Stimulus duration	0.51	.479	.01	0.47	0.02	.879	<.01	0.33	0.74	.392	.01	0.51
RSI x Attention	**0.94**	**.336**	**.01**	0.27	**0.98**	**.325**	**.01**	0.26	**0.24**	**.623**	**<.01**	0.12
Stimulus duration x Attention	**2.86**	**.095**	**.04**	0.84	**0.01**	**.921**	**<.01**	0.13	**4.54**	**.037**	**.06**	1.22
RSI x Transition	0.02	.880	<.01	0.12	0.92	.340	.01	0.15	0.11	.741	<.01	0.12
Stimulus duration x Transition	0.09	.769	<.01	0.12	11.07	.001	.13	0.65	6.24	.015	.08	1.15
RSI x Retention interval	0.23	.636	<.01	0.16	0.03	.869	<.01	0.13	0.87	.355	.01	0.34
Stimulus duration x Retention interval	0.79	.378	.01	0.31	0.01	.914	<.01	0.13	2.15	.147	.03	1.27

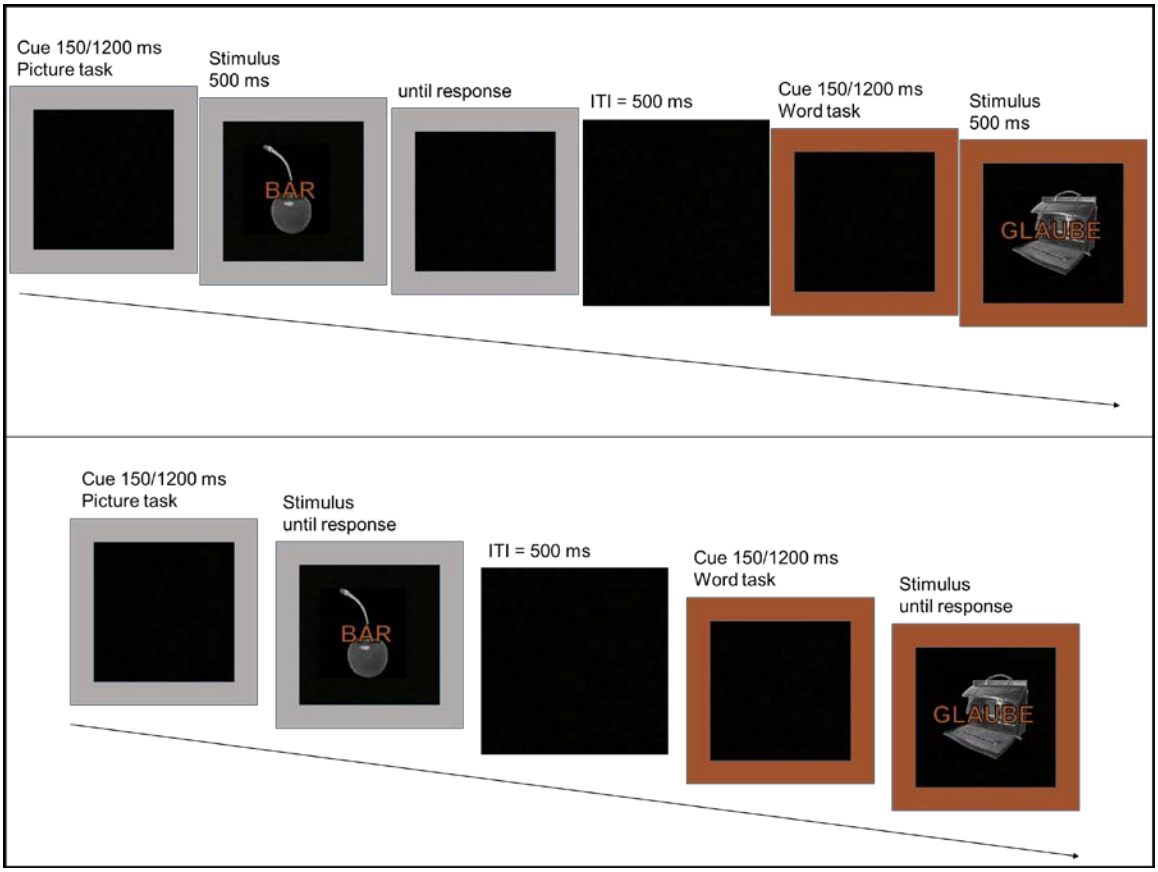
Attention x Transition	**15.70**	**<.001**	**.17**	8.73	**16.83**	**<.001**	**.19**	2.64	**0.28**	**.598**	**<.01**	0.11
Attention x Retention interval	**436.15**	**<.001**	**.85**	>100	**646.66**	**<.001**	**.90**	>100	**32.05**	**<.001**	**.31**	>100
Transition x Retention interval	0.98	.324	.01	0.15	2.30	.134	.03	0.21	9.39	.003	.12	2.73
RSI x Stimulus duration x Attention	<0.01	.959	<.01	0.05	0.03	.864	<.01	0.17	0.11	.739	<.01	0.19
RSI x Stimulus duration x Transition	0.93	.338	.01	0.23	0.26	.610	<.01	0.18	1.48	.228	.02	0.25
RSI x Stimulus duration x Retention interval	0.07	.795	<.01	0.16	0.66	.419	.01	0.42	1.97	.165	.03	1.58
RSI x Attention x Transition	3.72	.057	.05	0.45	0.20	.660	<.01	0.15	2.78	.100	.04	0.46
Stimulus duration x Attention x Transition	1.31	.257	.02	0.25	3.12	.082	.04	0.33	0.15	.697	<.01	0.18
RSI x Attention x Retention interval	0.01	.921	<.01	0.17	0.15	.697	<.01	0.21	0.22	.642	<.01	0.19
Stimulus duration x Attention x Retention interval	0.40	.530	.01	0.21	0.56	.458	.01	0.25	1.87	.176	.03	0.45
RSI x Transition x Retention interval	1.82	.182	.02	0.23	0.80	.375	.01	0.21	0.52	.475	.01	0.21
Stimulus duration x Transition x Retention interval	3.26	.075	.04	0.34	2.27	.137	.03	0.27	0.07	.786	<.01	0.13
Attention x Transition x Retention interval	**6.39**	**.014**	**.08**	0.78	**7.01**	**.010**	**.09**	0.87	**0.06**	**.803**	**<.01**	0.18
RSI x Stimulus duration x Attention x Transition	2.61	.111	.03	0.50	9.30	.003	.12	1.12	0.50	.481	.01	0.26
RSI x Stimulus duration x Attention x Retention interval	0.03	.860	<.01	0.20	0.09	.768	<.01	0.19	0.01	.926	<.01	0.20

RSI x Stimulus duration x Transition x Retention interval	<0.01	.980	<.01	0.28	0.26	.612	<.01	0.24	0.41	.523	.01	0.18
RSI x Attention x Transition x Retention interval	1.07	.304	.01	0.31	1.12	.294	.02	0.35	0.03	.867	<.01	0.19
Stimulus duration x Attention x Transition x Retention interval	0.62	.432	.01	0.24	2.34	.130	.03	0.45	0.37	.544	.01	0.24
RSI x Stimulus duration x Attention x Transition x Retention interval	0.23	.634	<.01	0.16	0.09	.761	<.01	0.24	0.34	.560	<.01	0.96

Note. Mean proportion of hits was analyzed by means of a 2 (response-to-stimulus interval [RSI]: 150 vs. 1200 ms) x 2 (stimulus duration: 500 ms vs. until response) x 2 (attention: target vs. distractor) x 2 (transition: switch vs. repeat trial) x 2 (retention interval: immediate vs. delayed test) repeated measures analysis of variance (ANOVA). The immediate test took place immediately after the incidental study phase. The delayed test took place after one week. The same ANOVA was conducted for remember-responses and for know-responses. Effects of interest are printed in bold. η^2_p indicates partial eta-squared. BF_{incl} represents the Bayes factor for a model including a specific effect compared to matched models excluding the effect.

Figure 1

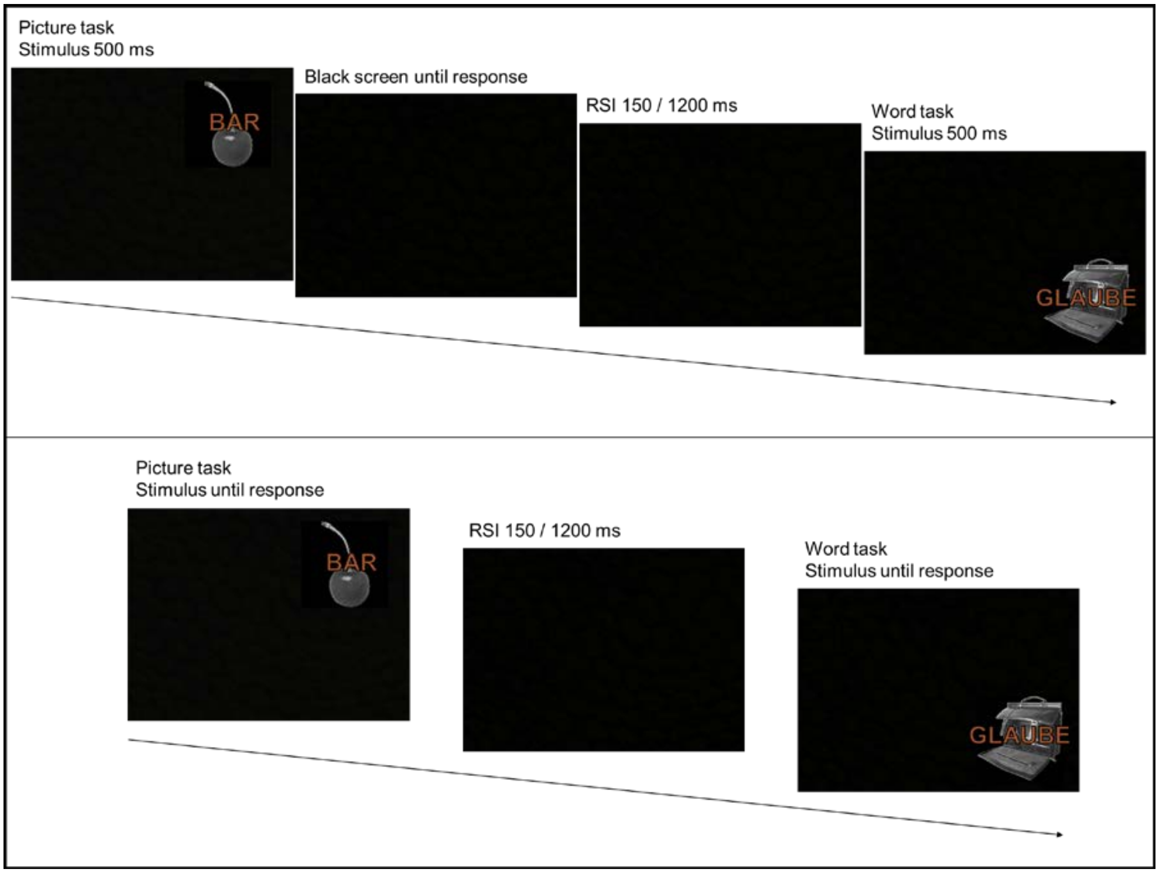
Trial Sequence of the Cued Task Switching Procedure



Note. ITI = inter-trial interval.

Figure 2

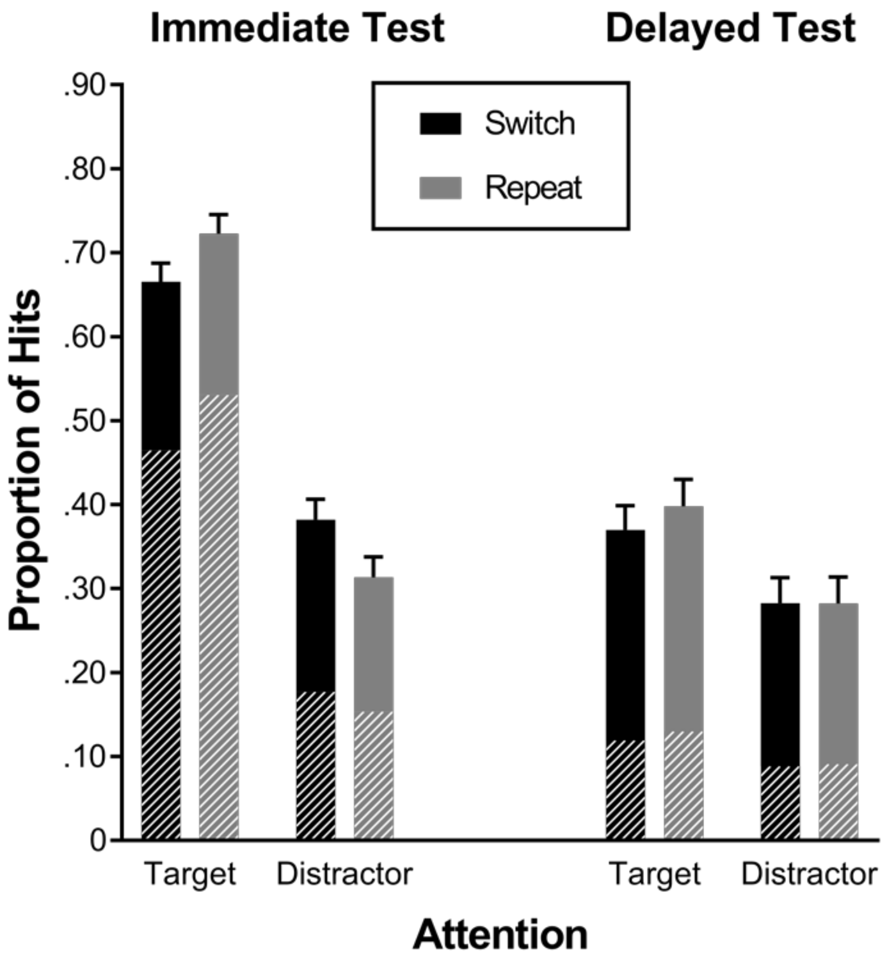
Trial Sequence of the Alternating Runs Task Switching Procedure



Note. RSI = response-to-stimulus interval

Figure 3

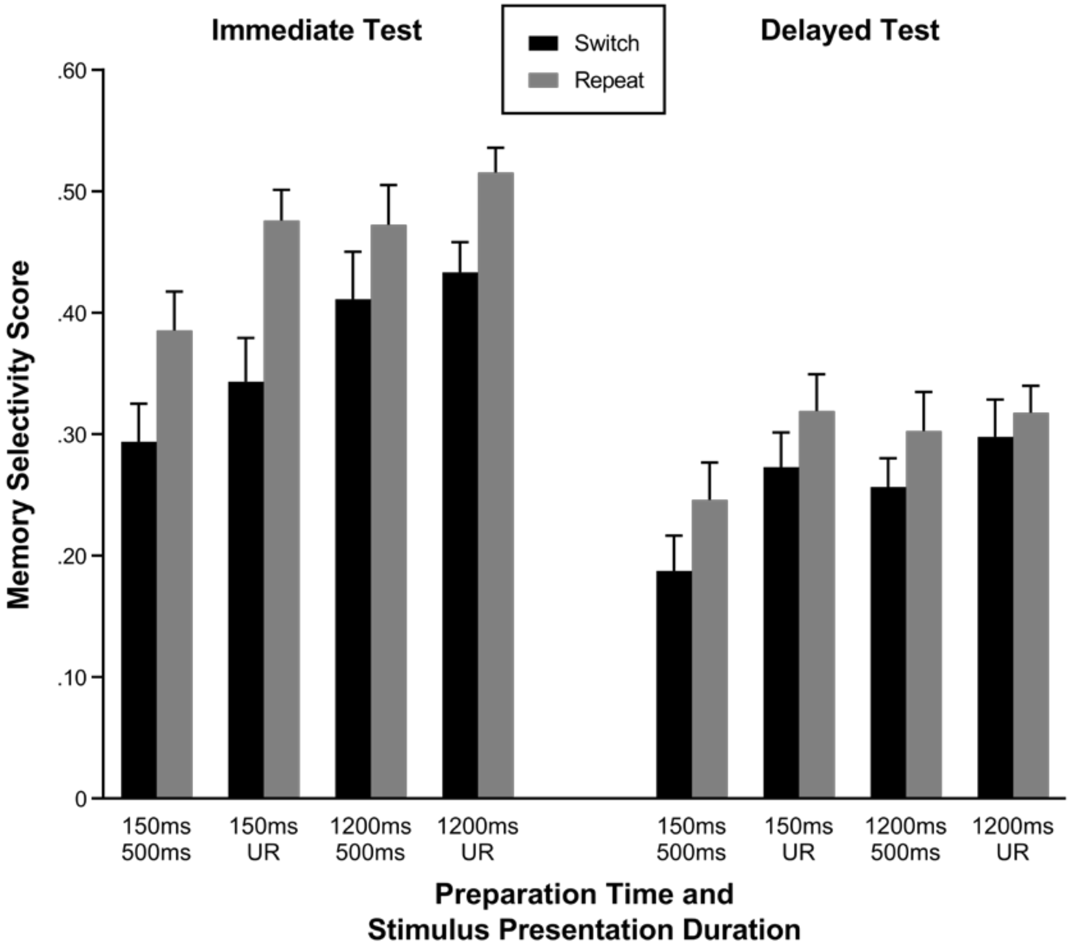
Experiment 1



Note. Mean proportion of correctly recognized old items (hits) as a function of attention (target vs. distractor), transition (switch vs. repeat trial), and retention interval (immediate vs. delayed test). The first recognition test (left part) followed immediately after the incidental study phase. The second test followed after one week (right part). The shaded areas reflect *remember*-; the solid areas represent *know*-responses. Error bars represent standard errors.

Figure 4

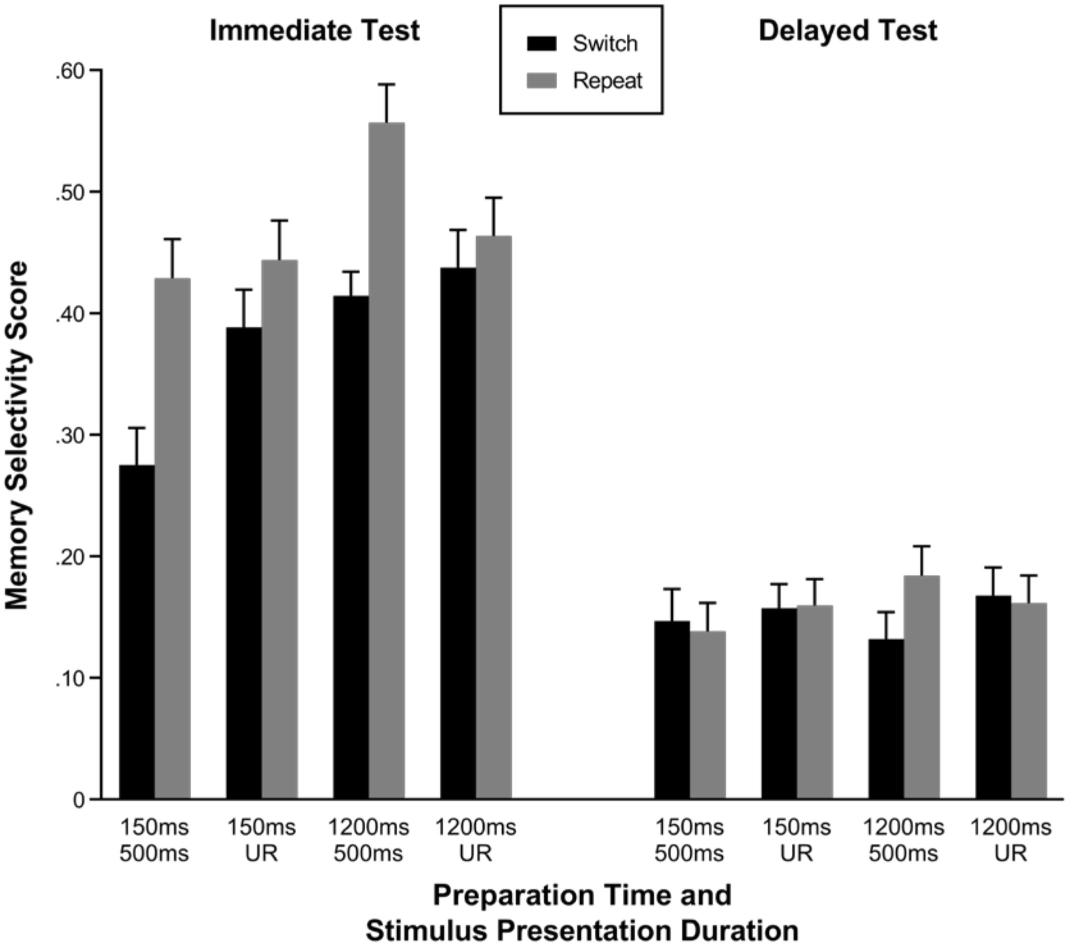
Experiment 2



Note. Memory selectivity as a function of transition (switch vs. repeat trial), CSI (150 vs. 1200 ms), stimulus duration (500 ms vs. until response [UR]), and retention interval (immediate vs. delayed test). The first recognition test (left part) followed immediately after the incidental study phase. The second test followed after one day (right part). Error bars represent standard errors.

Figure 5

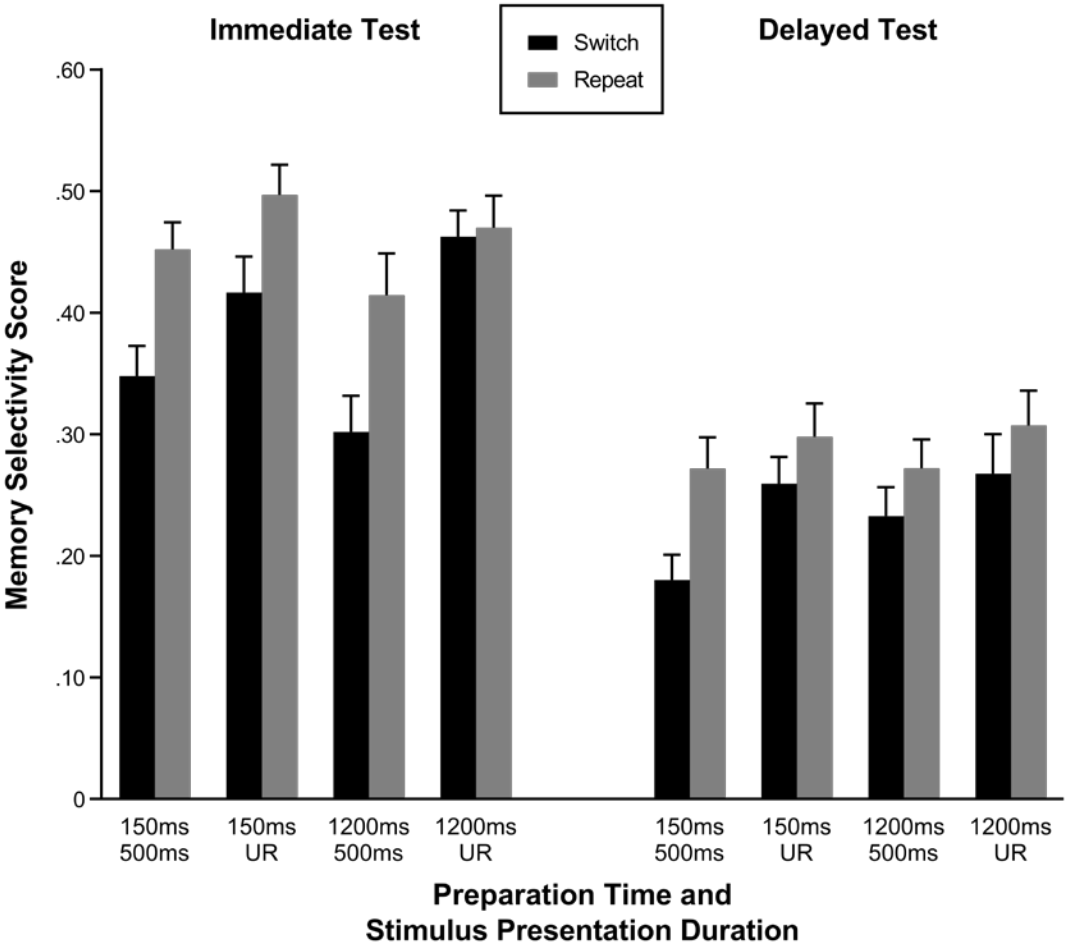
Experiment 3



Note. Memory selectivity as a function of transition (switch vs. repeat trial), CSI (150 vs. 1200 ms), stimulus duration (500 ms vs. until response [UR]), and retention interval (immediate vs. delayed test). The first recognition test (left part) followed immediately after the incidental study phase. The second test followed after one week (right part). Error bars represent standard errors.

Figure 6

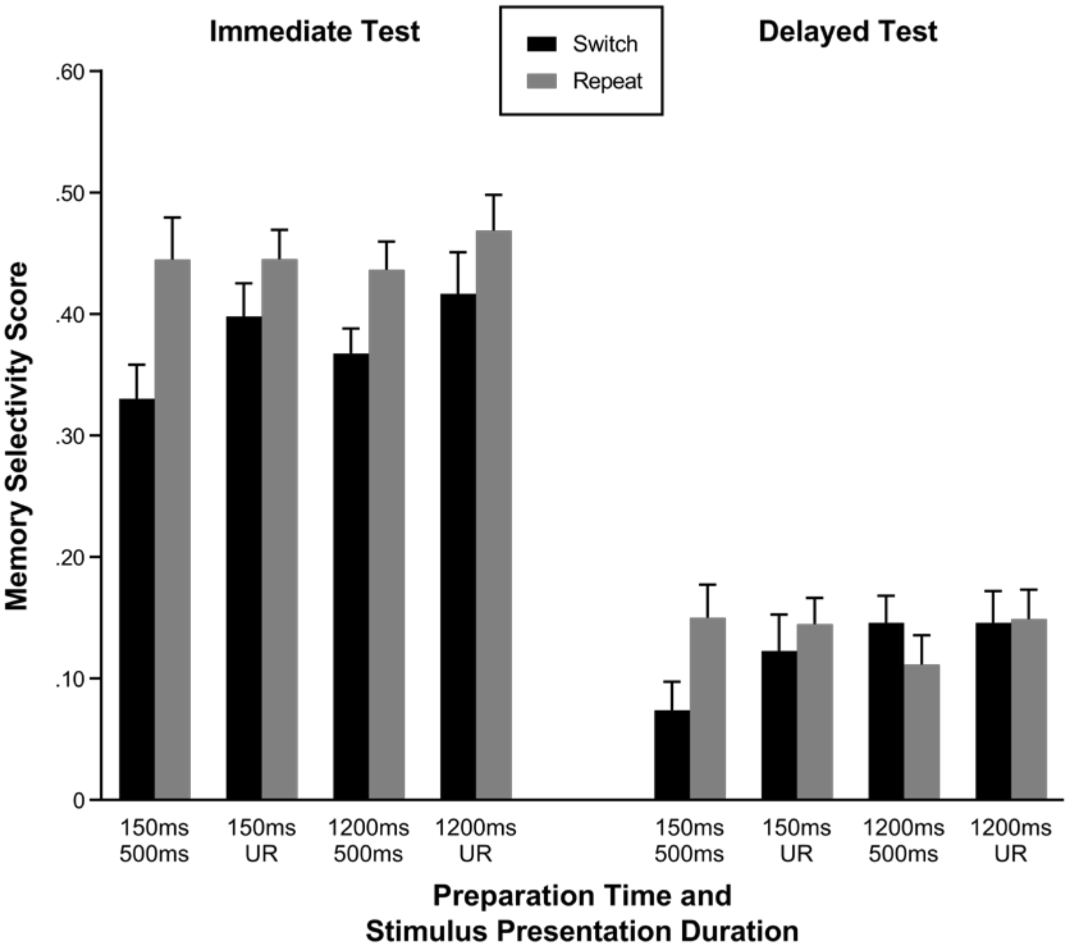
Experiment 4



Note. Memory selectivity as a function of transition (switch vs. repeat trial), RSI (150 vs. 1200 ms), stimulus duration (500 ms vs. until response [UR]), and retention interval (immediate vs. delayed test). The first recognition test (left part) followed immediately after the incidental study phase. The second test followed after one day (right part). Error bars represent standard errors.

Figure 7

Experiment 5



Note. Memory selectivity as a function of transition (switch vs. repeat trial), RSI (150 vs. 1200 ms), stimulus duration (500 ms vs. until response [UR]), and retention interval (immediate vs. delayed test). The first recognition test (left part) followed immediately after the incidental study phase. The second test followed after one week (right part). Error bars represent standard errors.

Supplemental Material

Results of the Study Phase

Experiment 1

Two-sided paired t-test were conducted on mean accuracy rates and median correct reaction times in milliseconds. Participants responded less accurately and more slowly on switch (*M* = .908, *SE* = .009; *M* = 1749, *SE* = 63) than repeat trials (*M* = .931, *SE* = .007; *M* = 1309, *SE* = 49), $t(38) = -3.96$, $p < .001$, and $t(38) = 13.87$, $p < .001$, respectively.

Experiment 2

Accuracy rates and reaction times of the study phase were analyzed separately by a 2x2x2 analysis of variance (ANOVA) with the within-subjects factor *transition* (switch vs. repeat trial) and the between-subjects factors *cue-to-stimulus-interval* (CSI; 150 vs. 1200 ms) and *stimulus duration* (500 ms vs. until response).

Accuracy Rates

A reliable switch cost emerged, $F(1, 74) = 6.03$, $p = .016$, $\eta_p^2 = .08$. Participants responded less accurately on switch (*M* = .929, *SE* = .005) than repeat trials (*M* = .940, *SE* = .005). A significant main effect of stimulus duration, $F(1, 74) = 10.91$, $p = .001$, $\eta_p^2 = .13$, indicated that participants in the 500ms-stimulus-duration condition responded less accurately (*M* = .920, *SE* = .008) than participants in the until-response-stimulus-duration condition (*M* = .949, *SE* = .005). The main effect of CSI was not significant, $F(1, 74) = 2.82$, $p = .097$, $\eta_p^2 = .04$. The main effect of transition was qualified by an interaction with CSI, $F(1, 74) = 10.67$, $p = .002$, $\eta_p^2 = .13$. While participants in the150ms-CSI condition showed reliable switch costs, $t(38) = -3.46$, $p = .001$, participants in the 1200ms-CSI condition did not, $t(38) = 0.74$, $p = .462$. Other interactions were not significant, all *F*'s < 2.00 and all *p*'s > .162.

Reaction Times

A reliable switch cost emerged, $F(1, 74) = 315.82$, $p < .001$, $\eta_p^2 = .81$. Participants were slower on switch ($M = 1680$, $SE = 49$) than repeat trials ($M = 1270$, $SE = 38$). A significant main effect of CSI, $F(1, 74) = 13.59$, $p < .001$, $\eta_p^2 = .16$, indicated that participants in the 150ms-CSI condition were slower ($M = 1617$, $SE = 56$) than participants in the 1200ms-CSI condition ($M = 1333$, $SE = 54$). The main effect of stimulus duration was not significant, $F(1, 74) = 0.31$, $p = .581$, $\eta_p^2 < .01$. The interaction between transition and CSI was significant, $F(1, 74) = 10.39$, $p = .002$, $\eta_p^2 = .12$, as well as the interaction between transition and stimulus duration, $F(1, 74) = 6.75$, $p = .011$, $\eta_p^2 = .08$. Participants in the 150ms-CSI condition had larger switch costs (482 ms), $t(38) = 14.16$, $p < .001$, than participants in the 1200ms-CSI condition (337 ms), $t(38) = 10.14$, $p < .001$. Participants in the 500ms-stimulus-duration condition had smaller switch costs (351 ms), $t(38) = 11.53$, $p < .001$, than participants in the until-response-stimulus-duration condition (467 ms), $t(38) = 12.34$, $p < .001$. The interaction between CSI and stimulus duration, $F(1, 74) = 1.94$, $p = .167$, $\eta_p^2 = .03$, and the three-way interaction, $F(1, 74) = 0.15$, $p = .699$, $\eta_p^2 < .01$, were not significant.

Experiment 3

Accuracy rates and reaction times of the study phase were analyzed separately by a 2x2x2 analysis of variance (ANOVA) with the within-subjects factor *transition* (switch vs. repeat trial) and the between-subjects factors *cue-to-stimulus-interval* (CSI; 150 vs. 1200 ms) and *stimulus duration* (500 ms vs. until response).

Accuracy Rates

Consistent with Experiment 2, a reliable switch cost emerged, *F*(1, 73) = 38.10, $p < .001$, $\eta_p^2 = .34$, as well as a main effect of stimulus duration, *F*(1, 73) = 5.14, $p = .026$, $\eta_p^2 = .07$, but no main effect of CSI, *F*(1, 73) = 1.99, $p = .163$, $\eta_p^2 = .03$. Participants responded less accurately on switch (*M* = .923, *SE* = .006) than repeat trials (*M* = .950, *SE* = .004). Participants in the 500ms-stimulus-duration condition responded again less accurately (*M* = .925, *SE* = .008) than participants in the until-response-stimulus duration condition (*M* = .947, *SE* = .006). Transition interacted significantly with stimulus duration, *F*(1, 73) = 4.92, $p = .030$, $\eta_p^2 = .06$, but not with CSI, *F*(1, 73) = 2.80, $p = .099$, $\eta_p^2 = .04$. Although significant switch costs emerged in both conditions, the costs were more than doubled in the 500ms-stimulus-duration condition (.037), *t*(36) = -5.06, $p < .001$, compared to the until-response-stimulus-duration condition (.017), *t*(39) = -3.25, $p = .002$. No other interactions were significant, all *F*’s < 3.40 and all *p*’s > .069.

Reaction Times

Consistent with Experiment 2, a reliable switch cost emerged, *F*(1, 73) = 332.41, $p < .001$, $\eta_p^2 = .82$, as well as a main effect of CSI, *F*(1, 73) = 25.37, $p < .001$, $\eta_p^2 = .26$, but no main effect of stimulus duration, *F*(1, 73) = 2.01, $p = .161$, $\eta_p^2 = .03$. Participants were slower on switch (*M* = 1641, *SE* = 42) than repeat trials (*M* = 1222, *SE* = 30). Participants in the 150ms-CSI condition were slower (*M* = 1580, *SE* = 41) than participants in the 1200ms-CSI condition (*M* = 1280, *SE* = 44). A significant interaction between transition and CSI, *F*(1, 73) = 10.26, $p = .002$, $\eta_p^2 = .12$, indicated larger switch costs in the 150ms-CSI condition (491 ms), *t*(38) = 13.24, $p < .001$, compared to the 1200ms-CSI condition (345 ms), *t*(37) = 12.72, $p < .001$. The interaction between transition and stimulus duration was not significant, *F*(1, 73) = 3.07, *p* = .084, η_p^2 = .04. Other interactions were not significant, all *F*'s < 0.44 and all *p*'s > .508.

Experiment 4

Accuracy rates and reaction times of the study phase were analyzed separately by a 2x2x2 analysis of variance (ANOVA) with the within-subjects factor *transition* (switch vs. repeat) and the between-subjects factors *response-to-stimulus interval* (RSI; 150 vs. 1200 ms) and *stimulus duration* (500 ms vs. until response).

Accuracy Rates

A reliable switch cost emerged, *F*(1, 74) = 11.10, *p* = .001, η_p^2 = .13. Participants responded less accurately on switch (*M* = .944, *SE* = .004) than repeat trials (*M* = .955, *SE* = .004). A significant main effect of stimulus duration, *F*(1, 74) = 13.14, *p* = .001, η_p^2 = .15, indicated that participants in the 500ms-stimulus-duration condition responded less accurately (*M* = .938, *SE* = .005) than participants in the until-response-stimulus-duration condition (*M* = .960, *SE* = .004). A significant main effect of RSI, *F*(1, 74) = 8.93, *p* = .004, η_p^2 = .11, indicated that participants in the 150ms-RSI condition (*M* = .958, *SE* = .004) responded more accurately than participants in the 1200ms-RSI condition (*M* = .940, *SE* = .005). The interaction between transition and stimulus duration was significant, *F*(1, 74) = 6.58, *p* = .012, η_p^2 = .08, indicating that the switch cost was only significant in the 500ms-stimulus-duration condition, *t*(37) = -3.88, *p* < .001, but not in the until-response-stimulus-duration condition, *t*(39) = -0.57, *p* = .569. No other interactions were significant, all *F*'s < 2.01 and all *p*'s > .161.

Reaction Times

A reliable switch cost emerged, *F*(1, 74) = 379.92, $p < .001$, $\eta_p^2 = .84$. Participants were slower on switch (*M* = 1624, *SE* = 41) than repeat trials (*M* = 1087, *SE* = 27). The interaction between transition and RSI was significant, *F*(1, 74) = 4.08, $p = .047$, $\eta_p^2 = .05$, indicating larger switch costs in the 150ms-RSI condition (591 ms), *t*(39) = 14.89, $p < .001$, than in the 1200ms-RSI condition (481 ms), *t*(37) = 12.36, $p < .001$. Other main effects or interactions were not significant, all *F*'s < 2.78 and all *p*'s > .100.

Experiment 5

Accuracy rates and reaction times of the study phase were analyzed separately by a 2x2x2 analysis of variance (ANOVA) with the within-subjects factor *transition* (switch vs. repeat) and the between-subjects factors *response-to-stimulus interval* (RSI; 150 vs. 1200 ms) and *stimulus duration* (500 ms vs. until response).

Accuracy Rates

A reliable switch cost emerged, *F*(1, 75) = 5.00, $p = .028$, $\eta_p^2 = .06$. Participants responded less accurately on switch (*M* = .938, *SE* = .005) than repeat trials (*M* = .948, *SE* = .005). A significant main effect of stimulus duration, *F*(1, 75) = 12.37, $p < .001$, $\eta_p^2 = .14$, indicated that participants in the 500ms-stimulus duration condition responded less accurately (*M* = .928, *SE* = .007) than participants in the 1200ms-stimulus duration condition (*M* = .958, *SE* = .005). The main effect of RSI was not significant, *F*(1, 75) = 0.02, $p = .899$, $\eta_p^2 < .01$. Interactions were not significant, all *F*'s < 0.59 and all *p*'s > .445.

Reaction Times

A reliable switch cost emerged, *F*(1, 75) = 375.76, $p < .001$, $\eta_p^2 = .83$. Participants were slower on switch (*M* = 1627, *SE* = 53) than repeat trials (*M* = 1089, *SE* = 30). A significant main effect of RSI, *F*(1, 75) = 8.55, *p* = .005, η_p^2 = .10, indicated that participants in the 150ms-RSI condition were slower (*M* = 1473, *SE* = 65) than participants in the 1200ms-RSI condition (*M* = 1246, *SE* = 43). The main effect of stimulus duration was not significant, *F*(1, 75) = 0.80, *p* = .375, η_p^2 = .01. Transition interacted significantly with RSI, *F*(1, 75) = 9.19, *p* = .003, η_p^2 = .11, indicating larger switch costs in the 150ms-RSI condition (623 ms), *t*(38) = 14.11, *p* < .001, compared to the 1200ms-RSI condition (455 ms), *t*(39) = 12.90, *p* < .001. Moreover, the effect of RSI was more pronounced on switch trials (310 ms), *t*(68.94) = 3.05, *p* = .003, than on repeat trials (143 ms), *t*(62.24) = 2.40, *p* = .020. The interaction between transition and stimulus duration missed significance, *F*(1, 75) = 3.73, *p* = .057, η_p^2 = .05. Other interactions were not significant, all *F*’s < 2.64 and all *p*’s > .108.

Reanalysis of Recognition Performance

As the conditions of lower memory selectivity (switch trials, short CSI, and short stimulus presentation duration) were associated with higher error rates, we rerun our analyses of recognition performance under the exclusion of trials on which individuals made errors during the study phase. Differences in the significance level are highlighted in yellow. As there are only minor changes in the significance levels of only a few effects, the results do not change our conclusions.

Experiment 1: Recognition (error trials excluded)

Predictor	*F*	*p*	η^2_p
Attention	211.66	<.001	.85
Transition	0.25	.618	.01
RetentionInterval	61.42	<.001	.62
Attention x Transition	**15.73**	**<.001**	**.29**
Attention x RetentionInterval	**206.40**	**<.001**	**.84**
Transition x RetentionInterval	3.04	.090	.07
Attention x Transition x RetentionInterval	**9.32**	**.004**	**.20**

Experiment 2: Recognition (error trials excluded)

Predictor	*F*	*p*	η^2_p
CSI	0.12	.729	<.01
StimulusDuration	1.38	.244	.02
Attention	985.88	<.001	.93
Transition	0.29	.593	<.01
RetentionInterval	159.63	<.001	.68
CSI x StimulusDuration	0.20	.653	<.01
CSI x Attention	**6.88**	**.011**	**.09**
StimulusDuration x Attention	**3.85**	**.054**	**.05**
CSI x Transition	2.79	.099	.04
StimulusDuration x Transition	0.28	.600	<.01
CSI x RetentionInterval	4.59	.035	.06
StimulusDuration x RetentionInterval	0.35	.556	<.01
Attention x Transition	**32.01**	**<.001**	**.30**
Attention x RetentionInterval	**142.74**	**<.001**	**.66**
Transition x RetentionInterval	0.05	.830	<.01
CSI x StimulusDuration x Attention	0.72	.398	.01
CSI x StimulusDuration x Transition	1.56	.216	.02
CSI x StimulusDuration x RetentionInterval	0.02	.884	<.01
CSI x Attention x Transition	1.77	.188	.02
StimulusDuration x Attention x Transition	0.03	.868	<.01
CSI x Attention x RetentionInterval	4.02	.049	.05
StimulusDuration x Attention x RetentionInterval	0.40	.530	.01
CSI x Transition x RetentionInterval	1.11	.295	.01
StimulusDuration x Transition x RetentionInterval	0.09	.760	<.01
Attention x Transition x RetentionInterval	**4.05**	**.048**	**.05**
CSI x StimulusDuration x Attention x Transition	0.07	.794	<.01
CSI x StimulusDuration x Attention x RetentionInterval	0.24	.624	<.01
CSI x StimulusDuration x Transition x RetentionInterval	0.51	.476	.01
CSI x Attention x Transition x RetentionInterval	0.04	.836	<.01
StimulusDuration x Attention x Transition x RetentionInterval	0.40	.528	.01
CSI x StimulusDuration x Attention x Transition x RetentionInterval	0.39	.536	.01

Experiment 3: Recognition (error trials excluded)

Predictor	*F*	*p*	η^2_p
CSI	0.16	.694	<.01
StimulusDuration	0.28	.595	<.01
Attention	1063.44	<.001	.94
Transition	0.06	.806	<.01
RetentionInterval	199.43	<.001	.73
CSI x StimulusDuration	1.40	.241	.02
CSI x Attention	**6.82**	**.011**	**.09**
StimulusDuration x Attention	**0.12**	**.730**	**<.01**
CSI x Transition	0.46	.500	.01
StimulusDuration x Transition	4.05	.048	.05
CSI x RetentionInterval	1.52	.222	.02
StimulusDuration x RetentionInterval	2.19	.143	.03
Attention x Transition	**13.94**	**<.001**	**.16**
Attention x RetentionInterval	**430.20**	**<.001**	**.85**
Transition x RetentionInterval	0.02	.878	<.01
CSI x StimulusDuration x Attention	1.26	.266	.02
CSI x StimulusDuration x Transition	0.56	.455	.01
CSI x StimulusDuration x RetentionInterval	0.10	.752	<.01
CSI x Attention x Transition	0.21	.645	<.01
StimulusDuration x Attention x Transition	6.57	.012	.08
CSI x Attention x RetentionInterval	6.53	.013	.08
StimulusDuration x Attention x RetentionInterval	0.02	.876	<.01
CSI x Transition x RetentionInterval	0.07	.794	<.01
StimulusDuration x Transition x RetentionInterval	0.24	.626	<.01
Attention x Transition x RetentionInterval	**11.84**	**.001**	**.14**
CSI x StimulusDuration x Attention x Transition	1.70	.196	.02
CSI x StimulusDuration x Attention x RetentionInterval	1.47	.230	.02
CSI x StimulusDuration x Transition x RetentionInterval	0.10	.752	<.01
CSI x Attention x Transition x RetentionInterval	0.71	.403	.01
StimulusDuration x Attention x Transition x RetentionInterval	3.07	.084	.04
CSI x StimulusDuration x Attention x Transition x RetentionInterval	0.18	.671	<.01

Experiment 4: Recognition (errors trials excluded)

Predictor	*F*	*p*	η^2_p
RSI	1.74	.191	.02
StimulusDuration	0.32	.573	<.01
Attention	1159.54	<.001	.94
Transition	0.36	.553	<.01
RetentionInterval	192.79	<.001	.72
RSI x StimulusDuration	1.03	.315	.01
RSI x Attention	**0.07**	**.799**	**<.01**
StimulusDuration x Attention	**7.49**	**.008**	**.09**
RSI x Transition	0.12	.730	<.01
StimulusDuration x Transition	0.09	.771	<.01
RSI x RetentionInterval	4.27	.042	.05
StimulusDuration x RetentionInterval	0.18	.671	<.01
Attention x Transition	**28.03**	**<.001**	**.27**
Attention x RetentionInterval	**283.77**	**<.001**	**.79**
Transition x RetentionInterval	4.60	.035	.06
RSI x StimulusDuration x Attention	0.13	.717	<.01
RSI x StimulusDuration x Transition	0.42	.521	.01
RSI x StimulusDuration x RetentionInterval	0.88	.350	.01
RSI x Attention x Transition	1.74	.191	.02
StimulusDuration x Attention x Transition	2.96	.090	.04
RSI x Attention x RetentionInterval	3.21	.077	.04
StimulusDuration x Attention x RetentionInterval	4.35	.041	.06
RSI x Transition x RetentionInterval	2.45	.122	.03
StimulusDuration x Transition x RetentionInterval	0.25	.617	<.01
Attention x Transition x RetentionInterval	**1.45**	**.232**	**.02**
RSI x StimulusDuration x Attention x Transition	0.00	.981	<.01
RSI x StimulusDuration x Attention x RetentionInterval	4.52	.037	.06
RSI x StimulusDuration x Transition x RetentionInterval	0.03	.863	<.01
RSI x Attention x Transition x RetentionInterval	0.04	.845	<.01
StimulusDuration x Attention x Transition x RetentionInterval	0.98	.326	.01
RSI x StimulusDuration x Attention x Transition x RetentionInterval	2.83	.097	.04

147 *Experiment 5: Recognition (error trials excluded)*

Predictor	*F*	*p*	η^2_p
RSI	3.36	.071	.04
StimulusDuration	0.35	.553	<.01
Attention	957.20	<.001	.93
Transition	0.02	.890	<.01
RetentionInterval	205.68	<.001	.73
RSI x StimulusDuration	0.54	.466	.01
RSI x Attention	**0.73**	**.397**	**.01**
StimulusDuration x Attention	**2.86**	**.095**	**.04**
RSI x Transition	0.13	.725	<.01
StimulusDuration x Transition	0.15	.698	<.01
RSI x RetentionInterval	0.15	.697	<.01
StimulusDuration x RetentionInterval	1.35	.248	.02
Attention x Transition	**13.74**	**<.001**	**.15**
Attention x RetentionInterval	**431.78**	**<.001**	**.85**
Transition x RetentionInterval	2.16	.145	.03
RSI x StimulusDuration x Attention	0.12	.735	<.01
RSI x StimulusDuration x Transition	1.26	.265	.02
RSI x StimulusDuration x RetentionInterval	0.05	.816	<.01
RSI x Attention x Transition	5.05	.028	.06
StimulusDuration x Attention x Transition	2.76	.101	.04
RSI x Attention x RetentionInterval	0.02	.881	<.01
StimulusDuration x Attention x RetentionInterval	0.04	.835	<.01
RSI x Transition x RetentionInterval	1.75	.190	.02
StimulusDuration x Transition x RetentionInterval	1.28	.261	.02
Attention x Transition x RetentionInterval	**7.81**	**.007**	**.09**
RSI x StimulusDuration x Attention x Transition	1.72	.193	.02
RSI x StimulusDuration x Attention x RetentionInterval	0.01	.930	<.01
RSI x StimulusDuration x Transition x RetentionInterval	0.23	.630	<.01
RSI x Attention x Transition x RetentionInterval	1.08	.303	.01
StimulusDuration x Attention x Transition x RetentionInterval	1.80	.184	.02
RSI x StimulusDuration x Attention x Transition x RetentionInterval	0.03	.854	<.01

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Research article

Stimulating the parietal cortex by transcranial direct current stimulation (tDCS): no effects on attention and memory

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Abstract: Selective attention is relevant for goal directed behavior as it allows people to attend to task-relevant target stimuli and to ignore task-irrelevant distractors. Attentional focus at encoding affects subsequent memory for target and distractor stimuli. Remembering selectively more targets than distractors represents memory selectivity. Brain imaging studies suggest that the superior parietal cortex is associated with the dorsal attentional network supporting top-down control of selective attention while the inferior parietal cortex is associated with the ventral attentional network supporting bottom-up attentional orienting. To investigate the roles of the dorsal and ventral networks in the effect of selective attention during encoding on long-term memory, we stimulated the left superior and the right inferior parietal cortex. Building on previous work, we applied transcranial direct current stimulation (tDCS) during a study phase where pictures and words were presented simultaneously and participants had to switch between a picture and a word decision. A subsequent recognition test assessed memory for target and distractor pictures and words. We hypothesized that a relative increase in activity in the dorsal network would boost selective attention while increased activity in the ventral network would impair selective attention. We also expected to find corresponding effects on memory. Enhanced selective attention should lead to higher memory selectivity, while impaired selective attention should lead to lower memory selectivity. Our results replicated that task switching reduced memory selectivity. However, we found no significant effects of tDCS. Thus, the present study questions the effectiveness of the present tDCS protocol for modulating attention during task switching and subsequent memory.

Keywords: brain stimulation; tDCS; parietal cortex; attention; memory; neuronal networks

1. Introduction

In order to navigate successfully through our environment (e.g., driving a car), we rely on two attentional systems; top-down focusing (e.g., on the road) and bottom-up orienting (e.g., to incoming cyclists). The interaction between the two systems allows us goal oriented behavior while flexibly adapting to changing environments [1,2]. However, attention control is costly as it consumes cognitive resources needed for solving cognitively demanding tasks. For example, switching between two tasks leads to switch costs not only for immediate performance but also for subsequent memory of task-relevant targets [3–7]. For task-irrelevant distractors, however, a memory benefit occurs [5,6,8]. On switch trials, when the appropriate task-set is reconfigured, attention is broadened so that more distractors are encoded at the expense of targets. This explanation is in line with fMRI studies suggesting a correspondence between attention control and episodic retrieval in the posterior parietal cortex [9]. As episodic memory can be modulated by stimulating parietal substrates of attention during encoding [10], in the present study, we applied transcranial direct current stimulation (tDCS) over the parietal cortex to establish a causal link between the activity of two neural networks involved in top-down and bottom-up control during task switching. Based on previous behavioral as well as brain imaging and stimulation findings, we assumed a corresponding effect on subsequent memory selectivity.

Attention is not a unitary construct and is neither associated with a single circumscribed brain area. Rather, attention is a result of the interaction of different brain areas that are organized in networks. Specifically, the dorsal attentional network, which includes the superior parietal and frontal cortex, is involved in top-down selection of goal-relevant stimuli, while the ventral frontoparietal network is involved in bottom-up selection of salient stimuli [1,11]. That is, the ventral system interrupts the dorsal system to direct attention towards potentially relevant stimuli (e.g., fast moving objects or animals signaling danger). This dual-attention perspective is supported by fMRI studies showing a relationship between parietal cortex activity during encoding and subsequent memory performance [9]. Increased activity in the dorsal parietal cortex is associated with subsequent memory success while increased activation in the ventral parietal cortex is associated with subsequent memory failure, suggesting that hippocampal encoding mechanisms are sensitive to attention modulations [9,12–14].

An elegant demonstration of the relationship between selective attention and subsequent memory selectivity comes from studies that used a task switching procedure as an incidental study phase and assessed subsequent memory for previously presented items [3–7]. In these studies, participants were asked to classify stimuli (i.e., pictures and words) according to either one of two classification tasks signaled by a cue. Switching tasks is typically associated with more errors and longer reaction times compared to repeating a task suggesting more efficient attention control on repeat trials [15]. As a consequence, task-relevant target stimuli are better remembered if they appeared on a repeat trial, while task-irrelevant distractor stimuli are better remembered if they appeared on a switch trial [5,6]. That is, task switching impairs selective attention and selective memory. Most relevant for the present study, event related potentials around stimulus presentation and functional brain activity point to the parietal cortex as a key region for task switching and subsequent memory effects [7,16,17]. However, the roles of dorsal and ventral parts of the parietal cortex for memory are not well understood.

Brain stimulation techniques proved useful in establishing a causal link between brain activation and behavior. As a safe noninvasive method to experimentally manipulate neuronal activity in certain brain areas, tDCS has been applied over frontal and parietal cortex areas to modulate cognition. For example, tDCS over the right intraparietal sulcus affected the detection of target and distractor stimuli, suggesting an involvement of the dorsal network in top-down control of selective attention [18]. More relevant for the present purpose is a study that applied tDCS over the superior and inferior parietal lobes targeting the dorsal and ventral attentional networks [10]. Participants were asked to learn a word list while receiving tDCS stimulation over the parietal cortex. They were assigned to one of two stimulation conditions. The first condition represented the selective attention condition entailing anodal stimulation over the left superior parietal cortex (a substrate of selective attention) and cathodal stimulation over the right inferior parietal cortex (a substrate of orienting). The second condition represented the orienting attention condition entailing the opposite polarity of stimulation. After the encoding phase, a recognition memory test was administered without tDCS. Participants in the selective attention condition recognized more words than participants in the orienting attention condition, suggesting that oppositional tDCS of parietal parts of two antagonistic attention networks modulates episodic encoding.

Following up on this study, we assume that the selective attention network is responsible for the benefit in memory performance, and thus we should find a dissociation between the two networks for memory selectivity. In the present study, we combined Richter and Yeung's [5,6] paradigm with Jacobson et al.'s [10] tDCS protocol. Participants completed a task switching procedure while active or sham tDCS was applied over the parietal cortex. In the stimulation conditions, the exact same protocols were used as in Jacobson et al.'s study [10]. Oppositional tDCS was applied over the left superior and the right inferior parietal cortex. Anodal stimulation enhances neuronal excitability by depolarizing the membrane potentials of the underlying neurons. Conversely, cathodal stimulation reduces neuronal excitability by hyperpolarizing the membrane potentials of the underlying neurons. We reasoned that anodal stimulation of the superior parietal cortex would enhance activity in the dorsal network and that cathodal stimulation of the inferior parietal cortex would reduce activity in the ventral network. Together, this stimulation setup should enhance selective attention while the opposite polarity should enhance orienting. To establish a baseline and for better comparability with previous studies, we also included a sham control condition. The following recognition test consisted of pictures and words that were presented on either repeat or switch trials and that were either attended or unattended during task switching.

Based on Richter and Yeung's studies [5,6], we expected switch costs on immediate performance and subsequent memory selectivity. Based on the dual attention theory and the study by Jacobson et al. [10], we predicted higher memory selectivity for participants in the selective attention condition compared to the baseline and even lower memory selectivity for the orienting attention condition. Critically, an interaction between task switching and stimulation condition would indicate that the effect of task switching on memory selectivity relies on the relative activity levels of the two attentional networks and would support the view that task switching reduces memory selectivity by impairing selective attention during encoding. To anticipate the main results, we replicated the switch costs on immediate performance and memory selectivity, but did not find any significant effects of tDCS.

2. Materials and methods

2.1. Participants

Sixty right handed participants (34 females and 26 males) aged between 18 and 28 years (*M* = 22, *SD* = 2) took part in the study. They were randomly assigned to one of three stimulation conditions (dorsal-anodal, sham, ventral-anodal). The investigator supervised the whole procedure while undergraduate students tested and interacted with the participants. Both, students and participants were blind with respect to stimulation condition. All participants gave written consent. The local ethics committee of the University of Bern approved the study.

2.2. Design

The experiment was a 3 × 2 × 2 mixed design. It consisted of the between-subjects factor stimulation condition (dorsal-anodal, sham, ventral-anodal) and two within-subject factors; attention (target vs. distractor), and transition type (repeat vs. switch trial). In each condition were 20 participants.

2.3. tDCS

tDCS was based on the protocol of Jacobson et al. [10]. Saline soaked sponge electrodes sized 5 × 5 cm and a DC Brain Stimulator Plus device (neuroConn, Ilmenau, Germany) were used. For stimulation of the left superior parietal cortex the electrode was placed over P3 and for stimulation of the right inferior parietal cortex the electrode was placed over P6. In the dorsal-anodal condition the anode was placed over P3 and the cathode over P6. In the ventral-anodal condition the cathode was placed over P3 and the anode over P6. In the sham condition the electrodes were placed as in the active stimulation conditions but the current was turned off after 30 s. Figure 1 shows a schematic presentation of the electrode positions. Stimulation was set at 1 mA. Fade in and fade out was set to 30 s each. The duration of tDCS depended on the time participants needed to complete the tasks (approx 10 min filler tasks for wash-in and 10 min task switching). After completing the critical task switching phase, tDCS was turned off. The total stimulation duration was approximately 20 min.

2.4. Stimuli

We adopted the stimuli from Richter and Yeung [5]. The set consisted of 288 words and 288 pictures. The words (originally from Poldrack et al., 1999 [19]) were abstract and concrete nouns translated into German and one to four syllables long. The pictures were monochrome photographs of natural and man-made objects on a black background (Hemera Photo Objects, Hull, Quebec, Canada). Words were printed in brown Arial font and superimposed over the pictures. Pictures and words were paired pseudo randomly to ensure an equal number of the four category combinations (abstract noun + man-made object, abstract noun + natural object, concrete noun + man-made object, concrete noun + natural object). The picture-word associations were held constant. The pairs were counterbalanced across participants.

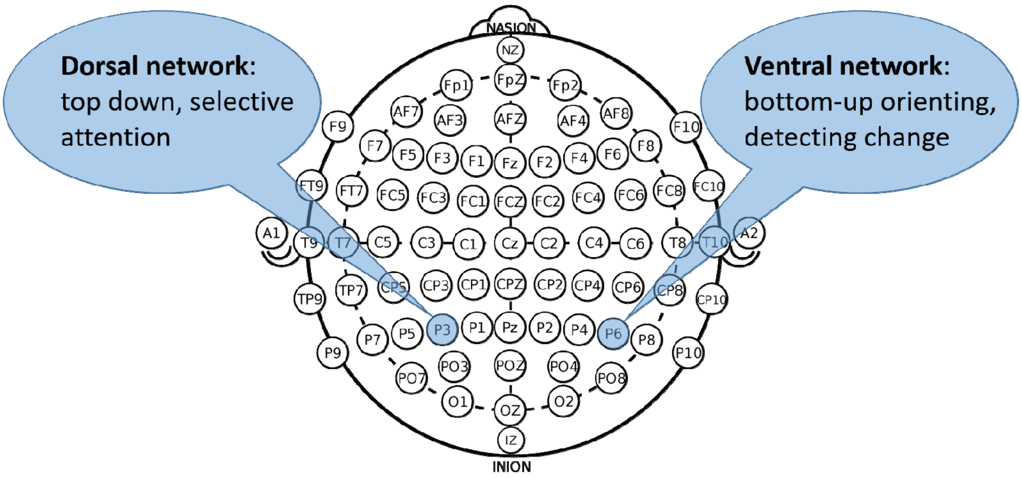

Figure 1. Schematic depiction of electrode positions.

2.5. Procedure

Participants were tested individually. The electrodes were placed over P3 and P6 and the stimulation was started (and turned off after 30 s in the sham condition). First, participants filled out the Edinburgh handedness inventory [20] and completed an unrelated filler task, assuring that at least 10 minutes elapsed between the start of the stimulation and the start of the experimental trials of the task switching procedure. After task switching the stimulation was turned off (in the case of the active stimulation conditions) and the electrodes were removed. Participants performed several filler tasks during a 20 min retention interval [10]. This extended retention interval served to make sure that the stimulation would not carry over to the recognition test. As tDCS may induce pain sensations [21] and to ensure that potential tDCS effects were not due to different levels of pain, we administered a numeric rating scale for pain. This scale was adapted from Hawker et al. [22]. Further, we asked participants to rate the (un-) pleasantness of their sensations on a 7-point scale. After completion, participants were debriefed, thanked and dismissed. In the following we describe the critical task switching procedure and the recognition test.

2.5.1. Task switching

Participants were instructed to categorize pictures as man-made or natural objects and words as abstract or concrete nouns as fast and correctly as possible. Participants gave their responses by keypress with their left middle and index fingers for the word task (x-key for abstract and c-key for concrete nouns) and the right middle and index fingers for the picture task (n-key for natural and m-key for man-made objects). The position of the picture-word pair on the screen cued the task [3,23]. If the pair appeared in the upper half of the screen, participants had to solve the picture task and if it appeared in the lower half, they had to solve the word task. Participants were informed that the stimuli would appear successively in adjacent quadrants, in continuous, clockwise rotation: top left, top right, bottom right, bottom left, top left, and so on. The stimuli were presented for 500 ms followed by a blank screen until participant's response. The next trial started after 150 ms. Figure 2 depicts the trial procedure. Participants practiced the task for 20 trials. The practice block repeated until the participant reached a minimum of 80% correct answers. After ensuring participant's comprehension of the task, the experimental block started with four warm-up trials that were discarded from analysis. The experimental block consisted of 192 experimental trials. In total, the task lasted for approximately 10 minutes.

2.5.2. Recognition test

Participants were informed that they will see pictures and words again, and that some of them were already presented in the previous task. They were instructed to identify these items by pressing the b-key for old and the n-key for new items in a forced-choice recognition test. The stimulus was presented in the middle of the screen until a key was pressed. After every "old" response a remember/know judgement was requested [3,24,25]. Participants had to press "1" if they were sure they remembered the item (recollection) and "2" if they had a feeling of knowing (familiarity). Words and pictures were tested in separate blocks. Two short practice blocks with four trials each, were administered before the experimental blocks. To attenuate the picture-superiority-effect [26], the word block was always administered before the picture block.

All 384 old items (192 pictures and 192 words) were presented randomly intermixed with 192 new items (96 pictures and 96 words). We chose a 2:1 ratio of old and new items in the test phase because only one half of the old items were attended during the encoding phase (targets) and the other half was not attended (distractors). The assignment of old and new items to one of the two test phases was counterbalanced across participants.

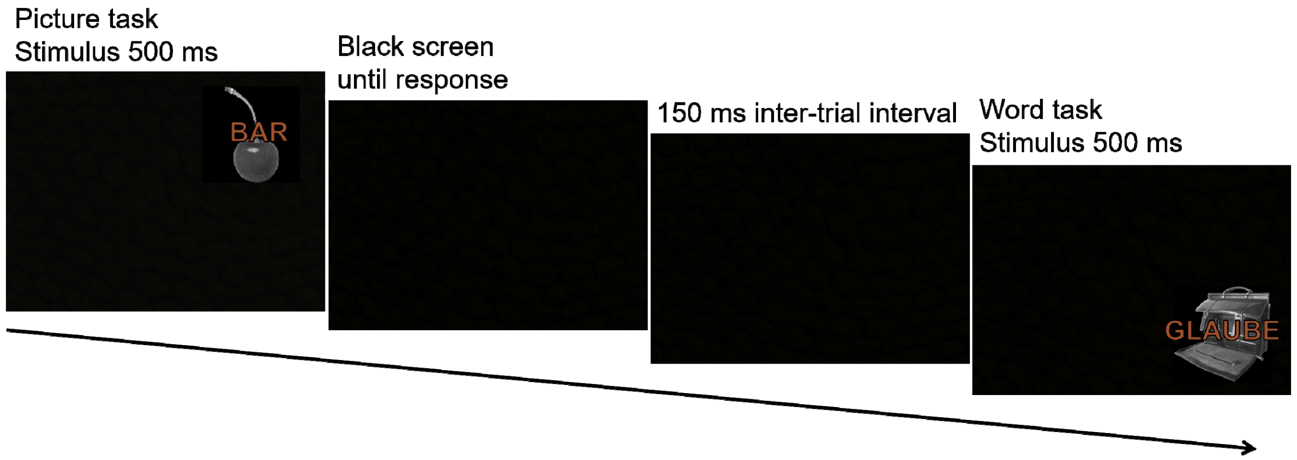

Figure 2. Two example trials of the task switching procedure. On the first trial the picture is the target and the word is the distractor as the picture task demands attention to be directed towards the picture. On the second example trial the picture is the distractor and the word the target.

3. Results

Analyses of variance (ANOVAs) were used for analyzing performance in task switching (accuracy rates and reaction times in ms) and in the recognition test (proportion of correctly recognized pictures and words, i.e., hits). Effect sizes (η_p^2) represent partial eta squared.

3.1. Task switching

Table 1 presents mean accuracy rates and reaction times. Accuracy rates and reaction times were subjected to a 3 (stimulation) × 2 (transition) ANOVA. The expected switch costs emerged for both performance measures, but no effect of stimulation was evident. Participants answered more correctly on repeat (*M* = 0.945, *SE* = 0.004) than switch trials (*M* = 0.916, *SE* = 0.007), as indicated by a significant main effect of transition, F (1,57) = 31.60, $p < 0.001$, η_p^2 = 0.36. Neither the main effect of stimulation, nor the interaction were significant for accuracy, F (2,57) = 0.57, $p = 0.567$, η_p^2 = 0.02, and F (2,57) = 0.38, $p = 0.684$, η_p^2 = 0.01, respectively. Participants answered faster on repeat (*M* = 1060, *SE* = 23) than switch trials (*M* = 1624, *SE* = 34), as indicated by significant main effect of transition, F (1,57) = 443.94, $p < 0.001$, η_p^2 = 0.89. Neither the main effect of stimulation, nor the interaction were significant for reaction times, F (2,57) = 2.20, $p = 0.120$, η_p^2 = 0.07, and F (2,57) = 0.83, $p = 0.440$, η_p^2 = 0.03, respectively.

Table 1. Task switching performance. Means and standard errors (in parentheses) for accuracy as the proportion of correct answers and reaction times in ms.

Measure	Transition	Stimulation		
		Dorsal-Anodal	Sham	Ventral-Anodal
Accuracy	Repeat	0.945 (0.008)	0.951 (0.006)	0.940 (0.008)
	Switch	0.909 (0.012)	0.926 (0.010)	0.913 (0.013)
Reaction times	Repeat	1063 (40)	1127 (47)	990 (27)
	Switch	1673 (65)	1653 (57)	1546 (52)

3.2. Recognition test

Overall hit rates and false alarm rates were highest in the dorsal-anodal condition (hits: *M* = 0.450, *SE* = 0.027; false alarms: *M* = 0.201, *SE* = 0.037), followed by the ventral-anodal (hits: *M* = 0.438, *SE* = 0.026; false alarms: *M* = 0.183, *SE* = 0.029), and sham conditions (hits: *M* = 0.395, *SE* = 0.029; false alarms: *M* = 0.150, *SE* = 0.020). To test the effects of stimulation condition, attention and transition, we conducted three separate 3 × 2 × 2 ANOVAs for recognition performance, remember-responses, and know-responses (the results for remember-responses and know-responses are presented in Table 2). Descriptive statistics are depicted in Figure 3. Attended target stimuli (*M* = 0.591, *SE* = 0.013) were better remembered than unattended distractor stimuli (*M* = 0.265, *SE* = 0.012), as indicated by the main effect of attention, F (1,57) = 572.92, $p < 0.001$, η_p^2 = 0.91. Stimuli from repeat trials (*M* = 0.439, *SE* = 0.021) were better remembered than stimuli from switch trials (*M* =

0.417, *SE* = 0.018), as indicated by a main effect of transition, *F* (1,57) = 12.63, $p < 0.001$, η_p^2 = 0.18. The significant interaction between attention and transition, *F* (1,57) = 35.03, $p < 0.001$, η_p^2 = 0.38, represents the switch costs on memory selectivity; *better* target memory for repeat (*M* = 0.621, *SE* = 0.017) compared to switch trials (*M* = 0.561, *SE* = 0.019), but *worse* distractor memory for repeat (*M* = 0.257, *SE* = 0.017) compared to switch trials (*M* = 0.273, *SE* = 0.018). The main effect of stimulation was not significant, *F* (2,57) = 1.14, $p = 0.326$, η_p^2 = 0.04, nor were the interactions with attention, *F* (2,57) = 0.74, $p = 0.480$, η_p^2 = 0.03, transition, *F* (2,57) = 0.01, $p = 0.985$, $\eta_p^2 <$ 0.01, or the three-way interaction, *F* (2,57) = 1.36, $p = 0.264$, η_p^2 = 0.05.

In order to assess the extent to which the data support the absence of stimulation effects we conducted a Bayesian analysis [27]. Using JASP (Version 0.13), we calculated a Bayesian ANOVA on recognition memory with the factors attention, transition, and stimulation. The Bayes Factors for all effects are presented in Table 3. The three-way interaction between attention, transition, and stimulation was the focus of the present study. Thus, we compared a model with the interaction to a model without the interaction. Including the three-way interaction in the model gives a Bayes Factor of 0.213, while excluding the three-way interaction gives a Bayes Factor of 4.702, suggesting that the data are 4.702 times more likely under the model without the three-way interaction than under the model that adds the interaction.

Table 2. Results of the recognition test for remember- and know-responses. Mean proportion of hits was analyzed by means of a 3 (stimulation: dorsal-anodal, sham, ventral-anodal) × 2 (attention: target vs. distractor) × 2 (transition: repeat vs. switch trial) analysis of variance (ANOVA). The same ANOVA was conducted separately for remember-responses and for know-responses. η^2_p indicates partial eta squared.

		Remember			Know		
Effects	*df*	*F*	*p*	η^2_p	*F*	*p*	η^2_p
Stimulation	2,57	0.30	0.74	0.01	1.52	0.23	0.05
Attention	1,57	414.15	<0.01	0.88	16.81	<0.01	0.23
Transition	1,57	29.10	<0.01	0.34	0.23	0.63	<0.01
Stimulation × Attention	2,57	0.19	0.83	0.01	0.99	0.38	0.03
Stimulation × Transition	2,57	0.02	0.98	<0.01	<0.01	>0.99	<0.01
Attention × Transition	1,57	52.15	<0.01	0.48	0.16	0.70	<0.01
Stimulation × Attention × Transition	2,57	0.04	0.96	<0.01	1.93	0.16	0.06

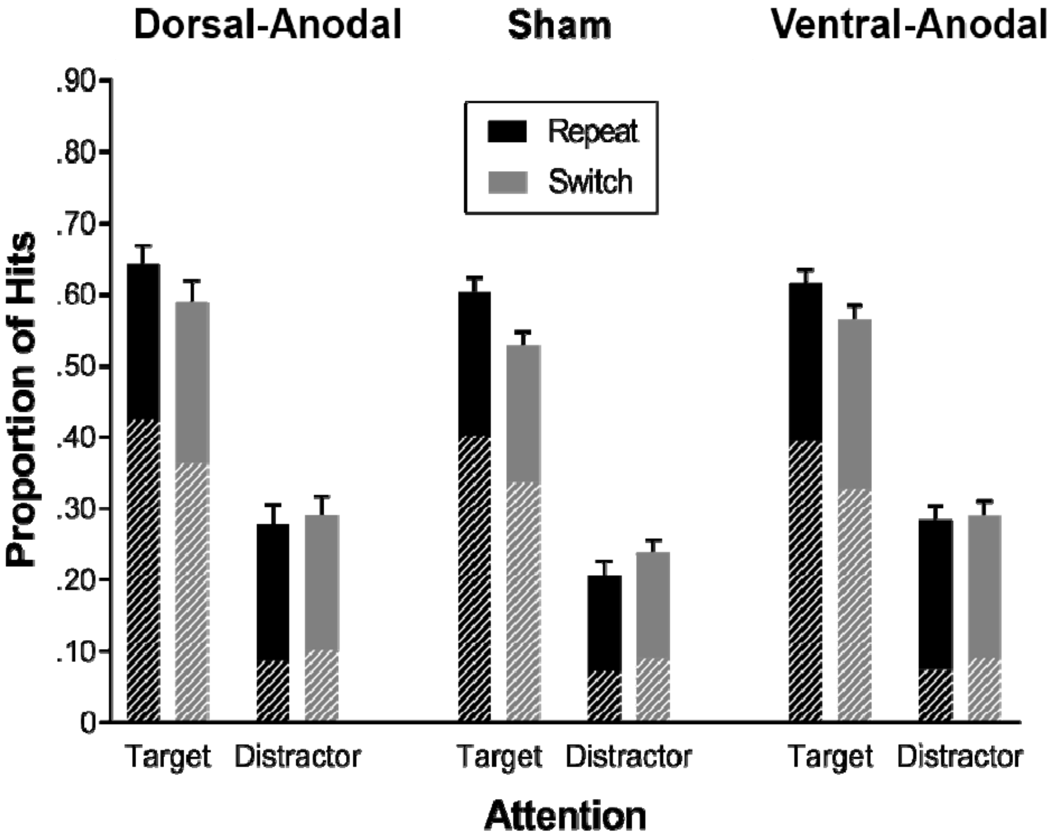

Figure 3. Memory performance. Mean proportion of correctly recognized old items (hits) as a function of stimulation (dorsal-anodal, sham, and ventral-anodal), attention (target vs. distractor), and transition (repeat vs. switch trial). The shaded areas reflect remember-responses, the solid areas reflect know-responses. Error bars represent standard errors.

Table 3. Results of the Bayesian analysis of memory performance. Models containing the effect were compared to equivalent models stripped of the effect. Given the data, the Bayes Factor indicates the likelihood of the model including the effect to a model excluding the effect.

Effects	Bayes Factor
Stimulation	1.541964
Attention	1.321946e + 75
Transition	1.548470
Stimulation × Attention	0.098741
Stimulation × Transition	0.030167
Attention × Transition	428.716171
Stimulation × Attention × Transition	0.212671

4. Discussion

The present study aimed to disentangle the roles of two attentional systems for selective memory by applying oppositional tDCS over the superior parietal cortex (a substrate of selective attention) and inferior parietal cortex (a substrate of orienting) during task switching. The results revealed a robust task switching effect on attention and memory selectivity, replicating previous research [5,6]. Compared to repeating a task, switching between two classification tasks led to longer reaction times and more errors, suggesting hampered attention control on switch trials. The subsequent recognition test revealed a corresponding task switching effect on memory: Worse target memory but better distractor memory for items presented on switch (vs. repeat) trials. That is, the difference between target memory and distractor memory was lower on switch than repeat trials, indicating that task switching reduces memory selectivity. As this effect was not modulated by the application of tDCS and we did not find any other tDCS effects, we conclude that the present tDCS protocol was not suitable to modulate task switching performance or memory performance.

This failure is somewhat surprising, as a large body of neuroimaging studies suggests that activation in ventral and dorsal parietal brain areas is associated with behavioral indicators of selective attention and subsequent memory effects [1,2,9,12,13]. Furthermore, several studies stimulated the parietal cortex by tDCS or a related method (i.e., transcranial magnetic stimulation) and were indeed successful in modulating attention and memory [10,18,28–30]. In fact, our tDCS protocol was identical to a previous study that found a memory benefit for the dorsal-anodal stimulation condition.

It is possible that differences in the study design and the materials are responsible for the lack of tDCS effects in the present study. To account for different study designs, we reanalyzed our data without the sham condition. However, the difference between the stimulation conditions was still not significant, suggesting that the sham condition did not mask any true stimulation effects. For practical reasons[1] we had to vary stimulation between subjects. Varying stimulation within-subject may be critical as individual's cortical activity upon arrival for testing affect polarity effects [31]. For example, alertness and caffeine intake can interact with stimulation and even inverse the effects of anodal and cathodal stimulation [32]. It could be that individual differences in cortical excitability obliterated the effects of anodal and cathodal stimulation on the mean grouping level. Another difference lies in the duration of tDCS. In Jacobson et al.'s [10] study tDCS lasted for 10 min while in the present study tDCS lasted for a total of approximately 20 min. By starting tDCS 10 min before the critical task switching phase, we aimed to reduce inter-individual differences in cortical activity upon arrival and ensure that the stimulation is fully effective at the start of the critical task switching phase. This could present a critical methodological difference between studies.

Furthermore, materials and tasks differed considerably between studies. Jacobson et al. [10] used word lists and instructed participants to encode the words for a later recognition test. In our study, however, a task switching procedure served as the incidental encoding phase and participants had no knowledge about the upcoming recognition test. A recent meta-analysis suggests that the

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[1] Repeating the task switching procedure and the recognition test within-subject would make the second recognition test not so surprising anymore. Informing participants about any upcoming recognition tests would alter their attentional control during task switching because they could engage strategies for better encoding.

cranial-cranial electrode pair placement is not effective in modulating executive functions (as opposed to an extracranial-cranial montage) [33]. Thus, it could be that the difference in demands posed on executive functions may explain why the cranial-cranial oppositional tDCS protocol was not effective in the present study. The explicit memory task used in the Jacobson et al.'s study [10] poses less demands on executive functions than the task switching procedure used in the present study. Because tDCS interacts with the brain activity elicited by a specific task [34], and because participants reported that the task switching experiment was cognitively demanding, it could be that our task demands already engaged the attentional networks (and probably also executive functions) so intensively that tDCS had no further impact. This interpretation is in line with a recent meta-analysis that found small and non-significant tDCS effects on memory and it suggests that tDCS exerts its influence only under specific conditions [35].

5. Conclusion

A stimulation protocol that successfully modulated memory in a previous study [10], was not successful in the present study when applied during incidental encoding of study materials presented during task switching. The fact that tDCS exerts its effect in one paradigm but not in another suggests that tDCS effects are highly task-specific. This conclusion converges with the inconsistent literature on parietal and frontal tDCS effects on attention and memory [33–41]. More research is needed to better understand how tDCS interacts with task-specific brain activation effects. Studies that systematically vary stimulation protocols with identical tasks and studies that use identical stimulation protocols with different tasks may be fruitful in identifying the circumstances under which tDCS effects emerge.

Author contributions

MD and BM designed the study. MD programmed the experiment, supervised data collection, and analyzed the data. MD and BM interpreted the results. MD wrote the first draft. BM provided critical revisions. Both authors approved the final version of the article.

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Conflict of interest

The authors declare no conflict of interest.

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