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Individual Differences in Task-switching Paradigms

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Summary

Previous attempts to completely eliminate task-switch costs by improving advance preparation (e.g., Schneider, 2016, 2017) and by extensive practicing task rules (e.g., Zhao, Wang & Maes, 2018) had limited success; most researchers reported significant “residual” switch costs in typical task-switching paradigms, suggesting incomplete preparation of tasks. In most task-switching studies it was ignored that participants may have different switching abilities and/or strategies. It has been shown, however, that some participants perform better than others, showing only small switch costs for specific target-response mappings (Lindsen & De Jong, 2010), or reduced switch costs after extended practice of task rules (Stoet & Snyder, 2007). Other researchers have claimed that a few select participants showed superior performance in multi-tasking as well as other cognitive and perceptual tasks (Haaf & Rouder, 2017, 2018; Ramon et al., 2016; Robertson, Noyes, Dowsett, Jenkins & Burton, 2016; Strayer & Watson, 2012). It is therefore possible that in task-switching a few participants may also perform considerably better than others, showing minimal or no errors and no switch costs across different conditions. The present thesis aimed to study individual differences in task switching by monitoring group-average as well as individual performance under different conditions.

Chapter 1 provides an overview of different task-switching paradigms and accounts to explain task-switch costs and residual switch costs. In particular, I discuss studies that considered individual differences in various tasks and experimental paradigms.

In order to detect superior performance in task switching and to study individual differences, I conducted an experiment and two follow-up studies that are documented in Chapter 2. I employed Generalised Linear Mixed-effects Models (GLMMs; Bolker et al., 2009) on single-trial RTs in order to investigate whether individual participants exhibit comparable switching effects and whether best performers vary across different conditions, paradigms, and experiments. Seven psychological scales and a Raven intelligence test were also employed in order to better understand possible factors that may be related to differences in performance in task switching. The results of Chapter 2 suggest that there are considerable individual differences in task switching and that smaller individual switch costs may be due to more efficient preparation during cue-stimulus intervals. Furthermore, I suggest that efficient task preparation may be linked to better executive control, general intelligence, higher motivation, and lower levels of impulsivity.

Since efficient preparation after task-cueing plays an important role in reducing or even eliminating switch costs, Chapter 3 sought to facilitate faster cue-based preparation, thereby reducing switch costs in typical participants. Previous research has suggested that task-switch costs are smaller for “transparent” compared to “non-transparent” or standard cues (e.g., Logan & Schneider, 2006; Schneider, 2016). In three experiments I compared “non-priming” cues with carefully designed “priming” cues that indicate the upcoming target feature and response mappings. I found that participants who used priming cues showed smaller and non-significant switch costs in their response times, independent of the interval between cue and target stimulus. These participants also showed more homogenous task-switching performance. In a related EEG study that investigated the temporal dynamics of preparation I provide evidence that priming cues elicited significantly larger cue-locked positivity in switch trials compared to repeat trials at electrode Pz, in different cue-stimulus intervals. Similar to previous results on transparent cues, this suggests that preparation can be facilitated (e.g., Karayanidis & Jamadar, 2014).

Gender-related individual differences in task switching are investigated in Chapter 4. Previous reports on gender differences have been controversial (e.g., Polunina, Bryun, Sydniaeva & Golukhova, 2018; Stoet, O’Connor, Conner & Laws, 2013). In Chapter 4 I studied whether gender differences are present in the preparation phase of task-switching by manipulating the cue-stimulus interval. The results of the experiment in Chapter 4 suggest that females may have a slight advantage in task switching for longer preparation intervals. While individual switch costs varied considerably for female and male participants, females showed smaller congruency effects in trials with task repetition. I suggest that female participants were faster than males in task preparation. In addition, some females seemed to employ a different strategy in repeat trials. For example, they may have performed different tasks by recalling cue-stimulus-response associations without applying the task rules.

In Chapter 5, I summarise possible reasons that may lead to superior switching performance and discuss other factors that may account for different switching performance across individuals. Limitations and future directions of research are also outlined. I suggest that individual differences should be considered and reported in order to improve model and hypothesis testing and to make results more replicable. Finally, I discuss whether superior switching abilities can be related to other tasks and situations.

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First, I would like to express my sincere gratitude to my primary supervisors Dr. Martin Lages and Prof. Gijsbert Stoet. I would like to thank Martin for his insightful comments and warm encouragement along the way. His guidance in research design, advanced methods and academic report-writing helped me in all the time of my PhD study and will also benefit my future research. My sincere thank also goes to Gijsbert who taught me fundamentals of conducting cognitive research and gave me endless support. It all started in Fall 2015 when he offered me such a great opportunity to start the PhD.

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Last but not the least, to my dearest parents and my husband, thank you for the warm love, continued patience and invaluable support in my everyday life.

Declaration

I declare the research reported in this thesis to be my own. It has not been submitted for any other degree at the University of Glasgow or any other institution. The research was completed between October 2015 and October 2018 in the School of Psychology and School of Education, University of Glasgow, under the supervision of Dr. Martin Lages and Professor Gijsbert Stoet.

Printed Name: _____

Signature: _____

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Li, X., **Li, B.**, Liu, X., Lages, M. & Stoet, G. (2019). Task-switching costs disappear if non-chinese participants respond to chinese characters. *Journal of Experimental Psychology: Learning, Memory, and Cognition*.

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CHAPTER 1 Literature Review

1.1 Overview of Chapter 1

In daily life, switching between two or multiple tasks rapidly is not easy and is usually accompanied by deteriorated performance, compared to completing one task after another. With the interest in understanding how people switch between tasks, a number of laboratory-based task-switching paradigms were developed in the past decades.

Most task-switching paradigms involve two tasks or more. In the past task-switching experiments, participants were required to judge (a) whether a given digit is greater or smaller than 5, or (b) whether the digit is odd or even (e.g., Koch, 2003; Sudevan & Taylor, 1987), or (c) whether the letter member is vowel or consonant (e.g., Rogers & Monsell, 1995; Nieuwenhuis & Monsell, 2002); judge (a) whether a target stimulus is on the upper or lower quadrants, or (b) whether the target is on the left or right quadrants (e.g., Meiran, 1996; Meiran, Chorev & Sapir, 2000); use “Stroop” stimuli and switch between (a) naming the ink colour of a printed word and (b) reading the word (e.g., Allport, Styles & Hsieh, 1994; Regev & Meiran, 2014). Task switching is either predictable (Koch, 2003; Monsell, Sumner & Waters, 2003; Rogers & Monsell, 1995) or unpredictable (Meiran, 1996; Meiran et al., 2000), or even being decided by participants themselves (Arrington & Logan, 2004, 2005; Arrington, Weaver & Pauker, 2010; Demanet & Liefoghe, 2014). In the Section 1.2 of this chapter, I first summarise key task-switching paradigms that were widely used in the past decades. I discuss their advantages and limitations while highlighting the related individual differences.

No matter what paradigms and experimental procedures are being employed, longer response times and higher error rates are typically reported when switching between tasks compared to repeating the same task. Significant differences suggest task-switch costs (for reviews see Kiesel et al., 2010; Koch, Poljac, Müller & Kiesel, 2018;

Vandierendonck, Liefoghe, & Verbruggen, 2010). However, it has been shown that individual differences in task-switching performance occur and that switch costs vary across individuals (e.g., Karayanidis et al., 2010; Lindsen & De Jong, 2010; Stoet & Snyder, 2007; Umemoto & Holroyd, 2016). Two major accounts have been proposed to explain the commonly observed task-switch costs and individual differences: the interference account (e.g., Allport et al., 1994; Mueller, Swainson & Jackson, 2007; Rubin & Koch, 2006; Waszak, Hommel & Allport, 2003), and alternatively, the preparation account (e.g., Altmann, 2004a, 2004b; Demanet & Liefoghe, 2014; De Jong, 2000; Fintor, Stephan & Koch, 2018; Koch & Allport, 2006; Lindsen & De Jong, 2010; Monsell & Mizon, 2006; Nieuwenhuis & Monsell, 2002; Rogers & Monsell, 1995; Schneider, 2016, 2017; Verbruggen, Liefoghe, Vandierendonck & Demanet, 2007). In Section 1.3 I critically discuss these two accounts. In addition, since switch costs are defined as impaired performance, i.e. increased RTs and ERs in task switching, researchers have tried to reduce or eliminate switch costs by improving task preparation (e.g., Nieuwenhuis & Monsell, 2002; Schneider, 2016, 2017) and by extensive practice of task rules (e.g., Stoet & Snyder, 2007; Strobach, Liepelt, Schubert and Kiesel, 2012; Zhao et al., 2018). However, most researchers reported significant “residual” switch costs in typical task-switching paradigms (e.g., Meiran et al., 2000; Nieuwenhuis & Monsell, 2002; Rogers & Monsell, 1995; Schneider, 2016, 2017; Zhao et al., 2018; but see Fintor et al., 2018, and Verbruggen et al., 2007). Their efforts of reducing switch costs are also summarised in Section 1.3.

Researchers have argued that residual switch costs cannot be eliminated because task preparation is unlikely to be completed before target stimulus onset (e.g., Hydock & Sohn, 2011; Mayr & Kliegl, 2003; Rogers & Monsell, 1995; Rubinstein, Meyer & Evans, 2001; Weidler & Abrams, 2013), does not occur in some of the switch trials (De Jong, 2000), and is completed only for specific stimulus-response pairs (Lien, Ruthruff,

Remington, & Johnston, 2005). However, recent studies have also provided evidence for individual differences in task-switching (Lindsen & De Jong, 2010; Stoet & Snyder, 2003, 2007; Stoet et al., 2013), multitasking (Medeiros-Ward, Watson & Strayer, 2014; Strayer & Watson, 2012; Watson & Strayer, 2010) and in other cognitive tasks (Haaf & Rouder, 2017, 2018), perceptual tasks (Robertson, et al., 2016; Russell, Duchaine & Nakayama, 2009) and memory tasks (Mallow, Bernarding, Luchtmann, Bethmann & Brechmann, 2015; Ramon et al., 2016). These studies suggested that there were a few select participants with superior performances in complex tasks that require high level of attentional and cognitive control. These exceptional participants may have superior executive control, better trait-like abilities, employ more efficient strategies and/or are more highly motivated. It is therefore possible that in task-switching experiments a few participants may also perform considerably better than others, showing minimal or no errors and no switch costs across different conditions. In Section 1.4 I critically discuss previous results considering individual differences under different tasks and conditions. Their approaches to reveal individual differences and to identify select individuals with superior performances are also highlighted. In Section 1.5 I state the general objective of the present thesis - to study individual differences in task switching by monitoring group-average and individual performance under different conditions. Generalised Linear Mixed-effects Models provide a powerful statistical tool to investigate this (GLMMs; Bolker et al., 2009).

1.2 Task-switching paradigms

The ability to switch between tasks has been investigated in both experimental and individual differences research using a variety of task-switching paradigms. In previous task-switching studies it has been suggested that different paradigms can measure a unique

switching ability along different dimensions of cognitive control. In this section I will summarise some of the pioneering work on task switching. I will also discuss the three main paradigms that have been used in past task-switching studies and highlight individual differences in performance.

1.2.1 List paradigm

The paper-and-pencil administered list paradigm of Jersild (1927) is typically cited as the first behavioural investigation into task-switching. Jersild (1927) had participants working through lists of items. Participants performed lists of the same task repeatedly or alternated between two different tasks in other lists. For example, Jersild (1927) asked participants to add 6 to each number in List 1 and subtract 3 from each number in List 2. Participants were also asked to work through two more lists - List 3 and 4, where responses alternate between adding and subtracting. The lists that consisted of only one type of task were called “pure lists” or “single-task lists” (List 1 and List 2 in Figure 1.1), and the lists that required alternately adding and subtracting were called “shift lists” or “mixed-task lists” (List 3 and List 4 in Figure 1). Jersild, using a stopwatch, compared the overall time for completing tasks in the single-task lists with the time in the mixed-task lists, and found a difference in completion time: Participants took longer time to complete the mixed-task lists than the single-task lists, indicating a *shift loss* of about 30 ms when mixed-task lists were performed first and of about 32 ms when mixed-task lists were performed after the single-task lists.

	List 1	List 2	List 3	List 4
	<i>add 6</i>	<i>subtract 3</i>	<i>alternate</i>	<i>alternate</i>
	21	19	39	42
	13	25	26	31
	45	31	13	50
	36	17	56	21
	⋮	⋮	⋮	⋮
	33	26	13	29
	67	53	29	33
	51	42	42	53

Figure 1.1. An add-6/subtract-3 example of Jersild (1927) list paradigm. Note that in the real experiment there were no white and black background in each trial, so that participants alternated between addition and subtraction tasks without explicit task cueing. The numbers here are examples, for illustrative purpose only.

According to Jersild (1927), an explanation for the shift loss was that when performing in the single-task lists participants only need to establish a set of task rule that is relevant to the currently performed list of tasks (e.g., a list of addition task), whereas when performing in the mixed-task lists participants need to alternate between different task goals and task representations leading to a loss in efficiency. For example, when switching from adding to subtracting, the adding rule, i.e., adding 6 to the number needs to be inhibited while the relevant subtracting rule, i.e., subtracting 3 from the number needs to be activated and applied to the current number-target.

However, later studies interpreted the performance differences between single-task and mixed-task list as increased working memory load for maintaining two different sets of tasks and keeping track of the sequence of tasks in mixed-task lists compared to attending to only one task in single-task lists (Philipp, Kalinich, Koch & Schubotz, 2008; Rogers &

Monsell, 1995). In order to compare the performance between repeat and switch trials to be appropriate, both types of trials must be performed under the same cognitive loads or demands. There was evidence that performance in task repetitions of mixed-task blocks was impaired (i.e., longer response times and higher error rates) compared to task repetitions of single-task blocks, reflecting different task conflicts and cognitive control processes between single-task and mixed-task blocks (Philipp et al., 2008; Rubin & Meiran, 2005). There were no task-repeat trials in Jersild's mixed-task lists. Therefore, Jersild's list paradigm was criticised as not measuring the pure task-switching process. Because of this issue, this experimental paradigm of task switching is seldom used nowadays.

1.2.2 Alternating-run paradigm

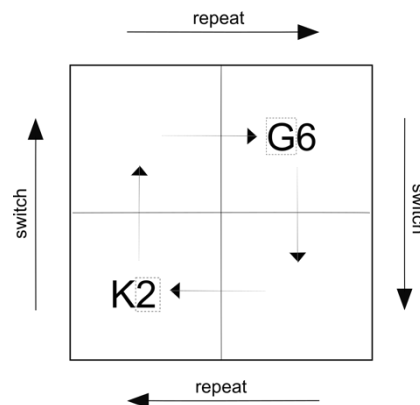
To overcome the problem of Jersild's list paradigm, Rogers and Monsell (1995) developed the alternating-run paradigm. In their study, task-repetitions were included in mixed-task blocks, allowing the study of both task-repeat and task-switch trials under equal working memory load. Similar to Jersild (1927), the task sequences were predictable.

In Rogers and Monsell (1995), a pair of a letter and a digit was presented in each trial. Participants switched between categorising a letter as a vowel or consonant and categorising a digit as odd or even in the letter-digit pair. To help participants to keep track of the task sequence, the letter-digit pair was presented on a 2*2 grid, moving clockwise (Figure 1.2A). Participants were told to perform the letter task and to respond to the letter only when the letter-digit pair was shown in one of the top two cells, and to perform the digit task and to respond to the digit only when the pair was shown in one of the bottom two cells. As a consequence, this paradigm requires participants to switch to another task in every second trial (e.g., letter-**digit**-digit-**letter**-letter-**digit**-digit; the bolded words are

task-switch trials and the unbolded words with underlines> are task-repeat trials).

Participants were asked to press the “left” key on the keyboard for even digits and consonants, and the “right” key for odd digits and vowels (Figure 1.2B). Compared to performance in task-repetition trials, participants had longer response times and higher error rates in task-switch trials. This switch-repeat difference was replicated in other studies, even though the upcoming task was simple and predictable, the preparation time was more than a second, and there was an external cue that helps participants to retrieve the relevant task set (Koch, 2003, 2005, 2008; Monsell, Sumner & Waters, 2003; Rogers & Monsell, 1995).

A.



B.

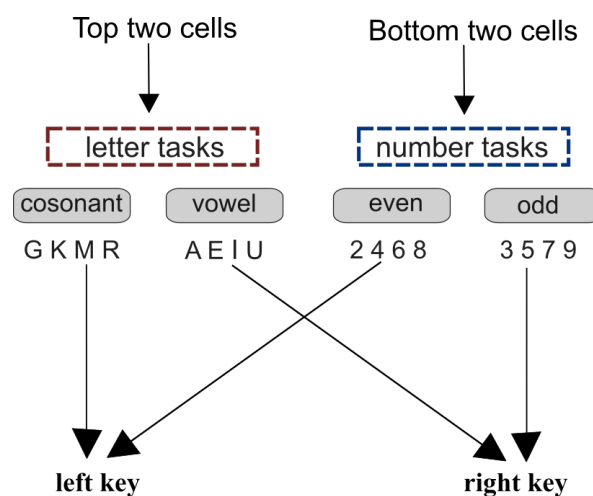


Figure 1.2. Alternating-run paradigm, adapted from Rogers and Monsell (1995, Figure1). **A.** Task-repeat and task-switch trials. The letter-digit pair moves clockwise resulting in an AABBA task order. **B.** task-response mappings.

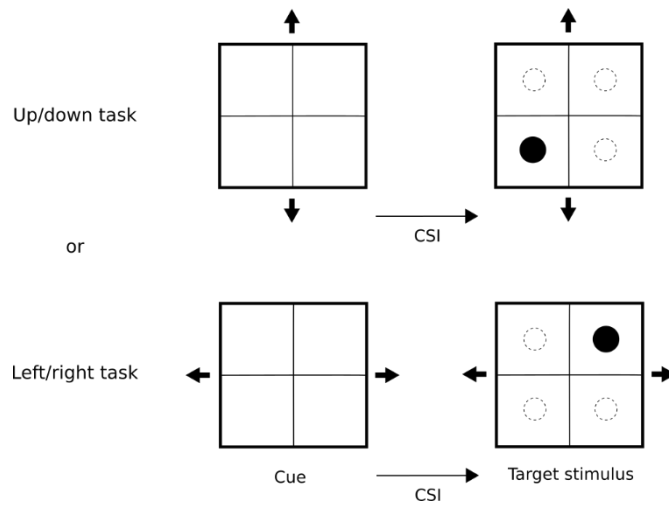
Variants of alternating-run paradigm were developed, such as varying the number of task repetitions in order to study recovery time from a recent task switch (Monsell et al., 2003); providing external task cues in order to study whether advance preparation can be facilitated (Koch, 2003); requiring implicit learning of the task sequence in order to study whether implicit learning and endogenous memory of the task sequence can improve task switching (Gotler, Meiran & Tzelgov, 2003; Heuer, Schmidtke & Kleinsorge, 2001; Koch, 2005, 2008). Although the variety of paradigms, an advantage of the alternating-run paradigm is that task-repeat and task-switch trials occur in the same block, allowing to study task switching in a block of trials with equal cognitive demands and conflicts.

There are limitations for alternating-run paradigms. According to Altmann (2007), alternating-run switch costs consist of not only costs of switching tasks but also costs specific to the first trial of each run due to functional setting up of task representations. These costs cannot be separated in the alternating-run procedure. In addition, since the upcoming task is predictable in the alternating-run paradigms, participants may keep track of the task sequence in memory in order to fast access tasks. Participants may have started preparing for an upcoming switch even when they are currently performing in a task-repeat trial (i.e., AA **BB** AA B, the bolded letters are task-repeat trials, in which a switch preparation may start). This may cause additional interference in the current task processing. According to Meiran and colleagues (1996, 2000), when task switch is unpredictable participants were unlikely to prepare the task switch while performing in a task-repeat trial, which facilitates the beneficial effect of task repetitions (but see Poljac, Koch & Bekkering, 2009).

1.2.3 Task-cueing paradigm

In order to overcome the limitations of the alternating-run procedure, task-cueing paradigms or explicit cueing paradigms were developed (Meiran, 1996, 2014; Meiran et al., 2000; Sudevan & Taylor, 1987). Task presentation in the task-cueing paradigms can be randomly, in contrast to the fixed sequence of task order in alternating-run paradigms. Participants know which task to perform in the upcoming trial based on a task cue preceding or accompanying the target stimulus. For a classic example, Meiran (1996) and colleagues (Meiran et al., 2000) asked participants to perform task switching on a 2 * 2 grid, in which the target could appear in one of the four cells without a fixed sequence. In each trial, there were two subtended arrowheads served as a task cue before the target stimulus was presented. The arrowheads that were positioned vertically signalled an up/down task, and that were positioned horizontally signalled a left/right task (Figure 1.3A). Participants can prepare the relevant task between the onset of the cue and target stimulus, and press the corresponding key to make a response as soon as the target stimulus is presented (Figure 1.3B). Consistent with alternating-run paradigms, researchers found that performance in task-switch trials was impaired (i.e., longer response times and higher error rates) compared to task-repeat trials, indicating significant switch costs (Altmann, 2004a, 2004b; Meiran, 1996, 2014; Meiran et al., 2000; Schneider, 2016, 2017).

A.



B.

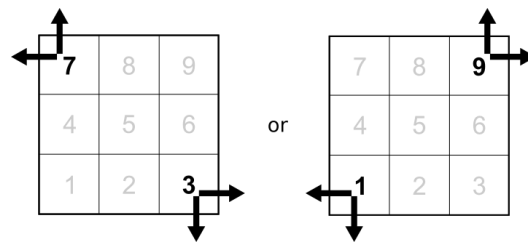


Figure 1.3. Task-cueing paradigm, adapted from Merian et al. (2000, Figure 1). **A.**

Example trials of the up/down task and left/right task. **B.** Task-response mappings were counterbalanced between experimental sessions. Each trial starts with a task cue indicating the upcoming task. Following the cue-stimulus interval (CSI), participants need to respond to the target stimulus based on the relevant task rule. As the examples shown in the figure, if the arrows point up and down, an up/down task needs to be performed in the current trial. In the example, participant need to press the down key (“3” or “1” depending on the experimental session) because the target stimulus appears in the bottom left cell. In another example, a right key (“3” or “9” depending on the experimental session) needs to be pressed because this is a left/right task and the target stimulus appears in the top right cell. Note that the target stimulus can appear in any of the four quadrants in each upcoming trial.

In addition to the unpredictable task sequences, there is another important advantage of the task-cueing paradigms. It allows to study cognitive control processing over two critical intervals: **(a)** the interval between the response in trial $n-1$ and the cue in trial n ; **(b)** the interval between the onset of the task cue and target stimulus in a trial. This would separate interference decay process (interval a) from task preparation process (interval b) in task switching. I will detail studies on these two control processes in Section 1.4. In short, the cognitive preparatory process of goal updating and rule activation can be involved in interval **b** whereas the interference from the previous task set and response mappings may dissipate gradually in interval **a** (e.g., Kiesel et al., 2010; Koch et al., 2018; Vandierendonck et al., 2010).

Past results showed individual differences in task-switching following a task cue because participants engaged differently in the cue-based preparation (e.g., Lavric, Mizon & Monsell, 2008; Lindsen & De Jong, 2010; for a review see Karayanidis et al., 2010). For example, few participants prepared more efficiently in every trial and therefore showed reduced RT switch costs when with a cue-stimulus interval of over a second. Other participants engaged in the cue-based preparation only in a proportion of trials (e.g., Lindsen & De Jong, 2010). Trials with effective preparation were found to be associated with faster responses, and more efficient brain activities (e.g., Karayanidis et al., 2010).

Task-cueing paradigm has limitations. Providing a task cue in each trial yields costs of restarting a task (e.g., Altmann & Gray, 2002). Studies showed that performance was impaired in cued trials compared to trials without a cue. Evidence can be found in task-switching paradigms with intermittent instructional cues, a cue indicates whether repeating the previous task or switching to a different task (Altmann & Gray, 2002; Gopher, Armony & Greenshpan, 2000; Poljac et al., 2009). This impaired performance in trials with a cue was explained as the disturbed rhythm of a sequential task execution (Gopher et al., 2000) and the processes related to cue-based task activation and interference control that arises

from a recent activated competing task when in the blocks where tasks are mixed (Poljac et al., 2009). However, the restart costs can be reduced by task predictability (Koch, 2005, 2008; Poljac et al., 2009).

In addition, task-switching performance using experimental manipulated task-cueing or a prespecified task sequence may overlook the ability to self-initiate a task. In task-cueing paradigms it is unlikely to study self-selected actions (i.e., an initialised goal-directed process that is related to self-control of attention and voluntary task selection, etc.), which however is more critical in daily life. This is appropriately investigated in voluntary task-switching paradigms.

1.2.4 Voluntary task-switching paradigm

Voluntary task switching involves active selection by the participants of which task they decide to perform in the upcoming trial while eliminating tight environmental controls such as explicit task-cueing, limited task sequence and preparation time (Arrington & Logan, 2004, 2005; Arrington et al., 2010; Demanet & Liefoghe, 2014; Liefoghe, Demanet & Vandierendonck, 2009; Mayr & Bell, 2006; Yeung, 2010).

Generally, voluntary task-switching experiments involve two or more simple categorization tasks. A well-known example of the voluntary task-switching is from Arrington and Logan (2004). In their study, participants voluntarily determined the upcoming task, performing either parity or magnitude judgement on a single digit. Specifically, responses made with the left hand using the *d* and *f* keys would indicate “lower than 5” and “higher than 5”, respectively, in the magnitude judgement task, while responses made with the right hand using the *j* and *k* keys would indicate “even” and “odd”, respectively, in the parity task. Participants received instructions that each task must

be performed about equally often and that the sequence of selected tasks is random. However, although participants were free to select which task to perform, performance significantly deteriorated in task-switch trials compared to task-repeat trials (e.g., Arrington & Logan, 2004).

An obvious advantage of voluntary tasks-switching paradigm is that this paradigm enables participants to voluntarily engage in an upcoming task, in addition to standard task performance measures of response times and error rates. This paradigm enables endogenous executive control that is indispensable for making a task choice and producing a correct response.

A critical limitation of this paradigm is that task-switching behaviours may exhibit consistent biases away from true randomness, even though participants are asked to produce a random sequence of trials. When free to choose which task to perform in a given trial, participants tend to repeat tasks more than switching to a different task, resulting in repetition bias. Repetition bias can be caused by different experimental manipulations. For examples, previous research has shown that the tendency to repeat a same task (perseveration) was larger when participants had short time between the response in the previous trial and the onset of the target stimulus in the current trial (e.g., Arrington & Logan, 2004, 2005; Demanet & Liefoghe, 2014; Liefoghe et al., 2009). In addition, participants were less likely to make voluntary task switching when there was an exact stimulus repetition (Arrington et al., 2010; Mayr & Bell, 2006), and even when there was a repetition of the stimulus features that were unattended in previous trial (Yeung, 2010).

However, a recent individual differences study on voluntary task switching and traits provided evidence that when participants in the condition where they were required to select the shape and location tasks at random and equally often, participants who had on average larger RT and ER switch costs were less likely to switch between tasks; they

tended to select the harder task (shape task) more often (Umemoto & Holroyd, 2016). Moreover, in this study participants who scored higher in persistence had greater compliance with task instructions associated with reduced task bias and on average reduced RT and ER switch costs. However, the more persistent participants showed on average longer response times and higher error rates. Umemoto and Holroyd (2016) concluded that individuals high in persistence were more concerned with the higher-level aspects of the meta-task (i.e., concerned with switching between tasks) than about performance on the tasks themselves. According to the results of an fMRI study by Kurniawan et al. (2010), Umemoto and Holroyd (2016) suggested that persistent individuals may have more activated anterior cingulate cortex with better cognitive control over task selection.

1.3 Task-switching – Main empirical findings and theoretical interpretations

In the task-switching research, task-switching abilities are studied from many perspectives and using three main paradigms: predictable task-switching paradigm, task-cueing paradigm, and voluntary task-switching paradigm. Based on the specific research purposes, the studies usually focus on different cognitive aspects and the data that are discussed reveal different task-switching processes. Nevertheless, whatever their focuses are and whatever paradigms being employed, it is often a consistent and important finding that responses are slower and error rates are higher in task-switch trials than in task-repeat trials, resulting in *task-switch costs* (e.g., Arrington & Logan; 2004, 2005; Jersild, 1927; Meiran, 1996, 2014; Meiran et al., 2000; Monsell et al., 2003; Rogers & Monsell, 1995; Schneider, 2016, 2017; for reviews see Kiesel et al., 2010; Koch et al., 2018; Vandierendonck et al., 2010). In previous research using typical task-switching paradigms, task-switch costs are considerable, even though (a) the tasks are simple; (b) the task

sequence is predictable; and (c) the to-be-performed task is entirely chosen by participants rather than decided by experimenters.

For examples, in an alternating-run paradigm by Rogers and Monsell (1995), on average participants responded approximately 200 ms slower and made approximately 4% more errors when switching between tasks, even though the task order was entirely predictable. Similarly, according to Meiran (1996), although participants were instructed by an explicit task cue at the beginning of each trial, responses were approximately 100 ms slower and error rates were approximately 2% higher in task switch trials. Using a voluntary task-switching paradigm, Arrington and Logan (2004) reported that although participants voluntarily decided which task to perform in an upcoming trial, the response time switch costs were significant, which is approximately 310 ms. However, there are results that indicated individual differences in task-switching performance and that switch costs varied across individuals (e.g., Karayanidis et al., 2010; Lindsen & De Jong, 2010; Stoet & Snyder, 2007; Umemoto & Holroyd, 2016). Two major accounts have been proposed to explain the commonly observed task-switch costs and individual differences in performance: the interference account, and alternatively, the preparation account.

1.3.1 Interference account

The interference account assumes that task-switch costs are due to persisting activation of previously activated task-set or proactive interference, stimulus-based interference that cannot be resolved in advance, and response-based interference when executing a response (e.g., Allport et al., 1994; Koch & Allport, 2006; Mueller et al., 2007; Rogers & Monsell, 1995; Rubin & Koch, 2006; Waszak et al., 2003; Yeung & Monsell, 2003; for reviews see Kiesel et al., 2010; Koch et al., 2018; Vandierendonck et al., 2010).

Proactive interference

Allport et al. (1994) published a seminal paper and attributed the task-switch costs to persisting interference from the previous trial with a different task. In Allport et al. Experiment 5 (1994), participants were asked to perform in several lists of Stroop word task, in which participants switched between colour naming and word reading (Stroop, 1935). There were pairs of trials and the second trial of a pair can be a task switch or task repetition. Since participants received task instructions indicating whether a task switch was required in the second trial of a pair, they could prepare the relevant task during the interval between the response to the first stimulus of a pair and onset of the second stimulus in the pair (RSI). However, Allport et al. (1994) found that increasing RSI from 20 ms to 1,100 ms did not significantly reduce task-switch costs, suggesting proactive interference that persists and cannot fully dissipate over the RSI (see also Meiran et al., 2000).

Proactive task-set interference is an involuntary after-effect of previous control states. Evidence that supports this comes from the observation of task-switch costs which are often asymmetrical when switching between two tasks differing in difficulty. For example, Allport and colleagues (1994) observed large switch costs when switching from the colour-naming to word-reading task, but no switch cost when switching from the word-reading to colour-naming task. In this study, participants typically performed better in the word-reading task compared to the colour-naming task, which means that word reading is more automatic and therefore dominant or easier whereas colour naming is less automatic and therefore nondominant or more difficult. When performing in task-switch trials, previous task set must be inhibited in order to perform the task in a given trial. Switching to the nondominant colour-naming task would require a strong inhibition of the dominant

word-reading task in the previous trial. However, when the dominant word-reading task becomes relevant again, participants must apply more cognitive resources and take longer time to recover from the strong inhibition. Therefore, the larger switch costs when switching to the word-reading can be accounted by different levels of task-set inhibition, with stronger inhibition of the easier task (see also Meuter & Allport, 1999). An alternative and simpler explanation was provided by Schneider and Anderson (2010) that suggested that the asymmetrical switch costs arises from sequential difficulty effects. Since performance was impaired after a difficult trial, response times were longer when switching to an easy task and when repeating a difficult task leading to asymmetrical switch costs (see their Figure 1).

The asymmetrical switch costs were replicated in many studies (Meuter & Allport, 1999; Schneider & Anderson, 2010; Yeung & Monsell, 2003; for reviews see Kiesel et al., 2010; Vandierendonck et al., 2010). However, Yeung and Monsell (2003, Experiment 1) observed larger switch costs when switching to the more difficult colour-naming task, reversed asymmetrical switch costs, if delaying the onset of the word for 160 ms or 320 ms after the onset of the colour attribute. In addition, Yeung and Monsell (2003, Experiment 3) also found reversed asymmetrical switch costs when both tasks differed in response category (i.e., using abstract meaning of responses, such as speaking “left”, “right”, “up”, and “down”, rather than saying “one”, “two”, “three”, and “four” to respond to colours of four digits “1”, “2”, “3”, “4”) and/or response modality (vocal, manual). Researchers concluded that reducing the interference between tasks led to decreased or even reversed asymmetrical switch costs.

More recently, there are studies suggesting individual differences in asymmetrical switch costs, which may be related to different interference control. Umemoto and Holroyd (2016) reported smaller asymmetrical switch costs in high persistent individuals. They proposed that higher persistence may be associated with larger activation in the brain area

that facilitates cognitive adaptations to conflicts. Other researchers found that video game players had reduced asymmetrical switch costs in a flanker task-switching paradigm possibly because more efficient strategy to control interference and/or improved executive functioning due to more experience with action video games (Cain, Landau & Shimamura, 2012).

Stimulus-based interference

In addition to proactive interference, there was stimulus-based interference in task switching. Allport et al. (1994) studied task-switching performance using both Stroop colour-word stimuli in which the word meaning was always incompatible with the ink colour (e.g., RED displayed in yellow) and neutral stimuli in which colour-words were printed in black or a string of five Xs was presented in one of five colours (e.g., either RED displayed in black, or XXXXX displayed in yellow). They found much smaller switch costs in neutral stimuli that afford only one task (37 ms) compared with Stroop stimuli that affords two tasks (150 ms). Allport et al. (1994) concluded that switch costs were in part from stimulus-triggered interference that cannot be resolved in advance.

Allport et al (1994) interference account of switch costs was supported by other studies (e.g., Allport & Wylie, 2000; Andreadis & Quinlan, 2010; Koch et al., 2003; Theeuwes, Atchley & Kramer, 2000; Rogers & Monsell, 1995; for reviews, see Kiesel et al., 2010; Koch, et al., 2018; Vandierendonck et al., 2010). Studies suggested that performance in task switching, switch costs particularly, is affected by whether or not the target stimulus was designed to afford only one task or different tasks. Stimulus was univalent or neutral if it only appears in one task whereas stimulus was bivalent if it serves as a target in two tasks. Compared with univalent stimuli, studies found larger switch costs

for bivalent stimuli because bivalent stimuli have features for both tasks and may increase response conflicts in some trials.

Indeed, bivalent stimuli are not only associated with features of both tasks, but also afford a response of the competing task. Bivalent stimuli are considered as “congruent” if they are related to the same response in the two tasks, and as “incongruent” if they are related to different/conflicting responses in the two tasks (e.g., Meiran, 2000; Rubin & Koch, 2006; Schneider 2015). For example, in Rubin and Koch (2006), participants were asked to decide whether the target square appears in the upper or lower cells of a 2*2 grid in an *up-down task* and whether it is in the left or right cells in a *left-right task*. Some participants were required to press the key *T* to indicate upper and left locations, and pressed key *M* to indicate lower and right locations. Therefore, if a target appears in the upper left cell or lower right cell, then participants press T and M, respectively, regardless of the *left-right task* or *up-down task*. This is the congruent condition. In contrast, for example, if the target appears in the upper right cell, then participants need to first recall the current task goal and then respond according to the appropriate task rules. This is the incongruent condition. Rubin and Koch (2006) found that participants on average responded more slowly in incongruent condition (500 ms) compared to congruent condition (455 ms). The performance difference between incongruent and congruent trials, $500 \text{ ms} - 455 \text{ ms} = 45 \text{ ms}$, is known as the *response-congruency effect* or *congruency effect*. According to Schneider (2015), congruency effects can be the result of either rule-based feature categorisation and conflicting feature-response selection or retrieval of conflicting target-response associations. The latter hypothesis was supported in a recent study by Li, Li, Liu, Lages and Stoet (2019a). This study suggested that conflicting target-response associations may play a more prominent role in producing congruency effects when in experiments where target stimuli were repeated.

The congruency effect is a robust finding in task-switching research when using bivalent targets (e.g., Kiesel, Kunde & Hoffmann, 2006; Kiesel, Wendt & Peters, 2007; Li et al., 2019a; Merian, 1996; Monsell & Mizon, 2006; Rogers & Monsell, 1995; Schneider, 2015; for reviews see Kiesel et al., 2010; Koch et al., 2018; Vandierendonck et al., 2010). However, researchers have reported that some participants had better interference control with reduced congruency effects (e.g., Haff & Rouder, 2017, 2018). In addition, recent research suggested that congruency effects can be halved in conditions that require participants to respond to target stimulus by target-response associations rather than by applying task rules (Li et al., 2019a). In previous studies it has been argued that congruency effects cannot be reduced by increasing preparation times (e.g., Merian, 1996, Rogers & Monsell, 1995), however other researchers found that by increasing the switch probability from 25% to 50% or 75%, longer preparation times reduced RT congruency effects (Monsell & Mizon, 2006). Another important finding was obtained by Kiesel et al. (2006), who observed that the congruency effects can be modulated by trial-to-trial congruency. They found that incongruent targets reduced congruency effects in the next trial with a task repetition, suggesting conflict adjustment according to the source of conflict.

The congruency effect is more prominent in task-switch trials compared to task-repeat trials and is related to switch costs (e.g., Allport et al., 1994; Bugg & Braver, 2016; Kiesel et al., 2007; Rogers & Monsell, 1995; Rubin & Koch, 2006; for reviews see Kiesel et al., 2010; Vandierendonck et al., 2010). In a task-switch trial with incongruent target stimulus, both target feature and the feature-response mapping that are related to the task in the previous trial need to be more inhibited in the present trial with a different task. That is, there is higher proactive interference in task-switch trials which requires more attentional control, especially in trials with incongruent target stimulus with features associating with conflicting responses. In contrast, proactive interference is smaller in task-repeat trials,

while the task-irrelevant feature may still capture attention and activate competing responses.

Taken together, there is stimulus-based interference in task switching and task-switch costs arise in part because of stimulus-based interference. Task-switching performance is impaired, if the target stimulus affords features of both tasks, and further deteriorated if the target features are associated with conflicting responses in the two tasks. In the following I will discuss task-switch costs that arise from response-triggered interference.

Response-based interference

Apart from the proactive interference and stimulus-based interference, there is evidence for response-based interference in task-switching. In previous task-switching studies, participants typically showed larger switch costs when two tasks are mapped to the same response set than when each task is associated with a unique set of responses (Brass et al., 2003; Meiran, 2005; Meiran et al., 2000; Yeung & Monsell, 2003; but see Astle, Jackson & Swainson, 2008; Mayr, 2001). For example, Meiran et al. (2000) required participants to press one key to indicate either up or left, on the basis of the task required, while a different key for down or right. This is the *bivalent-response condition*. In contrast, in the *univalent-response condition* participants were asked to press four different keys to indicate four different target locations. Meiran et al. (2000) found larger and significant switch costs in the bivalent-response condition compared to univalent-response condition. Researchers suggested that when two tasks shared the same response set the previously used task-response mapping persists and causes response interference in task-switch trials, resulting in large switch costs. The increased task-switch costs with bivalent responses can be explained by the need of inhibiting the competing responses.

Another response-based interference comes from response repetitions. Studies have shown that repeating the same response over two consecutive trials can lead to performance benefits for task repetitions but performance costs for task switches (Altmann, 2011; Mayr & Bryck, 2005; Meiran, 2005; Roger & Monsell, 1995; for reviews see Kiesel et al., 2010; Koch, 2018; Vandierendonck et al., 2010). This is because when the previously familiar task-stimulus-response association is not applicable to the current target stimulus with a different task, an alternative association needs to be established, which turns into a cost (Rogers & Monsell, 1995; Mayr & Bryck, 2005). Altmann (2011) suggested an episodic retrieval model arguing that response repetition costs in task switching is less robust as previously thought. In this retrieval model, retrieval of not only response but also stimulus, task, and task cue can affect performance. This is because any repeated feature between trials serves as a retrieval cue and other features in the retrieval trace facilitate or interfere with performance in the current trial depending on whether they match or mismatch, respectively, the current processing context (see also Hommel, Proctor & Vu, 2004).

In summary, proactive interference, stimulus-based interference, response-based interference and interference due to any mismatching of features between trials can lead to impaired performance in task-switch trials compared to task-repeat trials. Participants show worse performance in switch trials and significant switch costs because in task-switch trials they need to overcome the interference from the previously activated task set, the interference from the irrelevant target feature and response mappings. Therefore, the commonly observed switch costs represent the time needed to overcome these sources of interference.

1.3.2 Preparation account

Switch-specific or general task preparation

The preparation account is another account which assumes that task-switch costs reflect the additional time of task-set reconfiguration when a task switch is required in an upcoming trial (De Jong, 2000; Monsell & Mizon, 2006; Nieuwenhuis & Monsell, 2002; Rogers & Monsell, 1995; Sohn & Anderson, 2001; Rubinstein et al., 2001). Other studies indicated that the preparation process is not necessarily specific to switch-trials. Instead, increasing preparation time can benefit both task repetitions and task switches (Altmann, 2004a, 2004b; Demanet & Liefoghe, 2014; Koch, 2001, 2005, 2008; Koch & Allport, 2006). In addition, ERP studies on task switching have provided evidence supporting both switch-specific and general preparation processes (e.g., Karayanidis, Provost, Brown, Paton & Heathcote, 2011). Specifically, Karayanidis and colleagues extracted event-related potential (ERP) waveforms time-locked to cue onset. It was found that an early central-parietal positivity emerging at around 250-400 ms after cue onset was linked to faster RTs for switch but not for repeat trials, consistent with a switch-specific preparation process. A later pre-target negativity at around 500–600 ms was correlated with reduced RTs for both switch and repeat trials, consistent with the idea of a general preparation process (Karayanidis et al., 2011; see also Mansfield, Karayanidis & Cohen, 2012; Steinhauser, Maier & Ernst, 2017; for reviews see Karayanidis et al., 2010; Karayanidis & Jamadar, 2014, Jamadar, Thienel & Karayanidis, 2015). Accordingly, these results suggest that there is a switch-related task reconfiguration process that can be distinct from a general preparation. In addition, task preparation may involve multiple subprocesses.

Sub-processes of task preparation

Task preparation following cueing involves distinct subprocesses. Studies using electroencephalogram (EEG) measures have found at least two cue-related preparatory subprocesses: an earlier process that is associated with task-goal updating and a later process that is related to task-rule activation (Jamadar, Michie & Karayanidis, 2010a, Jamadar, Hughes, Fulham, Michie & Karayanidis, 2010b; Karayanidis et al., 2009, 2011; Lavric et al., 2008; Nicholson, Karayanidis, Poboka, Heathcote & Michie, 2005; Nicholson, Karayanidis, Davies & Michie, 2006; Travers & West, 2008; for a review see Karayanidis & Jamadar, 2014). Researchers identified that different time courses and neural-correlated information underlies different task preparation processes.

For example, Nicholson et al. (2006) compared difference waveform for *switch-to* with *switch-away* cues in long cue-stimulus intervals of 1000 ms. *Switch-to* cues specifically signalled the upcoming task, while *switch-away* cues signalled not repeating the same task as in the previous trial without specifying which task to perform in the upcoming trial. Nicholson et al., (2006) reported that response time switch costs were significantly smaller in *switch-to* trials compared to *switch-away* trials. They also observed that both cue types elicited an early cue-locked positivity at about 100 ms post-cue that was larger in switch trials than in repeat trials at central-parietal sites, indicating *differential switch positivity*, or *switch positivity* for short. The switch positivity was smaller and lasted shorter in *switch-away* cues, compared to *switch-to* waveforms over approximately 400-450 ms and 700-750 ms within the CSI. Nicholson and colleagues suggested that the early positivity was affected by the need to inhibit a previously relevant task-set and the need to activate a new task goal while the later positivity may reflect selection and activation of the relevant task rules (see also Jamadar et al., 2010a, 2010b; Karayanidis et al., 2009). The previous ERP results clearly identified different sub-

processes of task preparation and suggested that switch costs are caused by incomplete preparation in switch trials

Previous behavioural, ERP and fMRI studies have identified variability in advance preparation across trials and participants (e.g., De Jong, 2000; Jamadar et al., 2010a; Jamadar et al., 2010b; Lavric et al., 2008; Lindsen & De Jong, 2010; for a review see Karayanidis et al., 2010). For example, by establishing cumulative response time distributions, De Jong and colleague (De Jong, 2000; Lindsen & De Jong, 2010) found that RT distributions differed between switch and repeat trials, between trials with long and short preparation intervals, and varied across participants. Some participants had large overlaps for RT distributions between repeat and switch trials with long preparation interval, suggesting better preparation. Similarly, Lavric et al. (2008) indicated little or no switch costs in fast response trials (i.e., efficient preparation), whereas slow trials showed a large switch cost (i.e., less or no preparation). They also partitioned the ERP data into fast and slow RT trials. Their results showed a reliable switch-related posterior positivity in the prepared or fast trials, but not in the unprepared or slow trials. Furthermore, in an fMRI study by Jamadar (2010b), individual variability in preparation and RT switch costs was associated with activations in premotor cortex that subserves goal-related response planning and generation.

1.3.3 Residual switch costs

In previous task-switching research, it was established that switching between tasks slows responses and increases error rates (e.g., Kiesel et al., 2010). In order to make the performance to be efficiency in task-switch trials as in task-repeat trials, several studies had tried to reduce switch costs by increasing preparation times.

Evidence shows that prolonging the time interval before target stimulus onset reduces task-switch costs because participants have longer time to prepare the task, suggesting a preparation effect (for reviews see Kiesel et al., 2010; Koch et al., 2018; Vandierendonck et al., 2010). For example, in an alternating-runs paradigm, a between-block increase of response-stimulus interval from 150 ms to over half a second substantially reduced switch costs (e.g., Monsell et al. 2003; Rogers & Monsell, 1995). Similarly, using task-cueing paradigms researchers found that a within-subject increase of cue-stimulus interval leads to reduced switch costs (Altmann, 2004a, 2004b; Koch, 2001, 2005; Koch & Allport, 2006; Meiran, 1996, 2014; Meiran et al., 2000). Studies on voluntary task switching also indicated large preparation effect on switch costs when more time was available before selecting a task (Arrington & Logan, 2004, 2005; Demanet & Liefoghe, 2014; Liefoghe et al., 2009).

However, even with long preparation intervals most researchers found significant residual switch costs in typical task-switching paradigms (e.g., Altmann, 2004a, 2004b; Arrington & Logan, 2004, 2005; Demanet & Liefoghe, 2014; Koch, 2001, 2005; Koch & Allport, 2006; Liefoghe et al., 2009; Meiran, 1996; Meiran et al., 2000; Monsell et al. 2003; Rogers & Monsell, 1995; but see Verbruggen et al., 2007; Fintor et al., 2018). For example, Meiran et al. (2000) demonstrated that switch costs cannot be reduced further when the cue-stimulus interval reached 500 ms, resulting in a residual switch cost of 60 ms. Similarly, Monsell (2003) showed that the reduction in switch costs reached an asymptote after a response-stimulus interval of about 600 ms, resulting in substantial residual switch costs of 120 ms that cannot be reduced further beyond 600 ms. Task-switching models were proposed in order to explain these residual switch costs and are discussed in the following.

Compound-retrieval account

Researchers proposed compound-retrieval account and argued that task switching reflects additional cue processing (Logan & Bundesen, 2003; Logan & Schneider, 2010; Schneider & Logan, 2005, 2007). In other words, task-switch costs are not completely produced by the "endogenous" control operation triggered by task rules. At least a portion of the task-switching costs comes from a compound retrieval process. Researchers suggested that participants can form cue-target compounds and retrieve the correct response for each compound directly from memory (Logan & Bundesen, 2003; Logan & Schneider, 2010; Schneider & Logan, 2005, 2007). Since the cue also switches when task switching, task-switching costs may be due to an additional cue-encoding process or cue-switching costs that contributes to the observed task-switching cost.

For example, Logan and Bundesen (2003) employed two-to-one cue-task mappings and found large response time difference between cue-repeat trials and cue-switch but task repeat trials, whereas little difference between cue-switch task-switch trials and cue-switch but task repeat trials. They argued that task-switch costs are caused by switching cues. However, other studies suggested a number of conditions under which task switching is larger than cue switching (see a review in Jost, De Baene, Koch & Brass., 2013), such as the probability of task switching (e.g., Monsell & Mizon, 2006) and the type of cue (e.g., Logan & Schneider, 2006). The performance differences between task-switch and task-repeat trials are from more complex cognitive processes, such as establishing different task representations in working memory, rather than perceptual processing of the cue itself (Altmann, 2006; Grange & Houghton, 2010; Mayr & Kliegl, 2003; Monsell & Mizon, 2006).

Two-stage account of task reconfiguration

Other researchers have proposed two separate stages of task reconfiguration in task switching (Mayr & Kliegl, 2003; Rogers & Monsell, 1995; Rubinstein et al., 2001): an early *goal reconfiguration stage* that can be triggered as soon as participants are cued about the task, and a second *rule activation stage* that only starts when the target stimulus is presented. Residual switch costs reflect the second rule-activation stage where participants wait for the target stimulus onset before they can activate a specific task rule. This account has been supported by more recent studies (e.g., Hydock & Sohn, 2011; Weidler & Abrams, 2013). However, the assumption that residual switch costs arise from the postponed completion of reconfiguration has been challenged by De Jong's (2000) *failure-to-engage* account.

Failure-to-engage (FTE) account

According to De Jong's (2000) *FTE* account on task-set preparation, participants either prepare for the upcoming task or fail to do so. In trials in which active preparation occurs, the residual switch costs disappear because advance preparation is complete before the target stimulus is presented. In other trials, however, advance preparation is incomplete when the target stimulus is presented, and this may occur even after extended preparation intervals. Residual switch costs are therefore a consequence of participants who occasionally fail to engage in the preparation process. As De Jong (2000) pointed out, response time distribution of task-switch trials should reflect a mixture of prepared and unprepared processing states (see also Lindsen and De Jong, 2010; Nieuwenhuis & Monsell, 2002; Poboka, Karayanidis, & Heathcote, 2014). This implies that performance in fully prepared task-switch trials should be similar to performance in task-repeat trials. In

line with this, Poboka et al. (2014), for example, reported that switch and repeat trials had very similar RT distributions in conditions with long cue-target intervals.

Partial-mapping preparation (PMP) account

Lien and colleagues (Lien et al., 2005) proposed a *PMP* account and argued that task preparation is partial. There were three different stimulus-response pairs in their study: left, middle and right, in the order of English reading. They found non-significant switch costs for the left (first) stimulus-response pair, but significant costs for the middle and right stimulus-response pairs. They suggested that advance preparation for a task switch was much more effective for the first, or high-priority stimulus-response pair, and therefore concluded that full preparation is typically limited to a few specific stimulus-response pairs because of the limited capacity of working memory and focused attention (see also Monsell & Mizon, 2006). Residual switch costs therefore reflect the unprepared S-R pairs.

However, Lindsen and De Jong (2010) mimicked Lien et al. experimental procedures and failed to show any significant differences in the residual switch costs across three S-R pairs. Instead, Lindsen and De Jong found sizable and similar residual switch costs for all three S-R pairs. Their mixture-model analysis showed that the overlap between cumulative distribution for repeat and switch trials is similar for all three pairs of S-R mappings, and independent of preparation intervals. This pattern of results was observed in most participants. Therefore, the central tenet of the *FTE* account, suggesting that advance preparation probabilistically fails or succeeds, was supported. Residual switch costs reflect occasional failure of preparation. Then, an important question is how to motivate participants to engage in the task preparation and possibly eliminate residual switch costs.

1.3.4 Reducing residual switch costs by improved preparation

Some researchers have tried to eliminate residual switch costs by improving task preparation. For example, Nieuwenhuis and Monsell (2002) used visual feedback and payoffs after each block in order to reduce response times. In addition, they used blocks of only 16 trials in order to minimize fatigue and to sustain advance preparation throughout each block. Nonetheless, they still found substantial residual switch costs, the difference in mean RTs between switch and repeat trials, of +69 ms.

Another method to reduce residual switch costs was deployed by Verbruggen et al (2007). They were able to improve participants' task preparation by reducing the cue presentation time. Residual switch costs were smaller and non-significant when the cue was removed after a brief presentation of 96 ms rather than remaining present throughout each trial (see their Experiments 2, 3, and 4). Verbruggen et al. (2007) concluded that by using only a briefly presented cue participants were more likely to process the cue and therefore complete preparation for an upcoming task switch within cue-stimulus intervals (CSIs) of more than one second (see also Experiment 3 in Proctor, Koch, Vu & Yamaguchi, 2008). However, Schneider (2016, Experiment 5) was unable to replicate the results of Verbruggen et al. (2007) and instead found large and significant residual switch costs when the cue was followed by a mask, similar to a condition where the cue was visible for the entire CSI and remained present after target onset. These contrasting findings suggest that residual switch costs are not just modulated by cue availability during CSIs.

Moreover, Meiran and Chorev (2005), and Schneider (2017) tried to modulate residual switch costs by increasing participants' phasic alertness — a form of attention that is described by rapid and brief changes in sensitivity to external stimulation (Posner, 1978,

2008; Posner & Boies, 1971). Researchers inserted an alerting stimulus shortly before cue or target stimulus onset in some trials and compared them to trials with no such alert. Meiran and Chorev (2005) found reduced RT and small switch costs in alert trials associated with long alerting intervals. Similarly, Schneider (2017) also observed shorter RTs in trials with alert compared to trials without alert, suggesting that general task performance can be improved by increased phasic alertness. However, Schneider (2017) found no evidence that phasic alertness reduced residual switch costs.

More recently, Fintor et al. (2018) studied whether cue-target compatible modality can improve task preparation and reduce residual switch costs. In their study, a visual cue informed that responding only to the visual target stimulus, and the auditory cue informed that responding only to the auditory target stimulus. Participants were asked to indicate either the location of a visual or an auditory stimulus, based on the type of cue presented prior to the target stimulus. In their Experiment 1, researchers found eliminated residual switch costs for RT (3 ms) but not for ER (2.3%) when in cue-target compatible trials with a long cue-stimulus interval of 1,000 ms. They explained that when the cue modality was identical to the target-stimulus modality, cue-based preparation might have been facilitated within long CSIs. Fintor et al. (2018) suggested that task preparation can benefit from cue-target modality compatibility. Although their results seem to be less comparable with previous studies using typical task-switching paradigms with visual cues and target stimuli, the study by Fintor et al. (2018) did support the *FTE* account (De Jong, 2000) demonstrating that task preparation can be completed before target onset.

1.3.5 Reducing residual switch costs by practice

Research on task-switching has looked into practice effects and residual switch costs. For example, Rogers and Monsell (1995, Experiment 1) asked participants to

perform in an alternating-run paradigm on two consecutive days, with each day consisting of 4 blocks of 48 trials each. They found that reduced residual switch costs on the second day (186 ms) compared to the first day (263 ms). In addition, Meiran et al. (2000, Experiment 1) had participants perform in a task-cueing paradigm consisting of two one-hour sessions, with 480 trials in each session. The results revealed reduced residual switch costs in Session 2 (53 ms) compared to Session 1 (97 ms). Similarly, Koch (2001, Experiment 1) also showed significant reduction in residual switch costs after 5 blocks of 72 trials, with a switch cost of 284 ms in the first block and of 143 ms in the fifth block. Note that in all these studies residual switch costs remained sizable and did not disappear after moderate practice with hundreds of trials.

Other studies investigated the effect of more extended practice on residual switch costs. For examples, Kray and Lindenberger (2000) observed significant residual switch costs of over 100 ms after a practice of 8 sessions with a total of 6,144 trials. Berryhill and Hughes (2009) observed that following 5-month training of various task-switching paradigms participants still showed modest switch costs of about 20 ms. Similarly, Stoet and Snyder (2007) asked participants to perform at least over 23,000 trials in a colour/orientation task-switching paradigm. They found that all four participants showed significant residual switch costs in RT, ranging from 21 ms to 113 ms. They concluded that extensive practice does not eliminate human residual switch costs. This is because the evolutionary advantages of human cognitive control that enable human beings to maintain focused attention on one particular task for an extended period of time. Strobach et al. (2012) further confirmed reduced but significant residual switch costs (10 ms) after a practice of more than 7,000-trials on task switching. Strobach and colleagues found that practice did not eliminate residual switch costs even when each target stimulus was mapped onto a unique response. A very recent study by Zhao and coworkers (2018) provided more evidence that participants showed residual switch costs even after

performing the task-switching tasks on each of 21 successive weekdays. Accordingly, evidence suggests that residual switch costs cannot be eliminated by extensive practice of task rules.

1.4 Individual differences

It appears that residual switch costs are a robust phenomenon in typical task-switching paradigms despite various attempts that tried to eliminate them (e.g., Schneider, 2016, 2017). However, most researchers ignored individual differences in task switching performance. There is growing evidence that some participants learn to switch between tasks better than others, showing faster task switching and fewer errors (Lindsen & De Jong, 2010; Stoet & Snyder, 2003, 2007; Stoet et al., 2013). For example, Stoet and Snyder (2007) asked four participants to practice task switching for more than 20,000 trials. They observed individual differences in switch costs after extensive practice. Stoet and Snyder (2007) found that switch costs were roughly constant for Participant 1, decreased for Participant 2 and showed small increases for Participants 3 and 4. Their results suggest that participants were differently engaged over the course of task-switching learning. Similarly, Lindsen and De Jong (2010) found that 12 out of 18 participants showed high degree of overlap between the switch and repeat cumulative distribution of the response time for their first stimulus-response pair (i.e., the leftmost or high-priority pair of the three horizontally aligned stimulus-response pairs, initially assumed by Lien et al. 2005), corresponding to the smaller switch costs for this pair. Among the 12 participants there were 7 participants showing a large overlap between switch and repeat RT distributions for all stimulus-response pairs. These 7 participants showed relatively faster response and smaller RT switch costs, however their error rates were similar to other participants. Researchers suggested that this subgroup of participants may have been better prepared for

every upcoming trial (Lindsen & De Jong, 2010). Individual variability in task preparation can also be found in previous ERP and fMRI task-switching studies (e.g., Karayanidis et al., 2010).

In addition, using other related cognitive, perceptual and memory tasks, researchers have identified large individual differences with some even providing evidence that not every participant showed performance decrements in the more complex condition (e.g., Haaf & Rouder, 2017, 2018; Mallow et al., 2015; Russell et al., 2009; Strayer & Watson, 2012). For example, Haaf and Rouder (2018) re-analysed the data from a Stroop location task (Pratte, Rouder, Morey & Feng, 2010) in order to investigate whether every participant identified the word location more slowly when, for example, a word RIGHT was presented to the left side of the screen (incongruent trials) compared to the right side of the screen (congruent trials), showing a positive Stroop effect (Stroop, 1935). Haaf and Rouder (2018) observed that the average Stroop effect was 11.90 ms with individuals' effects ranging from -19 ms to +68 ms. They also developed a generalised spike-and-slab model that captures individual differences in Stroop effects and estimates posterior spike and slab probabilities of individuals' effect. The model consists of a spike referencing the point mass at zero and two slabs referencing the positive and negative distributions. According to this model, individuals' posterior probability of being in the slab varies considerably, ranging from 0.20 to 0.99. They concluded that some participants showed a true positive Stroop effect, whereas others show a true negative effect, whilst others show no effect at all (see Figure 5C in Haaf & Rouder, 2018).

For another example, Watson and Strayer (2010, 2012) reported "super-taskers" (2.5% of the sample) who demonstrated high levels of cognitive competence in a dual driving/memory task. These super-taskers showed no performance decrements with respect to performing single- and dual-task situations. They suggested an individual-difference variable accounts for the effect - executive attention. A related study by Medeiros-Ward et

al. (2014) investigated the brain activity of super-taskers with matched controls. Medeiros-Ward and colleagues measured brain activity using functional magnetic resonance imaging (fMRI) while participants performed a demanding dual N-back task with visual and auditory stimuli presented simultaneously. Researchers found that super-taskers had reduced activity in posterior frontopolar prefrontal and anterior cingulate cortices, suggesting more efficient recruitment of neural correlates of attentional control and better executive control functioning.

Examples of superior performance were also provided by Russell and colleagues (2009). They tested four people who claimed to have exceptional face recognition ability. They found that all four face “super-recognisers” performed better than control participants in two different face recognition tests: A Before They Were Famous (BTWF) test required participants to name famous individuals or provide a uniquely identifying description, based on a photo taken before each individual became famous; and an adapted version of the Cambridge Face Memory Test (CFMT; Duchaine & Nakayama, 2006) that required learning to recognise six unfamiliar faces. In both tests, super-recognisers performed at ceiling, showing higher scores than any of the control participants. In a follow-up Cambridge Face Perception Test (CFPT; Duchaine, Germine, & Nakayama, 2007) participants were required to sort a set of six images with frontal views of faces by similarity to a target face. The super-recognisers made fewer errors than a new set of control participants when the face image was upright. However, they did not perform better when the face image was turned upside down (inverted). Russell and colleagues (2009) provide evidence for the existence of people with exceptional recognition ability for upright faces and on-average ability when in the more difficult condition. That is, when super-recognisers were required to recognise an inverted face they showed significant inversion decrements similar to the control participants. More recently, the research by Robertson et al. (2016) suggested that there were police ‘super-recognisers’ who

performed well above normal levels on tests of unfamiliar and familiar face matching, independent of the image quality (degraded, high quality). These studies suggest that there are large individual variations in perceptual discrimination ability.

In addition to the existence of super-taskers and super-recognisers, there are also “superior memorisers”, who can recall long lists of numbers, sequences of images, or other data such as face-name associations over a short time (e.g., World Memory Championships in <http://www.world-memory-statistics.com/home.php>). Mallow et al. (2015) asked 11 super-memorisers who were successful in the World Memory Championships and 11 control participants to view 40 digits and memorise as many items as possible within 60s duration. Researchers found that super-memorisers were able to recall on average 35.4 of the 40 digits, while the control participants recalled on average only 10.8 digits. The super-memorisers recalled significantly more digits and spent significantly less time on digit recalling than the controls. Mallow and colleagues (2015) further demonstrated that compared to controls, super-memorisers showed on average more activations in the left superior parietal cortex and temporal gyrus during digit-encoding and -learning, and on average more activations in left anterior superior temporal gyrus and right motor cortex during digit recalling. An fMRI study by Ramon et al. (2016) gave similar behavioural results that super-memorisers reached higher scores in face-name association learning. Moreover, they were characterised by a lower variability in terms of learning time and recall performance, suggesting superior memory abilities and processing skills. However, they did not find a reliable association between hippocampal volume and exceptional memory skills for face-name associations. In addition, some control participants in the study by Ramon et al. (2016) were also able to achieve relatively high scores - especially the control participants who took more time during learning phases. This highlights motivational components that may play a important role when measuring memory skills.

Overall, by considering individual differences researchers found that there were exceptional individuals who outperformed others in the complex conditions. Previous studies used various approaches to study individual differences with different purposes (e.g., Haaf & Rouder, 2017, 2018; Lindsen & De Jong, 2010; Robertson et al., 2016; Strayer & Watson, 2012; Watson & Strayer, 2010, 2012). For example, the study by Russell and colleagues (2009) showed individual accuracy (number of correct or number of errors) in different face recognition tasks using dot plots. Their results indicated that few participants performed consistently above average in different tasks. Later, Lindsen and De Jong (2010, Experiment 1) used an individual-difference approach to identify the probability of advance preparation for three stimulus-response pairs. They compared the cumulative distributions for repeat and switch trials in all three stimulus-response pairs across 18 individual participants. Using yet another approach, Watson and Strayer (2010) monitored individual performance with the aim of identifying supertaskers with superior ability in multitasking. They focussed on participants who reached the top 25% of all single-task scores and showed no mean performance decline from single-task to dual-task condition. As a result, only 5 out of 200 participants met both criteria. Their Monte Carlo simulations based on 100,000 participants indicated that the frequency of supertaskers was significantly greater than chance. More recently, in order to identify whether some people have and other people do not have Stroop effects Haaf and Rouder (2018) plotted the observed individual effects from lowest to highest in rank order. Haaf and Rouder found that the Stroop effect normally distributed. Moreover, with the usage of a spike-and-slab model they identified individual posterior probability of having a true Stroop effect above or below zero.

In the task-switching paradigms, previous research has suggested varying preparation across participants, with more efficient preparation indicating better task-switching performance and smaller switch costs (e.g., Lindsen & De Jong, 2010;

Karayanidis et al., 2010). Similar to Haff and Rouder (2018) methods to study individual differences, in the present thesis I tried to find out whether RTs and switching costs are randomly distributed across participants, by plotting individual-specific intercepts and random effects based on GLMM model estimations. In addition, similar to the method employed by Watson and Strayer (2010), in Chapter 1 I developed strict selection criteria, aiming to identify participants with exceptional task-switching ability. Based on previous results on exceptional performance and various cognitive, perceptual and memory tasks, it seems reasonable to predict that a few participants may show minimal errors and no costs of task switching. If they exist, I wanted to study whether they have characteristics that set them apart in different task-switching paradigms and conditions. Another critical issue is whether individual differences in task switching may be related to certain underlying traits or other factors such as executive control, motivation, and strategies. Previous studies have suggested a number of factors that can affect cognitive performances (e.g., Benedek, Jauk, Sommer, Arendasy & Neubauer, 2014; Nadler, 2013; Pessoa, 2009).

In task-switching paradigms, although it has been widely reported that residual switch costs cannot be entirely eliminated with strong incentives for task engagement (e.g., Schneider, 2017) and with extended practice of task rules (e.g., Zhao et al., 2018), we cannot completely rule out the possibility that participants may have different executive control functioning that processes and regulates goal-directed thoughts and behaviours (for a review, see Diamond, 2013). It is possible that participants with highly efficient executive functioning would perform task switching more quickly and more accurately. Using a number of cognitive measures, researchers found that some participants had higher level of sustained attention, vigilance to the task-relevant information, and greater efficiency in working and long-term memory retrieval, suggesting better executive functioning (Miyake et al., 2000; Zeidan et al., 2010).

Researchers have argued that executive control functioning is strongly linked to several trait-related factors such as general intelligence and personality characteristics. For example, it has been suggested that general intelligence influenced the efficacy of executive controls, with higher intelligence scores were associated with better ability of information updating (Benedek et al., 2014; see also Friedman et al, 2006). Moreover, Murdock, Oddi and Bridgett (2013) reported that higher openness scores (i.e., a psychological characteristic of being open-minded to new experience; Gosling, Rentfrow & Swann, 2003) were significantly associated with better cognitive flexibility and information updating in working memory, whereas higher neuroticism scores (i.e., being anxious, moody and easily upset; Gosling et al., 2003) were significantly associated with poorer information updating.

In addition, Pessoa (2009) hypothesised that motivation impacts executive controls. In his proposed model, motivation fine-tunes executive functions that facilitate working memory updating. Increasing motivation in participants would also lead to improved efficiency in orientation and reorientation of attention in order to meet current behavioural demands and opportunities. Consistent with Pessoa (2009), Nadler (2013) suggested that motivation benefits cognitive flexibility and improves performance in categorisation learning. Studies on task switching have shown decreased response times and error rates when motivating participants using rewards, performance feedback and other experimental manipulations (e.g., Nieuwenhuis & Monsell, 2002; Schneider, 2016, 2017). Previous results on working memory tasks have revealed that incentive motivation can modulate cognitive performance through top-down signals with amplified activity over prefrontal and visual association regions (Krawczyk & D' Esposito, 2011). However, in the absence of external rewards, there is evidence that people who are intrinsically motivated - that is, who think a task is useful, interesting and important, and perceive themselves as skillful and competent - are more likely to engage in the task and use effective problem-solving

strategies (Deci & Ryan, 2008; Struthers, Perry & Menec, 2000; Wulf & Lewthwaite, 2016). It is possible that in task-switching experiments some participants are more interested in the tasks and therefore are more motivated and willing to engage in the switching process.

The question is whether all individuals show switch costs or not, simply because some participants may have better executive abilities, are more highly motivated, and/or have other traits that may be related to more efficient switching. This is similar to the general question posed by Haaf and Rouder (2017, 2018): Does everyone show the same effect in a cognitive task? More specifically, in a typical task-switching experiment, do individual participants have the same overall performance and show the same switch costs? Individual differences in task-switching may be obscured when reporting only averaged group performances across tasks, conditions and paradigms. It is necessary to investigate not only average performance of a group of participants but also to document individual variability whenever possible.

1.5 Aims of the thesis

In this thesis I investigated how participants, and how males and females differ in their task-switching performance. To achieve this, I employed Generalised Linear Mixed-effects Models (GLMMs; Bolker et al., 2009) on single-trial RTs to study individual differences in task switching, in addition to conventional ANOVAs on response times (RTs) and error rates (ERs) averaged across trials. I also aimed to find out the origins of individual differences in task switching. Therefore, I explored a number of possible factors, such as general intelligence, motivation, and personal traits, that may have an effect on individual variability in task switching. It was of particular interest whether there are superior task-switchers among typical participants, who perform in task switching

without showing switch costs in task-switch trials, and what characteristics sets them apart? According to previous results, efficient task preparation and reduced interference may be the key (Kiesel et al., 2010; Koch et al., 2018; Vandierendonck et al., 2010). If so, task-switching performance may be improved by specifically designed cues, however, individual differences in different cue types were also highlighted.

CHAPTER 2 Identifying Individual differences in Task-switching and Explaining the Differences Using Multiple Psychological Scales and Cognitive Measures

2.1 Introduction

Previous task-switching research has found that although participants are instructed and encouraged to prepare faster, performance is typically impaired with longer response times and higher error rates in task-switch trials than in task-repeat trials, even after training. Task-switch costs can be reduced by using a number of experimental manipulations but residual switch costs remain significant (e.g., Nieuwenhuis & Monsell, 2002; Schneider, 2016, 2017). Researchers typically *assume* that participants are fully engaged and motivated but previous results suggest that participants are unable to prepare for the task set in each upcoming trial (failure-to-engage; De Jong, 2000; Lindsen & De Jong, 2010) and pay more attention to task-set changes in some trials than in others (partial preparation; Lien et al., 2005).

In order to motivate participants to fast prepare the task set in each upcoming trial I used a novel procedure that encourages participants to engage in every single trial for an extended period. In Experiment 1A, participants were asked to finish the experiment early by making no error in a block of 200 consecutive trials with two randomly intermixed tasks. I suggest that this “zero-error policy” would motivate participants to fully concentrate on the task and reduce "failure-to-engage". However, it is still possible that not every participant fully engaged in the demanding experiment. I employed an Intrinsic Motivation Inventory (IMI; Deci & Ryan, 2011) to assess participants’ subjective experience as well as intrinsic motivation for the task-switching experiment. According to previous results in motivation and performance on learning and cognitive tasks (e.g., Deci & Ryan, 2008; Krawczyk & D’Esposito, 2011; Nadler, 2013; Nieuwenhuis & Monsell,

2002; Wulf & Lewthwaite, 2016), participants with higher scores in motivation scales may have improved performance in the task-switching experiment.

In addition, according to previous task-switching results on individual differences (e.g., Lindsen & De Jong, 2010; Stoet & Snyder, 2003, 2007) and individual differences in other related tasks (e.g., Watson & Strayer, 2010), participants may have different executive control and trait-like switching abilities. I employed a Web-based Executive Control Function scale (Webexec; Buchanan et al., 2010) to capture participants' overall experience of executive problems. As reported by Buchanan et al. (2010), there is a strong negative relationship between Webexec scores and the performance on cognitive tasks (mean $r = -.35$): Participants who reported more executive problems (or higher scores on Webexec) showed less well performance in the cognitive tasks, such as lower accuracy in a reverse digit-span task and less items recalled in a semantic frequency task.

Five other psychological traits including self-reported perfectionism, impulsivity, cognitive flexibility, trait self-control and personality were measured using Short Almost Perfect Scale (SAPS; Rice, Richardson & Tueller, 2013), Barratt's Impulsiveness Scale version 11 (BIS-11; Patton, Stanford, & Barratt, 1995), Cognitive Flexibility Scale (CFS; Martin & Rubin, 1995), Trait self-control scale (TSC; Tangney, Baumeister & Boone, 2004), and Ten-Item Personality Inventory (TIPI; Gosling, et al., 2003), respectively. A study by Richardson, Rice and Devine (2014) suggested that individuals who had higher scores in SAPS tended to be more critical to their performance in a stressful context. Other researchers found that perfectionists were less capable of self-regulating their anxiety after making an error in cognitive tasks (e.g., Perrone-McGovern et al., 2017). Using BIS-11 and several measures of executive control researchers concluded that higher impulsiveness was related to troubles in deleting no-longer-relevant information from working memory (Whitney, Jameson, & Hinson, 2004), difficulty associated with solving cognitive conflicts and inhibiting incorrect responses (Enticott, Ogloff & Bradshaw, 2006; Leshem, 2015).

Çelikkaleli (2014) employed CFS and showed a positive relationship between cognitive flexibility and effective problem-solving skills. A meta-analysis of 102 studies (de Ridder, Lensvelt-Mulders, Finkenauer, Stok & Baumeister, 2011) indicated that higher scores on TSC related to better control and inhibition of undesired behaviours. Similarly, personality traits assessed by TIPI were also found to be related to different cognitive characteristics (Gosling et al., 2003; Murdock et al., 2013). Accordingly, since successful performance in task switching requires sustained attention while fast goal updating before flexible switching, it is possible that all of those psychological factors play a role in the individual differences in task-switching performance.

I also studied general intelligence using a Raven's advanced intelligence test (Raven, Raven & Court, 1998). According to Raven et al. (1998), this test was ideal for identifying people with superior reasoning ability and the ability to solve complex problem. Deary and colleagues (2012) reported that some people can be better than others in the general intellectual abilities, largely due to genetic variances. Evidence has shown that intelligence closely links with critical executive control functioning and cognitive behaviours (Benedek et al., 2014; Friedman et al, 2006). In a task-switching experiment, I predicted that good-performing participants may have higher levels of intelligence.

In summary, the present chapter sought to investigate how participants differ in their task-switching performance using different tasks, conditions and paradigms, with particular focus on individual task-switching costs in one experiment and two follow-up studies. In addition, I employed seven different psychological scales and a Raven's intelligence test in order to investigate factors that may be related to the different task switching.

2.2 Experiment 1A

Experiment 1A aimed to study individual differences in task-switching using a highly-demanding procedure. In contrast to conventional task-switching experiments with a fixed number of experimental trials, I asked participants to keep trying until they completed 200 consecutive trials in a mixed-task block without committing a single mistake. Alternatively, testing continued until the experimental session exceeded 90 minutes. I asked participants to keep practicing the tasks for up to 90 minutes as previous results showed improved switching performance after extended training (e.g., Stoet & Snyder; 2007; Zhao et al., 2018).

I assumed that asking participants to complete the experiment by making no error in 200 trials would heighten participants alertness and motivation over each consecutive trial. In addition, this method provides a series of RT measurements that are not confounded by intermittent errors (Regev & Meiran, 2014; Van der Borght, Braem, Stevens & Notebaert, 2016).

According to previous research on individual differences in cognitive (Haff & Rouder, 2017, 2018; Lindsen & De Jong, 2010; Medeiros-Ward et al., 2014; Stoet & Snyder, 2003, 2007; Strayer & Watson, 2012; Watson & Strayer, 2010), perception (Robertson et al., 2016; Russell et al., 2009) and memory tasks (Mallow et al., 2015; Ramon et al., 2016), I anticipated that participants would perform differently in the task-switching experiment. I expected that a few highly-engaged participants may reach 100% accuracy in their best-performing block and show no apparent RT switch costs. Other participants may perform more poorly, making frequent errors in the mixed-task block, showing significant switch costs, or both.

In addition to task-switch costs, Experiment 1A also studied congruency effects by comparing congruent trials with incongruent trials. I predicted that congruency effects

would be smaller in the best-performing block where participants achieved maximum of correct responses because Bugg and Braver. (2016) found reduced congruency effects when better control of attention across trials.

In order to study whether individual differences in task switching can be related to the differences in personality and other psychological characteristics, I assessed participants' personality as well as other psychological factors including intrinsic motivation, impulsivity, trait self-control, executive function problems, cognitive flexibility, and perfectionism. Based on previous studies on cognitive performance and psychological traits, I predicted that few highly performing task-switchers would show higher scores in intrinsic motivation, trait self-control, cognitive flexibility, but lower scores in impulsivity, executive function problems and perfectionism.

2.2.1 Experiment 1A Method

Participants

I recruited a total of 62 students from the University of Glasgow and Caledonian University. I tried to establish a reasonably large sample that would represent typical task-switching participants including both highly engaged participants and participants with relatively lower motivation. All participants received a small reward for taking part and were entered into a prize draw to win a £5, £10, or £20. Two participants had to be excluded because they quit the experiment before completing the study. I also excluded two poorly performing participants because they only achieved a maximum of three trials in their mixed blocks. The 14 male and 44 female students in the remaining sample of 58 participants were between 20 and 34 years old ($M = 25.0$ years, $SD=3.1$). All participants passed a colour-blindness test (Ishihara, 1983), and they were naive with respect to the

task-switching paradigm and experimental purposes. The study was carried out in accordance with the recommendations of the BPS Code of Ethics and Glasgow University College of Science and Engineering Ethics Committee. All participants gave written consent to take part.

Apparatus

The experiment was conducted in a quiet and dimly-lit laboratory. Participants were seated in front of a computer screen at a viewing distance of approximately 57 cm. The experiment was programmed using PsyToolkit software (an open access software toolbox for programming psychological experiments based on Linux operating systems; Stoet, 2010, 2017) and run on a PC with a 24-inch screen. In order to improve response time measurement, a Black Box toolkit (BBTK) response pad was used to record button-press responses with millisecond precision. Two of the four white buttons on the response pad were used to record responses. All data were analysed in R version 3.4.2 (R Core Team, 2017).

Stimuli and Tasks

Colour-shape task-switching task

I employed a pre-cued colour/shape task-switching paradigm. Both cues and stimuli were displayed on a black background. The task cues were displayed at the centre of the screen. The cues were white isosceles triangles with side length of 35 mm and base length of 42 mm. A triangle pointing upwards indicated a colour task and a triangle pointing downwards indicated a shape task. I used four different rectangles as target stimuli: a vertically elongated (high) red or green bar, a horizontally elongated (wide) red or green bar. The size of the stimuli varied randomly across trials, with the shorter side ranging between 6.6 to 33 mm and the elongated side ranging between 46 to 73 mm. The

RGB colour of the stimuli also varied randomly across trials (red, green, and blue channels could range between 0 and 255, as is standard in many computer applications). For the red stimuli, the red channel value ranged between 200 and 255 whereas the green channel value equalled blue channel value varying between 0 and 100. For the green stimuli, the green channel value ranged between 200 and 255 whereas the red channel value equalled blue channel value varying between 0 and 100. The purpose of the variation in colour and size of the target stimuli was to encourage participants to use general task rules when making responses rather than recalling specific cue-stimulus-response associations from a “lookup table” (Stoet & Snyder, 2003, 2007; Dreisbach, Goschke & Haider, 2007; Forrest, Monsell & McLaren, 2014). Participants used the same pair of response keys for both tasks resulting in congruent and incongruent trials (Figure 2.1). In congruent trials, both task-relevant and task-irrelevant target features lead to the same (correct) response in both tasks. In incongruent trials the distracting target features, if erroneously attended to, would result in a different and therefore incorrect response (cf., Kiesel et al., 2007).

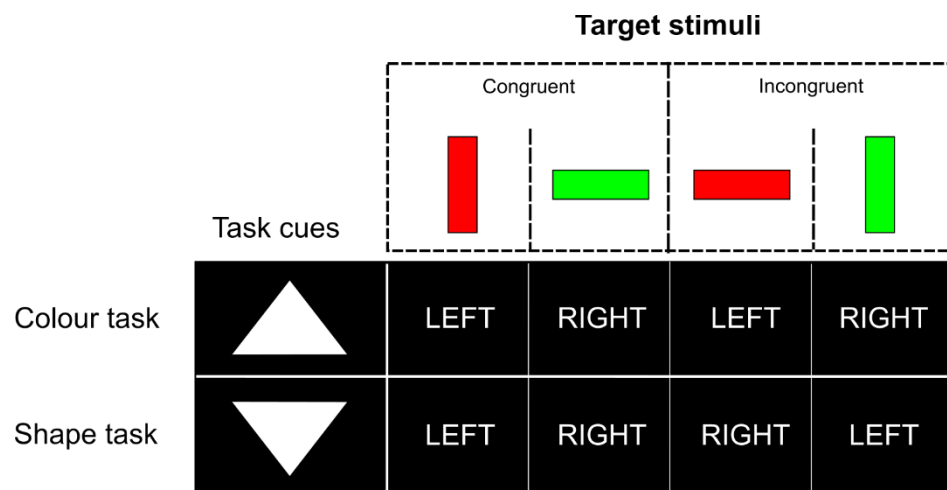


Figure 2.1. Illustration of the task rules in the colour/shape task-switching paradigm of Experiment 1A. The colour task cue was a white triangle pointing upward, and the shape task cue was a white triangle pointing downward. The target stimuli were four rectangular bars (colour = red, green; shape = high, wide). LEFT and RIGHT corresponds to pressing the left and right button on the response pad, respectively.

Psychological scales

Ten-Item Personality Inventory (TIPI). Personality was assessed by using a Ten-Item Personality Inventory (TIPI; Gosling et al., 2003). The scale contains 10 items to assess 5 personality dimensions: extraversion, agreeableness, conscientiousness, emotional stability and openness to experience. Participants rated themselves in a 7-Likert scale from 1 (*disagree strongly*) to 7 (*agree strongly*). Half of the items were reverse coded. TIPI is an ideal self-rating scale because of the concise description of each personality characteristics and reliable psychometric properties (mean test-retest reliability = .72).

Intrinsic Motivation Inventory (IMI). The Intrinsic Motivation Inventory (IMI; Deci & Ryan, 2011) was used to assess participants' subjective experience as well as intrinsic motivation when performing in the colour-shape task-switching experiment. The IMI consists of 22 items in four subscales: interest/enjoyment (7 items; $\alpha=.94$), perceived competence (5 items; $\alpha=.88$), perceived choice (5 items; $\alpha=.90$), and pressure/tension (5 items; $\alpha=.86$). The interest/enjoyment subscale measures participants' self-reported intrinsic motivation in the task-switching task (e.g., I found the task very interesting); perceived competence subscale involves questions concerning the self-assessed competence towards the task they have just experienced (e.g., I felt pretty skilled at this task); the perceived choice subscale includes questions about whether they participate in the task on their own initiative (e.g., I felt like I was doing what I wanted to do while I was working on the task); the pressure/tension subscale reflects the negative emotion to the task (e.g., I felt pressured while doing the task), which are considered as a negative predictor of intrinsic motivation. The items are rated on a 7-point Likert scale from 1 (*not at all true*) to 7 (*very true*), with the total scores ranging between 22 and 154. Ratings were reversed in valence if absence of these aspects of intrinsic motivation indicated above (e.g., I didn't really have a choice about doing the task). A higher overall score indicates greater intrinsic motivation in the colour-shape task-switching experiment.

Web-based Executive Control Function (Webexec). The web-based executive control function (Webexec; Buchanan et al., 2010) is an online self-report questionnaire which was designed for capturing participants' overall experience of executive problems. Webexec has 6 items (Cronbach's alpha = .785) assessing problematic thoughts and behaviours (e.g., Do you have difficulty carrying out more than one task at a time?). Participants respond on a 4-Likert scale (from 1 = *no problems experienced* through 4 = *a great many problems experienced*), with the scores ranging between 6 and 24. A higher score indicates more executive problems.

Short Almost Perfect Scale (SAPS). The Short almost perfect scale (SAPS; Rice et al., 2013) was employed to measure perfectionism. SAPS consists of two subscales: Standards (4 items for assessing the standards people set for themselves; e.g., I have high expectations for myself.) and Discrepancy (4 items for measuring negative self-evaluation of performance or perfectionistic self-criticism; e.g., I am hardly ever satisfied with my performance). Participants rated each item on a 7-Likert scale from 1 (*strongly disagree*) to 7 (*strongly agree*), with the total score ranging between 8 and 56. A higher score refers to more self-defeating thoughts and behaviours. Rice et al. (2013) reported good internal consistency coefficients for the Standards subscale ($\alpha = .87$) and Discrepancy subscale ($\alpha = .84$).

Barratt's Impulsiveness Scale version 11 (BIS-11). The Barratt's Impulsiveness Scale version 11 (BIS-11; Patton et al., 1995) is a 30-item self-report questionnaire, which is developed to measure different sub-traits of impulsiveness: Non-planning impulsiveness (10 items; e.g., I say things without thinking), Attentional impulsiveness (10 items; e.g., I do not pay attention.) and Motor impulsiveness (10 items; e.g., I make-up my mind quickly.). Each answer is rated on a 4-point ordinal scale, from 1 (*Rarely/Never*) through 4 (*Almost Always/Always*), indicating the ways people act and think in different situations. A

review on BIS-11 by Stanford et al. (2009) demonstrated reliable internal consistency (Cronbach's alpha = .59 to .74) and test-retest reliability ($r = .61$ to $.72$).

Cognitive Flexibility Scale (CFS). Cognitive Flexibility Scale (CFS; Martin & Rubin, 1995) was employed to measure one's ability to switch cognitive sets to adapt to environmental change. The CFS is a 12-item 6-point Likert scale. Participants point out a number from 1 (*Strongly Disagree*) to 6 (*Strongly Agree*) that best shows their agreement with each statement (e.g., In any given situation, I am able to act appropriately). Martin and Rubin (1995) reported high reliability of the scale (test-retest $r = .83$).

Trait self-control scale (TSC; Brief version). To assess individual differences on trait self-control or self-regulation, I used a trait self-control scale developed by Tangney et al. (2004). The scale is a 13-item 5-point Likert scale (1 "not at all" to 5 "very much"). Nine of the items in the scale are reversely scored in order to avoid response bias (e.g., I have trouble concentrating). Tangney et al. (2004) reported a high internal consistency coefficient of .85 and a test-retest reliability of .87.

Procedures

The task-switching experiment lasted up to 90 minutes. Before testing, each participant received verbal and written instructions that introduced the task rules for the colour and shape task and how they were cued (Figure 2.1).

Each trial started with the presentation of a task cue signalling the relevant task that had to be performed (Figure 2.2). The cue was shown for 250 ms before it was covered by a mask for 250 ms followed by a blank screen for 150 ms. Altogether the cue-stimulus interval (CSI) lasted 650 ms. The mask could help participants to focus on the cue and to initiate task preparation before the target stimulus was presented. The procedure with cue masking was similar to Verbruggen et al. (2007) and Schneider (2016). Immediately after

the CSI, a target stimulus appeared and remained on screen until the participant gave a response or until the maximal RT of 1,500 ms was exceeded. A correct response would trigger the next trial after an inter-trial interval (ITI) of 500 ms. If participants failed to respond within 1,500 ms, the message “Too slow” appeared for 2,000 ms. If participants pressed the wrong key, an error warning was displayed for 2,000 ms. At the end of each block or after an incorrect response, each participant received individual feedback indicating their mean RTs and the number of consecutive correct trials.

Participants were asked to fully engage in the experiment with the incentive to finish early if they made no error in 200 consecutive trials of the mixed-task block. Once a participant gave the wrong response or did not respond in time (counted as incorrect) in the mixed-task block, the attempt of reaching zero errors was aborted and the participant would receive practice trials in the colour and the shape task for additional task-rule practice. The experiment lasted until a participant performed 200 consecutive trials in the mixed-task block without mistakes. In case a participant did not manage to reach zero errors, the experiment was terminated after 90 minutes, after which participants completed 7 online psychological scales: TIPI, IMI, Webexec, SAPS, BIS-11, CFS, and TSC. The total procedure of questionnaires lasted about 20 minutes.

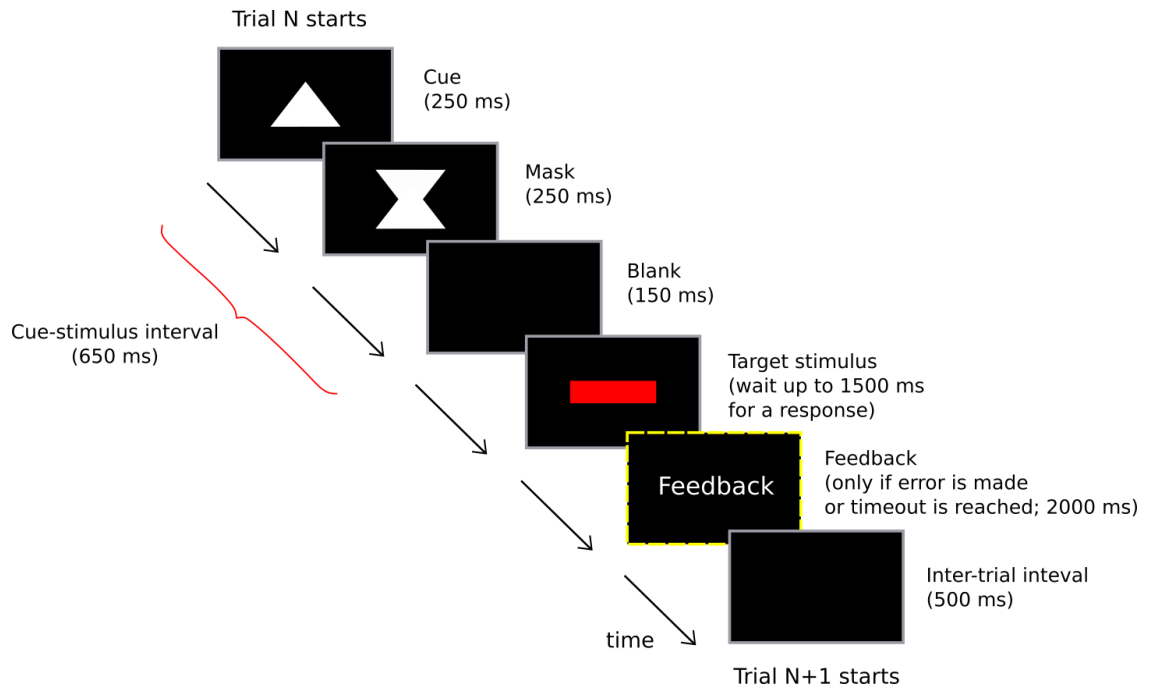


Figure 2.2. Experiment 1A. Schematic timeline of a trial in the colour/shape task-switching block.

2.2.2 Experiment 1A Results

Task-switching task

I examined individual differences in task switching using a novel procedure that encouraged participants to make zero mistakes. I first conducted conventional ANOVAs on response times (RTs) and error rates (ERs) averaged across conditions from all mixed blocks. In addition, I employed Generalised Linear Mixed-effects Models (GLMMs; Bolker et al., 2009) using the gamma link-function in order to study individual differences in RTs from the mixed-task block with the maximum number of responses (MAX block). Each individual can have a different number of trials in their MAX block. GLMMs can take into account imbalanced data and typically provide better model fits than conventional ANOVAs. In order to guard against model overfitting, I employed information criteria AIC (Akaike information criterion; Akaike, 1973) as well as BIC (Bayesian information

criterion; Schwarz, 1978) that penalise more complex models. The fixed effects of a GLMM reflect group-level performance whereas random effects reveal individual variability in RTs. I predicted that participants may vary in their task-switching performance, particularly in the MAX blocks, since participants may be differently motivated and may have different characteristics.

Mean RTs and ERs from All Mixed Blocks

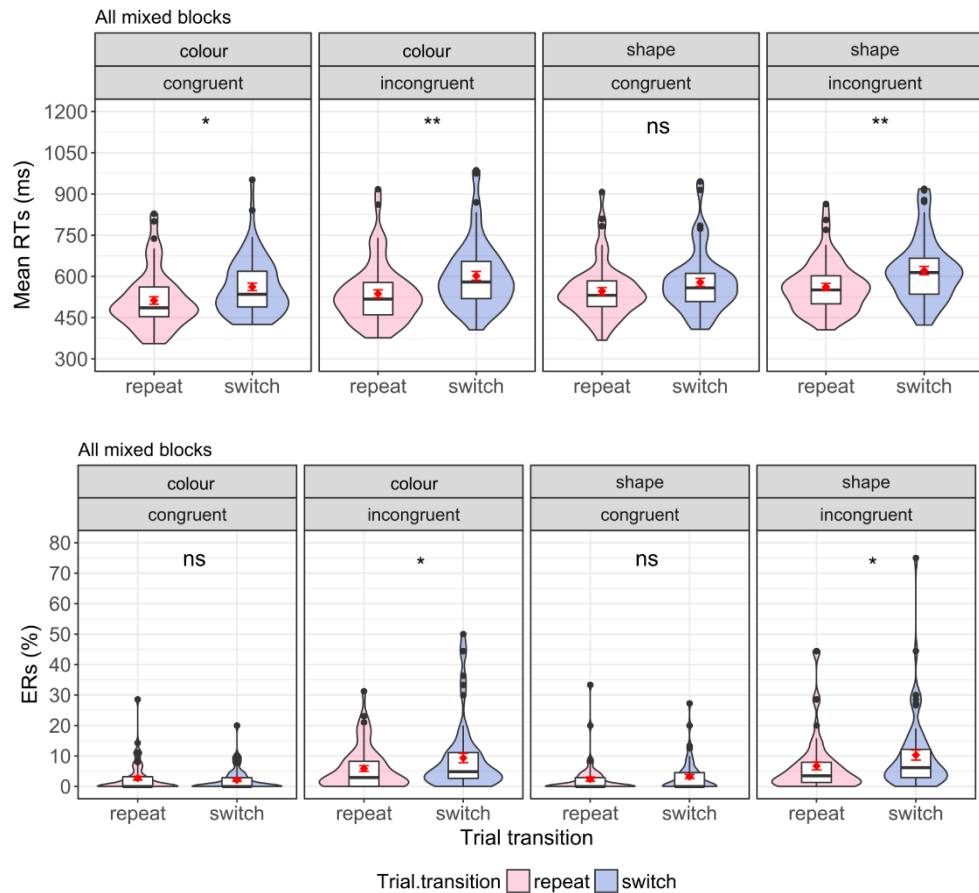
The first trial of each block was discarded from the analyses because it cannot be classified as a switch or a repeat trial. Error trials were also excluded from the RT analysis. Since participants had to start a new block whenever they made an error, it was not necessary to exclude trials after an error. Mean RTs and ERs for each participant (see Figure 2.3) were entered into separate three-way ANOVAs with repeated measurements on factor Task (colour, shape), Trial transition (repeat, switch) and Congruency (congruent, incongruent).

For mean RTs, I observed three statistically significant main effects. There was a significant main effect of Task, $F(1, 57) = 22.30, p < .001, \eta^2_p = .28$. Participants responded on average more slowly in the shape task (577 ms) than in the colour task (553 ms). In addition, there was a significant main effect of Congruency, $F(1, 57) = 30.69, p < .001, \eta^2_p = .35$, with slower mean responses for incongruent trials (581 ms) compared to congruent trials (550 ms).

More importantly and in line with previous findings, I found a statistically significant main effect of Trial transition, $F(1, 57) = 76.53, p < .001, \eta^2_p = .57$. Responses were slower in trials with task-switching (591 ms) compared to trials with task repetition (540 ms), indicating an average RT switch cost of +51 ms. The switch cost was larger in

the incongruent trials (SC = switch - repeat = +61 ms, $p < .001$) than in the congruent trials (SC = +41 ms, $p = .015$), indicating a statistically significant interaction between Trial transition and Congruency, $F(1, 57) = 5.99$, $p = .018$, $\eta^2_p = .10$. No other interaction effects were statistically significant.

For ERs, I found a significant main effect of Congruency, suggesting more errors in incongruent trials (8.08%) than in congruent trials (2.62%), $F(1, 57) = 43.63$, $p < .001$, $\eta^2_p = .43$. As in the RT analysis, I found a statistically significant main effect of Trial transition, suggesting more errors in switch trials (6.26%) than in repeat trials (4.44%), $F(1, 57) = 13.08$, $p < .001$, $\eta^2_p = .19$, indicating a significant ER switch cost of +1.82%. The ER switch costs were larger in the incongruent condition (SC = +3.52%, $p < .001$) than in the congruent condition (SC = +0.13%, $p = .904$), $F(1, 57) = 10.37$, $p = .002$, $\eta^2_p = .15$. No other effects reached statistical significance.



Note: ** $p < .01$; * $p < .05$; ns = non-significant

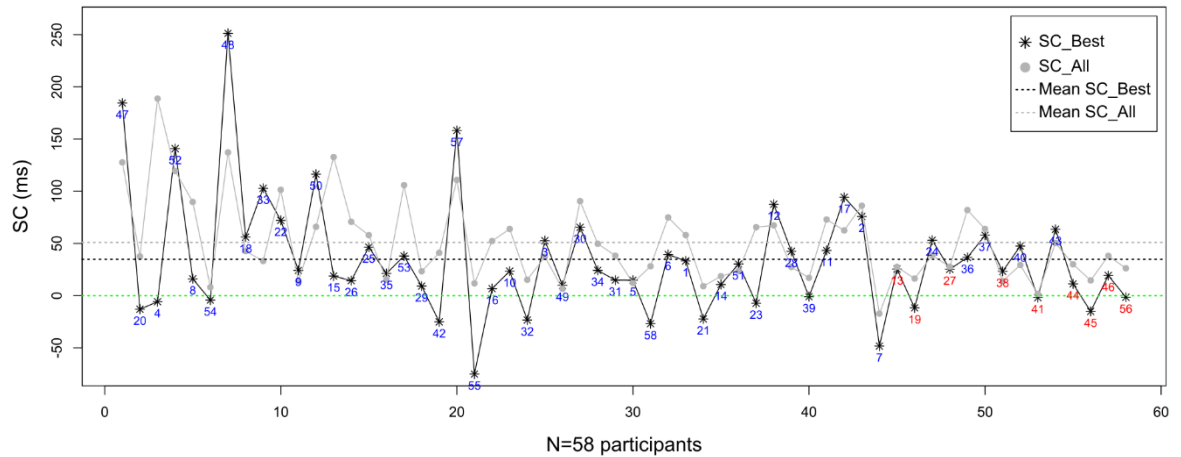
The results of the ANOVAs indicate that significant RT and ER switch costs occurred, even though participants were asked to make no errors. It is likely that most participants only fully engaged in the mixed block where they achieved their maximum number of consecutive correct responses and may show no switch costs. Therefore, I considered only performance in the MAX blocks in the following analysis. I tried to identify how participants differed in their best-performing block (i.e., the MAX block): Did some participants perform better than others, e.g., by not making a single error in their

MAX block? Did individuals who were fully engaged and highly motivated in their MAX block also have zero switch costs?

MAX Blocks

Participants had different numbers of correct trials in their MAX block (Figure 2.4A). Only a few valid observations were available for poorly performing participants but up to 200 observations for some exceptional participants, leading to imbalanced numbers of observations across conditions ($M = 109$ trials, ranging between 5 to 200 trials). Similarly, the individual analyses of RT switch costs showed that individual switch costs ranged between -75 ms to +251ms, with an average switch cost of +35 ms in the MAX block (Figure 2.4B).

A.



B.

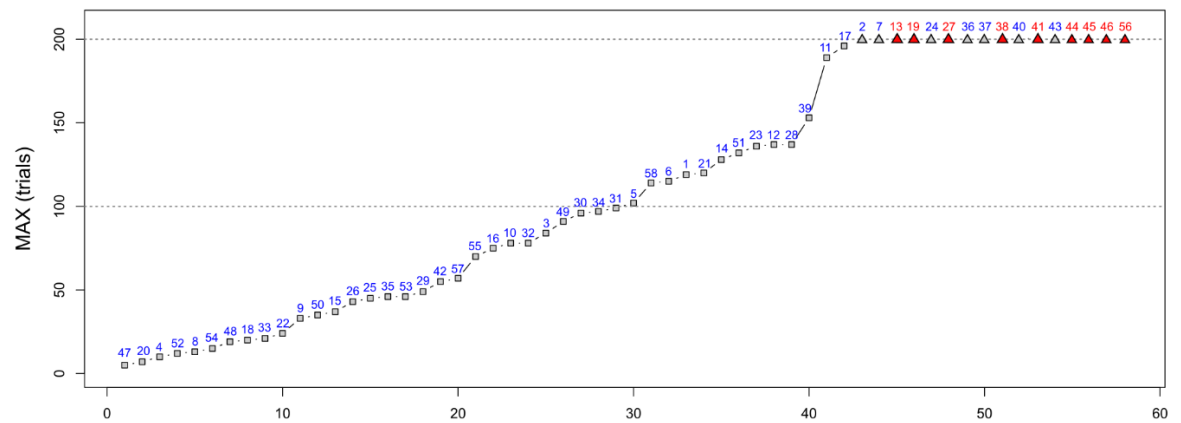


Figure 2.4. Experiment 1A. Individual variation in task switching. **A.** Individual switch cost (SC from MAX blocks, and from all mixed blocks, in *ms*). **B.** MAX trials (maximum number of consecutive trials correct). Triangles and corresponding numbers reflect participants who did not make any mistakes in MAX trials. Among them, red triangles and the corresponding red numbers in the two plots denote the 9 best-performing participants. Please note that the zero-error performers who labeled with grey triangles in panel B showed significant switch costs. Participant 7 had zero mistakes and showed significantly negative switch costs (switch - repeat = -47 ms, $p = .011$). Therefore, Participant 7 was not considered as a typical best-performer (be accurate and fast in task-switch trials similar as in task-repeat trials). Other participants (labeled with grey squares) made frequent errors in their MAX block.

Best-performing participants in MAX blocks

I found that after an average practice of 1,233 trials (ranging from 540 to 1,956) before the MAX block, a total of 16 participants from the sample were able to finish the experiment early by completing 200 consecutive trials in the MAX block without making a single error. Among the 16 participants, I identified 9 *best-performing participants* or *best performers* who learned to switch between tasks without error after relatively few trials (mean number of trials before MAX = 1,102 trials, ranging from 540 to 1,656 trials). Each of these 9 participants had no significant RT differences between task-switch and task-repeat trials (mean switch cost of +5 ms). For comparison, the remaining 7 participants, who also made no errors in the MAX block, responded more slowly in task-switch than in task-repeat trials (mean switch cost of +42 ms). Note that among these 7 participants, a two-sample t-test showed that Participant 7 performed significantly faster in task-switch trials compared to task-repeat trials showing a negative switch cost of -48 ms ($p = .011$, Cohen's $d = .37$). This participant was different from the best-performing performers who showed the same accuracy and speed in task-switch as in task-repeat trials.

In order to study whether the 9 best-performing participants varied in RTs over the course of their MAX block, I split the 200 trials from their MAX blocks into the first and second 100 (c.f. De Jong, 2000). The corresponding averaged RT data were then submitted to a four-way repeated-measure ANOVA with factor Trial transition (task-repeat, task-switch), Congruency (congruent, incongruent), Task (colour, shape) and Block half (first, second). The results showed non-significant main effects of Trial transition ($F < 1$) and Congruency ($F = 3.67$, $p = .092$). Best performers showed non-significant switch costs (+5 ms) and congruency effects (+13 ms). Importantly, the results indicated non-significant effects involving Block half, suggesting that the 9 best-performing participants showed non-significant change in RTs between the first and the second half of the MAX blocks.

The switch costs were +7 ms in the first half and +4 ms in the second half. The congruency effects were +8 ms in the first half and +18 ms in the second half.

RT analyses and individual differences in MAX blocks

In order to study RTs and individual task-switching performance in MAX blocks, I employed Generalised Linear Mixed-effects Models (GLMMs). Although participants had different numbers of responses in their MAX block, hierarchical models can accommodate imbalanced RT data and provide estimates of group-level fixed effects as well as individual random effects (Baayen, Davidson & Bates, 2008). The latter can capture individual differences in task-switching performance.

I modelled the skewed RT data from the MAX blocks using the lme4 package in R (Bates, Mächler, Bolker, & Walker, 2015). I tested models with full factorial design (fixed effects for Task, Congruency and Trial Transition, and their interactions) and identified the most parsimonious model that converged (GLMM 1A.2 in Table 2.1). The model had by-subject random effects for mean RT (intercepts), Trial transition (slopes) and Task (slopes).

Table 2.1

Experiment 1A GLMM comparisons based on 58 participants' RT data in the MAX block (the best model is in bold; GLMM 1A.2).

Model names	Models (family = Gamma (link = "identity"))	df	AIC	BIC	Log lik	dev	Chi-sq	p-value (>Chisq)
GLMM1 A.1	RT ~Task + Trial.transition + Congruency +(1 subject)	6	79191	79231	-39589	79179		
GLMM 1A.2	RT ~Task * Trial.transition *Congruency +(1+Task+ Trial.transition subject)	15	79115	79216	-39543	79085	93.77	< .001 ***
GLMM1 A.3	RT ~Task * Trial.transition * Congruency +(1+Task* Congruency subject)	26	79174	79349	-39561	79122	0.00	1.00

Note. The model formulas are stated in the syntax of the lme4 package in R.

In order to report p -values for fixed effects, I used the asymptotic Wald test where each “ t value” is computed as a ratio between estimated and standard error. In the following I report these t -values and the corresponding p -values without degrees of freedom (Bates et al., 2015). The fixed effects of the GLMM in Experiment 1A suggest that responses were 24 ms slower in the shape task (598 ms) compared to the colour task (574 ms), $t = 6.52$, $p < .001$; 28 ms slower in switch trials (600 ms) compared to repeat trials (572 ms), $t = 5.85$, $p < .001$; and 18 ms slower in the incongruent condition (595 ms) compared to the congruent condition (577 ms), $t = 6.18$, $p < .001$. The two-way interaction between Task and Trial transition was statistically significant ($t = -2.75$, $p = .006$), suggesting larger switch costs when switching to the colour task (+34 ms) than switching to the shape task (+23 ms). There also was a statistically significant three-way interaction

between Task, Trial transition and Congruency ($t = 2.69, p = .007$), suggesting that switch costs were larger in the colour-congruent condition (+37 ms), compared to the colour-incongruent condition (+30 ms), the shape-incongruent condition (+25 ms) and the shape-congruent condition (+20 ms).

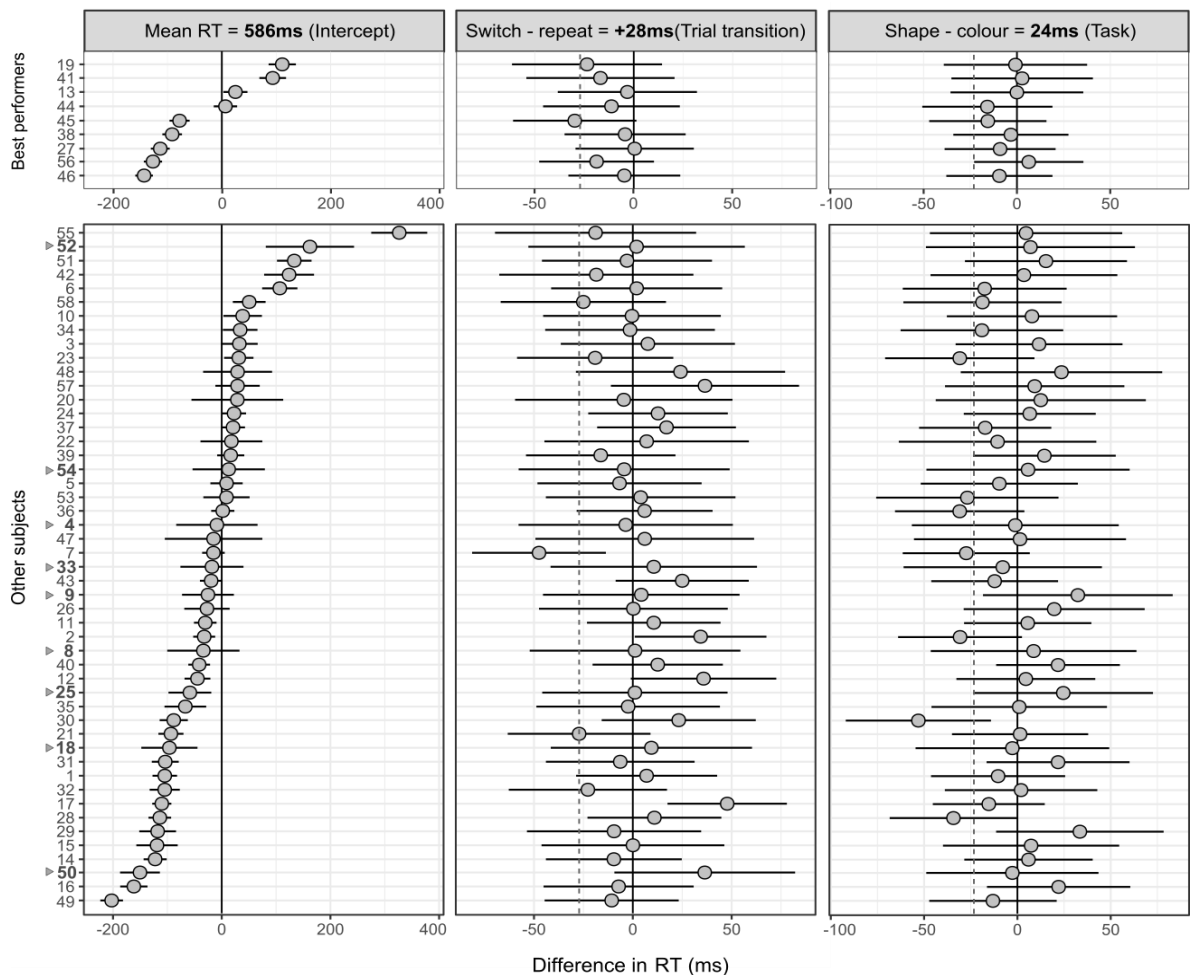


Figure 2.5. Experiment 1A. Illustration of by-subject random effects for RTs. Subject numbers on the left identify individual participants. Dotplots in the three top panels show random intercepts and random slopes of the best performers (no errors and no significant switch costs), and the dotplots in the three bottom panels illustrate the random effects of the other participants/subjects. Dotplots in the left column illustrate individual deviations (dots) and 95% confidence interval (horizontal error bars) from the estimated mean RT of the $N = 58$ participants. The dotplots in the middle and right column show individual deviations from the fixed effect of Trial transition and Task (random slopes). The solid vertical lines centred on zero in the left, middle and right panels correspond to the estimated mean RT (Intercept = grand mean RT of 586 ms), mean switch cost (Trial

transition; switch - repeat = +28 ms), and mean task difference (Task; shape - colour = 24 ms), respectively. The dashed vertical line in the middle and right plot indicate zero switch cost and zero task difference, respectively. Please note the differently scaled x -axes (in ms) in the left and right panels.

Figure 2.5 illustrates that participants varied considerably in their mean RTs (Intercepts) from the overall average. Participant 49, for example, was on average 203 ms faster and Participant 55 was 327 ms slower than the grand average RT in the sample (586 ms). The 9 best-performing participants also showed a considerable spread in their mean RTs. For example, Participant 46 responded significantly faster and Participant 19 responded significantly slower than the total average.

The individual differences in RT switch costs (Trial transition), however, were less pronounced and appeared to be independent of individual RTs (Pearson's $r = -.07$). I found clear deviations from the group-average switch costs of +28 ms in only 3 out of 58 participants: Participant 7 (-47 ms), Participant 2 (+34 ms), and Participant 17 (+48 ms). Not surprisingly, the 9 best-performing participants (Figure 2.5; top middle panel) showed smaller switch costs deviating only marginally from the mean switch cost (solid vertical line) and none of them deviated significantly from zero switch costs (dashed vertical line). In comparison, 12 out of 49 other participants (Participant 2, 11, 12, 17, 24, 28, 30, 37, 40, 43, 50, and 57) showed switch costs that were significantly larger than zero.

Similarly, the individual differences in RT task-difference showed a random pattern and appeared to be independent of individual RTs (Pearson's $r = .02$) as well as individual switch costs (Pearson's $r = -.02$). None of the best-performing participants showed a significant difference between colour and shape tasks and only five of the other participants (Participant 9, 16, 29, 31, 40) showed a significant difference between colour and shape tasks.

Task-switching performance and psychological scales

Spearman's correlations (2-tailed) were conducted between task-switching performance and psychological traits in $N = 58$ participants. The task-switching performance was indicated by variables including mean RT and RT task-switch costs from all mixed blocks and from the MAX block. In addition, the number of trials in the MAX block was studied (MAX No.). Error rates from all mixed blocks were also included. Significant correlations at the significance level of .05 are presented in Table 2.2.

I found that the mean RT from all mixed block (ALL_Mean RT) was negatively related to the overall score of intrinsic motivation (*IMI_overall*), and particularly the score of feeling interested (*IMI_Interest*) and competent (*IMI_Perceived_competence*) in the task. In addition, the mean RT from the MAX block (MAX_Mean RT) was only negatively related to the motivation subscale of feeling interested (*IMI_Interest*).

The switch costs from all mixed blocks (ALL_SC) were positively related to executive function problems (*WebECF*), the overall perfectionism scores (*SASP_Overall*), and the score of feeling disappointed to themselves in the task (*SAPS_Discrepancy*). However, the costs from all mixed blocks were negatively related to the score of being emotionally stable (*TUPI_Emotionably_Stable*), the overall score of being intrinsically motivated (*IMI_overall*), and the score of feeling competent in task switching (*IMI_Perceived_competence*).

With respect to the switch costs from MAX block (MAX_SC), the costs were positively related to the score of attentional impulsivity (*BIS_Attentional*) and executive function problems (*WebECF*). However, the switch costs were negatively related to the score of being emotionally stable (*TUPI_Emotionably_Stable*), the score of trait self-control

(*TSC*) and the score of feeling that they were actively participating in the task-switching experiment (*IMI_Perceived_choice*).

Error rates (*ALL_ER*) were positively related to executive control problems (*WebECF*), the overall score of impulsivity (*BIS_Overall*), and the score of the subscale non-planning impulsivity (*BIS_Impulsivity*). However, error rates (*ALL_ER*) were negatively related to trait self-control (*TSC*), the overall score of feeling intrinsically motivational (*IMI_Overall*) and the score of feeling interested (*IMI_Interest*) and competent (*IMI_Perceived_competence*).

MAX No. was positively related to the overall score of intrinsic motivation (*IMI_Overall*), the score of the subscale interest (*IMI_Interest*) and competence (*IMI_Perceived_competence*). MAX No. was negatively related to the score of non-planning impulsivity (*BIS_Nonplanning*) and executive function problems (*WebECF*).

Best performers and their psychological traits

As shown in Figure 2.6, best performers appeared to have higher scores compared to other participants in trait self-control (*TSC*; $t = 3.22, p = .005$), overall intrinsic motivation (*IMI_Overall*; $t = 6.51, p < .001$), and the subscale interest (*IMI_interest*; $t = 3.11, p = .009$) and competence (*IMI_Perceived_competence*; $t = 4.30, p < .001$). However, best performers appeared to have lower scores compared to other participants in executive function problems (*WebECF*; $t = 3.54, p = .003$), overall impulsivity (*BIS_Overall*; $t = 4.04, p < .001$), and the subscale attentional impulsivity (*BIS_Attentional*; $t = 4.46, p < .001$) and non-planning impulsivity (*BIS_Nonplanning*; $t = 3.63, p = .001$).

Table 2.2

Experiment 1A. Spearman's correlations between task-switching performances and psychological traits.

Scales	All_ Mean RT	ALL_ SC	ALL_ ER	MAX_ Mean RT	MAX_ SC	MAX _ No.
IMI_Interest	-.40**		-.37**	-.31*		.40**
IMI_Perceived_choice					-.28*	
IMI_Perceived_competence	-.30*	-.28*	-.46**			.55**
IMI_Pressure						
IMI_Overall	-.37**	-.30*	-.51**			.59**
TIPI_Extraversion						
TIPI_Agreeableness						
TIPI_Conscientiousness						
TIPI_Emotionally_stable		-.29*			-.30*	
TIPI_Openness						
SAPS_Standards						
SAPS_Discrepancy		.37**				
SAPS_Overall		.37**				
BIS_Nonplanning			.34**			-.29*
BIS_Attentional					.28*	
BIS_Motor						
BIS_Overall			.29*			
WebECF		.35**	.38**		.33*	-.36**
CFS						
TSC			-.30*		-.34*	

Note. IMI = Intrinsic Motivation Inventory; TIPI = Ten-Item Personality Inventory; WebECF = Web-based Executive Control Function; SASP = Short Almost Perfect Scale; BIS = Barratt's Impulsiveness Scale; CFS = Cognitive Flexibility Scale; TSC = Trait Self-control Scale. ALL_RT = Mean RT from all mixed blocks; ALL_SC = Switch costs from all mixed blocks; ALL_ER = Error rates from all mixed blocks; MAX_RT = Mean RT from the MAX block; MAX_SC = Switch costs from the MAX block; MAX_No. = Maximum number of consecutive trials correct.

* $p < .05$; ** $p < .01$; blanks represent correlations that were not significant at the .05 level (two-tailed).

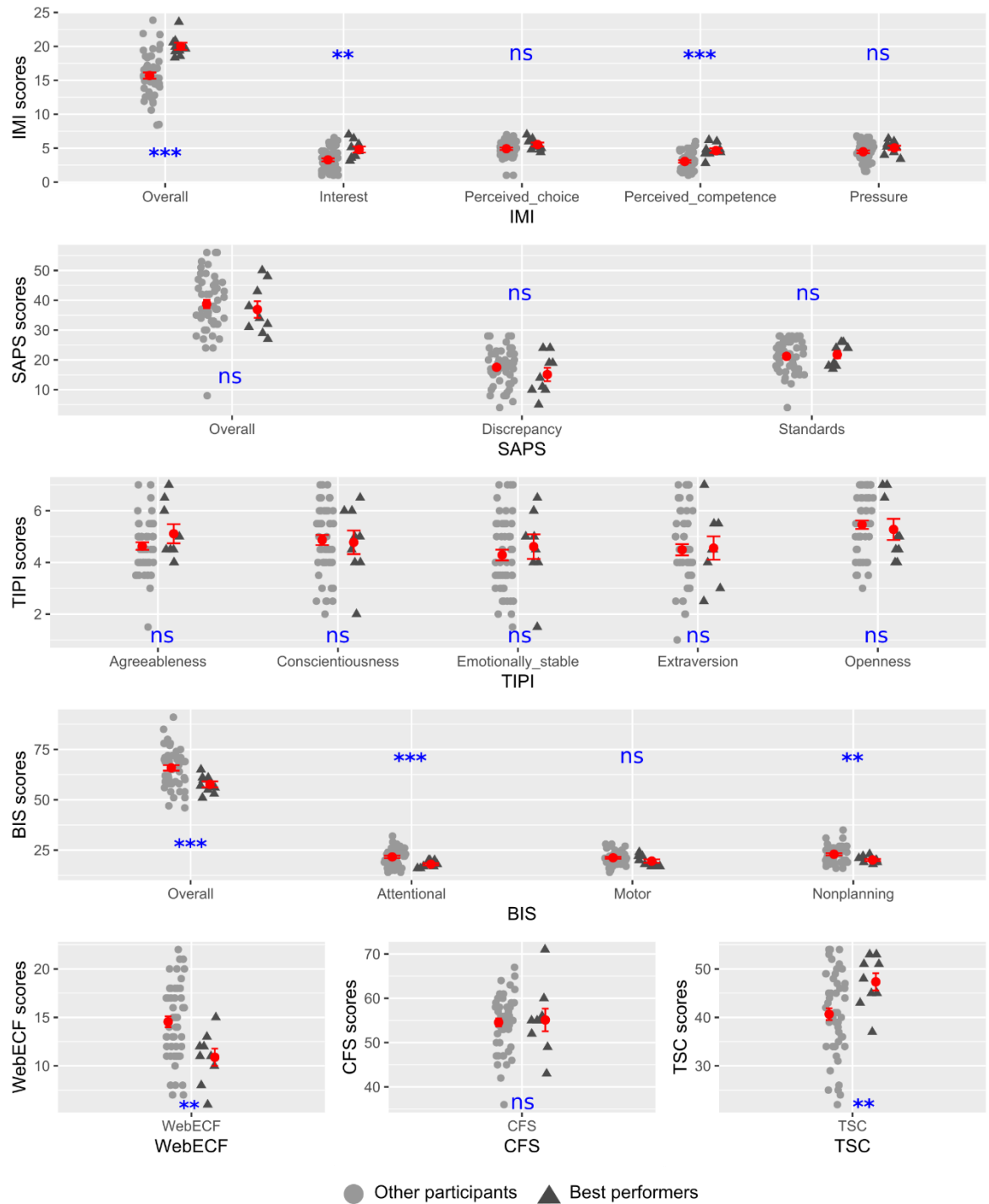


Figure 2.6. Scores of each of the psychological scales between best performers ($N = 9$) and other participants ($N = 49$). The red dots and error bars represent mean and standard error, respectively.

Note. *** $p < .001$, ** $p < .01$, ns = non-significant

2.2.3 Experiment 1A Discussion

Experiment 1A investigated and revealed individual differences in task switching using a novel experimental procedure. I conducted both conventional ANOVAs and mixed-effect models to study their task-switching performance. I observed a significant RT switch cost of +51 ms averaged across all trial conditions, mixed blocks, and participants. However, RT switch costs were reduced to +28 ms in the MAX block. In addition, RT congruency effects reduced from +31 ms averaged across all blocks to +18 ms in the MAX block. The reduced congruency effects suggested that participants had better attentional control with reduced interference in the MAX block (Bugg & Braver, 2016). The reduction in the task-switch costs can be attributed to increased engagement and motivation, possibly relating to more efficient task-switching strategies in the MAX block. It may be argued that switch costs in the MAX block and in all mixed blocks were relatively small compared to other task-switching studies. Schneider (2017), for example, found significant switch costs of +128 ms for a response-time limit of 2,500 ms. With a narrower response window of 1,500 ms, our participants experienced more time pressure and were more motivated to respond faster in each trial. This may have attenuated RT differences between switch and repeat trials.

I inspected individual performances in MAX blocks in order to identify participants who maximally engaged in task switching over many consecutive trials. I found that 16 participants managed to complete the experiment early by making no error in 200 consecutive trials in the mixed-task block (100% accuracy). Among these 16 participants, 9 (about 15% of the total sample) showed non-significant RT switch costs. I labelled these high-performing individuals as *best performers*. The other participants made an error and/or showed significant switch costs in their MAX block, even after practicing the tasks for over an hour. Surprisingly, Participant 7 showed a negative RT switch cost. This

participant might have employed a strategy that led to faster responses in task-switch compared to task-repeat trials.

As expected the GLMM on RTs in the MAX block indicates individual differences in task-switch costs although the differences were relatively small throughout our sample of participants. It appears that the best performers showed task-switching characteristics that were comparable to most other participants. However, the task-switching procedure in Experiment 1A was extremely demanding as it encouraged the highest level of accuracy (100% accuracy). A participant who completed the 200 trials without making a single mistake had to maintain full attention. Therefore the 9 best performers were quite exceptional because they were not only 100% accurate in their switching performance over 200 trials, but also performed task-switch trials as quickly as task-repeat trials. According to the *failure-to-engage* account (De Jong, 2000; Lindsen & De Jong, 2010), these participants were able to fully engage in each upcoming trial for an extended period of time. In contrast, other participants seemed less capable during task-switching. They occasionally failed to engage in the task and therefore made mistakes and/or showed significant switch costs in their MAX block.

The identification of best performers supports previous studies on individual differences in task-switching (Stoet & Snyder, 2003, 2007), multi-tasking (Medeiros-Ward et al., 2014; Strayer & Watson, 2012; Watson & Strayer, 2010) and related cognitive tasks (Haff & Rouder, 2017, 2018). In these studies some participants learned tasks better than others, suggesting superior cognitive abilities or higher motivation.

It is possible that the best-performing participants also had superior cognitive control. In an additional ANOVA I split the MAX block into the first and last 100 trials. The results indicated that these participants did not show significant switch costs or even congruency effects in either half. Previous research suggested that reduced switch costs

may reflect high-level task engagement (Lindsen & De Jong, 2010; De Jong, 2000), and reduced congruency effect may reflect better control of attention that is maintained across trials (Bugg & Braver, 2016). I conclude that the best performers were highly engaged in each trial for an extended period demonstrating better cognitive control.

It is also possible that by using a novel experimental procedure where participants were encouraged to make no mistake, best performers were more strongly motivated by the zero-error policy. Using seven different psychological scales I confirmed that better task-switching performance was associated with higher levels of motivation. This is in line with previous studies suggesting that motivation can influence the efficacy of cognitive flexibility (Nadler, 2013; Pessoa, 2009), modulate performance on working memory tasks (Krawczyk & D'Esposito, 2011) and facilitate effective problem-solving strategies (Deci & Ryan, 2008; Struthers et al., 2000; Wulf & Lewthwaite, 2016). Best performers rated the task-switching experiment as more interesting and they felt more competent in the experiment, which may be associated with improved cognitive functioning and efficient switching strategies.

Other psychological factors may also play a role accounting for the different switching performance between best performers and other participants. Compared with others, best performers had relatively lower scores in impulsivity. Best performers reported that they were able to focus on the task at hand (BIS_Attentional) and plan the task in advance (BIS_Nonplanning), in line with previous results that showed a negative relationship between trait impulsivity and cognitive performance (Enticott et al., 2006; Leshem, 2015; Whitney et al., 2004). These participants reported also better self-control whereas fewer executive function problems experienced in their daily life. These results support de Ridder and colleagues (2011) who suggested that higher self-control related to better inhibition of goal-irrelevant behaviours, and Buchanan and colleagues (2010) who suggested that fewer executive function problems correlated with improved cognitive

performance. Accordingly, in line with my prediction, the exceptional task-switching performance may not only be due to superior cognitive abilities, but also be linked with various psychological factors, i.e. higher intrinsic motivation and self-control, while lower levels of impulsivity and executive control problems.

It is unclear whether the best performers also show exceptional switching performance in more conventional task-switching paradigms, where participants are allowed to make mistakes. To test this, in the following I invited the best performers to take part in follow-up Experiment 1B, in which the experimental conditions were critically manipulated. I tried to find out whether best performers would show high accuracy and no switch costs, independent of experimental conditions. In a second follow-up, Experiment 1C, I compared the 9 best performers with 9 control participants who had made frequent errors in Experiment 1A, using classic task-switching paradigms.

2.3 Experiment 1B

Experiment 1B was designed as a follow-up on the best-performers in Experiment 1A. I sought to study the switching abilities of the best performers by using the same colour/shape tasks in a more conventional experimental setting where participants can make mistakes without having to start again. In particular, I investigated the cue-stimulus interval (CSI) and inter-trial interval (ITI) as critical factors that may affect the task-switching performance of the best performers. I also tried to identify whether there are individuals who would show more superior task-switching performance across different conditions and paradigms.

Experiment 1A had a fixed CSI of 650 ms and a fixed ITI of 500 ms in every trial. It therefore remained unclear whether CSI or ITI was critical for their task-switching

performance. According to both the *FTE* account and the task-set reconfiguration account, the CSI is considered as more important for reducing residual switch costs because task-set reconfiguration occurs during this interval (Altmann, 2004a, 2004b; De Jong, 2000; Lindsen & De Jong, 2010; Meiran et al., 2000). One possible explanation for the reduced switch costs is that best performers may be more efficient in their advance preparation during the CSI. According to the proactive interference account, residual switch costs should be reduced for longer ITIs because interference from a previous task set decays gradually over time (Allport et al., 1994; Meiran et al. 2000; Koch & Allport, 2006; but see Horoufchin, Philipp & Koch, 2011; Grange, 2016). This leads to the alternative explanation that interference may have decayed more quickly in the best performers. It is also possible that both accounts play a role in task-switching because switch costs can be the result of both preparation and interference from the previously executed task set (e.g., Vandierendonck et al., 2010).

I sought to investigate these possibilities in the nine best performers by systematically varying the CSI from 0 to 650 ms and the ITI between 150 ms and 500 ms in different blocks. I made three predictions. First, I predicted that a longer CSI (650 ms) and a longer ITI (500 ms) in Experiment 1B should result in no significant switch costs in best performers, replicating their individual results in Experiment 1A. Second, according to the *failure-to-engage* and the task-set reconfiguration account I predicted that the task-switching performance should be significantly impaired if the CSI was reduced from 650 ms to 0 ms. Similarly, according to the proactive interference account, I predicted impaired task-switching performance if the ITI was reduced from 500 ms to 150 ms. Third, I postulated that the participants who were more exceptional in task switching should be resilient to these changes, showing no errors, no switch costs, no congruency effects independent of the manipulation of CSI and ITI.

2.3.1 Experiment 1B Methods

Participants

Nine participants who were identified as the best performers in Experiment 1A (3 males, 6 females) were invited back to take part in this follow-up experiment approximately one month later. Participants were paid £10 each for taking part.

Apparatus and stimuli

All aspects of the stimulus presentation were identical to the colour/shape task-switching paradigm as used in Experiment 1A, except for a change of the task cue in the two composite conditions without CSI. That is, in the conditions without CSI, the filled white triangles (30 mm each side) were replaced by a bigger isosceles triangle with a base length of 29 cm and side lengths of 24 cm. In each trial, both the cue and the target stimulus were located at the centre of the screen. The target stimulus always appeared inside a triangle which served as the task cue.

Procedure

Different from the colour/shape paradigm used in Experiment 1A, both cue-stimulus interval (CSI: 0, 650 ms) and inter-trial interval (ITI: 150, 500 ms) were systematically manipulated within participants leading to four task-switching conditions: Condition 650-500, 650-150, 0-500, and Condition 0-150 (see Figure 207). In a pilot study I found that performing in the conditions with CSI 650 ms before the condition with CSI 0 ms helped participants to better recall the task rules, reducing the error rates in the more difficult Condition 0-500 and 0-150. The entire experiment lasted approximately 1 hour. In each condition, there was a block of 50 trials with the colour task, then a block of 50 trials with the shape task, followed by a block of 200 trials with randomly mixed tasks. Participants always completed the two single-task blocks to practice the task rules before

starting the mixed-task blocks. In this experiment, the zero-error policy was not applied because I wanted to study participants' performance in a more conventional task-switching paradigm.

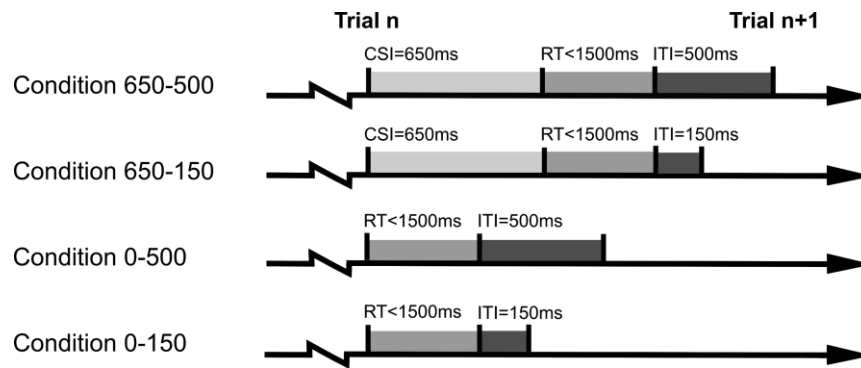


Figure 2.7. Experiment 1B. Schematic depiction of the four combinations of cue-stimulus interval CSI (CSI 650 ms, 0 ms) and inter-trial interval (ITI 500 ms, 150 ms) in the colour/shape task-switching paradigm.

2.3.2 Experiment 1B Results

The first trial of each mixed-task block, error trials and the trial following an error were excluded from the RT analysis. In contrast to Experiment 1A where the mixed block expired once an error was made, in Experiment 1B all trials that immediately followed an error were excluded because it is not possible to classify them as task-switch or task-repeat trials. I also excluded trial n if it had the same cue-stimulus combination as the preceding trial $n - 1$ because in the conditions with CSI 0 ms cue and the target stimulus were presented simultaneously, and a participant could simply repeat the same response as previous trial without cognitive processing of the task. After exclusion of these trials, the number of valid trials ranged between 665 and 794 per participant, with 156 to 199 RT measurements in each condition. I first conducted a conventional ANOVA on mean RTs and ERs. In addition, I applied GLMMs to capture individual differences among the best-performing participants.

Mean RTs and ERs in task switching

Mean RTs and ERs are depicted in Figure 2.8. They are collapsed across ITIs which had no significant effects on performance (see Table 2.3 for all conditions). RTs and ERs were analysed separately using a four-way ANOVA with repeated measures on factor Trial transition (task-repeat, task-switch), Congruency (congruent, incongruent) CSI (0 ms, 650 ms), and ITI (150 ms, 500 ms).

Table 2.3

Experiment 1C. Mean (SE) of RTs (in ms) and error rates (ER as %) of 9 best performers

ITI	Trial transition and Congruency	CSI = 0 ms		CSI = 650 ms	
		<i>RT</i>	<i>ER</i>	<i>RT</i>	<i>ER</i>
150 ms	RepCon	679 (34.01)	1.53 (1.23)	457 (35.66)	.26 (.26)
	RepInc	738 (27.35)	7.45 (2.61)	469 (29.78)	1.98 (.92)
	SwiCon	759 (32.60)	1.27 (.70)	451 (29.65)	.69 (.47)
	SwiInc	812 (24.01)	6.23 (1.87)	474 (30.50)	4.97 (2.11)
	Repeat	708 (22.37)	4.49 (1.57)	463 (22.58)	1.12 (.51)
	Switch	786 (20.63)	3.75 (1.14)	462 (20.82)	2.83 (1.17)
	Congruent	719 (24.87)	1.40 (.69)	454 (22.51)	.48 (.27)
	Incongruent	775 (19.77)	6.84 (1.56)	471 (20.69)	3.47 (1.17)
500 ms	RepCon	691 (20.33)	2.45 (1.15)	446 (22.71)	2.31 (.86)
	RepInc	754 (14.04)	5.74 (1.72)	469 (28.53)	3.29 (1.10)
	SwiCon	792 (24.09)	3.12 (1.06)	456 (23.86)	1.14 (.60)
	SwiInc	824 (16.56)	6.69 (2.30)	478 (22.66)	5.67 (1.67)
	Repeat	723 (14.18)	4.10 (1.08)	458 (17.93)	2.80 (.69)
	Switch	808 (14.70)	4.90 (1.30)	467 (16.19)	3.41 (1.02)
	Congruent	742 (19.56)	2.78 (.76)	451 (16.03)	1.73 (.53)
	Incongruent	789 (13.54)	6.22 (1.40)	474 (17.70)	4.48 (1.01)

Note. RepCon = Repeat Congruent; RepInc = Repeat Incongruent; SwiCon = Switch

Congruent; SwiInc = Switch Incongruent.

RTs

For RTs, I found three significant main effects. There was a significant main effect of Trial transition, $F(1, 8) = 30.53$, $p < .001$, $\eta^2_p = .79$, with longer mean RTs for task-switch trials (631 ms) than task-repeat trials (588 ms), participants showing a task-switch cost of +43 ms. There was a significant main effect of Congruency, $F(1, 8) = 60.06$, $p < .001$, $\eta^2_p = .88$. RTs were longer in incongruent trials (627 ms) than in congruent trials (591 ms), indicating a congruency cost of +36 ms. There was a significant main effect of CSI, $F(1, 8) = 275.34$, $p < .001$, $\eta^2_p = .97$, participants showing faster responses in CSI 650 ms (462 ms) compared to CSI 0 ms (756 ms). The main effect of ITI did not reach significance ($F < 1$).

More importantly, trial transition interacted with CSI, $F(1, 8) = 12.49$, $p = .008$, $\eta^2_p = .61$. RT switch costs decreased by 76 ms when the CSI was increased from 0 ms (SC = +81 ms, $p < .001$) to 650 ms (SC = +5 ms, $p = .810$). In addition, Congruency interacted with CSI, $F(1, 8) = 6.88$, $p = .030$, $\eta^2_p = .46$. RT congruency effects were +52 ms ($p < .001$) in CSI 0 ms and were +21 ms ($p < .001$) in CSI 650 ms. A post-hoc comparison after Holm correction (Holm, 1972) showed that the congruency effects were equivalent between CSIs, $p = .065$. No other effects reached statistical significance.

ERs

For ERs, there was a significant main effect of Congruency, $F(1, 8) = 16.75$, $p = .003$, $\eta^2_p = .68$. Participants made more errors in incongruent trials (5.25%) than in congruent trials (1.60%), showing a congruency effect of +3.65%. In addition, I found a significant three-way interaction between Congruency, Trial transition and CSI, $F(1, 8) = 5.43$, $p = .048$, $\eta^2_p = .40$. A post-hoc comparison showed that participants had no

significant and equivalent ER switch costs in both congruent and incongruent trials with CSI 0 ms and CSI 650 ms. No other effects reached statistical significance.

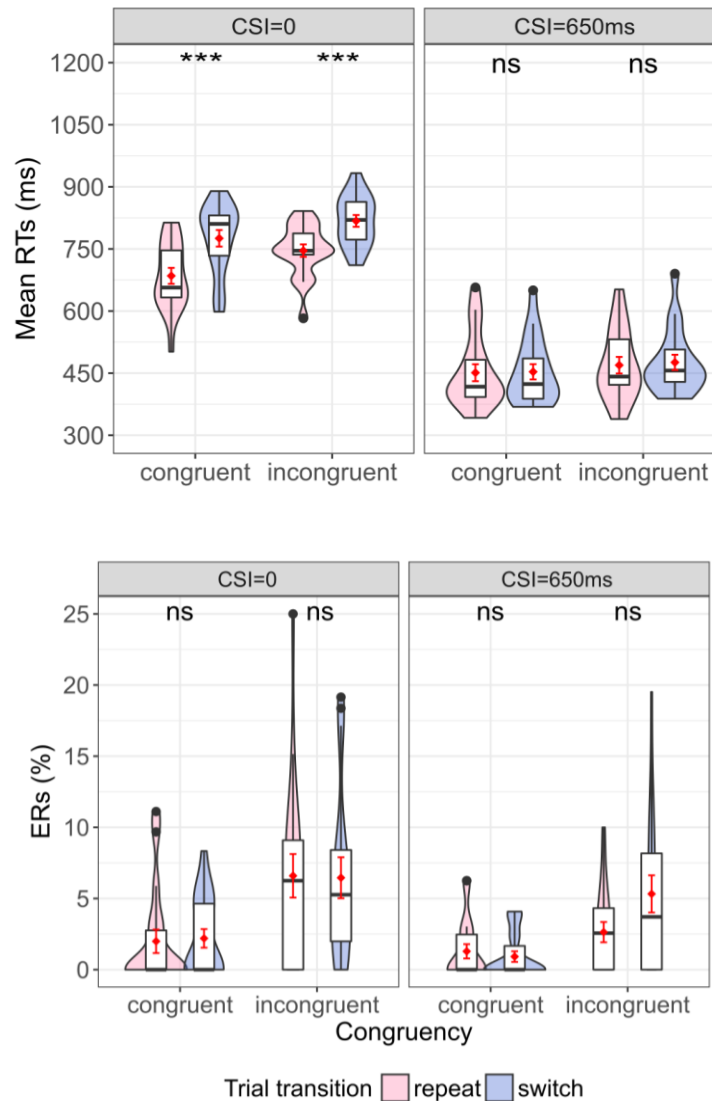


Figure 2.7. Results of Experiment 1B. RTs (top panel) and ERs (bottom panel) for repeat and switch trials across CSIs (0 ms, 650 ms) and Congruency (congruent, incongruent).

Black dots represent outliers whereas red diamonds and error bars denote means and standard errors, respectively.

Note. *** $p < .001$, *ns* = non-significant.

Similar to Experiment 1A, I split the trials in the mixed block into two halves and analysed the RT data accordingly. The corresponding RT data were then submitted to a

five-way repeated-measure ANOVA with factors Trial transition (task-repeat, task-switch), Congruency (congruent, incongruent), CSI (0 ms, 650 ms), ITI (150 ms, 500 ms) and Block half (first, second). Again, I found a significant interaction between Trial transition and CSI, $F(1, 8) = 16.39$, $p = .003$, $\eta^2_p = .67$. Participants did not show significant RT switch costs in the condition with CSI 650 ms (+5 ms, $p = .300$), but showed significant costs in the condition with CSI 0 ms (+88 ms, $p < .001$). Block half did not significantly interact with Trial transition ($F < 1$) and CSI ($F = 1.30$, $p = .287$). I did not find a significant three-way interaction between Trial transition, Block half and CSI ($F < 1$). Similarly, there was no interaction between Congruency and Block half ($F < 1$). There was no three-way interaction between Congruency, Block half and CSI ($F < 1$). These results suggest that switching performance did not differ between the two halves of the block. When in trials with a CSI of 650 ms, switch costs were +7 ms in the first half and +6 ms in the second half. Congruency effects were +19 ms in the first half and +23 ms in the second half. When in trials with a CSI of 0 ms, switch costs were +95 ms in the first half and +83 ms in the second half. Congruency effects were +40 ms in the first half and +61 ms in the second half. No other effects reached statistical significance.

Individual Differences

I conducted GLMMs to capture individual differences among the best-performing participants. The raw RT data were modelled by gamma distributions in a full factorial design for fixed effects and different by-subject random effects. I identified the most parsimonious model (see GLMM 1B.3 in Table 2.4). Trial transition, Congruency, CSI and ITI, and all interactions were entered as fixed effects. The intercept, the main effect of CSI, ITI, and the interaction between CSI and Trial transition were featured as by-subject random effects.

Table 2.4

Experiment 1B GLMM comparisons based on 9 best-performers' RT data (the best model is in bold; GLMM 1B.3).

<i>Model names</i>	<i>Models (family = Gamma (link = "identity"))</i>	<i>df</i>	<i>AIC</i>	<i>BIC</i>	<i>Log lik</i>	<i>dev</i>	<i>Chi-sq</i>	<i>p-value (>Chisq)</i>
GLMM 1B.1	RT ~ Trial.transition + Congruency + CSI + ITI (1 subject)	7	75589	75635	-37787	75575		
GLMM 1B.2	RT ~ Trial.transition * Congruency * CSI * ITI+ (1 subject)	18	75586	75706	-37775	75550	24.80	.001 **
GLMM 1B.3	RT ~ Trial.transition * Congruency * CSI * ITI+ (1+ CSI + ITI + Trial.transition : CSI subject)	32	75294	75508	-37615	75230	319.33	< .001 ***
GLMM 1C.4	RT ~ Trial.transition * Congruency * CSI * ITI+ (1+ CSI + ITI + Congruency + Trial.transition : CSI subject)	38	75299	75553	-37611	75223	7.75	.257

Note. The model formulas are stated in the syntax of the lme4 package in R.

The fixed effects are consistent with the ANOVA results that responses were slower in CSI 0 (763 ms) compared to CSI 650 ms (471 ms), $t = 49.83$, $p < .001$. Responses were slower in task-switch trials (637 ms) compared to task-repeat trials (597 ms), $t = 10.94$, $p < .001$. Responses were slower in incongruent trials (636 ms) than in congruent trials (598 ms), $t = 11.89$, $p < .001$. Trial transition significantly interacted with CSI, $t = 7.65$, $p < .001$, with smaller switch costs in CSI 650 ms (+4 ms) than in CSI 0 ms (+78 ms). Switch costs were not different between ITIs, $t = 1.21$, $p = .226$. Congruency significantly interacted with CSI, $t = 7.41$, $p < .001$, with smaller congruency effects in CSI 650 ms (+22 ms) than in CSI 0 ms (+56 ms). No other effects reached significance.

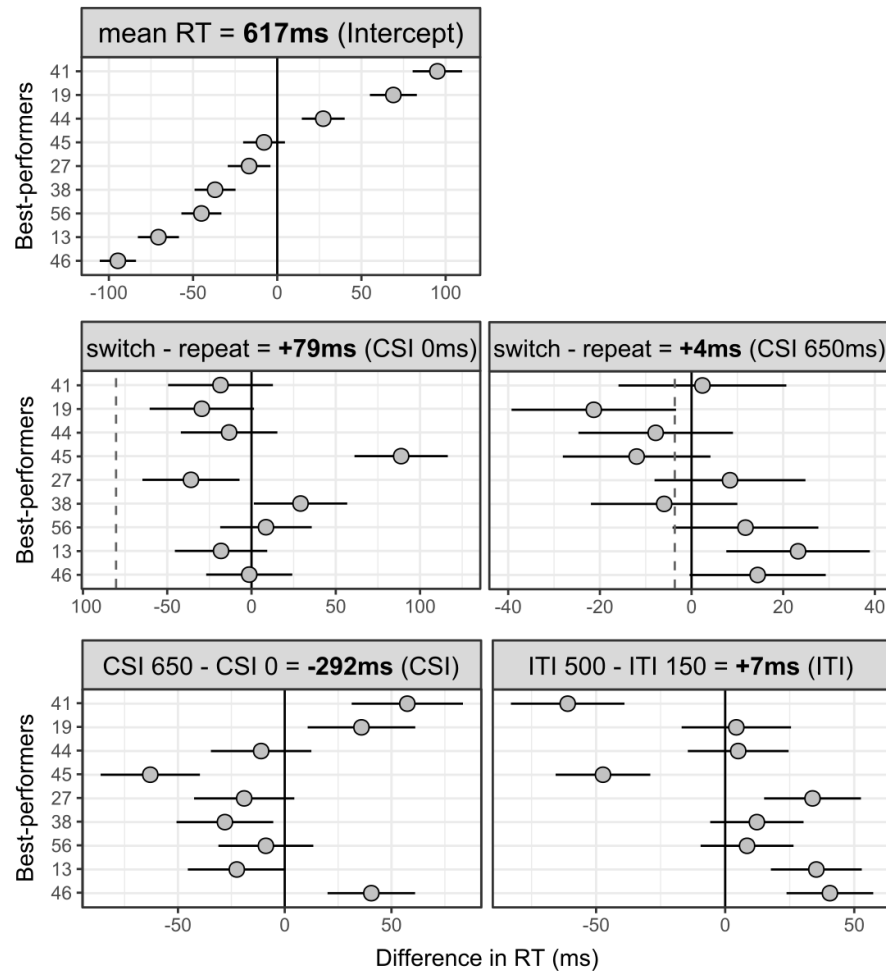


Figure 2.8. Experiment 1B. Illustration of by-subject random effects. Subject IDs on the left correspond to the Subject IDs in Experiment 1A. Top panel: Dotplot illustrates individual deviations (dots) and 95% confidence intervals (horizontal error bars) from mean target RT (Intercept = group-average target RT of 617 ms, indicated by the solid vertical line centred on zero). Middle panel: Dotplots illustrate individual deviations (dots) and 95% confidence intervals (horizontal error bars) from the mean switch costs in CSI 0 ms (+79 ms) and CSI 650 ms (+4 ms) collapsed over ITIs. The dashed vertical lines in the plots of the middle panel indicate zero switch cost in each condition. Bottom panel: Dotplots illustrate individual deviations (dots) and 95% confidence intervals (horizontal error bars) from the main effect of CSI (mean RT in CSI 650 ms - mean RT in CSI 0 ms = -292 ms,) and ITI (mean RT in ITI 500 ms - mean RT in ITI 150 ms = +7 ms). Please note the different RT scales on the x -axes across plots.

The by-subject random effects explained considerable variance. The top panel of Figure 2.8 shows large individual deviations from the grand mean RT (Intercept). When comparing Figure 2.5 with Figure 2.8 regarding mean RTs (Intercepts), I found that most best performers were consistent in their mean RTs across experiments. For example, Participant 46 was the fastest best-performer in Experiment 1A as well as 1B. Participant 19 and 41 who were the slowest best-performers in Experiment 1A were again slower in the present experiment. However, Participant 13 who was slightly slower in Experiment 1A performed faster in the present experiment.

The bottom panel of Figure 2.8 shows individual deviations between different CSIs and ITIs. Participant 38 and 45 showed improved RT performance when the CSI was increased to 650 ms, while Participant 19, 41, and 46 showed less improved performance. Participant 41 and 45 showed faster responses in ITI 500 ms than in ITI 150 ms, while other participants performed more slowly in ITI 500 ms.

Figure 2.8 also shows individual differences in RT switch costs (middle panel). Participants showed different deviations from the mean switch costs (solid vertical line) and zero switch costs (dashed vertical line) in the CSI 650 ms and in the CSI 0 ms condition. Seven participants did not significantly deviate from zero switch cost in the CSI 650 ms condition whereas Participant 13 and 46 had switch costs significantly higher than zero. In contrast, all participants had switch costs significantly higher than zero in the CSI 0 ms condition.

2.3.3 Experiment 1B Discussion

The results of Experiment 1B show that on average the best performers developed RT switch costs when the CSI was reduced to 0 ms but showed non-significant switch

costs for both RTs and ERs when the CSI was 650 ms, confirming the results in Experiment 1A. This finding is in line with studies that identified preparation effects on task-switching costs (e.g., Altmann, 2004a, 2004b; De Jong, 2000; Lindsen & De Jong, 2010; Meiran et al., 2000; Monsell, 2003; Schneider, 2016; 2017). However, in none of these studies switch costs were eliminated even when preparation intervals were as long as 2,000 ms (e.g., Meiran et al., 2000; Schneider, 2017). Here, the best performers prepared very efficiently within a CSI of 650 ms, showing no significant switch costs except for Participant 13 and 46.

Importantly, the best performers were only affected by CSI. An increase of ITI from 150 ms to 500 ms did not improve their switching performance. This is inconsistent with the proactive interference account where longer ITIs should lead to reduced switch costs (Allport et al., 1994; Meiran et al. 2000; Koch & Allport, 2006; but see Horoufchin et al., 2011; Grange, 2016). I conclude that the reduced switch costs in best-performers can be attributed to efficient task preparation during CSIs.

Why can best performers prepare more efficiently for a task or reconfigure a task set during relatively short CSIs whilst other participants cannot? In the present experiment, best performers showed reduced switch costs, even without the zero-error policy. This result seems to suggest that the best performers maintained superior switching abilities independent of the zero-error policy. However, not all best performers showed trait-like switching abilities. For example, Participant 13 and 46 varied considerably in terms of switch costs between Experiment 1A and 1B. Since many other participants in Experiment 1A also performed well, showing no mistakes or non-significant switch costs in their MAX block, I need further evidence that sets apart best performers from other participants.

In order to address this question I studied best performers in different task-switching paradigms. Yehene and Meiran (2007) suggested that participants should exhibit

general task-switching abilities across paradigms. Experiment 1C was conducted to compare the general task-switching abilities of best performers with a control group.

2.4 Experiment 1C

The purpose of this follow-up experiment was to compare the best-performers with a control group in conventional task-switching paradigms using different tasks and without applying the zero-error policy. Best performers may have better trait-like switching abilities if they show significantly smaller or even no switch costs across different tasks and conditions compared to controls.

In addition, I employed Raven's advanced progressive matrices (APM, Raven et al., 1998) in order to test whether both groups of participants differed in general intelligence. Studies suggested that general intelligence affects the efficacy of cognitive control (Benedek et al., 2014; Friedman et al., 2006) which plays an important role in task-switching. I therefore made a prediction that group differences in task switching may be related to group differences in general intelligence.

2.4.1 Experiment 1C Methods

Participants

Nine best-performing participants (3 males and 6 females, $M = 23.89$ years, $SD = 1.96$) were invited to take part in this follow-up experiment approximately two months after Experiment 1A. I also invited 9 other participants from Experiment 1A as controls (1 male and 8 females, $M = 23.00$ years, $SD = 1.80$). The control participants are highlighted by an open triangle next to the Subject ID in Figure 2.5. I did not select the worst-

performing participants as controls because they might not sufficiently engage in each trial. The participants in the control group matched the best performers in terms of mean RTs (Intercepts; see Figure 2.5) but made frequent mistakes even though they had practiced the colour/shape task in thousands of trials ($M = 1,626$ trials, ranging from 1,137 to 2,215 trials) in Experiment 1A. They had a MAX of less than 50 trials ($M = 13$ trials, ranging from 10 to 45 trials) in their experimental session over 90 minutes. Participants were paid £10 each for taking part.

Apparatus, tasks and stimuli

The apparatus for stimulus presentation and response collection was identical to Experiment 1A and 1B.

Colour/shape paradigm. All aspects of the colour/shape task-switching paradigm were the same as in Experiment 1A, except that I did not apply the zero-error policy.

Shape/filling paradigm. The shape/filling task was the same as the task used by Stoet and colleagues (2013, Experiment 1). In the shape task, participants were asked to press a left button if a diamond-shaped target appeared (30.7 mm each side) and a right button if a square-shaped target appeared (30.7 mm each side), ignoring the dots inside. In the filling task, participants were asked to press the left button for two vertically arranged dots and the right button for three vertically arranged dots, ignoring the surrounding shape. All stimuli were printed in yellow and presented on the top or bottom of a rectangular yellow frame (70 × 80 mm). Participants responded to the surround shape when the target was presented in the upper part of the frame and responded to the filling dots when the target was presented in the lower part. The “Shape” and “Filling” cues were visible throughout each trial to remind participants of the currently relevant task. The inter-trial interval was 800 ms.

Letter/number paradigm. The letter/number task was the same as the task used by Rogers and Monsell (1995, Experiment 1). Participants received a letter/number pair in each trial. The task was to either categorise the letter as a vowel or consonant, or to categorise the digit as being odd or even. The odd numbers were drawn from the set 3, 5, 7, 9, and the even numbers were drawn from the set 2, 4, 6, 8, displayed on screen in yellow sans-serif with font size 22. The consonant letters were drawn from the set G, K, M, R and vowel letters from the set A, E, I, U, also displayed on screen in yellow sans-serif with font size 22. To help participants to keep track of the task sequence, the letter/number pair was presented on a 2*2 yellow grid (5 cm each side), moving around clockwise inside the grid. Participants were told to respond to the letter only when the letter/number pair was shown in one of the top two cells, and to respond to the number only when the pair was shown in one of the bottom two cells. In the number task, participants were asked to press the left button if the number was odd and the right button if the number was even. In the letter task, participants were asked to press the left button if the letter was a consonant and the right button if the letter was a vowel. The inter-trial interval was 150 ms.

Intelligence test. Raven's advanced progressive matrices (Raven et al., 1998) were used to measure non-verbal reasoning ability. The Raven advance test is the most difficult of the Raven's Matrices tests, and was designed to differentiate among people with "superior intellectual ability" (Raven et al., 1998). This paper-and-pencil test has 48 items, consisting of 2 sets, with 12 diagrammatic puzzles in Set I (for practice) and 36 puzzles in Set II (for data analysis, with a full score of 36). Each item in the test contains a figure with a missing piece, and participants are required to select one out of eight possible answers to fit the missing space from the pattern.

Procedures

Participants in the control group completed all three paradigms. Best performers completed only the shape/filling paradigm and the letter/number paradigm. Since the colour/shape task was the same as the Condition 650-500 in Experiment 1B, I re-used the data of the best performers from this condition only. As before, participants had up to 1,500 ms to make a response after target onset. If no or an incorrect response was given within 1,500 ms, error feedback appeared on screen for 1 second. In each paradigm, participants completed a 50-trial block of each single task to practice the task rules, followed by a 200-trial mixed block with both tasks intermixed. Note that the tasks were randomly mixed in the mixed block of the colour/shape and the shape/filling paradigms but not in the number/letter paradigm. After completing the task-switching paradigms, all participants took part in a one-hour Raven's intelligence test.

2.4.2 Experiment 1C Results

Data pre-processing was the same as in Experiment 1B. After exclusion of trials, the number of valid trials ranged between 486 and 583 (ranging between 144 and 195 RT measurements per paradigm) for the nine best-performing participants and between 376 and 519 (ranging between 86 and 192 RT measurements per paradigm) for the nine participants in the control group. Next, I conducted conventional ANOVAs on mean RTs and ERs. In addition, I applied GLMMs to confirm group effects and to capture individual differences in RTs.

Task-switching analyses

Mean RTs and error rates (ERs) are summarised in Table 2.5. Two four-way ANOVAs with mixed effects were conducted on the mean RTs and ERs of each

participant. Group (best-performing, control) served as between-subjects factor whereas Trial transition (task-repeat, task-switch), Congruency (congruent, incongruent) and Paradigm (colour/shape, shape/filling, and letter/number) were within-subjects factors.

Table 2.5

Experiment 1C. Mean (SE) of RTs (in ms) and error rates (ER as %)

Paradigms	Trial transition and Congruency	Best performers ($N = 9$)		Controls ($N = 9$)	
		<i>RT</i>	<i>ER</i>	<i>RT</i>	<i>ER</i>
Colour/ shape	RepCon	446 (22.71)	2.31 (.86)	508 (28.04)	5.04 (2.11)
	RepInc	470 (28.53)	3.29 (1.10)	529 (24.13)	15.94 (4.52)
	SwiCon	456 (23.86)	1.14 (.60)	574 (36.02)	5.10 (1.35)
	SwiInc	478 (22.66)	5.67 (1.67)	611 (28.27)	22.26 (5.67)
	Repeat	458 (17.93)	2.80 (.69)	519 (18.12)	10.49 (2.76)
	Switch	467 (16.19)	3.41 (1.02)	592 (22.65)	13.68 (3.51)
	Congruent	451 (16.03)	1.73 (.53)	541 (23.53)	5.07 (1.21)
	Incongruent	474 (17.70)	4.48 (1.01)	570 (20.56)	19.10 (3.60)
Shape/ filling	RepCon	629 (21.75)	1.02 (.72)	679 (32.42)	2.13 (.79)
	RepInc	661 (21.88)	4.25 (1.50)	701 (24.29)	5.65 (1.68)
	SwiCon	738 (26.77)	.22 (.22)	854 (32.98)	1.91 (.85)
	SwiInc	796 (19.13)	4.68 (1.37)	879 (30.53)	13.12 (2.79)
	Repeat	645 (15.45)	2.64 (.90)	690 (19.83)	3.89 (1.00)
	Switch	767 (17.47)	2.45 (.86)	866 (22.00)	7.52 (1.96)
	Congruent	683 (21.31)	.62 (.38)	767 (30.87)	2.02 (.56)
	Incongruent	728 (21.67)	4.46 (.99)	790 (28.68)	9.39 (1.82)
Letter/ number	RepCon	579 (27.27)	.97 (.51)	633 (39.94)	2.96 (1.35)
	RepInc	567 (22.92)	1.43 (.52)	675 (39.19)	5.44 (.90)
	SwiCon	701 (30.49)	2.38 (.71)	827 (48.16)	4.06 (1.49)
	SwiInc	734 (33.86)	4.97 (1.35)	842 (37.49)	10.47 (1.87)
	Repeat	573 (17.34)	1.20 (.36)	669 (27.18)	4.20 (.84)
	Switch	717 (22.46)	3.68 (.80)	834 (29.66)	7.26 (1.40)
	Congruent	640 (24.73)	1.68 (.46)	745 (36.23)	3.51 (.98)
	Incongruent	650 (28.31)	3.20 (.82)	758 (33.20)	7.95 (1.18)

Note. RepCon = Repeat Congruent; RepInc = Repeat Incongruent; SwiCon = Switch

Congruent; SwiInc = Switch Incongruent

RTs

For mean RTs, I observed a significant main effect of Group, $F(1, 16) = 9.12, p = .008, \eta^2_p = .36$. Best-performing participants (605 ms) had significantly faster responses compared to the participants in the control group (695 ms). There was a significant main effect of Trial transition, $F(1, 16) = 133.89, p < .001, \eta^2_p = .89$. Task-switch trials (707 ms) were slower compared to task-repeat trials (592 ms), indicating a statistically significant RT switch cost of +115 ms. There was a significant main effect of Congruency, $F(1, 16) = 58.32, p < .001, \eta^2_p = .78$. Incongruent trials (662 ms) were slower compared to congruent trials (638 ms), indicating a congruency effect of +24 ms. Participants performed differently across paradigms, $F(2, 32) = 69.71, p < .001, \eta^2_p = .81$. Post-hoc comparisons, corrected after Holm (Holm, 1979), revealed that participants were significantly faster in the colour/shape paradigm (509 ms) compared to the letter/number (698 ms) and shape/filling paradigm (742 ms).

Trial transition significantly interacted with Paradigm, $F(2, 32) = 28.14, p < .001, \eta^2_p = .64$. Post-hoc analyses revealed that the switch costs were significant in the letter/number (SC = switch – repeat = +155 ms, $p < .001$) and shape/filling paradigms (SC = +149 ms, $p < .001$), but not in the colour/shape paradigm (SC = +42 ms, $p = .160$). Trial transition also interacted with Congruency, $F(1, 16) = 5.36, p = .034, \eta^2_p = .25$. Post-hoc analyses revealed that switch costs were smaller in congruent trials (SC = +107 ms, $p < .001$) compared to incongruent trials (SC = +123 ms, $p < .001$). Importantly, Trial transition significantly interacted with Group, $F(1, 16) = 5.43, p = .033, \eta^2_p = .25$. As shown in Figure 2.9, best performers (SC = +92 ms, $p = .002$) showed smaller switch costs compared to the control group (SC = +138 ms, $p < .001$). I did not find a significant interaction between Group and Paradigm ($F < 1$). Other interaction effects involving Group were not significant.

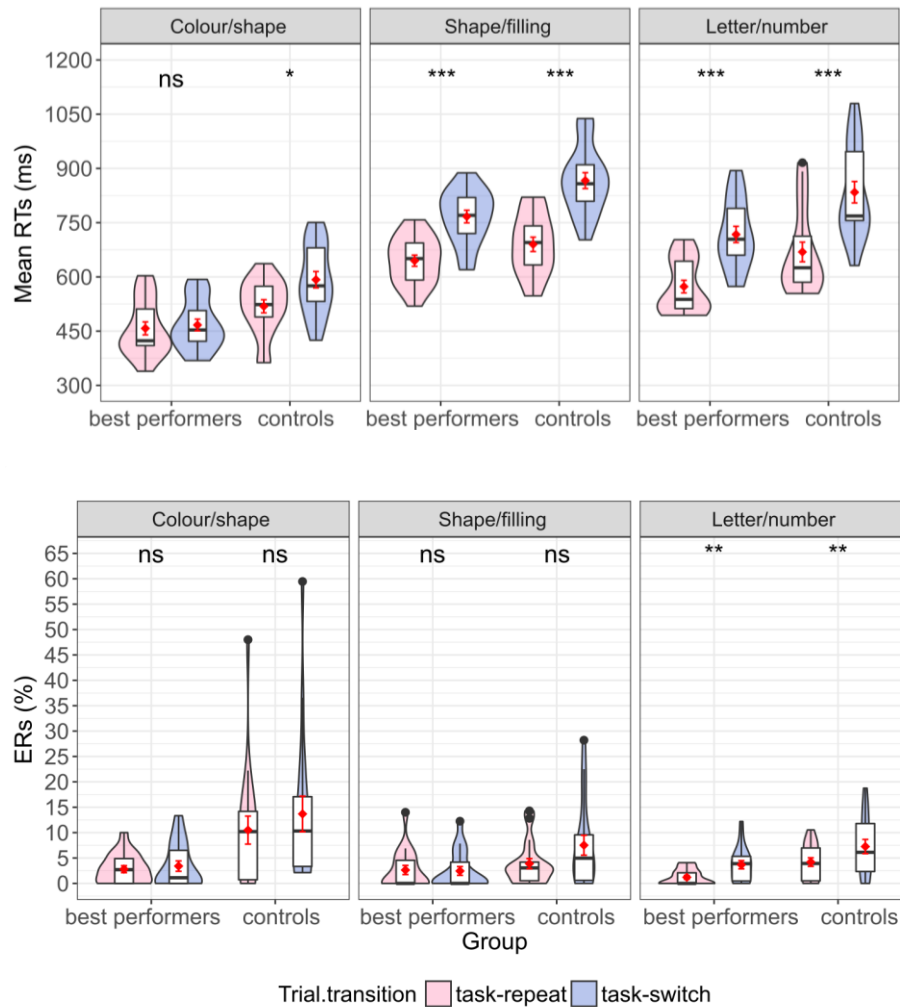


Figure 2.9. Results of Experiment 1C. Mean RTs (top panels) and ERs (bottom panels) for repeat and switch trials are shown in separate box/violin plots for Group (best-performing, control) and in separate panels for Paradigm (colour/shape, shape/filling, letter/number). Black dots represent outliers whereas red diamonds and error bars denote means and standard errors, respectively.

Note. *** $p < .001$; ** $p < .01$; * $p < .05$; ns = non-significant

ERs

For error rates, all four main effects were statistically significant. I observed a significant main effect of Group, $F(1, 16) = 9.62$, $p = .007$, $\eta^2_p = .38$, as best-performing participants made fewer errors (2.70%) compared to participants in the control group (7.84%). There was a significant main effect of Trial transition, $F(1, 16) = 16.19$, $p < .001$, $\eta^2_p = .50$. Participants made more errors in task-switch trials (6.33%) compared to task-

repeat trials (4.20%), indicating a significant ER switch cost of +2.13%. There was a significant main effect of Congruency, $F(1, 16) = 35.20, p < .001, \eta^2_p = .69$. Participant made more errors in incongruent trials (8.10%) compared to congruent trials (2.44%), indicating a significant congruency effect of +5.66%. Error rates were also different across paradigms, $F(2, 32) = 9.57, p < .001, \eta^2_p = .37$. Post-hoc analyses indicated that colour/shape paradigm (7.60%) had more errors compared to the letter/number paradigm (4.09%) and shape/filling paradigm (4.12%).

Trial transition significantly interacted with Congruency, $F(1, 16) = 18.35, p < .001, \eta^2_p = .53$. Post-hoc analyses showed that the switch costs were larger in incongruent trials (SC = +4.20%, $p = .007$) than in congruent trials (SC = +.07%, $p = .961$). As illustrated in Figure 8, Group significantly interacted with Trial transition, $F(1, 16) = 4.83, p = .043, \eta^2_p = .23$. Post-hoc analyses showed that best performers (SC = +0.97%, $p = .478$) had smaller ER switch costs compared to the control group (SC = +3.29%, $p = .049$). In addition, Group significantly interacted with Paradigm, $F(1, 16) = 6.49, p = .004, \eta^2_p = .29$. Post-hoc analyses revealed that best performers had significantly fewer errors (3.11%) than the control group (12.09%) in the colour-shape paradigm ($p < .001$), whereas there was no significant group difference in the letter/number paradigm and shape/filling paradigm. Other interaction effects involving Group did not reach statistical significance.

Individual Differences

In order to study individual differences in RTs, I analysed the RT measurements from each trial using GLMMs as in Experiments 1A and 1B. I compared the most parsimonious model with Group effects (GLMM 1C.3) with a corresponding model without Group effects (GLMM 1C.2) in order to determine whether factor Group and its

interactions improved the model fit. In other words, the model comparison tested whether the distinction between best performers and controls was an important predictor of RTs.

Table 2.6

Experiment 1C GLMM comparisons on RT data (the best model is in bold; GLMM 1C.2).

<i>Model names</i>	<i>Models (family = Gamma (link = "identity"))</i>	<i>df</i>	<i>AIC</i>	<i>BIC</i>	<i>Log lik</i>	<i>dev</i>	<i>Chi-sq</i>	<i>p-value (>Chisq)</i>
GLMM 1C.1	RT ~ Trial.transition + Congruency + Paradigm + Group+ (1 subject)	8	114873	114930	-57428	114857		
GLMM 1C.2	RT ~ Congruency* Trial.transition* Paradigm + (1+Paradigm: Trial.transition+ Paradigm subject)	34	113985	114225	-56958	113917	940.24	< .001 ***
GLMM 1C.3	RT ~ Congruency* Trial.transition* Paradigm*Group + (1+Paradigm: Trial.transition+Paradigm subject)	46	113991	114317	-56950	113899	17.50	.13

Note. The model formulas are stated in the syntax of the lme4 package in R.

The GLMM 1C.2 turned out to be more parsimonious than 1C.3, suggesting that the distinction between best-performers and controls explained little additional variance in RTs (Table 2.6). In GLMM 1C.2, Trial transition, Congruency and Paradigm, and their interactions were treated as fixed effects. The random effects captured individual deviations from the grand mean RT (Intercept), from the main effect of Paradigm and from the interaction between Trial transition and Paradigm. The fixed effects without Group effects mirror the ANOVA results on RTs. Response times were shorter in task-repeat trials (604 ms) than in task-switch trials (723 ms), $t = 32.52$, $p < .001$, suggesting a switch

cost of +119 ms. Response times were shorter in congruent trials (651 ms) than incongruent trials (676 ms), $t = 10.28$, $p < .001$, suggesting a congruency effect of +25 ms. Responses were more quickly in the colour/shape paradigm (522 ms), than in the letter/number paradigm (716 ms; $t = 65.59$, $p < .001$) and shape/filling paradigm (752 ms; $t = 72.41$, $p < .001$).

In addition, the model reveals significant two-way interactions. Switch costs were smaller in congruent trials (+109 ms) than in incongruent trials (+127 ms), $t = -6.50$, $p < .001$. Switch costs were smaller in the colour/shape paradigm (+44 ms) than in the letter/number (+160 ms), $t = -32.68$, $p < .001$; and than in the shape/filling paradigm (+150 ms), $t = -36.17$, $p < .001$. Congruency effects in the colour/shape paradigm (+25 ms) were slightly larger than in the letter/number paradigm (+13 ms), $t = 3.32$, $p < .001$; but slightly smaller than in the shape/filling paradigm (+38 ms), $t = -4.81$, $p < .001$. No other effects were statistically significant.

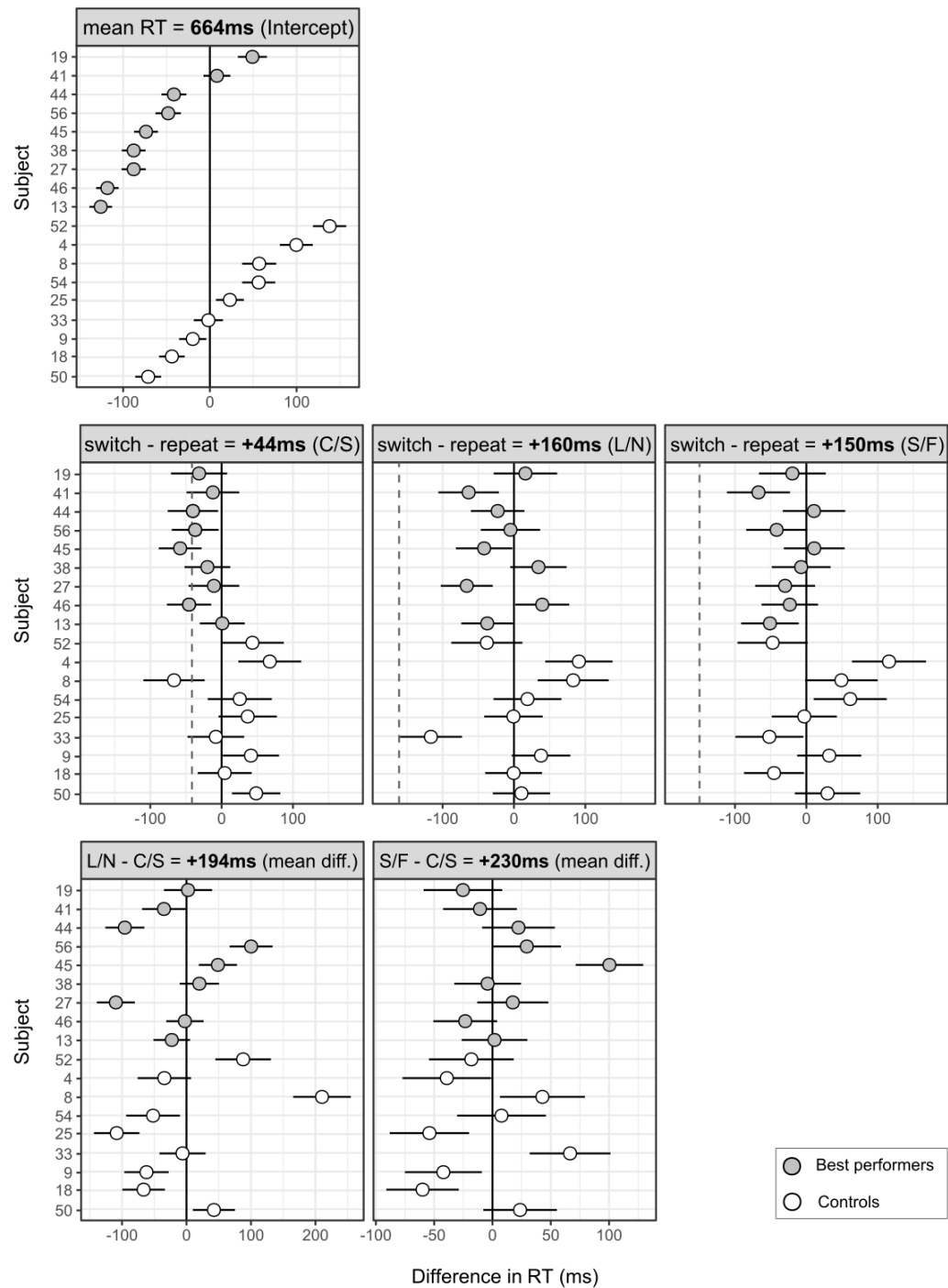


Figure 2.10. Experiment 1C. Illustration of by-subject random effects in best performers and control participants. Subject IDs on the left correspond to participants as in Experiment 1A and 1B. Top panel: The dotplot shows individual deviations (dots) and 95% confidence intervals (horizontal error bars) from mean RTs (Intercept = grand mean RT of 664 ms, as indicated by the solid vertical line centred on zero). Middle panel: The dotplots from left to right illustrate individual deviations from mean switch costs in the colour/shape (+44 ms, as indicated by the solid vertical line centred on zero), letter/number (+160 ms) and shape/filling (+150 ms) paradigm, respectively. The dashed vertical line in each plot indicates zero switch cost for each paradigm. Bottom panel: The dotplots illustrate

individual deviations from the RT difference between letter/number and colour/shape paradigm (mean difference = +194 ms, as indicated by the solid vertical line centred on zero), and between shape/filling and colour/shape paradigm (mean difference = +230 ms). Please note the different RT scales on the x -axis across plots.

Note. C/S = Colour/shape paradigm, L/N = Letter/number paradigm, S/F = Shape/filling paradigm

The by-subject random effects explained considerable RT variance. Figure 2.10 shows individual differences in mean RTs (top panel), with both groups of participants showing significant deviations from the grand mean RT. Seven of the best performers were significantly faster than average compared to three fast-performing participants in the control group. Comparing Figure 2.10 with Figure 2.5 in terms of individual mean RTs (Intercepts) indicates that most participants performed consistently in terms of mean RTs across both experiments. In the control group, for example, Participant 52 was the slowest whereas Participants 18 and 50 were the fastest, ranking similarly in terms of mean RTs in both experiments. In the group of best-performers, Participant 19, who was slower than the sample average RT in Experiment 1A, also responded more slowly in Experiment 1C. In addition, I found that five of the best performers, Participant 27, 38, 45, 46 and 56, responded faster than the sample average in both experiments. Participant 13, however, varied considerably in mean RT. This participant was one of the slowest best performers in Experiment 1A but the fastest participant in Experiment 1C.

Figure 2.10 also shows that across the three paradigms, some of the participants showed significant deviations from the mean switch costs (middle panel). Importantly, in the colour/shape paradigm, all of the best performers except for Participant 13 were close to zero RT switch costs (dashed vertical line), while participants in the control group showed switch costs significantly larger than zero with the exception of Participants 8 and 33. Both groups of participants demonstrated similar switching performance with

significant deviations from zero switch costs (dashed vertical lines) in the letter/number and shape/filling paradigm, although best performers exhibited somewhat more homogenous random effects in those paradigms.

Note that best performers and controls deviated significantly from the mean RT difference between paradigms (the bottom panel of Figure 2.10), suggesting that participants from both groups varied considerably in their RTs between tasks and conditions.

Raven's intelligence scores

The intelligence scores for best performers and controls were compared in a two-sample t-test. I found a statistically significant difference between groups, $t(16) = 2.52$, $p = .023$, Cohen's $d = 1.19$. The best performers had on average significantly higher intelligence scores ($Mean = 28.33$, ranging from 17 to 34) compared to the control group ($Mean = 22.33$, ranging from 14 to 29).

2.3.3 Experiment 1C Discussion

In line with my prediction, Experiment 1C confirmed that, even though the zero-error policy was not applied, best performers showed better task-switching performance than participants in the control group. The results of the ANOVAs suggest that best performers had on average shorter RTs and reduced ERs than controls across different paradigms. Moreover, the analyses suggest that the best-performing participants had on average smaller RT and ER switch costs compared to the controls. The difference in task-switching performance between the two groups may be related to their difference in

general intelligence scores, supporting previous studies that have showed a relationship between cognitive abilities and general intelligence (Benedek et al., 2014; Friedman et al., 2006).

Although the comparison between models with and without Group effects suggests that the distinction between best performers and controls was not important, a significant group difference for RT switch costs was detected in the colour/shape paradigm: 8 out of 9 best performers had smaller and non-significant switch costs. In contrast, only 2 out of 9 controls showed non-significant switch costs. This confirms the finding from Experiment 1A where the best performers also showed more consistent and more efficient task-switching in this paradigm.

In the shape/filling and the letter/number paradigms, however, the best-performing participants showed significant RT switch costs similar to the control group. In the shape/filling and letter/number paradigm both the cue and the target stimulus were presented simultaneously leaving no or little opportunity to prepare for the upcoming task. As suggested by the *failure-to-engage* and the task-set reconfiguration account, the cue-stimulus interval (CSI) is important because the relevant task-set can be re-configured within a certain CSI (e.g., Lindsen & De Jong, 2010). The critical advantage of the best performers may have been that they were able to efficiently prepare each task-set following a cue, suggesting better cognitive control. This may be related to their higher general intelligence scores and other superior traits as shown in Experiment 1A. However, consistent with the results in Experiment 1B, their advantage disappeared as soon as the cue-stimulus interval was reduced to zero. None of them showed more exceptional switching performance with minimal errors and no switch costs independent of tasks and conditions.

2.5 General Discussion

In an experiment and two follow-ups I examined individual differences in task switching. In a reasonably large sample of participants, I tried to identify whether few participants show superior task-switching performance independent of tasks, conditions and paradigms.

In Experiment 1A I applied a “zero-error policy” to motivate participants to maintain full attention and high engagement during a block of randomly mixed tasks. I found reduced switch costs in their MAX block. In addition, I found large individual differences in participant’s mean RTs and ERs. I identified the 9 best-performing participants in the sample who showed no errors and no significant switch costs. I reasoned that their superior performance may be due to increased motivation to engage in task switching, superior task-switching abilities, or both. Using 7 different psychological scales, best performers indeed had relatively higher scores in motivation and self-control, while lower scores in impulsivity and executive problems experienced in daily life. These results are in line with previous studies suggesting a positive relationship between motivation and cognitive/attentional flexibility (Deci & Ryan, 2008; Krawczyk & D'Esposito, 2011; Nadler, 2013; Pessoa, 2009; Struthers et al., 2000; Wulf & Lewthwaite, 2016) but negative relationship between impulsivity and working memory capacity, information processing and interference resolving (Enticott et al., 2006; Whitney et al., 2004).

In two follow-up experiments, in which participants could make mistakes without the need to restart a block, the best performers were still able to eliminate switch costs in trials with a CSI of 650 ms but not in trials with a CSI of 0 ms. Only in conditions with CSIs, did best performers show better task-switching performance than controls. The results of the two follow-up experiments suggest that the reduced switch costs in best performers is unlikely to be attributed to increased motivation or task engagement in order

to make no mistakes because in both follow-up experiments there was less pressure to avoid mistakes.

Alternatively, best performers may have task-switching abilities and/or efficient strategies that can be applied across different task-switching conditions (cf., Yehene & Meiran, 2007). However, there was no convincing evidence that the best performers had extraordinary trait-like switching abilities. GLMMs revealed that best performers shared RT characteristics with many other participants. In addition, their switching abilities cannot be generalised to other tasks and conditions with simultaneous presentation of cue and target stimulus. In the two follow-ups, I confirmed that best performers were only able to eliminate switch costs when there was a cue-stimulus interval of 650 ms. I attribute this superior performance to more efficient task preparation following a cue.

The reduced switch costs of the best performers support the *failure-to-engage* account of task-set reconfiguration (De Jong, 2000; Lindsen & De Jong, 2010; Mayr & Kliegl, 2003; Rogers & Monsell, 1995) suggesting that full reconfiguration of the task-set during a CSI of 650 ms is achievable, at least for some participants. In contrast, the findings on best performers seem incompatible with the two-stage theory (Hydock & Sohn, 2011; Mayr & Kliegl, 2003; Rogers & Monsell, 1995; Rubinstein et al., 2001; Weidler & Abrams, 2013). This theory posits that task-rule reconfiguration can only start after onset of a target stimulus which would make it impossible for participants to eliminate switch costs. As a result, each participant should have significant residual switch costs across different conditions.

The identification of best performers addresses the general question, also posed by Haff and Rouder (2017, 2018), whether everyone shows the same “true effect” in cognitive tasks. I found that some individuals showed significant switch costs while a few individuals did not display any switch costs in the pre-cued conditions. In previous studies

it was reported that even after extended preparation times (> 2,000 ms), significant residual switch costs were found (Meiran et al., 2000, Poboka et al., 2014; Rogers & Monsell, 1995; Schneider, 2016, 2017). Several authors have tried to increase the motivation of participants so that they would prepare for upcoming tasks more efficiently but these studies had limited success in eliminating switch costs (Lien et al., 2005; Meiran & Chorev, 2005; Nieuwenhuis & Monsell, 2002, Schneider, 2016, 2017; see however Verbruggen et al., 2007). These results suggest that, on average, switch costs can be reduced but not eliminated by task preparation so that residual switch costs should always remain. Although this may be true for most individuals, it ignores individual differences in task-switching because participants may be motivated differently, have different characteristics, and may have different cognitive abilities and strategies. Striking evidence of individual differences has been reported in a variety of cognitive, memory and perceptual tasks (Haff & Rouder, 2017, 2018; Lindsen & De Jong, 2010; Mallow et al., 2015; Medeiros-Ward et al., 2014; Ramon et al., 2016; Robertson et al., 2016; Russell et al., 2009; Stoet & Snyder, 2003, 2007; Strayer & Watson, 2012; Watson & Strayer, 2010).

I studied individual differences in task switching. I first conducted ANOVAs on averaged RTs and ERs and found significant mean switch costs, confirming the results of previous task-switching experiments. In addition, I employed general linear mixed models (GLMMs) on single-trial RTs in order to study how individuals varied in their performance across conditions, paradigms, and experiments. I identified best performers, who seemed more capable in task-switching, and showed minimal switch costs in some experimental conditions. Nevertheless, their superior performance did not generalise to conditions and paradigms with simultaneous presentation of cue and target stimulus. Here they also showed individual differences and significant switch costs similar to a control group. I argue that analysing averaged performances may overlook individual variability across conditions and paradigms, and may be responsible for the commonly observed residual

switch costs in previous task-switching studies (e.g., De Jong, 2000; Meiran et al., 2000; Schneider, 2016, 2017). It is possible that although significant residual switch costs were reported, a good number of participants may have successfully eliminated switch costs in various conditions.

Further studies are needed because it is unclear what gave the best performers an advantage in task switching over controls. The Raven's intelligence test suggests that best performers had slightly higher general intelligence, which may be related to improved executive functioning and cognitive abilities. More specifically, best performers may have developed more efficient cue encoding, rule activation, or both. Compared to a paradigm with "two-to-one cue-task mappings", task switching with simpler "one-to-one cue-task mappings" should simplify perceptual processing of multiple cues. With simpler one-to-one cue-task mappings best performers might quickly translate a task cue (i.e., a solid triangle) into a "task-name mediator" (e.g., "colour" in trials with triangle pointing upward), followed by earlier task-goal and task-rule retrieval. This is consistent with the idea of *mediated retrieval* (Logan & Bundesen, 2003; Logan & Schneider, 2006). It is also possible that best performers employed other more specific switching strategies: Based on the *cue-task association hypothesis* proposed by Arbuthnott & Woodward (2002), the best performers may have established stronger associations between task cues and task representations after extensive practice of the colour/shape tasks. As soon as a cue is presented, the relevant task feature and response mappings are immediately activated in working memory, so that responses in task-switch trials are as fast and accurate as responses in task-repeat trials. As mentioned before, another explanation may be that participants with no or reduced switch costs did not "fail to engage" (De Jong, 2000; Lindsen & De Jong, 2010; Poboka et al., 2014). In contrast, participants with switch costs "failed to engage" in task-set reconfiguration, effectively performing task switching according to the two-stage theory (Hydock & Sohn, 2011; Mayr & Kliegl, 2003; Rogers &

Monsell, 1995; Rubinstein et al., 2001; Weidler & Abrams, 2013). These possibilities may be addressed in future research.

The difference in general intelligence between best performers and controls has to be interpreted with caution. Previous studies indicated a strong relationship between information updating and general intelligence (Benedek et al., 2014; Friedman et al, 2006), suggesting that higher intelligence scores may be related to improved goal-updating capabilities, resulting in fewer errors and lower switch costs in task switching. However, there are multiple sub-processes involved in preparation that may collectively lead to improved task-switching performance. Thus, it remains unclear whether the group differences in general intelligence can fully explain group differences in task-switching performance.

In sum, the results of Chapter 2 collectively suggest that there were large individual differences in task-switching. By focusing on individual response times and error rates, I identified best performers who showed superior switching performance in conditions with cue-stimulus intervals. However, in two follow-up experiments the best-performing participants exhibited no superior task-switching in conditions and paradigms with simultaneous presentation of cue and target, performing similar to a group of control participants. The advantage of the best performers may be related to faster than average processing of cue information and rapid task-set reconfiguration before target onset. Accordingly, individuals differed in the degree of efficient switching, which is mainly due to different preparation process after cueing. In next chapter, Chapter 3, I will try to improve task preparation in participants using carefully designed “priming” cues while monitoring individual differences between the priming cues and standard or “non-priming” cues. Meanwhile, I will employ electroencephalogram (EEG) measures to investigate the temporal dynamics of preparation between two types of cues.

CHAPTER 3 Effect of Cue type on Task-switching Performance and ERP Components

3.1 General Introduction

In this Chapter, I studied the effect of cue type on task-switching performance and related ERP components. By employing a novel cue type, I sought to maximally facilitate efficient task preparation and reduce switch costs in typical participants. In addition, I studied individual differences in task-switching using different task cues and response conditions.

Previous research has suggested that task-switch costs are typically smaller for “transparent” compared to “non-transparent” or standard cues (e.g., Arbuthnott & Woodward, 2002; Logan & Schneider, 2006; Mayr & Kliegl, 2000; Miyake, Emerson, Padilla, & Ahn, 2004; Schneider, 2016). Transparent cues are directly associated with the task goals minimizing the difficulty of cue interpretation, whereas non-transparent cues require learning of a cue-task association in order to improve task preparation and ultimately task switching (Logan & Schneider, 2006; Mayr & Kliegl, 2000). Moreover, researchers have suggested that associations between transparent cues and task goals are stronger than associations between non-transparent cues and task goals, so that the relevant task rules or goals can be retrieved more quickly for transparent cues (Arbuthnott & Woodward, 2002; Miyake et al., 2004).

Even though switch costs can be reduced with transparent cues, significant residual switch costs remained. In a recent study, Schneider (2016) conducted task-switching experiments in which participants were asked to categorize single digits according to their parity or magnitude. Both transparent (“odd-even” or “small-large” in Experiment 1, 2 and 3) and non-transparent cues (“C” or “U” in Experiment 4) were employed in this study.

Schneider (2016) found significant residual switch costs for both types of cues, although on average the switch costs were reduced for transparent cues (+73 ms) compared to non-transparent cues (+110 ms).

I argue that task-switch costs can be further reduced or even eliminated if typical participants prepare tasks similar to best-performers. Improved task preparation may be achieved by providing cues that not only inform about the task goal but also pre-activate the task-response mappings and prime the relevant features of the upcoming target. Studies have successfully employed transparent target-feature cues in a target location task (Grange & Houghton, 2010; Houghton, Pritchard & Grange, 2009) where the cues contained a visual representation of the target feature. With the help of these cues the target location was more quickly identified. They suggested that such a transparent cue makes the activation of the target feature in working memory relatively easy. According to load theory of selective attention and cognitive control (Lavie, Hirst, Fockert, & Viding, 2004), a transparent target-feature cue may reduce cognitive load thereby freeing capacity in working memory for task preparation.

If typical participants are instructed by a cue that primes both the target feature and the response mapping, they should be able to prepare more efficiently. These participants may be able to complete task preparations before the target stimulus is presented, assimilating the performance of best performers. In order to test the task-switching differences between standard cues and priming cues, I compared trials with standard cues with trials featuring target-feature cues. Importantly, by comparing these two types of cues, I can test the assumption of the two-stage theory (e.g., Hydock & Sohn, 2011; Rubinstein et al., 2001) which suggests that task preparation can only be completed after target stimulus onset, therefore contributing to the residual switch costs. If residual switch costs can be eliminated with the help of priming cues, then this would support the *FTE* account by De Jong and colleague (2000, 2010) instead of the two-stage theory. According to *FTE*,

preparation can start at any time within a CSI and may be completed before the target stimulus is displayed.

I manipulated cue types between subjects in Experiment 2A, and within-subjects in Experiment 2B. In order to better understand the temporal dynamics of the task-preparation process for the two types of cues, I studied the cue-locked and the target-locked event-related potentials (ERPs) and related topographies in Experiment 2C, where the cue types varied within subjects.

3.2 Experiment 2A

I conducted Experiment 2A to achieve two main goals. First, I sought to investigate whether a priming cue, compared to a non-priming (standard) cue, would enable participants to reduce or even eliminate switch costs. In the experiment, all participants were asked to perform the colour task and the shape task using coloured rectangular bars as target stimuli. Half of the participants had priming cues and the other half had non-priming cues. Based on previous results on transparent cues I predicted that priming cues would facilitate task preparation. The responses should be faster and task-switch costs should be smaller in the group with priming cues compared to the group with non-priming cues because participants in the latter group need to recall the task-relevant features as well as retrieve task-response mappings in order to respond to a target stimulus.

Second, Experiment 2A also investigated whether there are differences in cue processing between the two types of cues by employing a double-response procedure in half of the trials with long CSI. The double-response procedure in task switching was first developed by Arrington, Logan and Schneider (2007, Experiment 3). Arrington and colleagues asked participants to first respond to the cue by a key/button press in order to

indicate the task they were expected to perform before they responded to the target stimulus itself. However, their study did not investigate individual differences in cue response times for different cue types, whereas the present experiment explicitly addressed this issue. Similar to the study by Arrington et al. (2007), each participant responded to the task cue before they responded to the target stimulus at CSIs of 1100 ms and 1700 ms in some trials. I labelled the trials with additional cue responses the “cue-response condition” whereas trials with no cue response were called “standard condition”. Observing both cue-response times and target-response times should help us to better understand processing of the different cue types and therefore the task preparation process. According to previous results (Arrington et al., 2007), I predicted that participants would respond faster in cue-repetition trials than in cue-switch trials showing cue-switch costs. In addition, I predicted that participants would process the cue differently and therefore show individual differences in cue-response times for two cue types.

3.2.1 Experiment 2A Method

Participants

Forty-four students from the University of Glasgow took part and received £8 for participation in the experiment. The sample size was determined by power analysis (power = .85, $\alpha = .05$, effect size Cohen's $f = .25$; Faul, Erdfelder, Lang & Buchner, 2007).

Participants were randomly assigned to the group with priming or non-priming cues. There were 23 participants (7 males and 16 females, *mean age* = 21.70 years, *SD* = 3.92) with non-priming cues and 21 participants (6 males and 15 females, *mean* = 21.95 years, *SD* = 2.92) with priming cues. All participants were naive as to task switching, and had normal or corrected-to-normal vision. All participants passed a colour-blindness test (Ishihara, 1983). Two participants (1 male and 1 female) in the non-priming group had to be

excluded because their overall accuracy was below a predetermined inclusion criterion of 80% correct.

Tasks and Stimuli

The tasks and the target stimuli were the same as the colour/shape task-switching stimuli employed in Experiment 1A. However the task cues, the mask and the cue-stimulus intervals were different. In the trials with the non-priming cues, the task cue was either a circle (diameter 4 cm) or a hexagon (4 cm x 4 cm), signalling the colour and shape task, respectively. In the trials with priming cues, the colour cue consisted of two horizontally adjacent plus signs “++” (7 cm x 3.4 cm), with a red “+” sign appearing on the left and a green “+” sign appearing on the right. The shape task cue was similar in appearance to the colour cue, showing a grey “++” sign (7 cm x 3.4 cm) with a highlighted vertical bar on the left “+” sign and a highlighted horizontal bar on the right “+” sign (Figure 3.1A). A fixation cross (4 cm x 4 cm) was displayed between the cue and the target stimulus. Responses to cues and target stimuli were made with the right and left hand, respectively. Cue responses were made with the right hand by pressing the keys E (colour task) or X (shape task) on a QWERTY keyboard. Target responses were made with the left hand by pressing the keys A (red/high) or S (green/wide). Please note that the position of the keys on the left and right corresponded with the colour/shape arrangement of the priming cues.

Procedure

Participants were randomly assigned to one of the two cue-type conditions. Instructions were presented on screen and were also explained verbally by the experimenter. After receiving instructions, participants completed a practice block with 36 trials before they started the experiment proper. The experiment had two sessions. The first session consisted of 12 blocks with 64 standard trials in each block (4 blocks for each of the three CSI conditions: 650 ms, 1100 ms and 1700 ms). The second session consisted of

8 blocks with 64 cue-response trials in each block (4 blocks for each of the two CSI conditions: 1100 ms and 1700 ms). Most participants finished both sessions on consecutive days.

In a standard trial, a cue appeared briefly at the centre of the screen for 250 ms and was replaced by a fixation sign that was displayed for 400 ms, 850 ms, or 1,450 ms. This corresponds to a CSI of 650 ms, 1,100 ms, and 1,700 ms, respectively. CSI varied randomly across blocks. The fixation sign was then replaced by a target stimulus which remained on the screen until a response was given or until the maximum response time of 1,500 ms expired. If the response was incorrect or if no response was made, the corresponding feedback (“mistake”, “too slow”) appeared for 3 seconds at the centre of the screen.

The cue-response condition was similar to the standard condition with the exception that only CSIs of 1,100 ms and 1,700 ms were included in the cue-response condition. A shorter CSI would have been too demanding for a cue response. Critically, participants were asked to also respond to the task cue by pressing a separate key for each cue within each CSI. If the participant managed to respond to the task cue, a stimulus appeared after the remaining CSI expired ($\text{CSI remaining} = \text{CSI total} - \text{RT cue}$). If an incorrect cue response was given or when the total CSI was exceeded, feedback appeared for 3 seconds as in the standard trials. The next trial started after an inter-trial interval (ITI) of 500 ms (Figure 3.1B).

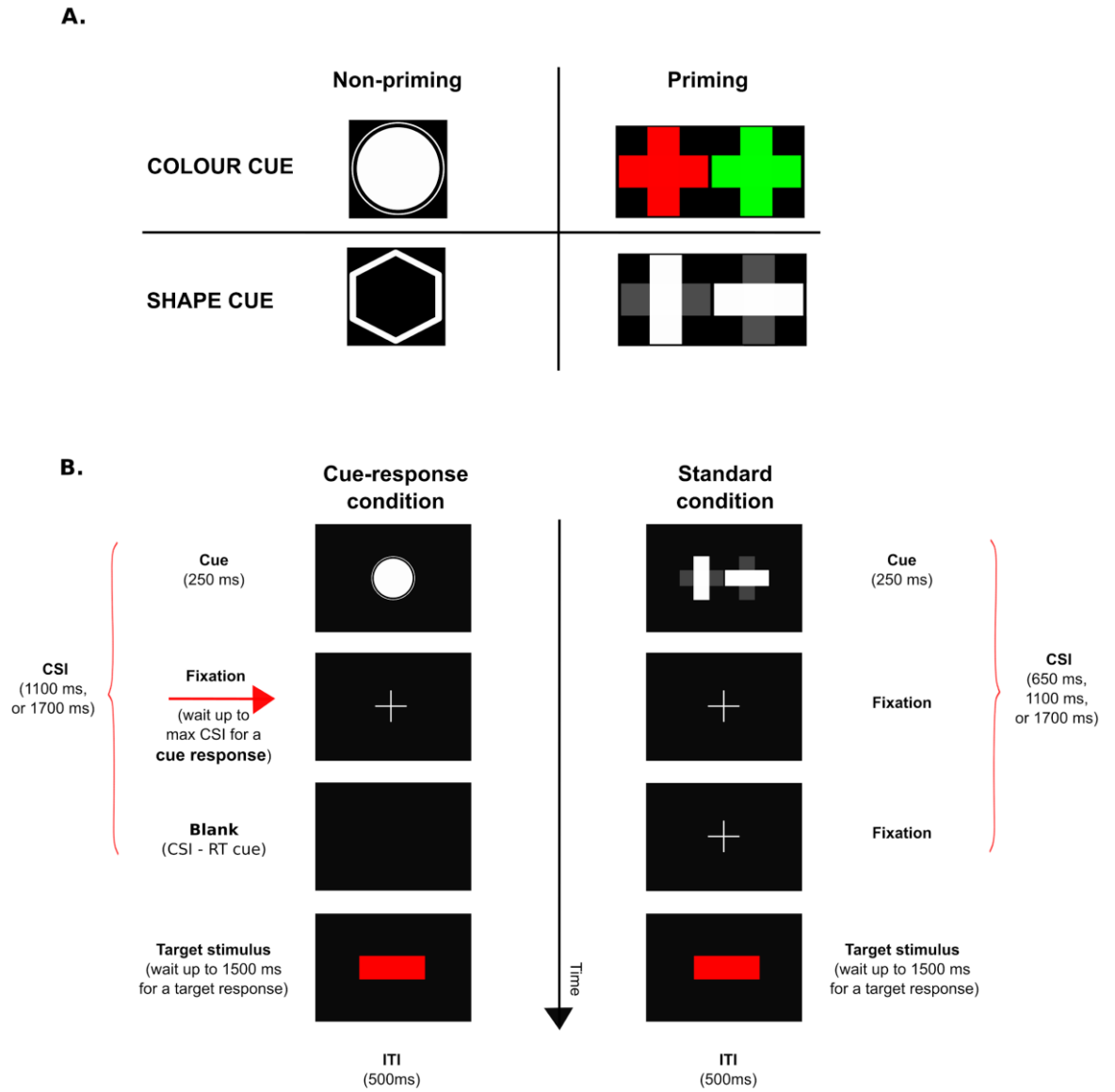


Figure 3.1. Experiment 2A. Illustration of cues and timeline of trials. **A.** Non-priming cues and priming cues in the colour and shape task. **B.** Timeline of a single trial with a non-priming cue in the cue-response condition (left timeline) and a trial with a priming cue in the standard condition without cue response (right timeline).

3.2.2 Experiment 2A Results

The first trial of each block and the trial immediately following an error were excluded from further analyses. Error trials were excluded from the RT analysis. After exclusion, first, I conducted task-switching analyses on cue and target RTs and ERs using

conventional ANOVAs. In addition, I conducted GLMMs on single trial RTs to investigate individual differences in cue and target RT performance.

Task-switching analyses

Effect of cue type on task switching (responses on target stimuli)

This analysis focused on the standard condition with trials that did not require a cue response. I tried to determine whether cue type affected task-switching performance across different CSIs. In order to simplify the design and statistical analyses, I did not include factor Congruency as a prior analysis suggests no difference for the congruency effect between cue types ($F < 1$). This experiment aimed to investigate whether priming cues can reduce or eliminate residual switch costs. Mean target RTs and ERs in the standard condition are presented in Table 3.1. ANOVAs for a mixed design were conducted on averaged individual target RTs and ERs. Cue type (non-priming, priming) was varied between subjects whereas Task (colour, shape), Trial transition (task repeat, task switch) and CSI (650 ms, 1100 ms, and 1700 ms) were varied within subjects.

Table 3.1

Experiment 2A. Mean target response times (RTs in ms) and error rates (ERs, in %).

Task	Trial transition and CSIs	Cue-response condition		Standard condition	
		<i>target RT</i>	<i>target ER</i>	<i>target RT</i>	<i>target ER</i>
Priming cue (N = 21)					
Colour	Repeat				
	650	-	-	503 (24.02)	2.77 (0.79)
	1100	473 (23.38)	8.67 (1.16)	481 (25.15)	3.37 (1.18)
	1700	467 (18.20)	8.56 (1.33)	514 (29.34)	3.17 (0.84)
	Switch				
	650	-	-	532 (26.85)	6.95 (1.21)
	1100	508 (20.39)	13.75 (1.57)	496 (23.78)	5.49 (1.20)
	1700	482 (17.99)	7.73 (1.47)	529 (26.04)	5.68 (1.20)
Shape	Repeat				
	650	-	-	519 (27.26)	4.99 (1.46)
	1100	490 (21.35)	10.85 (1.14)	499 (27.06)	5.74 (1.46)
	1700	491 (18.33)	10.49 (1.61)	532 (30.87)	4.05 (1.28)
	Switch				
	650	-	-	549 (31.05)	8.65 (1.58)
	1100	527 (24.38)	11.35 (1.66)	524 (28.27)	8.16 (1.49)
	1700	498 (18.85)	10.77 (1.69)	540 (27.89)	7.66 (1.62)
All	Repeat	481 (10.09)	9.64 (.66)	508 (11.05)	4.02 (.49)
	Switch	503 (10.25)	10.90 (.82)	528 (11.06)	7.10 (.57)
Non-priming cue (N = 21)					
Colour	Repeat				
	650	-	-	506 (13.57)	5.51 (1.13)
	1100	521 (19.25)	10.68 (1.42)	505 (11.20)	6.13 (1.11)
	1700	523 (14.89)	8.69 (1.10)	542 (17.13)	3.79 (0.67)
	Switch				
	650	-	-	565 (15.70)	10.24 (1.25)
	1100	568 (23.47)	14.42 (1.81)	560 (14.63)	8.99 (1.65)
	1700	585 (19.86)	12.08 (1.63)	577 (17.34)	8.64 (1.70)
Shape	Repeat				
	650	-	-	519 (13.58)	5.71 (1.25)
	1100	522 (20.16)	12.44 (1.53)	503 (12.48)	3.74 (0.72)
	1700	523 (14.44)	10.06 (1.20)	520 (15.49)	4.24 (0.89)
	Switch				
	650	-	-	576 (16.24)	8.90 (1.56)
	1100	594 (25.56)	16.91 (1.69)	559 (16.08)	7.03 (0.99)
	1700	583 (22.88)	12.76 (1.48)	570 (21.64)	5.93 (1.14)
All	Repeat	522 (8.53)	10.47 (.67)	516 (5.74)	4.85 (.40)
	Switch	582 (11.35)	14.04 (.84)	568 (6.86)	8.29 (.58)

Note. Standard errors are presented in parentheses

I did not find a statistically significant main effect for Cue type ($F < 1$) and Task ($F = 3.89, p = .060, \eta^2_p = .09$) on mean RTs. However, I found a significant main effect of Trial transition, $F(1, 40) = 70.64, p < .001, \eta^2_p = .64$. The averaged RTs were longer in task-switch trials (548 ms) than in task-repeat trials (512 ms), indicating a task-switch cost of +36 ms. There was a significant main effect of CSI, $F(2, 80) = 4.45, p = .015, \eta^2_p = .10$. RT difference between CSI 650 ms (534 ms) and CSI 1700 ms (541 ms) was not significant, $p = .252$. The difference between CSI 1100 ms (516 ms) and CSI 1700 ms was significant, $p < .001$; as well as the difference between CSI 650 ms and CSI 1100 ms, $p < .001$. The interaction between Trial transition and CSI did not reach statistical significance, $F(2, 80) = 2.85, p = .064, \eta^2_p = .07$.

As predicted, there was a significant interaction between Cue type and Trial transition, $F(1, 40) = 13.22, p < .001, \eta^2_p = .25$ (Figure 3.2). Task-switching costs were reduced by more than 50% for priming cues (+20 ms, $p = .319$) compared to non-priming cues (+52 ms, $p < .001$). Target responses in task-switch trials with priming cues were 39 ms faster compared to non-priming cues ($p = .009$) whereas there was no significant difference between the two cue types in task-repeat trials ($p = .641$). No other effects were statistically significant.

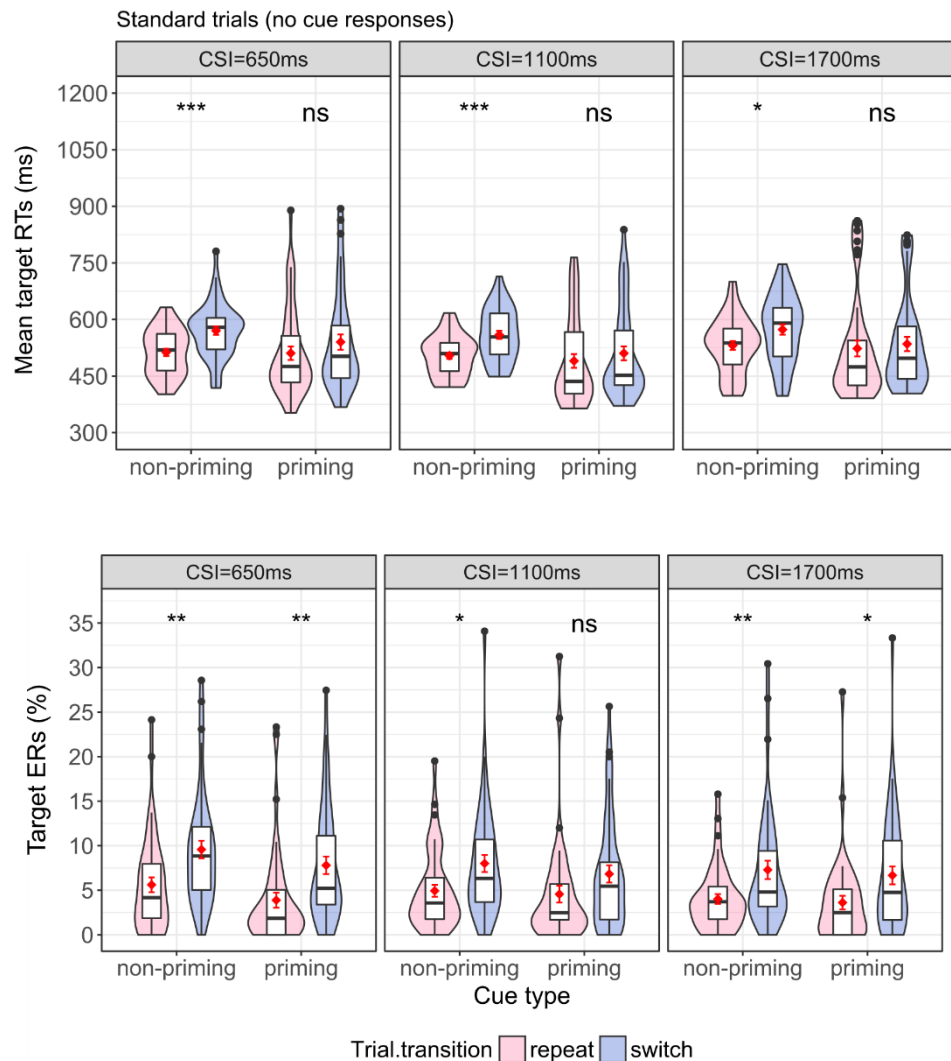


Figure 3.2. Results of Experiment 2A. Violin/box plots of target responses in standard trials without cue responses. Mean target RTs (top panel) and ERs (bottom panel) for CSI, Cue type, and Trial transition.

Note. *** $p < .001$, ** $p < .01$, * $p < .05$, *ns* = non-significant.

In terms of mean target ERs, participants made more errors in task-switch trials (7.69%) than in task-repeat trials (4.44%), $F(1, 40) = 63.93$, $p < .001$, $\eta^2_p = .62$. ERs were slightly different across CSIs, $F(2, 80) = 3.17$, $p = .047$, $\eta^2_p = .07$. Post-hoc pairwise comparisons (corrected after Holm) indicated that ERs were reduced by 1.32% from 6.72% for a CSI of 650 ms to 5.40% for a CSI of 1700 ms ($p = .044$). There was no main effect of Task ($F < 1$) or Cue type ($F < 1$) for ERs. However, participants in the group with non-

priming cues made more errors in the colour task (7.22%) than in the shape task (5.93%), whereas participants in the group with priming cues made more errors in the shape task (6.54%) compared to the colour task (4.57%), resulting in a significant interaction between Cue type and Task, $F(1, 40) = 6.75, p = .013, \eta^2_p = .17$. No other effects were statistically significant.

I also compared target RTs and ERs of the cue-response condition with the standard condition for CSIs of 1100 ms and 1700 ms (mean RTs and ERs for all conditions are presented in Table 3.1). The results of the corresponding ANOVAs are presented in Appendix A and show the same pattern of results for Cue type as the results for the standard condition with only no-cue-response trials.

Effect of cue type on cue processing (responses on cues)

Cue RTs and ERs (Table 3.2) were analysed in a mixed design ANOVA with between-subjects factor Cue type (non-priming, priming) and within-subjects factors Trial transition (task-repeat, task-switch), Task (colour, shape) and CSI (1100 ms, 1700 ms). Cue responses in cue-response trials were considered “correct” regardless of the target response. Statistical testing suggested that cue RT was not significantly affected by Cue type, $F(1, 40) = 1.43, p = .239, \eta^2_p = .03$, and CSI, $F(1, 40) = 2.61, p = .114, \eta^2_p = .06$. Task had a significant main effect on cue RT, $F(1, 40) = 20.19, p < .001, \eta^2_p = .34$, indicating that on average the shape-task cue (344 ms) was processed 22 ms faster than the colour-task cue (366 ms).

Table 3.2

Experiment 2A. Mean cue RTs (in ms) and error rates (ERs in %).

Task	Trial transition and CSIs	Priming cue		Non-priming cue			
		cue RT	cue ER	cue RT	cue ER		
Colour	Repeat	1100	356 (18.98)	5.39 (0.85)	322 (18.00)	6.37 (1.29)	
		1700	389 (24.39)	4.94 (1.08)	337 (18.25)	4.58 (0.84)	
	Switch	1100	385 (20.07)	7.88 (0.99)	360 (19.68)	6.40 (1.29)	
		1700	402 (25.11)	3.39 (0.78)	377 (17.83)	4.07 (0.84)	
	Shape	Repeat	1100	346 (18.15)	5.06 (0.82)	310 (16.75)	6.62 (0.99)
			1700	364 (23.47)	4.19 (0.79)	314 (18.91)	5.01 (0.92)
Switch		1100	348 (17.51)	3.63 (0.58)	343 (17.11)	7.62 (1.27)	
		1700	367 (24.67)	3.53 (0.75)	355 (18.98)	4.56 (1.09)	
All	Repeat	364 (10.72)	4.90 (.44)	321 (8.91)	5.65 (.51)		
	Switch	375 (11.04)	4.61 (.44)	359 (9.14)	5.66 (.58)		

Note. Standard errors are presented in parentheses.

Since each cue was matched with a single task, “cue-switch trials” and “cue-repeat trials” indicate task-switch and task-repeat trials, respectively. Correspondingly, the RT difference between cue-repeat trials and cue-switch trials indicate “cue-switch costs” in cue RTs, which is analogous to task-switch costs for target RTs. Trial transition had a significant main effect on cue RTs, $F(1, 40) = 29.56, p < .001, \eta^2_p = .42$, demonstrating a significant difference of +24 ms in cue RTs between cue-switch trials (367 ms) and cue-repeat trials (343 ms), suggesting a significant cue-switch cost.

In addition, Task interacted with Trial transition, $F(1, 40) = 4.97, p = .032, \eta^2_p = .11$, revealing that cue-switch costs were significantly larger when switching from the shape to the colour task (SC = +30 ms, $p = .036$) compared to switching from the colour to the shape task (SC = +19 ms, $p = .173$). Importantly, as in the analysis on target RTs, Trial

transition interacted with Cue type, $F(1, 40) = 8.17, p = .007, \eta^2_p = .17$ (Figure 3.3). Post-hoc analyses showed that cue-switch costs were only significant for non-priming cues (SC = +38 ms, $p = .032$) whereas the costs were not statistically significant for priming cues (SC = +11 ms, $p = .817$). Post-hoc analyses also indicated that cue RTs in trials with repeated non-priming cues were significantly shorter compared to repeated priming cues (-43 ms, $p = .013$) whereas no significant difference emerged between the two cue types in trials with cue-switching ($p = .696$). No other effects reached statistical significance.

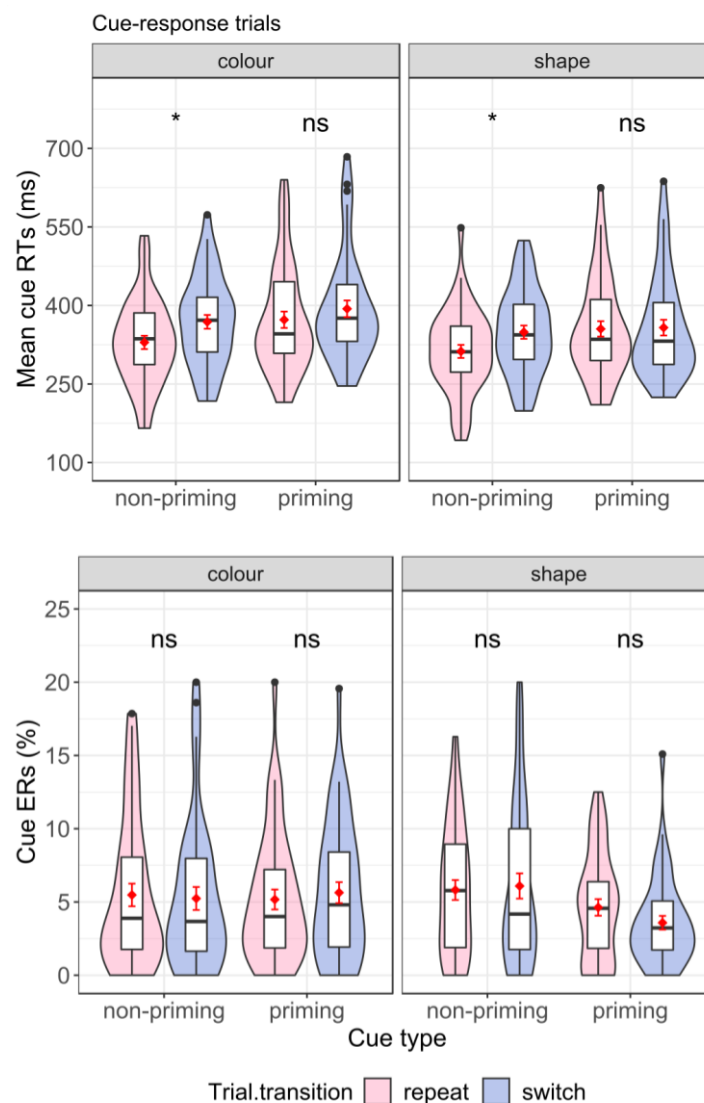


Figure 3.3. Results of Experiment 2A. Violin and box plots of mean cue RTs and ERs for Task, Cue type and Trial transition.

Note. * $p < .05$, ns = non-significant.

For the cue-response ERs, there was no significant main effect for Trial transition ($F < 1$), Cue type ($F < 1$), and Task ($F < 1$). However, there was a significant main effect of CSI, $F(1, 40) = 14.64$, $p < .001$, $\eta^2_p = .27$. Participants made 1.83% more errors in trials with a CSI of 1100 ms (6.12%) compared to trials with a CSI of 1700 ms (4.29%).

There was a significant interaction between CSI and Trial transition for ERs, $F(1, 40) = 4.89$, $p = .033$, $\eta^2_p = .11$, suggesting that cue-switch costs were larger for CSI of 1100 ms (SC = +0.53%) than for CSI of 1700 ms (SC = -0.80%). Moreover, Task significantly interacted with Cue type, $F(1, 40) = 4.81$, $p = .034$, $\eta^2_p = .11$ (Figure 3.3), indicating that ERs for responses to shape cues were increased by 1.85% for trials with non-priming cues (5.95%) compared to trials with priming cues (4.10%). This difference was not significant for colour cues. There were no other statistically significant effects.

Relationship between cue RT and the followed target RT

RT distribution for cue and target responses and their relationships in each cue type and trial condition are presented in Figure 3.4. I found that cue RT was positively correlated with target RT in different trial conditions and cue types. Participants with priming cues showed a significant correlation between cue RT and target RT, for repeat and switch trials.

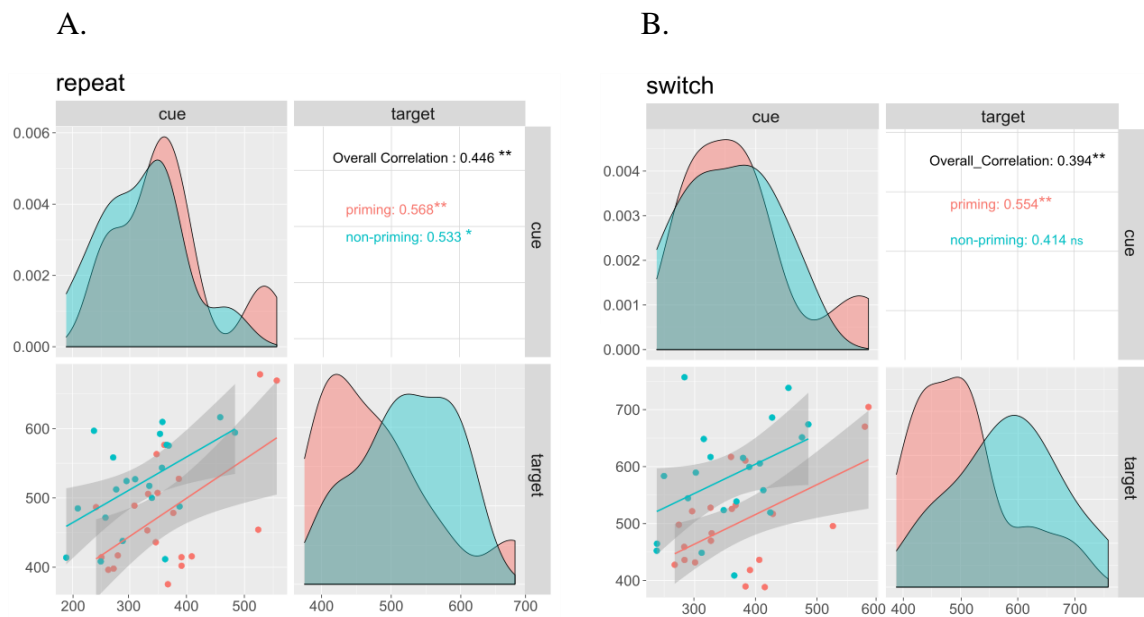


Figure 3.4. Relationship between cue RT and target RT for priming (red) and non-priming cues (green) in repeat (matrix A) and switch trial conditions (matrix B). In the lower diagonal of matrix A and B, each dot in the scatter plot illustrates individual mean cue and target response times in *ms* for priming and no-priming cue. The regression line shows linear relationship between cue RT and target RT in each cue type (95% CI is in grey shades). RT Distributions for cue responses and target responses are on the diagonal and correlations are written in the upper diagonal.

Note. ** $p < .001$, * $p < .05$, ns = non-significant.

Individual differences in target RTs and cue RTs

Individual differences in target RTs

In order to investigate individual differences in target RTs for the two types of cues, I analysed the single-trial target RTs using GLMMs. In order to study whether there were significant differences in target RTs between the two types of cues, I tested the model, GLMM 2A.2, without a main effect of Cue type and all interactions involving Cue type, while keeping the random-effects structure the same as in GLMM 2A.3. However, the most complex model tested here, GLMM 2A.3, turned out to be the model with the lowest AIC and BIC values (Table 3.3). The model with fewer fixed effects, GLMM 2A.2,

was worse than the model with full factorial design, GLMM 2A.3, with differences in information criteria of $\Delta AIC = 139$, $\Delta BIC = 42$. This suggests that the differences between target RTs for trials with priming and non-priming cues were important and explained a substantial amount of variability.

In GLMM 2A.3, the factor “Task”, “Trial transition”, “Cue type” and “CSI” outside the parentheses denote fixed effects and their interactions. The terms inside the parentheses denote the random intercept, Task and Trial transition for each participant or subject.

Table 3.3

Experiment 2A GLMM comparisons based on target RT data (the best model is in bold; GLMM 2A.3).

<i>Model names</i>	<i>Models (family = Gamma (link = “identity”))</i>	<i>df</i>	<i>AIC</i>	<i>BIC</i>	<i>Log lik</i>	<i>dev</i>	<i>Chi-sq</i>	<i>p-value (>Chisq)</i>
GLMM 2A.1	Target.RT~ Task+Trial.transition + Cuetype+CSI+(1 subject)	8	336719	336785	-168352	336703		
GLMM 2A.2	Target.RT~ Task*Trial.transition* CSI+(1+Task+ Trial.transition subject)	1 9	336512	336668	-168237	336474	228.96	< .001 ***
GLMM 2A.3	Target.RT~ Task*Trial.transition* Cuetype*CSI+ (1 + Task +Trial.transition subject)	3 1	336373	336626	-168155	336311	163.32	< .001 ***

Note. The model formulas are stated in the syntax of the lme4 package in R.

In contrast to the ANOVA results on target RTs, GLMM 2A.3 suggests that all main effects were statistically significant for target RTs – responses were faster in task-repeat trials (521 ms) compared to task-switch trials (558 ms), $t = 24.5$, $p < .001$; and

responses were faster in trials with a CSI of 1100 ms (527 ms) compared to the CSI of 650 ms (545 ms), $t = 15.3, p < .001$, whereas there was no significant difference between CSI 650 ms and CSI 1700 ms (547 ms), $t = 1.8, p = .075$. These results were in line with the results of ANOVA. However, in contrast to the ANOVA results, responses were faster in priming cues (532 ms) compared to non-priming cues (547 ms), $t = 10.5, p < .001$; and target responses were faster in colour tasks (535 ms) compared to shape task (545 ms), $t = 6.4, p < .001$.

Consistent with the ANOVA results on target RTs, Trial transition significantly interacted with Cue type, $t = 17.7, p < .001$. Task-switch costs were smaller in priming cues (SC = +22 ms) compared to non-priming cues (SC = +52 ms). However, different to the ANOVA results, the GLMM 2A.3 further suggests that the difference between priming and non-priming cues was significantly larger for CSI 1,100 ms (non-priming - priming = 23 ms) compared to CSI 1,700 ms (15 ms), $t = 4.9, p < .001$, and also compared to CSI 650 ms (7 ms), $t = 10.3, p < .001$.

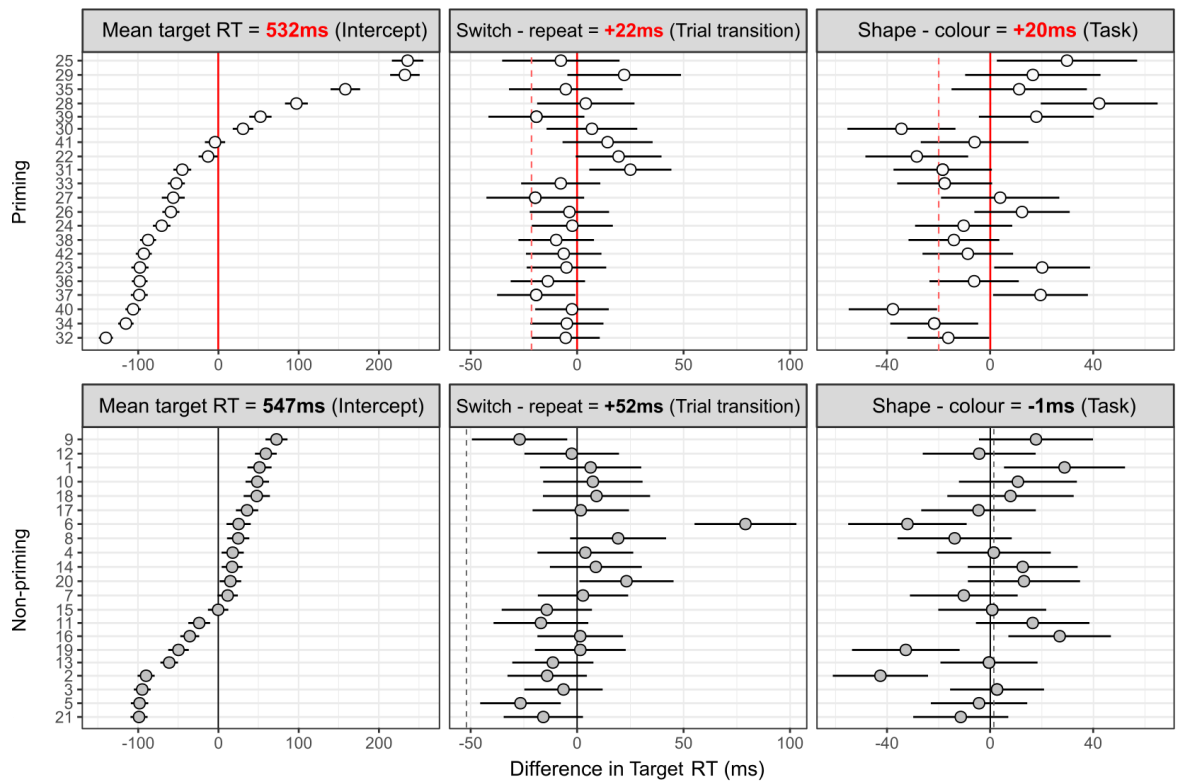


Figure 3.5. Results of Experiment 2A. Illustration of by-subject random effects for target RT. Dotplots in top row show target performance with priming cues and in the bottom row with non-priming cues. Dotplots from the left to right illustrate individual deviation (dot) and 95% confidence intervals (horizontal error bar) from conditional mean target RT, and individual deviations from the fixed effects of Trial transition and Task for each type of cue. In the top row, the solid vertical red lines centred on zero in the left, middle, and right panel denote the group-level RT for priming cues (Intercept = priming mean target RT of 532 ms), fixed effects of Trial transition (switch cost = switch - repeat = +22 ms) and Task (shape - colour = +20 ms), respectively. In the bottom row, the solid vertical black lines centred on zero in the left, middle, and right panel denote the non-priming group-level RT (Intercept = non-priming mean target RT of 547 ms), fixed effects of Trial transition (switch cost = switch - repeat = +52 ms) and Task (shape - colour = -1 ms) in non-priming cues, respectively. Please note the different scales on the *x*-axes (in ms) in the plots. The dashed vertical red and black line in the middle and on the right plot indicates zero task-switch costs and zero differences between tasks, for priming and non-priming cue, respectively.

The random effects of GLMM 2A.3 explained individual deviations from the mean target RTs (Intercept) as well as deviations from mean task-switch costs (Trial transition) and mean differences between the colour and shape tasks, as illustrated in Figure 3.5. There were large individual deviations from the group-average RT (Intercept) for each cue type. Participants with priming cues showed slightly more variability around the group mean compared to the participants with non-priming cues. However, the priming-cue group was more homogeneous in terms of task-switch costs, with all participants not significantly deviating from the group mean switch costs except for Participant 31 and 37. Fourteen out of twenty-one participants in the priming-cue group had switch cost estimates that were not significantly different from zero switch costs. In contrast, all participants in the non-priming cue group showed significant switch costs and most participants with the non-priming cues, except for Participant 5, 9, 20 and particularly 6, did not significantly deviate from the group mean switch costs.

The individual differences for the main effect of Task were similar for the priming and non-priming cues group. Many participants in the group with non-priming cues performed the shape task as quickly as the colour task, suggesting no difference in target response times between tasks.

Individual differences in cue RTs

In addition to the individual differences in target RTs, I also studied individual differences in cue responses. In order to study whether the differences between the two types of cues were important, I tested the model without the main effect of Cue type and all interactions involving Cue type, while including the same random-effect structure as in GLMM 2A.6. However, the more complex model GLMM 2A.6 gave lower AIC and BIC values ($\Delta\text{AIC} = 1$, $\Delta\text{BIC} = 38$, see also Table 3.4). The model, GLMM 2A.5, with fewer

fixed effects was worse than the model, GLMM2.6, with full factorial design. This suggests that the fixed effect of Cue type was important and that both groups differed significantly in cue RTs. In GLMM 2A.6, the factor “Task”, “Trial transition”, “Cue type” and “CSI” outside the parentheses denote fixed effects and their interactions. The terms inside the parentheses denote the random intercept, Task, Trial transition and CSI for each participant or subject.

Table 3.4

Experiment 2A GLMM comparisons based on cue RT data (the best model is in bold; GLMM 2A.6).

<i>Model names</i>	<i>Models (family = Gamma (link = “identity”))</i>	<i>df</i>	<i>AIC</i>	<i>BIC</i>	<i>Log lik</i>	<i>dev</i>	<i>Chi-sq</i>	<i>p-value (>Chisq)</i>
GLMM 2A.4	Cue.RT ~ Task +Trial.transition + Cuetype + CSI + (1 subject)	7	213862	213916	-106924	213848		
GLMM 2A.5	Cue.RT ~ Task * Trial.transition *CSI+ (1+Trial.transition+ Task+ CSI subject)	19	211981	212228	-105971	211943	1904.99	< .001 ***
GLMM 2A.6	Cue.RT ~ Task * Trial.transition * Cuetype * CSI + (1+Trial.transition+ Task+ CSI subject)	27	211980	212190	-105963	211926	16.54	.035 *

Note. The model formulas are stated in the syntax of the lme4 package in R. The ID/name of the model for cue RT data follows the ID/name of the model for target RT data.

Inconsistent to the ANOVA results on cue RTs, GLMM 2A.6 suggests that all fixed effects were statistically significant on cue RT- cue responses were faster in priming cues (350 ms) compared to non-priming cues (383 ms), $t = 13.35$, $p < .001$; responses were faster in shape task (354 ms) compared to colour task (379 ms), $t = -13.86$, $p < .001$;

responses were faster in repetitions (354 ms) compared to switches (379 ms), $t = 16.72$, $p < .001$; and responses were faster in trials with a CSI of 1100 ms (357 ms) compared to the CSI of 1700 ms (376 ms), $t = 11.23$, $p < .001$.

In addition, GLMM 2A.6 shows significant interactions similar as the ANOVA results on cue RTs. Trial transition interacted with Cue types, $t = -15.64$, $p < .001$, implying that cue-switch costs were smaller in priming cues (+12 ms) compared to non-priming cues (+38 ms). GLMM 2A.6 also indicated a significant interaction between Trial transition, Cue type and Task, $t = -7.98$, $p < .001$; and a significant interaction between Trial transition, Cue type and CSI, $t = -7.21$, $p < .001$. The difference between cue types in cue-switch cost was more pronounced in the shape task (SC non-priming - SC priming = +32 ms) than in the colour task (+17 ms); and more pronounced with CSI 1700 ms (+30ms) than with CSI 1100 ms (+19 ms).

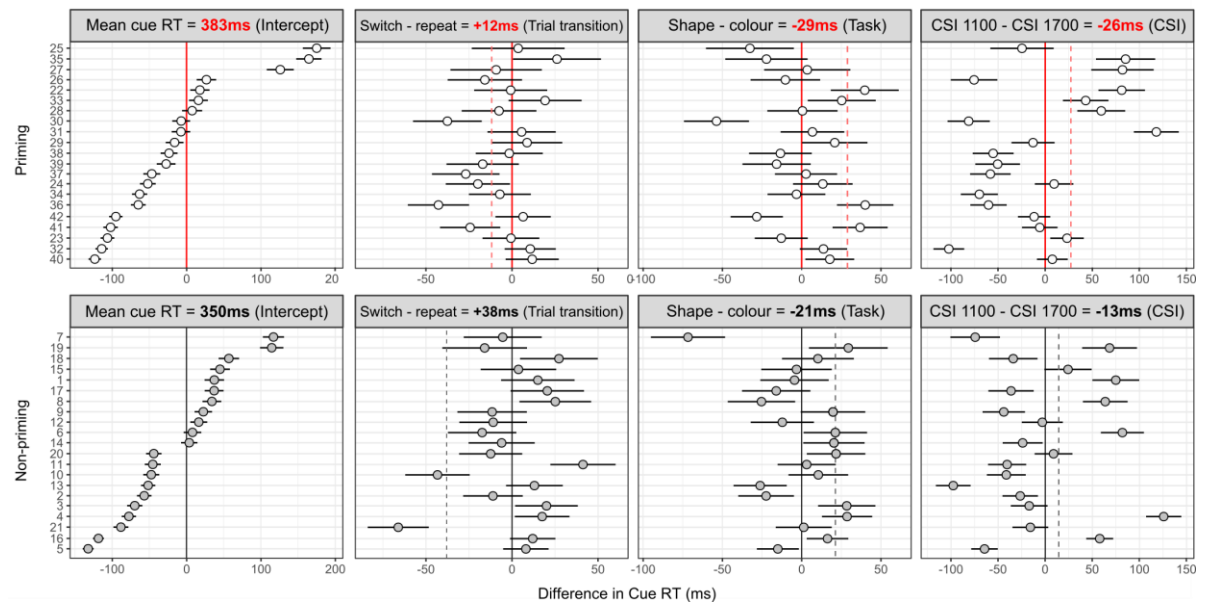


Figure 3.6. Results of Experiment 2A. Illustration of by-subject random effects for cue RT. Subject IDs on the left correspond to the Subject IDs for target RT in Figure 3.5. Dotplots in top row show performance with priming cues and in the bottom row with non-priming cues. Dotplots from the left to right panel illustrate individual deviation (dot) and 95% confidence intervals (horizontal error bar) from conditional mean cue RT and individual deviations from the fixed effect of Task, Trial transition and CSI for each type of cue. In the top row, the solid vertical red lines centred on zero from left to right denote the priming group-level RT (Intercept = priming mean cue RT of 383 ms), fixed effects of Trial transition (switch cost = switch - repeat = +12 ms), Task (shape - colour = -29 ms) and CSI (CSI 1100 ms - CSI 1700 ms = -26 ms), respectively. In the bottom row, the solid vertical black lines centred on zero from left to right panel denote the non-priming group-level RT (Intercept = priming mean cue RT of 350 ms), fixed effects of Trial transition (switch cost = switch - repeat = +38 ms), Task (shape - colour = -21 ms) and CSI (CSI 1100 ms - CSI 1700 ms = -13 ms), respectively. Please note the different scales on the x -axes (in ms) in the plots. The dashed vertical red and black line, in the three plots for cue RTs indicates zero switch cost, zero difference between tasks, and zero difference between CSI 1,100 ms and CSI 1,700 ms, for priming and non-priming cue respectively.

Similar to the individual difference in target RTs, Figure 3.6 illustrates large individual deviations from the mean cue RTs for each type of cues. Figure 3.6 also shows that participants in the group of priming cues had smaller deviation from the group mean

cue-switch costs and zero cue-switch costs. Fourteen out of 21 participants with priming cues, did not show significant cue-switch costs. In contrast, participants in the group of non-priming cues appeared to be less homogenous in their cue-switch costs, with only two participants showing switch costs no different from zero. Both groups of participants showed significant deviations from the main effect of Task and CSI.

Many Individual participants showed consistent performance ranking similar in their cue RT and target RT. For example, Participant 25 who was the slowest in cue RT performed also slowly in target RT. Similarly, Participant 1, 8, 9, 12, 17, 18, 35 showed slower than average responses for cue and target. Many other participants, e.g., Participant 5, 16, 32, 40 responded faster than average with shorter cue RT and target RT. However, Participant 15 and 19 with non-priming cues and Participant 22, 23, 26, 27 with priming cues who were more slowly in cue responses, responded quickly for targets.

3.3 Experiment 2B

In order to confirm the difference between task-switch costs for the two types of cues, I conducted a follow-up experiment varying cue types within-subjects rather than between-subjects.

3.3.1 Experiment 2B Method

Participants

Twenty-nine students (7 males and 22 females; *mean age* = 21.62 years, *SD* = 2.27) from the University of Glasgow participated in this study and received £12. The sample

size was determined by power analysis (power = .85, $\alpha = .05$, effect size Cohen's $f = .25$; Faul et al., 2007). None of the students had participated in the previous experiments.

Task, Stimuli and Procedure

The tasks, task cues, and target stimuli were identical to Experiment 2A. All participants completed a session of priming cues (about 45-50 min) and a session of non-priming cues (about 45-50 minutes). Both sessions were completed on separate days within a week. The order of the cue types was counterbalanced across participants. Unlike in Experiment 2A, only standard-trial condition without cue responses were included in the present experiment. Otherwise, the experimental procedures were identical to Experiment 2A.

3.3.2 Experiment 2B Results

First, I conducted task-switching analyses on target RTs and ERs using conventional ANOVAs. Then, I conducted a GLMM to investigate the individual differences in target RT performance.

Effect of cue type on task switching

Mean RTs and ERs are presented in Table 3.5. A four-way ANOVA with repeated measurements was conducted on averaged individual target RTs and ERs. Cue type (non-priming, priming), Task (colour, shape), Trial transition (task repeat, task switch) and CSI (650 ms, 1100 ms, and 1700 ms) were varied within subjects. There was a significant main effect of Trial transition, $F(1, 28) = 68.99, p < .001, \eta^2_p = .71$, with responses 31 ms faster in task-repeat trials (467 ms) than in task-switch trials (498 ms). Unlike in Experiment 2A,

there was a main effect of Cue type, $F(1, 28) = 9.17, p = .005, \eta^2_p = .24$, revealing responses that were 42 ms faster for priming cues (462 ms) compared to non-priming cues (504 ms).

Table 3.5

Experiment 2B. Mean target response times (RTs in ms) and error rates (ERs in %).

Task	Trial transition and CSIs	Priming		Non-priming	
		target RT	target ER	target RT	target ER
Colour	Repeat				
	650	453 (12.74)	2.88 (.45)	478 (14.49)	4.14 (.60)
	1100	441 (11.43)	2.13 (.36)	471 (10.80)	3.35 (.50)
	1700	444 (11.65)	2.45 (.39)	489 (13.63)	3.22 (.50)
	Switch				
	650	479 (15.65)	6.56 (.76)	535 (19.77)	7.65 (1.05)
	1100	463 (12.64)	4.80 (.68)	527 (17.73)	7.10 (.94)
	1700	461 (13.16)	4.83 (.62)	539 (18.04)	7.54 (.83)
Shape	Repeat				
	650	470 (13.89)	3.21 (.77)	481 (13.28)	4.05 (.67)
	1100	458 (13.14)	3.63 (.56)	478 (12.21)	2.89 (.50)
	1700	457 (11.57)	3.63 (.67)	491 (13.55)	3.09 (.44)
	Switch				
	650	479 (12.73)	5.37 (.76)	527 (19.61)	7.51 (.64)
	1100	468 (12.11)	5.77 (.83)	505 (15.25)	5.20 (.67)
	1700	471 (12.52)	5.06 (.63)	521 (16.94)	4.10 (.52)
All	Repeat	454 (5.06)	2.99 (.23)	482 (5.27)	3.46 (.22)
	Switch	470 (5.33)	5.40 (.29)	526 (7.27)	6.52 (.34)

Note. Standard errors are presented in parentheses

Task significantly interacted with Trial transition, $F(1, 28) = 11.72, p = .002, \eta^2_p = .29$. The task-switch costs were significant when switching from the shape to the colour task (SC = +38 ms, $p < .001$) and when switching from the colour to the shape task (SC = +23 ms, $p = .025$). A post-hoc comparison showed that the switch costs were larger when switching to the colour task, $p = .002$.

As in Experiment 2A, Trial transition significantly interacted with Cue type, $F(1, 28) = 24.58, p < .001, \eta^2_p = .47$ (see Figure 3.7). Task-switch costs were reduced to +16 ms for priming cues ($p = .096$) compared to +44 ms for non-priming cues ($p < .001$). No other effects on RT were statistically significant.

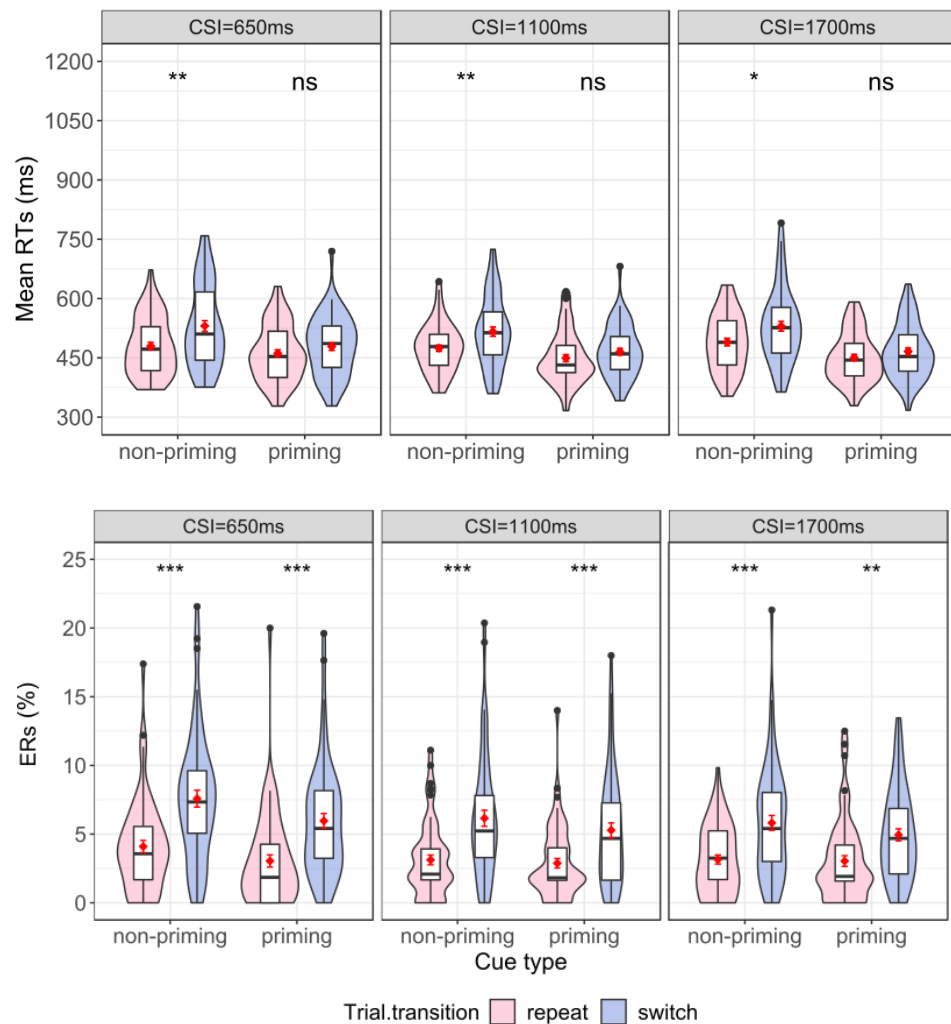


Figure 3.7. Results of Experiment 2B. Mean target RTs (top row) and ERs (bottom row) for CSI, Cue type, and Trial transition.

Note. *** $p < .001$, ** $p < .01$, * $p < .05$, ns = non-significant.

In terms of mean ERs, participants made more errors in task-switch trials (5.96%) compared to task-repeat trials (3.22%), $F(1, 28) = 72.77, p < .001, \eta^2_p = .72$. ERs varied across CSIs, $F(2, 56) = 5.14, p = .009, \eta^2_p = .16$. There were more errors in CSI 650 ms

(5.17%) compared to CSI 1100 ms (4.36%), $p = .047$. Error rates were also higher in CSI 650 ms than in CSI 1700 ms (4.24%), $p = .028$. Participants made more errors in trials with non-priming cue trials (4.99%) compared to priming-cue (4.19%), $F(1, 28) = 6.04$, $p = .020$, $\eta^2_p = .18$.

Task significantly interacted with Trial transition, $F(1, 28) = 6.39$, $p = .017$, $\eta^2_p = .19$. Participants had significant ER switch costs when switching to the colour task (SC = +3.39%, $p < .001$) and when switching to the shape task (SC = +2.08%, $p < .001$). A post-hoc pairwise comparison showed that switch costs were significantly larger when switching from the shape to the colour task, $p = .017$.

Task significantly interacted with Cue type, $F(1, 28) = 5.20$, $p = .030$, $\eta^2_p = .16$. With non-priming cues, ERs were slightly higher in the colour task (5.50%) than in the shape task (4.47%), $p = .052$. No statistically significant difference between tasks was found for priming cues, $p = .598$. No other effects reached statistical significance.

Individual differences in target RTs

In order to investigate individual differences in target RTs for the two types of task cues, I analysed the target RTs using GLMMs. The models listed in Table 3.6 range from a simple GLMM 2B.1 with main fixed effects and random intercept only to a more complex GLMM 2B.3 with full factorial fixed effects and specific random effects. GLMM 2B.3 had the lowest AIC and BIC values of the models tested. The factor “Task”, “Trial transition”, “Cue type” and “CSI” outside the parentheses denote fixed effects and their interactions. The terms inside the parentheses denote the random intercept, the random effect of Cue type, and the random effect of Trial transition for different types of cues.

Table 3.6

Experiment 2B GLMM comparisons based on target RT data (the best model is in bold; GLMM 2B.3).

<i>Model names</i>	<i>Models (family = Gamma (link = "identity"))</i>	<i>df</i>	<i>AIC</i>	<i>BIC</i>	<i>Log lik</i>	<i>dev</i>	<i>Chi-sq</i>	<i>p-value (>Chi sq)</i>
GLMM 2B.1	Target.RT~ Task+Trial.transition +Cuetype+CSI+(1 subject)	8	502867	502936	-251426	502851		
GLMM 2B.2	Target.RT~ Task* Trial.transition *Cuetype*CSI+(1+Cuetype+ Trial.transition subject)	31	499585	499852	-249762	499523	3328.07	< .001 ***
GLMM 2B.3	Target.RT~ Task* Trial.transition* Cuetype*CSI+ (1+Cuetype+ Cuetype: Trial.transition subject)	35	499481	499782	-249706	499411	114.39	< .001 ***

Note. The model formulas are stated in the syntax of the lme4 package in R.

GLMM 2B.3 shows that all main effects were statistically significant for target RT – target responses were slightly faster in the colour task (488 ms) compared to the shape task (491 ms), $t = 3.5$, $p < .001$; responses were faster in task-repeat trials (473 ms) compared to task-switch trials (506 ms), $t = 27.63$, $p < .001$; responses were faster for priming cues (468 ms) compared to non-priming cues (511 ms), $t = -29.88$, $p < .001$; and responses were faster in trials with a CSI of 1,100 ms (484 ms) compared to the CSI of 650 ms (493 ms), $t = 9.22$, $p < .001$, and CSI 1,700 ms (491 ms), $t = 6.20$, $p < .001$.

In addition, in line with the ANOVA results on RTs, Trial transition significantly interacted with Cue type, $t = -18.77$, $p < .001$. Task-switch costs were smaller in priming cues (SC = +18 ms) compared to non-priming cues (SC = +49 ms). Task significantly

interacted with Trial transition, $t = -9.72$, $p < .001$. Task-switch costs were larger when switching from the shape to the colour task (SC = +39 ms) compared to switching from the colour to the shape task (SC = +28 ms). Different from the ANOVA results, the model estimates suggest that the difference between priming and non-priming cues was smaller for CSI 1100 ms (non-priming - priming = 41 ms) than for CSI 1700 ms (52 ms), $t = -11.03$, $p < .00$, but larger for CSI 1100 ms than for CSI 650 ms (37 ms), $t = 2.62$, $p = .009$.

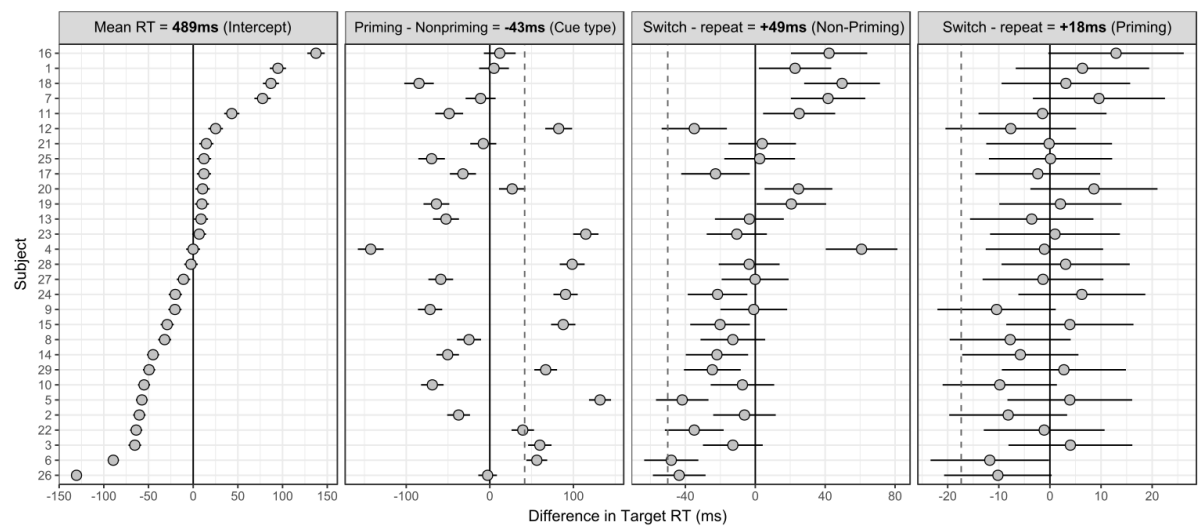


Figure 3.8. Results of Experiment 2B. Illustration of by-subject random effects for target RT. Dotplots from the left to right illustrate individual deviation (dot) and 95% confidence intervals (horizontal error bar) from mean target RT (Intercept = grand mean target RT of 489 ms) and individual deviations from the fixed effect of Cue type (priming – non-priming = -43 ms) and Trial transition for non-priming cues (switch - repeat = +49 ms) and priming cues (switch - repeat = +18 ms). The vertical lines centred on zero denote the group-level RT or conditional fixed effects. Please note the different scales on the x -axes (in ms) in each plot. The dashed vertical lines in the right three panels (from left to right) indicate zero difference between cue types, zero task-switch costs for non-priming cues and for priming cues, respectively.

Figure 3.8 illustrates individual deviations from the mean RT (Intercept), from the mean effect of Cue type, and from the mean task-switch costs (Trial transition) in non-

priming and priming cues. Individual variability is most prominent for mean RTs and the effect of cue type, explaining considerable variance. Overall task-switch costs are more than halved for priming cues compared to non-priming cues. The individual variability is reduced for priming cues, with seven participants performing not significantly different from zero switch costs compared to four participants in the non-priming condition. In the condition with priming cues the participants appeared to be more homogenous in their task-switch costs, replicating the results of Experiment 2A.

3.3.3 Discussion of Experiment 2A and 2B

Several important findings emerged from the results of the between-subject design in Experiment 2A and the within-subject design in Experiment 2B. First, task-switch costs for both RT and ER remained significant in trials with non-priming cues. In trials with priming cues, in line with my prediction, RT task-switch costs were reduced and no longer statistically significant, irrespective of CSIs. This finding supports my hypothesis that priming cues can facilitate efficient task preparation, resulting in reduced RT in switch trials and therefore reduced RT task-switch costs. The results of the GLMM suggest that typical participants had more homogenous task-switch costs and improved switching performance if appropriate priming cues are employed. Although I observed no task-switch costs in RTs in trials with priming cues, there were significant task-switching costs in terms of error rates in priming and non-priming cues of Experiment 2A and 2B.

The non-significant residual switch costs for RTs in the condition with priming is consistent with previous results showing that “transparent” cues can substantially decrease residual switch costs because task goals are activated more easily (e.g., Arbuthnott & Woodward, 2002; Logan & Schneider, 2006; Mayr & Kliegl, 2000; Miyake et al., 2004; Schneider, 2016). However, residual switch costs remained significant although

transparent task cues were employed in these studies. The critical difference in the present experiment was that I employed “priming” cues that not only pre-activate the upcoming task features of the target but also inform about the task-response mappings for the upcoming task, essentially providing a shortcut for task-rule retrieval and response selection. This type of cue may improve preparatory adjustments and may help trial-by-trial task-set retrieval.

Measuring cue RTs in Experiment 2A provided evidence of individual differences and different task-switching preparation for the two different types of task cues. I found that priming cues had smaller and non-significant cue-switch costs, although the average cue RTs were longer in trials with priming cues. Participants spent longer time to process the information of priming cues, which may imply more elaborate cue processing in cue-repeat and cue-switch trials. In contrast, participants with non-priming cues showed larger and significant cue-switch costs in RTs. Non-priming cues were visually simpler and therefore led to faster cue processing. However, participants with non-priming cues responded even more quickly if the cue (i.e., task) was repeated from the previous trial. Different performance between two types of cues may explain the different task-switching performance after target onset. Indeed, the correlation analyses showed a positive relationship between cue RT and target RT, providing evidence that fast target encoding and fast response execution may be related to fast cue processing and cue-based preparation.

The present results suggest that participants were able to better prepare in trials with priming cues. The suggestion that task preparation can be completed within a shorter interval for priming cues seems incompatible with the two-stage theory (e.g., Hydock & Sohn, 2011; Rubinstein et al., 2001). This theory posits that task-rule activation can only be completed after onset of a target stimulus. On the other hand, the present results favour

De Jong and colleague's (2000, 2010) *FTE* account because completed preparation within a relatively long CSI is possible so that residual switch costs can be considerably reduced.

In addition to more efficient preparation, it seems reasonable to assume that in a condition with priming cues participants experienced less interference in task-switch trials. This is because when judgments are required in visual detection or discrimination tasks, cues that prime target features provide more depictive representations and have the advantage of being self-explanatory (see Grange & Houghton, 2010; Houghton et al., 2009). Consistent with the load theory of selective attention and cognitive control (Lavie et al., 2004), in the task-switching context with attention shifting between the colour and the shape, iconic feature cues can reduce the cognitive load of task-set reconfiguration because these feature cues depict a clear image about the upcoming task. Meanwhile, reduced cognitive load may allocate selective attention towards task-relevant features (e.g., if in the colour task, focus on the colour exclusively) and away from irrelevant features (e.g., if in the colour task, ignore the shape completely), resulting in less interference when target onset in trials with priming cues.

In summary, the results of Experiment 2A and 2B show that RT task-switch costs can be reduced to a non-significant level when priming cues are used, irrespective of CSI. This finding can be explained by reduced cognitive load for priming cues: There was more working memory capacity available to prepare task-relevant responses while minimizing interference. A separate analysis on cue responses in Experiment 2A indicated different levels of task preparation for the different types of cues, which helps to understand differences in task switching. Moreover, Experiment 2A revealed substantial individual differences, not only for cue RTs but also for target RTs. Experiment 2B showed a similar pattern of results as in Experiment 2A, while strengthening the interpretation of more efficient task preparation because the same participants showed smaller differences in task-

switch costs for priming compared to non-priming cues, reminiscent of best performers in Experiment 1A, 1B and 1C.

In the next experiment, Experiment 2C, in order to test whether there are differences between the temporal dynamics underlying the preparation process for priming and non-priming cues, I employed EEG measures while conducting the task-switching experiment. I studied cue-locked and target stimulus-locked ERPs and related brain topographies.

3.4 Experiment 2C

A number of electrophysiological task-switching studies have measured brain potentials that are time-locked to cue onset and target stimulus onset, providing neural evidence of when preparation occurs and the approximate brain areas that are involved in the preparation process (for reviews see Jamadar et al., 2015; Karayanidis et al., 2010; and Karayanidis & Jamadar, 2014).

Cue-locked ERPs and scalp topographies

Research has identified several cue-locked ERP components related to preparation process but these components vary strongly across paradigms and tasks (Jamadar et al., 2015; Karayanidis et al., 2010; Karayanidis & Jamadar, 2014). However, during the cue-based preparation interval, researchers have consistently reported that there is a larger positive waveform for task-switch trials compared to task-repeat trials that is most evident over central and parietal electrodes, labelled as the *differential switch positivity* or *switch positivity* (e.g., Jamadar et al., 2010a, 2010b; Karayanidis et al., 2009; Li, Wang, Zhao &

Fogelson, 2012; Nicholson et al., 2005, 2006; Steinhauser et al., 2017). The cue-locked centrally switch positivity can emerge as early as about 80 - 150 ms after cue onset and typically peaks around 350-400 ms post cue over centro-parietal sites. In addition, these studies also indicated that within the CSI, the switch positivity is often followed by a centro-parietally maximal negativity that peaks at onset of the target stimulus in short CSI (i.e., 150 ms) and can complete before target stimulus onset in longer CSI (i.e., 600 ms, 1050 ms).

It has been consistently suggested that cue-locked switch positivity reflects a state of preparation, including a general switch preparation and a task-specific preparation (Elchlepp, Lavric, Mizon & Monsell, 2012; Jamadar et al., 2010a, 2010b; Jost, Mayr & Rosler, 2008; Karayanidis et al., 2009; Nicholson et al., 2005, 2006; but see Travers & West, 2008). For example, Nicholson et al. (2006) compared differential waveform for “switch-to” cues with “switch-away” cues within the long preparation intervals of 1000 ms. The switch-to cues indicated an upcoming task, in contrast, the switch-away cues indicated performing a different task in the upcoming trial. Nicholson and colleagues observed that both cue types elicited an earlier cue-locked switch positivity, emerging from about 100 ms post cue at central sites and later stronger at parietal and occipital sites from about 400-450 ms post cue. However, the switch positivity was smaller in amplitude and lasted shorter in switch-away cues centro-parietally over approximately 400-450 ms and 700-750 ms post cue. Nicholson et al. (2006) concluded that the early positivity is associated with a general preparation of a task switch. The later positivity may reflect more specific task preparation, which was only elicited by switch-to cues. Similar results were found by Jamadar et al. (2010a, 2010b) using informatively cues and non-informatively cues.

Elchlepp and colleagues (2010) found no significant difference between switch costs for word cues (i.e., “COLOUR” represents colour task, and “SHAPE” represents

shape task) and for picture cues (i.e., colour task is cued by a collage of the four overlapped colours, shape task is cued by a collage of the four overlapped shapes). Correspondingly, they observed no reliable difference in cue-locked switch positivity between word and colour cues, suggesting no difference in the cue-based preparation between two types of cues. Accordingly, these studies suggest that the amplitude and the duration of the cue-locked switch positivity are related to the process of task preparation, with a larger cue-locked switch positivity being associated with better preparation and smaller RT switch costs.

In addition, there is a cue-locked pre-target negativity that is associated with anticipatory attention and task preparedness. A larger pre-target negativity was found to be associated with faster responding to the upcoming target. In Nicholson et al., (2006), participants showed faster responses in switch-to trials than in switch-away trials. They found that the switch negativity in switch-away trials appeared later (~360 ms) than switch-to trials (~200 ms), and returned to baseline around 700 ms post cue similar to switch-to trials. Switch-to cues that provided valid information about the identity of the upcoming task improved task preparedness and led to faster responses. Similar studies and findings were summarised by Karayanidis and Jamadar (2014).

Therefore, one purpose of conducting Experiment 2C was to study the cue-locked ERP difference waveforms for priming and non-priming cues in different CSIs. Based on the results of Experiment 2A and 2B, I expected large and significant cue-locked switch positivity in priming cues, corresponding to shorter response times and smaller response time switch costs.

Target-locked ERPs and scalp topographies

Although ERP studies of task switching have focused primarily on preparation-related processes occurring during the CSI, ERPs also show robust effects of task switching after target stimulus onset. Target-locked ERP waveforms measure task-switch versus task-repeat differences after target stimulus appears and can test the cognitive control processes necessary to overcome target-driven interference from the irrelevant task set. Researchers have consistently reported that target-locked ERPs were more negative over fronto-central and parietal regions in task-switch than task-repeat trials, indicating a *differential switch negativity* or *switch negativity*. This negativity reflects greater difficulty of task implementation and increased target-driven interference in task-switch trials compared to task-repeat trials, i.e., the task-irrelevant target feature can attract attention especially when the feature was relevant in the previous trial with a different task (e.g., Elchlepp, et al., 2012; Jamadar et al., 2010a, 2010b; Lavric et al., 2008; Li et al., 2012; Nicholson et al., 2005, 2006; for reviews see Jamadar et al., 2015; Karayanidis et al., 2010; and Karayanidis & Jamadar, 2014).

Nicholson et al. (2005) reported that in trials with a CSI of 600 ms, switch negativity emerged as early as 40 ms post target at parietal and occipital sites and peaked around 400 ms post target over central and parietal scalp. The switch negativity was larger for 600-ms than for 1050-ms cue-stimulus intervals. Similar results were reported in Li et al. (2012). Accordingly, with a long and informative preparation interval before target onset, ERP data suggests reduced interference on decision and response selection when target stimulus is presented.

In another study, Nicholson et al. (2006) found that switch-to trials showed an early and prolonged centro-parietally switch negativity from around 200 ms after target onset. In contrast, switch-away trials showed an early switch positivity approximately 150 ms after

target onset, spread across all midline sites. This early positivity in the switch-away trials was quickly replaced with a switch negativity around 360 ms following the target stimulus, spread broadly across the scalp. Nicholson and colleagues (2006) suggested that the post-target differential positivity for switch-away cues reflects the delayed activation of the relevant task-set, since for switch-away cues it is only possible to initiate the task-set reconfiguration after the target stimulus has been presented. However, Elchlepp and colleagues (2012) also studied post-target activity between different types of cues, but they did not find differences between switch negativity for trials with word cues and with picture cues following either short (200 ms) or long CSIs (800 ms) and after either univalent or bivalent stimulus. RT switch costs were not different between two cue types. Both word and picture cues may provide equal amount of valid information about an upcoming task, leading to similar preparation and interference.

Therefore, the second purpose of conducting Experiment 2C was to study the target stimulus-related activity. Based on my previous results on priming and non-priming cues, I predicted that priming cues should elicit small target-locked negativity. This is because priming cues which informed target feature and response mappings should facilitate feature categorisation/discriminability with reduced interference after target stimulus onset.

3.4.1 Experiment 2C Method

Participants

Nineteen students (7 males and 12 females; *mean age* = 24.42 years, *SD* = 2.63) from the University of Glasgow participated in this study and received £15. The sample size was determined by power analysis (power = .85, α = .05, effect size Cohen's f = .30; Faul et al., 2007). I excluded 6 participants because their response accuracy was below

than a preset inclusion criterion of 80 % (~50 trials) for each of the trial conditions in CSI 650 ms, CSI 1100 ms and CSI 1700 ms. I also excluded one other participant due to irreducible scalp impedance ($>30\text{ k}\Omega$ for most electrodes). For the rest of 12 participants, all were right-handed and none of the them had participated in Experiment 2A and 2B. All had normal or corrected-to-normal colour vision.

Task and Apparatus

The colour/shape discrimination task was identical to the task of Experiment 2A and 2B, with the exception that in Experiment 2C the task was programmed in PsychoPy software (Peirce & MacAskill, 2018) and displayed on a 27-inch monitor ($60 \times 34\text{ cm}$). Target responses were made with the left and right index finger by pressing the arrows *left* (red/high) or *right* (green/wide), respectively, on a QWERTY keyboard.

Procedure

All participants were seated comfortably 75 cm away from the monitor during the testing. They were required to focus on the centre of the screen in an acoustically and electrically shielded booth with dim light. Before the testing session, each participant was trained in a session without EEG recording; it consisted of 6 blocks of 24 mixed-task trials, in which both colour and shape tasks were randomly mixed. The testing session consisted of 12 blocks of 64 mixed-task trials in which participants were tested with two blocks for each CSI condition (650 ms, 1100 ms, and 1700 ms) of each cue type (priming cue, non-priming cue). CSI was constant throughout a block and changed randomly between blocks. The order of the cue types was counterbalanced across participants.

Participants were instructed to respond as quickly and accurately as possible when the target stimulus onset. If a response was incorrect or if no response was made, a corresponding feedback appeared for 1 second at the centre of the screen. Following each

block, mean RTs and error rates were displayed on the screen and participants were encouraged to improve their performance.

EEG Recording and Pre-processing

The electroencephalogram (EEG) signals were recorded during the testing session, using a plastic cap (EASYCAP, Falk Minow, Munich, Germany) with 64 electrodes from channels Fp1, Fp2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T7, T8, P7, P8, Fz, Cz, Pz, Oz, AF1, AF2, FC1, FC2, CP1, CP2, PO1, PO2, FC5, FC6, CP5, CP6, F1, F2, C1, C2, P1, P2, AF5, AF6, FC3, FC4, CP3, CP4, PO5, PO6, F5, F6, C5, C6, P5, P6, AF7, AF8, FT7, FT8, TP7, TP8, PO7, PO8, Fpz, FCz, CPz, NFpz as well as an electrode on the left mastoid served as reference and an electrode on the chin served as ground. The EEG was sampled continuously at 1000 Hz and connected to BrainAmp amplifiers (Brain Products, Munich, Germany). The impedances of all electrodes were kept below 20 k Ω .

EEG data pre-processing and data analyses were performed using EEGLAB version 11.0.5 (<http://www.sccn.ucsd.edu/eeglab>) running under MATLAB 2012b (MathWorks, Natick, MA). EEG data were band-pass filtered off-line to 0.5 - 40 Hz and were transformed to average reference, before signals were segmented into event-related epochs of different lengths (cf., Elchlepp et al, 2012; Jost et al., 2008). Cue-locked epochs were extracted from 100 ms before cue onset to the end of the CSI (i.e., 750 ms-long epochs for the CSI 650 ms condition, 1,200 ms-long epochs for the CSI 1,100 ms condition and 1,800 ms-long epochs for the CSI 1,700 ms condition). Stimulus-locked (target-locked) epochs were extracted from 100 ms before target stimulus onset to 700 ms after target onset. The baseline was set to 100 ms before the onset of the task cue and the onset of target stimulus.

As in Elchlepp et al. (2012), cue-locked and stimulus-locked epochs were visually inspected and rejected for muscle, drift and other non-ocular artefacts. As in the

behavioural data pre-processing of Experiment 2A and 2B, the first epoch of every block, epochs associated with an incorrect response, epochs immediately following an incorrect response were excluded. In addition, epochs on which RTs were shorter than 200 ms were also excluded from data analyses. Eye-movement and eye-blink artefacts from the remaining epochs were de-noised using Independent Component Analysis (ICA, Bell & Sejnowski, 1995). After data pre-processing, cue-locked individual ERP waveforms included 317 ± 23 epochs in the priming cues and 314 ± 23 epochs in the non-priming cues. Stimulus-locked individual ERP waveforms included 325 ± 22 epochs in the priming cues and 328 ± 24 epochs in the non-priming cues.

3.4.2 Experiment 2C Results

Behavioural Data

Mean RTs and ERs are presented in Table 3.7. Three-way ANOVAs with repeated measurements was conducted on individual mean RT and ER. Cue type (non-priming, priming), Trial transition (task repeat, task switch) and CSI (650 ms, 1100 ms, and 1700 ms) were varied within subjects, in order to focus on studying the differences between task-switch costs for two cue types across CSIs.

For RTs, there was a significant main effect of Trial transition, $F(1, 11) = 5.16, p = .044, \eta^2_p = .32$. Participants showed slightly faster responses in task-repeat trials (526 ms) than in task-switch trials (537 ms), indicating a switch cost of only +11 ms. However, I did not find statistically significant effect of CSI ($F < 1$) and Cue type ($F = 2.10, p = .175$) in RT. It is worth noting that RT was 517 ms in priming cues and 546 ms in non-priming cues. Participants had a RT of 539 ms in CSI 650 ms condition, a RT of 524 ms in CSI 1100 ms condition, and a RT of 531 ms in CSI 1700 ms conditions. A planned post-

hoc comparison showed that RT was equivalent across CSIs, with $p > .100$. There were no significant interactions in RT. A planned post-hoc comparison showed that the switch costs were marginally significant in non-priming cues (switch - repeat +15 ms, $p = .059$), but not significant in priming cues (+8 ms, $p = .192$).

For ERs, there was a significant main effect of Trial transition, $F(1, 11) = 11.84$, $p = .006$, $\eta^2_p = .52$. Participants made more errors in task-switch trials (6.84%) than in task-repeat trials (5.44%), indicating a switch cost of +1.40%. There was a significant main effect of CSI, $F(2, 22) = 8.61$, $p = .002$, $\eta^2_p = .44$. Participants made more errors in CSI 650 ms condition (7.56%) than in CSI 1100 ms (5.72%) and CSI 1700 ms conditions (5.14%). A post-hoc analysis showed that the difference between CSI 650 ms and CSI 1100 ms was significant, $p = .020$. The difference between CSI 650 ms and CSI 1700 ms was also significant, $p < .001$. There was no significant main effect of Cue type, $F < 1$. The ERs were 6.12% in priming cues and 6.17% in non-priming cues. There were no statistically significant interactions. A planned post-hoc analysis showed that switch costs were not significant for priming (switch - repeat = +1.15%, $p = .280$) and non-priming cues (+1.65%, $p = .310$). The switch costs were not different between cue types, $p = .210$.

Table 3.7

Experiment 2C. Mean RTs (in ms) and error rates (ERs, as %).

Trial transition and CSIs	Priming		Non-priming	
	<i>RT</i>	<i>ER</i>	<i>RT</i>	<i>ER</i>
Repeat				
650	518 (24.28)	7.38 (1.37)	549 (24.33)	7.27 (1.48)
1100	504 (26.62)	4.30 (1.22)	533 (16.83)	4.38 (1.20)
1700	518 (22.54)	4.94 (1.34)	536 (17.07)	4.38 (1.47)
Switch				
650	525 (26.92)	7.82 (1.39)	563 (29.66)	7.76 (1.84)
1100	521 (28.81)	6.30 (1.25)	543 (16.55)	7.93 (1.44)
1700	516 (22.20)	5.93 (1.23)	555 (18.05)	5.29 (.82)
All_Repeat	513 (13.79)	5.54 (.76)	539 (11.11)	5.34 (.81)
All_Switch	521 (14.65)	6.68 (.73)	554 (12.53)	7.00 (.83)

Note. Standard errors are presented in parentheses

Analyses of individual differences in target RTs

As in Experiment 2A and 2B, I conducted GLMMs on RTs in order to investigate individual differences in task switching between two types of task cues. Models listed in Table 3.8 range from a simple GLMM 2C.1 with main fixed effects and random intercept to a complex GLMM 2C.3 with full factorial fixed effects and specific random effects. GLMM 2C.3 was the most parsimonious model giving the lowest AIC and BIC values. The factor “Trial transition”, “Cue type” and “CSI” outside the parentheses denote fixed effects and their interactions. The terms inside the parentheses denote the by-subject random intercept, the by-subject random effect of Cue type, CSI, and of the interaction between Trial transition and Cue type.

Table 3.8

Experiment 2C GLMM comparisons based on target RT data (the best model is in bold; GLMM 2C.3).

<i>Model names</i>	<i>Models (family = Gamma (link = "identity"))</i>	<i>df</i>	<i>AIC</i>	<i>BIC</i>	<i>Log lik</i>	<i>dev</i>	<i>Chi-sq</i>	<i>p-value (>Chisq)</i>
GLMM 2C.1	RT~ Trial.transition + CSI+ Cuetype + (1 subject)	7	101495	101543	-50740	10148 1		
GLMM 2C.2	RT~ Trial.transition*CSI* Cuetype + (1 + Trial.transition + Cuetype subject)	19	101133	101266	-50548	10109 5	385.53	< .001 ***
GLMM 2C.3	RT~ Trial.transition*CSI * Cuetype + (1 + CSI + Cuetype + Cuetype : Trial.transition subject)	34	100759	100996	-50345	10069 1	404.43	< .001 ***

Note. The model formulas are stated in the syntax of the lme4 package in R.

Similar to the results of ANOVA in RTs, the fixed effects of GLMM 2C.3 indicate that responses were significantly faster in task-repeat trials (536 ms) than in task-switch trials (547 ms), $t = 4.20$, $p < .001$. Different from the results of ANOVA, the model indicates that responses were significantly faster in CSI 1100 ms (535 ms) than in CSI 650 ms (551 ms), $t = 3.39$, $p < .001$. Responses were faster in priming cues (528) than in non-priming cues (555 ms), $t = 6.21$, $p < .001$. In addition, switch costs were statistically smaller in priming cues (+6 ms) than in non-priming cues (+16 ms), $t = 2.94$, $p = .003$. The differences between switch costs for priming and non-priming cues were statistically significant in CSI 650 ms (SC priming = +7 ms, SC non-priming = +13 ms; $t = 2.03$, $p = .042$) and CSI 1700 ms (SC priming = -1 ms, SC non-priming = +21 ms; $t = 6.70$, $p < .001$).

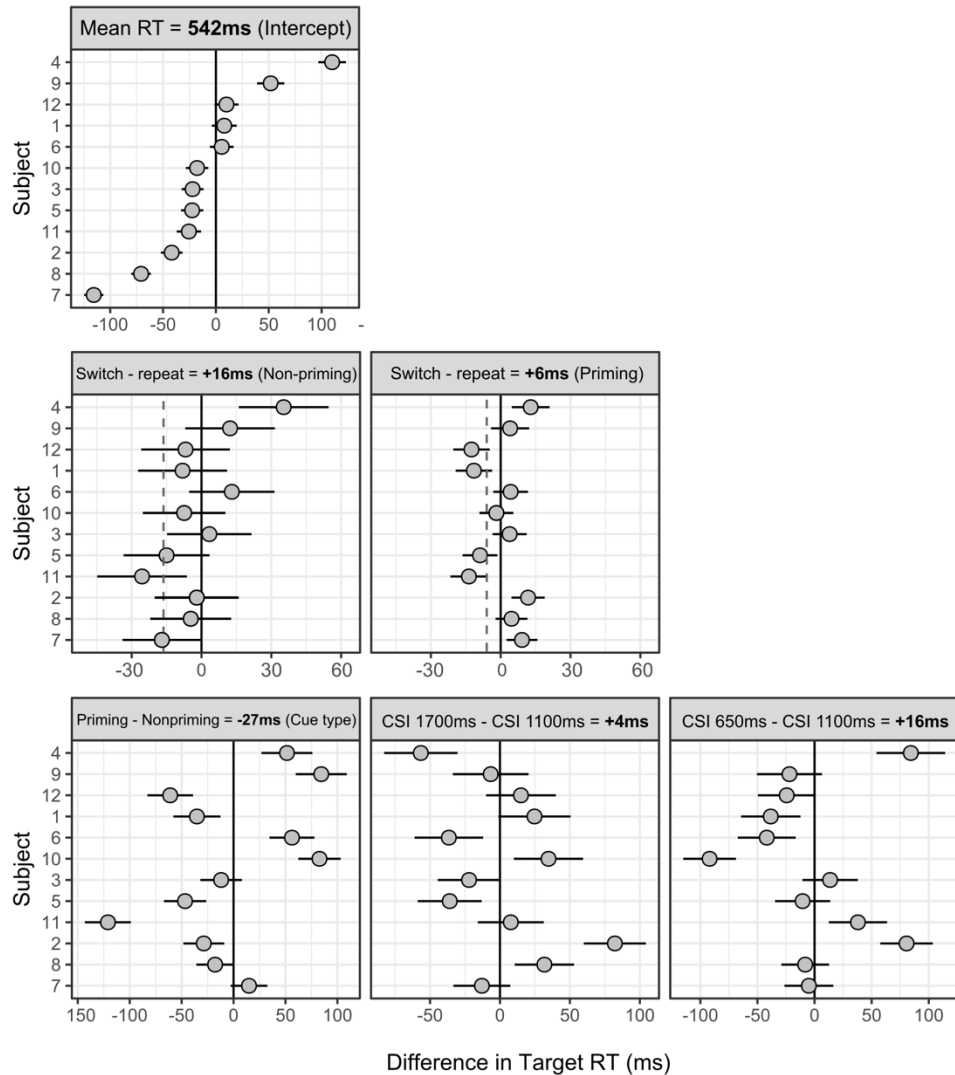


Figure 3.9. Results of Experiment 2C. Illustration of by-subject random effects for target RT. Dotplots in top row illustrate individual deviation (dot) and 95% confidence intervals (horizontal error bar) from mean RT (Intercept = grand mean RT of 542 ms). Dotplots in the left and right of the middle row illustrate individual deviations and 95% confidence intervals from the fixed effect of Trial transition in non-priming cues (mean switch cost = switch - repeat = +16 ms) and in priming cues (mean switch cost = switch - repeat = +6 ms). The dashed vertical lines indicate zero task-switch costs. Dotplots from the left to right panel of the bottom row illustrate individual deviations and 95% confidence intervals from the fixed effect of Cue type (mean difference = priming – non-priming = -27 ms), and from the difference between CSI 1700 ms and CSI 1100 ms (mean difference = 4 ms), and between CSI 650 ms and CSI 1100 ms (mean difference = 16 ms). The solid vertical lines centred on zero in each dotplot denote the group-level RT or fixed effects. Please note the different scales on the x -axes (in ms) in the plots.

Figure 3.9 illustrates that participants varied considerably in their mean RTs (Intercepts) from the overall average, similar to the pattern of individual differences in my previous experiments. Moreover, some participants varied significantly from the mean task-switch costs in priming and non-priming cues. However, Participant 3, 6, 8, 9, 10 did not deviate significantly from the mean switch costs in both types of cues. Participant 1, 5, 10, 11, 12 did not deviate significantly from the zero switch costs in both cue types. Comparing switch costs in priming cues with switch costs in non-priming cues I found that participants with priming cues showed narrower confidence intervals representing more precise estimation in individual RTs. The individual differences in non-priming cues was positively related to the differences in priming cues (Pearson's $r = .76$).

Figure 3.9 also shows that the individual differences in RT difference between cue types showed a random pattern. Only three participants (i.e., Participant 3, 7, 8) showed no RT difference between two types of cues. Similarly, the individual differences in RT between CSIs also showed a random pattern, with participants varying considerably between CSI conditions.

ERP Data

Individual-averaged ERPs for task-repeat and task-switch trials were obtained in priming and non-priming cues at each of the three CSI conditions (650 ms, 1,100 ms and 1,700 ms). Therefore, there were 12 cue-locked and 12 stimulus-locked ERP average waveforms for each participant at each of the 64-electrode site. All averages were based on a minimum of 40 trials (*Maximum* = 64 trials, *Mean* = 53 trials).

Cue-locked (Figure 3.10A) and stimulus-locked (Figure 3.11A) waveforms for switch and repeat trials are depicted at four midline sites across cue types (priming, non-priming cues) for each of the 3 CSI conditions (650 ms, 1100 ms, 1700 ms). Figure 3.10B and Figure 3.11B illustrate cue- and stimulus-locked difference waveforms at electrode Pz, at which the largest difference between switch and repeat trials was reported in the previous studies (Jost et al., 2008; Nicholson et al., 2005, 2006; Steinhauser et al., 2017; for a review see Karayanidis & Jamadar, 2014). As in these studies, difference waveforms in each CSI condition were derived by subtracting the average ERP waveforms for task-repeat trials from the average ERP waveforms for task-switch trials. I conducted point-by-point *t*-tests to establish time points of significant difference between switch and repeat trials at electrode Pz. Only significant differences at the significance level of .01 were summarised in Table 3.9 and highlighted in Figure 3.10B and Figure 3.11B. In addition, cue-locked scalp topographies of mean amplitude (400-600 ms time window) for each condition and the related significant difference sites ($\alpha = .01$) across all 12 participants are displayed in the left panel of Figure 3.12. Stimulus-locked scalp topographies of mean amplitude (500-700 ms time window) for CSI 1100 ms condition and the related significant difference sites ($\alpha = .01$) across all participants are displayed in the right panel of Figure 3.12.

Cue-locked ERPs

Figure 3.10 shows that cue-locked ERP waveforms were similar between two types of cues in different CSI conditions. For both priming and non-priming cues, parietal site showed that there was a switch-related positivity that emerged approximately 200 ms in CSI 650 ms and approximately 400 ms in CSI 1,000 ms and 1,700 ms after cue onset. The switch positivity peaked around 500-550 ms post cue for all CSI conditions (Figure

3.10B), and returned to the baseline around 700 ms for priming cues in the longer CSI conditions (1,100 ms, 1,700 ms) while for non-priming cues around 700 ms in CSI 1,100 ms and around 900 ms in CSI 1,700 ms, suggesting different efficiency in task preparation between two types of cues. Participants were more efficient in priming cues in CSI 1700 ms. Compared with long-CSI conditions, in trials with a short CSI (650 ms) switch positivity did not return to the baseline level before stimulus onset, for both priming and non-priming cues.

The results of point-by-point analysis of parietally cue-locked difference waveforms are summarised in Table 3.9. Both types of cues elicited a similar pattern of switch positivity in CSI 650 ms and 1700 ms. However, when in trials with CSI 1100 ms, switch positivity was only significant in priming cues (482-537 ms), followed by a significant switch-related pre-stimulus negativity (921-941 ms). Correspondingly, scalp topographies in a time window of 400-600 ms after cue onset show that the switch-repeat contrast was most significant over central-parietal electrode sites in priming and non-priming cues (the left panel of Figure 3.12).

Stimulus-locked ERPs

Figure 3.11A shows that priming and non-priming cues were similar in switch and repeat stimulus-locked ERPs in different CSIs at electrode Fz, Cz and Oz. In contrast, Figure 3.11B depicts stimulus-locked difference waveforms for the three CSI conditions at Pz where the effects were maximal. It was found that in CSI 650 ms and CSI 1700 ms, the stimulus elicited a switch negativity (non-significant) in both priming and non-priming cues. In CSI 1100 ms, Table 3.9 and Figure 3.11B demonstrate that the stimulus in priming-cue condition elicited a significant switch positivity, started from approximately 500 ms and spread to approximately 700 ms post stimulus. The stimulus in non-priming

cue condition elicited a short-lasting switch positivity around 569 ms post stimulus. Correspondingly, scalp topographies in a time window from 500 to 700 ms after target stimulus onset show that switch versus repeat contrast was most significant in the parietal region for non-priming cues and in the frontal and parietal sites for priming cues (the right panel of Figure 3.12).

Table 3.9

Results of point-by-point analysis of cue- and stimulus-locked difference waveforms at Pz (switch minus repeat waveforms)

	cue-locked			Stimulus-locked		
	650 ms	1100 ms	1700 ms	650 ms	1100 ms	1700 ms
Priming	533-543	482-537	524-543		504-515	
	578-590	921-941	617-646		538-553	
	593-608				563-582 627-693	
Non-Priming	465-479		513-521		569-571	
	496-530		536-595			
	557-559					
	604-611					

Note. The numbers in the table represent regions (in *ms*) where the switch waveform was significantly different from the repeat waveform, at the significance level of .01.

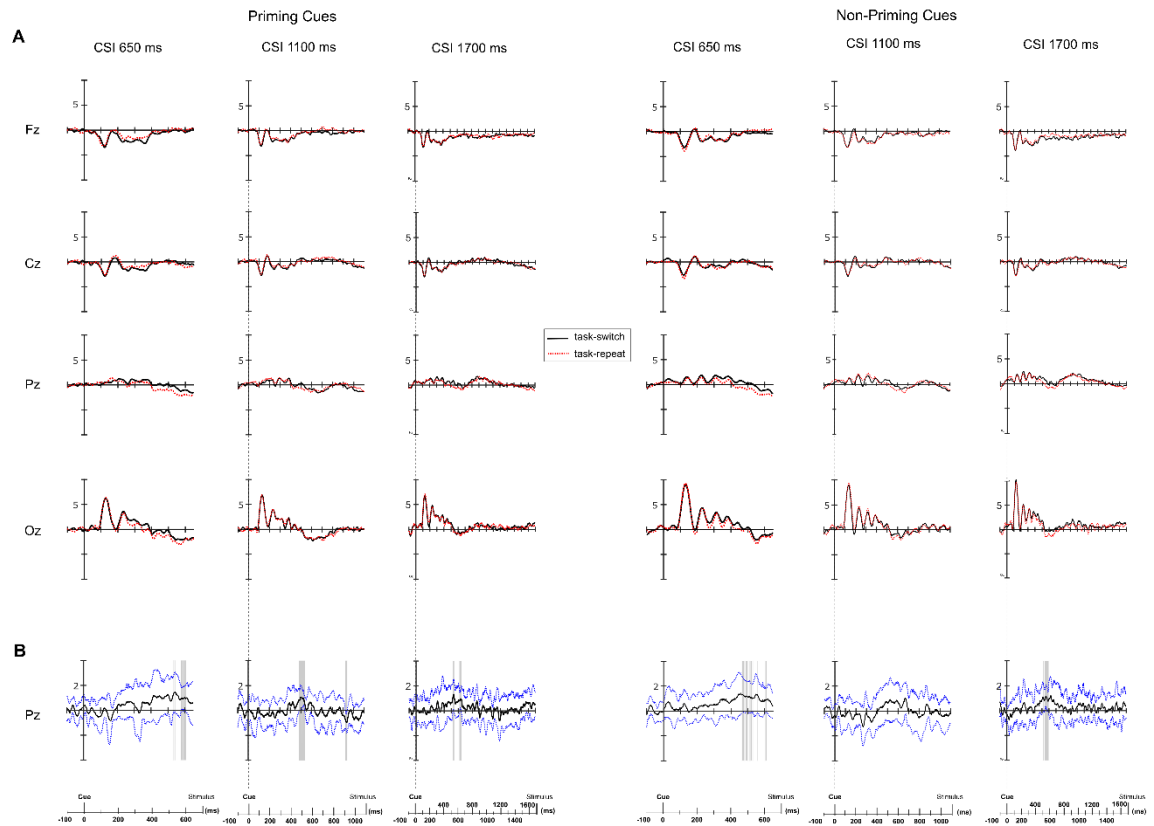


Figure 3.10. A: Cue-locked ERP waveforms for switch and repeat trials at four midline sites (Fz, Cz, Pz, and Oz) for each condition. **B:** Cue-locked switch-repeat difference waveforms (black solid lines) and standard deviations (blue dotted lines) and time point with significant differences (grey bar) at electrode Pz for each condition. The x -axis indicates the timeline (in ms) of each trial. The ticks on the x -axis reflect 100- ms increments, consistently for all CSIs. The y -axis indicates ERP potentials (μV), with differing scales for panel A and for panel B. The ticks on the y -axis reflect 5 μV increments in panel A and 2 μV in panel B. The origin of the x - and y -coordinates indicates cue onset in both panels.

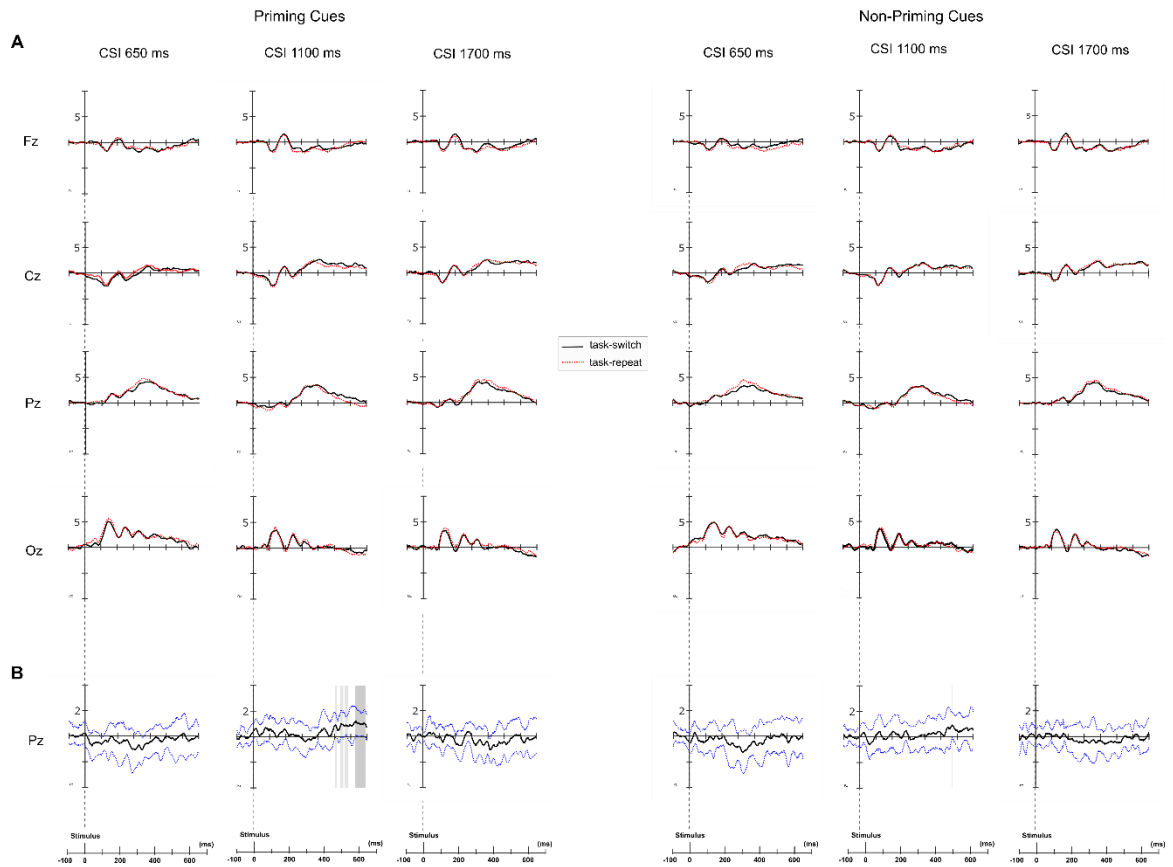


Figure 3.11. A: Stimulus-locked ERP waveforms for switch and repeat trials at four midline sites (Fz, Cz, Pz, and Oz) for each condition. **B:** Stimulus-locked switch-repeat difference waveforms (black solid lines) and standard deviations (blue dotted lines) and time point with significant differences (grey bar) at electrode Pz for each condition. The x -axis indicates the timeline (in ms) of a trial. The ticks on the x -axis reflect 100- ms increments, consistently for all CSIs. The y -axis indicates ERP potentials (μV), with differing scales for panel A and panel B. The ticks on the y -axis reflect 5 μV increments in panel A and 2 μV in panel B. The origin of the x - and y -coordinates indicates target-stimulus onset in both panels.

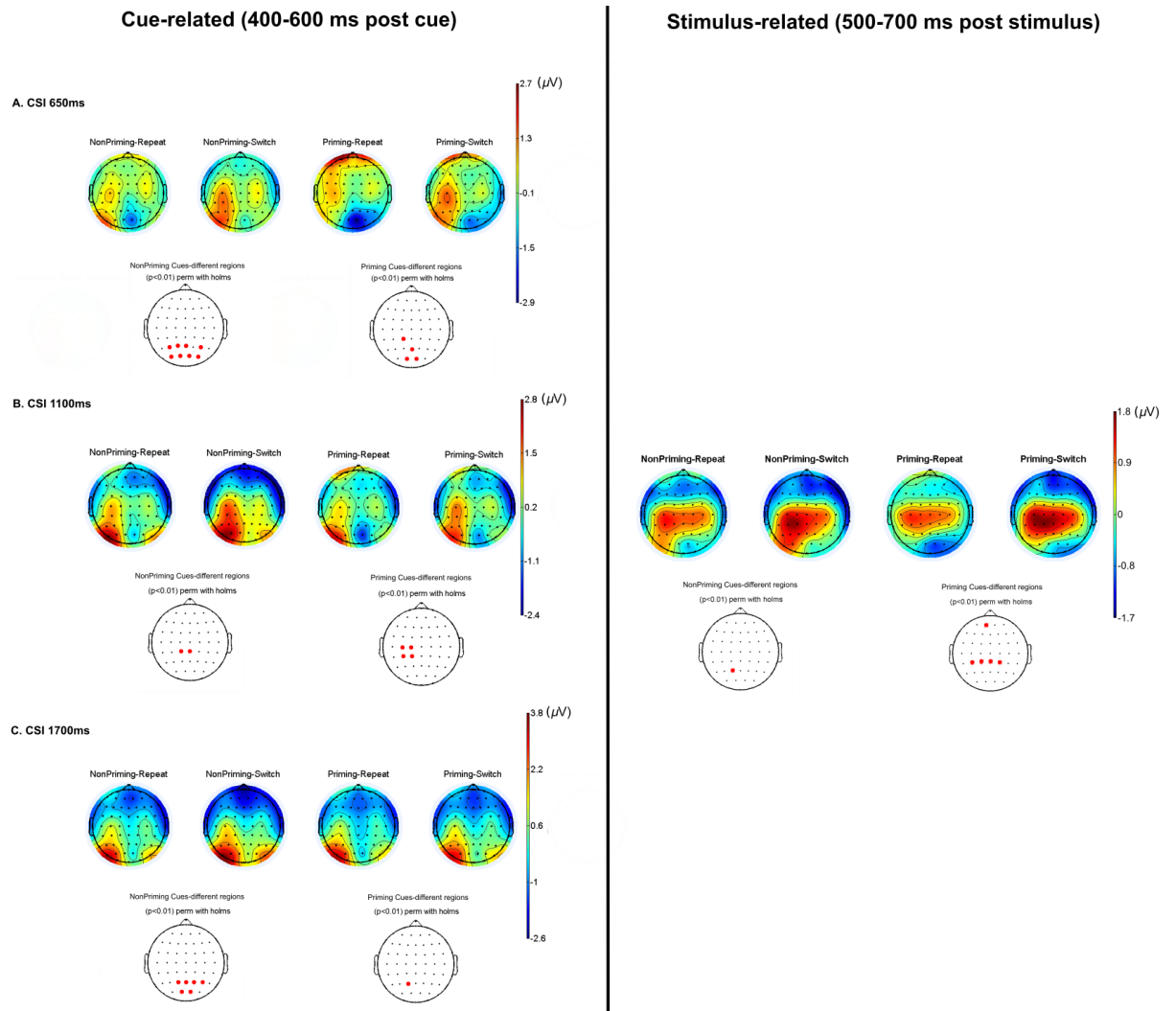


Figure 3.12. Cue-locked scalp topographies (μV ; left) and electrode sites of significant contrast ($\alpha = .01$; red dots) between switch and repeat trials in different CSIs (650 ms, 1100 ms, 1700 ms) averaged over a time window of 400–600 ms after cue onset. Stimulus-locked scalp topographies (μV ; right) and electrode sites of significant contrast (at $\alpha = .01$; red dots) between switch and repeat trials in CSI 1100 ms averaged over a time window of 500–700 ms after target stimulus onset. Please note different colour scales from different CSI conditions and different time windows.

3.4.3 Experiment 2C Discussion

The behavioural data of the present experiment showed that although switch costs were relatively small for both types of cues, RT switch costs were reduced further by nearly a half for priming cues than for non-priming cues, collapsing across different CSIs. This is consistent with the results of Experiment 2A and 2B where participants showed on average smaller switch costs in trials with priming cues than non-priming cues. However, inconsistent with previous experiments, the participants in the present experiment showed much smaller switch costs for both types of cues, suggesting that participants might have been highly engaged in task preparation independent of the type of task cues.

Cue-locked ERPs and topographical maps

At electrode Pz, I found cue-locked ERP positivities that were larger for switch trials compared to repeat trials, consistent with previous ERP studies on task switching (e.g., Jamadar et al., 2015; Karayanidis & Jamadar, 2014). The differential switch positivity was significant for priming cues in each CSI condition. In contrast, in CSI 1100 ms non-priming cues did not elicit a significant switch positivity. Previous studies reported that cue-locked switch positivity indicates advance preparation associated with small RT switch costs (e.g., Jamadar et al., 2015; Karayanidis & Jamadar, 2014). Participants with priming cues showed efficient preparation independent of CSIs. In addition, priming cues elicited a significantly stronger pre-stimulus negativity for switch trials than repeat trials in CSI 1100 ms, suggesting high task preparedness (e.g., Jamadar et al., 2015; Karayanidis & Jamadar, 2014). These ERP results corresponds to their behaviour data showing that switch costs were on average relatively smaller in priming cues (+8 ms, +1.15%) than in non-priming cues (+15 ms, +1.65%).

Scalp topographies suggested that by averaging over 400-600 ms after cue onset there was a significant difference between task-repeat and task-switch trials over central-

parietal sites for each cue type in each CSI condition, consistent with previous results that switch-repeat contrast was most significant at central-parietal electrodes around 400 ms after cue onset (Jamadar et al., 2010a, 2010b; Jost et al., 2008; Karayanidis et al., 2009; Nicholson et al., 2005, 2006; for reviews see Jamadar et al., 2015; Karayanidis & Jamadar, 2014). Studies have suggested that central and parietal regions are associated with switch-specific preparation such as task-set updating.

Stimulus-locked ERPs and topographical maps

Inconsistent with previous ERP studies on task-switching that a greater stimulus-locked negativity for switch compared to repeat trials over central-parietal sites (Jamadar et al., 2010a, 2010b; Jost et al., 2008; Karayanidis et al., 2009; Nicholson et al., 2005, 2006), at electrode Pz I found a non-significant differential switch negativity in stimulus-locked ERPs for either cue type in any CSI condition. Previous studies suggested that switch-induced negativity is related to attentional conflicts from task-irrelevant target dimension and response conflicts. However, studies also suggested that the differential negativity was smaller when following a univalent stimulus compared to bivalent stimulus, because univalent stimulus contains perceptual attributes associated with responses in only one of the tasks and therefore should lead to reduced conflicts from the competing task-set (Elchlepp et al., 2012). Based on previous results, the non-significant stimulus-locked negativity may imply that participants had small level of interference from irrelevant target feature and irrelevant response set in each trial. The post-stimulus EEG data supports the behavioural results showing on average a rather small RT switch costs in the present experiment.

Interestingly, the present EEG data showed that in trials with both CSI 1100 ms and priming cues there was a significant differential positivity at parietal site between 500-700 ms after target stimulus onset. Similarly, in trials of CSI 1100 ms and with non-priming

cues there was a transient parietally switch positivity emerging around 569 ms after the target stimulus was presented. These results are not predicted. However, according to a recent study by Barceló and Cooper (2018), the fronto-parietal ERP positivity that is elicited by the target stimulus is associated with cognitive control of task switching. In this case, the cognitive control process may have lasted longer in trials with priming cues, suggesting that participants with priming cues could also have facilitated goal-directed attention and information processing.

3.5 General Discussion

In this chapter, I studied the effect of cue type on task switching. By manipulating two types of cues between- and within-subjects in Experiment 2A and 2B, respectively, I found that priming cues reduced RT switch costs but not ER switch costs. Participants with priming cues showed smaller and non-significant switch cost across CSIs. Participants also showed smaller deviations in task-switching performance in the priming cues. This finding is consistent with studies reporting smaller switch costs with transparent cues than with non-transparent cues (e.g., Arbuthnott & Woodward, 2002; Logan & Schneider, 2006; Mayr & Kliegl, 2000; Miyake et al., 2004; Schneider, 2016), although in all of these studies residual switch costs were significant even with transparent cues. Arbuthnott and Woodward (2002) suggested that associations between transparent task cues and task goals were stronger than associations between non-transparent task cues and task goals (see also Miyake et al., 2004). It is possible that the priming cues associated stronger with the task goals, therefore, participants activated the relevant task set more quickly compared to the non-priming cues. In addition, according to the mediated retrieval hypothesis in other studies (Mayr & Kliegl, 2000; Logan & Schneider, 2006), priming cues directly linked to the task goal, in contrast, participants with non-priming cues may need an additional step of

translating the task cue to a “task-name mediator” (i.e., link circle to the colour task and link hexagon to the shape task) before retrieving specific task goals. Since the priming cues also provided target features and response mappings, in this condition participants showed facilitated task preparation.

In order to study the differences in preparation between two types of cues, I measured cue-locked and stimulus-locked ERPs in Experiment 2C. Surprisingly, the behaviour results showed that participants had on average small switch costs of only +11 ms, which was even much smaller in priming (+8 ms) than in non-priming cues (+15 ms). Five participants did not show switch costs in either cue type. Consistent with previous ERP results on task switching, cue-locked ERP positivity was larger for switch trials compared to repeat trials at the parietal electrode (e.g., Jamadar et al., 2015). The differential switch positivity was significant for priming cues in each of the CSI conditions, but was not significant in non-priming cues with CSI 1100 ms. As suggested by previous studies (Jamadar et al., 2010a, 2010b; Jost et al., 2008; Karayanidis et al., 2009; Nicholson et al., 2005, 2006), the large and significant cue-locked switch positivity may indicate efficient preparation associated with small RT switch costs in priming cues, independent of CSIs. In addition, priming cues elicited a pre-stimulus negativity that was larger for switch trials in CSI 1100 ms, suggesting high level of anticipatory attention and task preparedness before target stimulus onset (Jamadar et al., 2010a, 2010b; Jost et al., 2008; Karayanidis et al., 2009; Nicholson et al., 2005, 2006).

Stimulus-locked ERP activity was different between priming and non-priming cues. At electrode Pz, priming cues elicited a significant and long-lasting switch positivity after target stimulus onset in CSI 1100 ms, which may be associated with facilitated cognitive control during target processing (e.g., Barceló & Cooper, 2018). In both types of cues participants showed non-significant post-target switch negativity, which may be associated with reduced conflicts. This is inconsistent with previous studies indicating that proactive

control can reduce but not eliminate post-target interference for switch trials (e.g., Jost et al., 2008; Nicholson et al., 2005, 2006). One explanation could be that the participants in Experiment 2C may have consistently engaged in cue-based preparation despite cue types. Consequently, they were less affected by the interference arising from carryover activation/inhibition of task sets and/or triggered by conflicting target-response mappings after target stimulus onset. In addition, as suggested by Elchlepp et al. (2012), stimulus-locked differential negativity at central-posterior sites was larger for bivalent stimuli than for univalent stimuli, because no conflicts from the competing task sets associated with a univalent stimulus. It is possible that participants might have maintained high level of attention across trials, they fast attending to the relevant feature as soon as target onset. Thus, they were less affected by the competing task dimension with less conflicts during response selection, similar to the processing of a univalent target (e.g., Elchlepp et al., 2012; Mueller et al., 2007). Priming cues informed about the relevant task feature and task-response mappings, which should have helped participants to less attend to the wrong task category in the upcoming trial. However, it is lack of evidence why there was no sign of post-target conflicts in trials with non-priming cues, even in trials with short preparation interval (i.e., CSI 650 ms).

In sum, participants with priming cues on average showed faster responses and smaller RT switch costs. In addition, the GLMM results in three experiments consistently showed that participants with priming cues deviated smaller than with non-priming cues from the mean conditional task-switch costs. However, similar to previous studies on cue types (e.g., Logan & Schneider, 2006; Schneider, 2016), some participants showed significant task-switch costs in both cue types, although their switch costs were relatively smaller in priming cues. ERP analyses showed that trials with priming cues were associated significant cue-locked switch positivity, independent of cue-stimulus interval. There was no target stimulus-locked switch negativity for both types of cues. Participants

also varied considerably in ERP amplitudes, suggesting large individual variability in cue-locked and stimulus-locked processing and the related cognitive control process. These results may point to the importance of studying individual differences in task switching with different types of cues.

CHAPTER 4 Gender Differences in Task Switching

4.1 Experiment 3 Introduction

In this chapter, I studied gender differences in order to understand individual differences in task switching. Currently, there are only a few studies on gender differences and task-switching abilities, showing inconsistent results. Some studies have reported that males outperformed females in task switching (Beeri et al., 2006; Tun & Lachman, 2008). For example, Tun and Lachman (2008) asked 4,428 participants, aged between 32 and 85 years, to perform in a cued Stop and Go task-switching paradigm via telephone. Participants were told to say *stop* when hearing *Red* and say *go* when hearing *Green* in one task (congruent response condition), and say *go* when *Red* and say *stop* when *Green* in another task (incongruent response condition). In a mixed-task block of 29 trials, participants switched between task rules based on the given cue. Tun and Lachman (2008) found that male participants were faster than female participants in the middle-age and older groups. Females showed larger congruency effect and switch costs than males.

However, some studies found the opposite pattern, reporting that females were superior than males in switching abilities and interference control (Friedman et al., 2016; Stoet et al., 2013; Van der Elst, Van Boxtel, Van Breukelen, & Jolles, 2006; Weiss et al., 2006). For example, Stoet and colleagues (2013) studied 240 participants in a shape/filling task-switching paradigm. They found that females outperformed males in blocks with randomly intermixed tasks, while both gender groups did not differ in the single-task blocks. They suggested that females had an advantage when performing tasks in a more complex situation.

There are other studies that did not find gender differences in task-switching activities (Christakou et al., 2009; Munro et al., 2012; Polunina et al., 2018; Reimers & Maylor, 2005). Reimers and Maylor (2005) reported advantages of female participants in

task switching until age 30, but they also reported that the difference disappeared and even reversed through adulthood. Recently, in a large study on about 31,000 participants from 13 European countries conducted by the Rockefeller University it was suggested that with improved living conditions and educational opportunities, there was a tendency for increased gender differences, favouring females in general cognitive functions including memory retrieval (Weber, Skirbekk, Freund & Herlitz, 2014). However, Weber and colleagues (2014) suggested reduced gender differences in numeracy, and no gender differences in category fluency. More recently, a study by Polunina et al. (2018), using a sample of 258 participants, indicated no gender differences in at least two important cognitive functions, such as interference control and cognitive flexibility.

Previous studies employed different experimental paradigms and manipulations, showing varying results creating a controversy whether females or males were better in task switching abilities. The main aim of Experiment 3 was to study 40 males and 40 females in a critically manipulated task-switching paradigm. I was particularly interested whether the effect of gender on task switching performance is modulated by different preparation intervals. In order to test this, in Experiment 3 the cue-stimulus interval (CSI) was either short (CSI = 100 ms) or long (CSI = 900 ms), leading to short and long cue-based preparation, respectively. According to previous research that has identified gender differences in task switching (Beeri et al., 2006; Reimers & Maylor, 2005; Stoet et al., 2013; Tun & Lachman, 2008; Van der Elst et al., 2006; Weber et al., 2014; Weiss et al., 2006), I expected that male and female participants would show differences in the effect of preparation interval (CSI) on task switching. This would inform which gender group is more efficient in task switching and task preparation, and refine the previous results. However, a more recent study found no detectable gender differences in many cognitive abilities (Polunina et al., 2018). Therefore, according to their results both genders may

have similar switching performance, showing similar task-switch costs and congruency effects independence of CSI.

In addition, previous studies employed large sample sizes but researchers typically tested only mean performances across ages, neglecting individual variability (e.g., Polunina et al., 2018; Weber et al., 2014). The present experiment explored whether there are gender differences during the preparation phase of a colour/shape task-switching paradigm. I documented both group average and individual response time performance using a sample of young participants. I plotted Individual-specific intercepts and random effects based on GLMM model estimations. It is possible that the previously observed gender advantage could be due simply to the superior switching performance of a few individuals, while their superior performance may be hidden in a group-averaged performance analysis.

4.2 Experiment 3 Method

I planned to test task-switching effects and congruency effects in two groups (male, female) in an ANOVA with repeated measurements as within-between interactions. A statistical power analysis (Faul et al., 2007) indicated an optimal sample size of $N = 54$ for a medium effect size $f = 0.25$, $\alpha = 0.05$, and power = 0.95 with 27 participants in each group.

Participants

A total of 80 participants, 40 males ($Mean = 22.10$ year, $SD = 3.12$) and 40 females ($Mean = 21.63$; $SD = 3.53$), from the University of Glasgow took part in the current experiment and received £6 each for participation. All participants reported normal or correct-to-normal vision and were naive about the purposes of the experiment. None of

them had previously participated in a task-switching experiments. I excluded 7 participants (4 males, 3 females) because their overall accuracy in either CSI 100 ms or CSI 900 ms was below a preset inclusion criterion of 80% correct responses. For the remaining 73 participants, there were 36 males (*Mean* = 22.06 years, *SD* = 3.18) and 37 females (*Mean* = 21.58 years, *SD* = 3.48). A two-sample *t*-test showed no significant age differences between groups, $t(70.71) = .63, p = .534$.

Tasks, stimuli and apparatus

The apparatus for stimulus presentation and response keys were identical to Experiment 1 and 2. The only difference was that in the present experiment I employed a colour/shape task with letter cues displayed in yellow (RGB = 255, 255, 0). The colour and the shape task were cued by the letter “C” and “S” (1 cm × 1 cm), respectively.

Procedure

Each trial began with the display of a task cue. Each task cue was presented for a CSI of either 100 ms or 900 ms, before it was replaced by a target stimulus. Participants had up to 2 seconds to respond. The response-stimulus interval was constant at 1,000 ms, to control for possible interference from the previous trial (Altmann, 2006; Meiran, 1996). Therefore, after a correct response, there was an ITI of 1,000 ms minus the CSI, resulting in a condition of CSI 900 ms and ITI 100 ms (900-100) and a condition of CSI 100 ms and ITI 900 ms (100-900). Incorrect responses or no responses within 2 seconds will be followed by an error message which stayed on for 3 seconds.

Participants completed a block of 24 trials with randomly mixed tasks in each of the two CSI conditions before the actual experiment. In the actual experiment, participants completed two blocks of 96 trials with randomly mixed tasks in the 900-100 condition and another two blocks of 96 mixed trials in the 100-900 condition. The presentation of these

blocks was counterbalanced across participants. Participants took breaks between each block of trials.

4.3 Experiment 3 Results

Training trials, the first trial of each block and trials immediately following an error were excluded from all analyses. Error trials were also excluded from the RT analysis. After exclusion, I first conducted task-switching analyses on mean RTs and ERs using conventional ANOVAs. Then, I conducted GLMMs to investigate the gender-related individual differences in RT performance. For all data analyses, I used statistical software package R, version 3.4.2 (R Core Team, 2017).

Task-switching analyses and gender differences

Mean RTs and error rates (ERs) are summarised in Table 4.1. Five-way ANOVAs with mixed effects were conducted on averaged individual RTs and ERs. Gender (males, females) was a between-subject factor whereas Task (colour, shape), Trial transition (task-repeat, task-switch), Congruency (congruent, incongruent) and CSI (900 ms, 100 ms) were within-subject factors.

Table 4.1

Experiment 3. Mean RTs (in ms) and error rates (ER as %) for all conditions in males and females

Paradigms	Trial transition and Congruency	Males (<i>N</i> = 36)		Females (<i>N</i> = 37)	
		<i>RT</i>	<i>ER</i>	<i>RT</i>	<i>ER</i>
CSI = 100 ms					
Colour	RepCon	642 (20.06)	2.71 (.63)	609 (22.90)	1.61 (.39)
	RepInc	713 (22.01)	7.49 (1.12)	640 (23.31)	5.41 (.77)
	SwiCon	731 (23.87)	3.99 (.74)	706 (30.24)	2.36 (.78)
	SwiInc	776 (17.94)	14.17 (1.47)	768 (26.64)	14.82 (1.64)
Shape	RepCon	675 (21.87)	3.50 (.61)	649 (21.95)	1.66 (.43)
	RepInc	728 (21.40)	6.40 (1.12)	676 (20.93)	6.69 (1.01)
	SwiCon	790 (25.98)	3.85 (.91)	735 (26.34)	4.60 (.80)
	SwiInc	858 (24.06)	12.66 (1.52)	811 (25.73)	12.08 (1.93)
	Repeat	689 (10.93)	5.03 (.48)	642 (11.21)	3.84 (.39)
	Switch	789 (12.07)	8.67 (.72)	755 (13.89)	8.46 (.81)
	Congruent	709 (12.34)	3.51 (.36)	675 (13.28)	2.56 (.33)
	Incongruent	769 (11.62)	10.18 (.71)	722 (13.33)	9.75 (.77)
CSI = 900 ms					
Colour	RepCon	491 (18.49)	1.82 (.44)	497 (21.81)	2.13 (.62)
	RepInc	531 (20.53)	5.71 (1.10)	514 (22.57)	3.93 (.61)
	SwiCon	558 (24.22)	3.51 (.70)	528 (21.10)	2.25 (.53)
	SwiInc	603 (24.62)	9.80 (1.38)	568 (25.86)	9.16 (1.54)
Shape	RepCon	551 (17.88)	3.72 (.72)	554 (22.53)	2.80 (.81)
	RepInc	578 (22.37)	6.04 (.89)	570 (24.96)	3.93 (.82)
	SwiCon	603 (25.87)	4.93 (.86)	589 (23.16)	2.62 (.63)
	SwiInc	622 (24.11)	9.62 (1.42)	606 (28.27)	5.94 (1.43)
	Repeat	538 (10.19)	4.32 (.43)	534 (11.64)	3.20 (.36)
	Switch	596 (12.38)	6.96 (.61)	573 (12.48)	4.99 (.60)
	Congruent	551 (11.33)	3.49 (.36)	542 (11.31)	2.45 (.32)
	Incongruent	583 (11.71)	7.79 (.62)	564 (12.91)	5.74 (.61)

Note. Standard errors are presented in parentheses

RepCon = Repeat Congruent; RepInc = Repeat Incongruent; SwiCon = Switch Congruent;

SwiInc = Switch Incongruent

Main effects in RTs

For mean RTs, there were four significant main effects. There was a significant main effect of Task, $F(1, 71) = 75.57, p < .001, \eta^2_p = .52$. Participants responded more slowly in the shape task (662 ms) compared to the colour task (617 ms). There was a significant main effect of Trial transition, $F(1, 71) = 198.41, p < .001, \eta^2_p = .74$. On average task-switch trials (678 ms) were 77 ms slower compared to task-repeat trials (601 ms), indicating a significant switch cost of +77 ms. There was a significant main effect of Congruency, $F(1, 71) = 107.72, p < .001, \eta^2_p = .60$. On average incongruent trials (660 ms) were 41 ms slower compared to congruent trials (619 ms), showing a significant congruency effect of +41 ms. In addition, there was a significant main effect of CSI, $F(1, 71) = 240.65, p < .001, \eta^2_p = .77$. The responses were 158 ms slower for CSI 100 ms (718 ms) than for CSI 900 ms (560 ms). However, males and females did not significantly differ in their mean response times, $F < 1$. Females' average response time was 626 ms and males' average response time was 653 ms.

Two-way interactions in RTs

Trial transition significantly interacted with CSI, $F(1, 71) = 57.59, p < .001, \eta^2_p = .45$. Switch costs were significant in both CSI 100 ms (switch – repeat = +106 ms, $p < .001$) and CSI 900 ms (+49 ms, $p < .001$). A post-hoc comparison adjusted after Holm (1979) showed that switch costs were significantly smaller for CSI 900 ms than for CSI 100 ms, $p < .001$.

Congruency significantly interacted with CSI, $F(1, 71) = 14.23, p < .001, \eta^2_p = .17$. Congruency effects were significant for both CSI 100 ms (incongruent - congruent = +53 ms, $p < .001$) and CSI 900 ms (incongruent - congruent = +27 ms, $p < .001$). A post-

hoc comparison showed that congruency effects were significantly smaller in CSI 900 ms than in CSI 100 ms, $p < .001$.

I performed three planned pair comparisons between males and females in order to study whether there were gender differences in switch costs, congruency effects and between CSIs. The results showed that switch costs were significant in both male (switch - repeat = +79 ms, $p < .001$) and female participants (+76 ms, $p < .001$). Switch costs were equivalent for both genders, $p = .784$. Congruency effects were marginally significant in females (incongruent - congruent = +35 ms, $p = .046$), and significant in males (+46 ms, $p = .005$). Congruency effects were equivalent for both gender groups, $p = .164$. Females (698 ms) were significantly faster than males (739 ms) in CSI 100 ms, $p = .002$. However, there was no difference between females (553 ms) and males (567 ms) in CSI 900 ms, $p = .267$.

Three-way interactions in RTs

There was a significant three-way interaction between Gender, Trial transition and CSI, $F(1, 71) = 4.98$, $p = .029$, $\eta^2_p = .07$. Post-hoc analyses showed that the switch costs in CSI 900 ms were statistically significant for male participants (switch - repeat = +59 ms, $p = .004$) but not for female participants (+39 ms, $p = .097$). Both male (+99 ms, $p < .001$) and female participants (+113 ms, $p < .001$) showed significant and equivalent switch costs in CSI 100 ms (Figure 4.1A).

Gender significantly interacted with Trial transition and Congruency, $F(1, 71) = 5.58$, $p = .021$, $\eta^2_p = .07$. As shown in Figure 4.1B, Female participants had non-significant congruency effects (incongruent - congruent = +21 ms, $p = .264$) in task-repeat trials, while male participants had significant congruency effects (+48 ms, $p = .013$). Both groups

showed significant and equivalent congruency effects in task-switching trials: Females had a congruency effect of +49 ms ($p = .011$) and males had a congruency effect of +44 ms ($p = .022$). No other effects reached statistical significance.

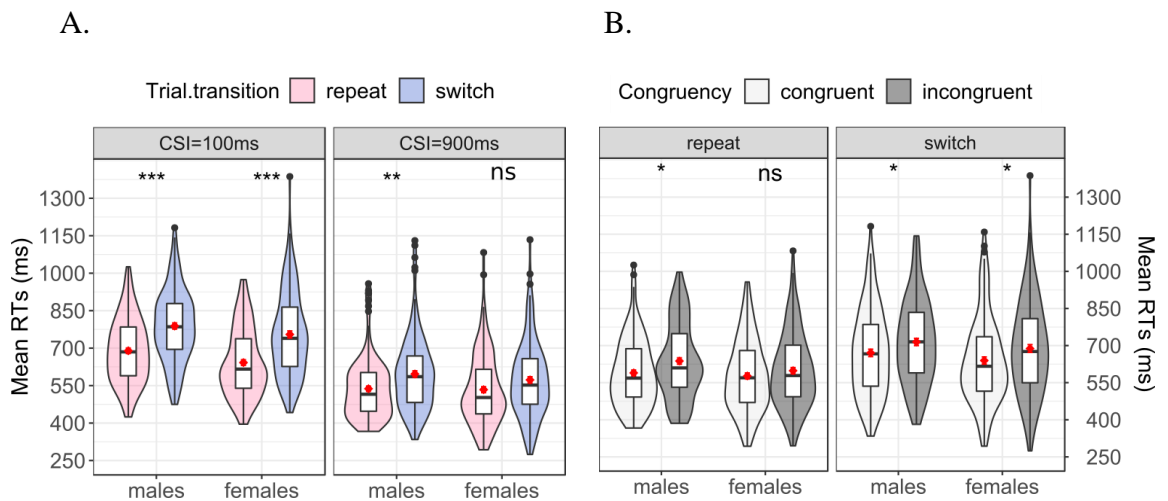


Figure 4.1. Results of Experiment 3. Mean RTs (in *ms*) of male and female participants in different trial conditions. A. The violin plots illustrate the RT distributions in repeat and switch conditions in male and female participants across CSIs (CSI 100 ms, 900 ms). B. The violin plots illustrate the RT distributions in congruent and incongruent conditions in male and female participants across Trial transition (repeat, switch). Bold horizontal bars and boxes denote medians and interquartile ranges, respectively. Black dots represent outliers whereas red diamonds and error bars denote means and standard errors, respectively.

Note. *** $p < .001$, ** $p < .01$, * $p < .05$, *ns* = non-significant.

Main effects in ERs

For error rates, I found three significant main effects. There was a significant main effect of Trial transition, $F(1, 71) = 126.22$, $p < .001$, $\eta^2_p = .64$. Participants made more errors in task-switch trials (7.26%) than in task-repeat trials (4.09%), indicating a switch cost of +3.17%. There was a significant main effect of Congruency, $F(1, 71) = 139.71$, p

$< .001$, $\eta^2_p = .66$. Participants made more errors in incongruent trials (8.36%) than in congruent trials (3.00%), showing a congruency effect of +5.36%. There was a significant main effect of CSI, $F(1, 71) = 22.30$, $p < .001$, $\eta^2_p = .24$. Participants on average made 2.06% more errors in CSI 100 ms (6.15%) than in CSI 900 ms (4.09%). No statistically significant main effects of Task ($F < 1$) and Gender ($F = 3.08$, $p = .084$) were found. For interest, females had a mean ER of 5.12% and males had a mean ER of 6.24%.

Two-way interactions in ERs

There were four significant two-way interactions. Congruency interacted with Task, $F(1, 71) = 5.19$, $p = .026$, $\eta^2_p = .07$. Congruency effects were significant and equivalent in the colour task (+6.26%, $p < .001$) and in the shape task (+4.46%, $p < .001$).

Congruency interacted with CSI, $F(1, 71) = 23.00$, $p < .001$, $\eta^2_p = .24$. Congruency effects were significant in CSI 100 ms (incongruent - congruent = +6.93%, $p < .001$) than in CSI 900 ms (+3.79%, $p < .001$). Congruency effects were significantly larger in CSI 100 ms than in CSI 900 ms, with $p < .001$.

Trial transition interacted with Congruency, $F(1, 71) = 41.96$, $p < .001$, $\eta^2_p = .37$. Switch costs were significant in congruent (switch - repeat = +1.02%, $p = .001$) and incongruent trials (+5.33%, $p < .001$). Switch costs were significantly larger in incongruent trials than in congruent trials, with $p < .001$.

Trial transition interacted with CSI, $F(1, 71) = 11.62$, $p = .001$, $\eta^2_p = .14$. Switch costs were significant in CSI 100 ms (switch - repeat = +4.14%, $p < .001$) and in CSI 900 ms (+2.21%, $p < .001$), and were significantly larger in CSI 100 ms than in CSI 900 ms, $p = .001$. No other two-way interactions reached statistical significance.

Three planned comparisons were performed between Gender and Trial transition, Gender and Congruency, and Gender and CSI. I found that both males (switch - repeat = +3.14%, $p < .001$) and females (+3.21%, $p < .001$) showed significant ER switch costs, and the costs were equivalent between genders. Both males (incongruent - congruent = +5.48%, $p < .001$) and females (+5.24%, $p < .001$) showed significant and statistically equivalent ER congruency effects. Females (4.09%) made significantly fewer errors than males (5.64%) in CSI 900 ms, $p = .033$. However, females (6.15%) and males (6.85%) did not differ in their error rates in CSI 100 ms, $p = .476$. No other effects reached statistical significance.

Analyses of individual differences

In order to study individual differences in RTs, I analysed the RT measurements from each trial using GLMMs as in the previous experiments. Table 4.2 presents models from the simplest one to the most complex one that converged. I compared the most parsimonious model with full-factorial design including Gender (GLMM 3.3) with a corresponding model without Gender (GLMM 3.2) in order to determine whether factor Gender and its interactions improved the model fit. In other words, the model comparison tested whether the distinction between male and female participants was an important predictor of RTs.

The GLMM 3.2 and GLMM 3.3 seem to be comparable although GLMM 3.2 was slightly more parsimonious with lower AIC and BIC ($\Delta AIC = 2$, $\Delta BIC = 132$). However, the result of a model comparison suggests that the distinction between males and females explained additional variance in target RTs. In order to study gender effect and compare with the results of ANOVA, GLMM 3.3 with full-factorial design was selected. In GLMM 3.3, Task, Trial transition, Congruency, CSI and Gender, and their interactions were treated

as fixed effects. The random effects captured individual deviations from the grand mean RT (Intercept), from the main effect of CSI and from the interaction between Trial transition and CSI.

Table 4.2

Experiment 3. GLMM model comparisons based on RT data (GLMM 3.3 was selected).

<i>Model names</i>	<i>Models (family = Gamma (link = "identity"))</i>	<i>df</i>	<i>AIC</i>	<i>BIC</i>	<i>Log lik</i>	<i>dev</i>	<i>Chi-Sq</i>	<i>p-value (>Chisq)</i>
GLMM 3.1	RT~ Task+Trial.transition + Congruency+CSI+ Gender + (1 subject)	8	327700	327765	-163842	327684		
GLMM 3.2	RT~ Task* Trial.transition* Congruency* CSI + (1 + CSI + CSI: Trial.transition subject)	27	326568	326787	-163257	326514	1169.76	< .001 ***
GLMM 3.3	RT~ Task*Trial.transition* Congruency*CSI* Gender + (1 + CSI + CSI: Trial.transition subject)	43	326570	326919	-163242	326484	30.01	.018 *

Note. The model formulas are stated in the syntax of the lme4 package in R.

The fixed effects of GLMM 3.3 mirror the ANOVA results on RTs, except for the effect of gender. On average, responses were faster in the colour task (634 ms) than in the shape task (679 ms), $t = 37.29$, $p < .001$; responses were faster in task-repeat trials (616 ms) than in task-switch trials (697 ms), $t = 50.99$, $p < .001$; responses were faster in congruent trials (637 ms) than in incongruent trials (676 ms), $t = 33.45$, $p < .001$; responses were faster for CSI 900 ms (580 ms) than for CSI 100 ms (733 ms), $t = 86.58$, $p < .001$. Different from the ANOVA results, females (642 ms) were significantly faster compared to males (671 ms), $t = 17.54$, $p < .001$

In line with the results of the ANOVA, CSI interacted significantly with Trial transition ($t = 35.52, p < .001$), and with Congruency ($t = 26.88, p < .001$). Switch costs were larger in CSI 100 ms (SC = +107 ms) than in CSI 900 ms (SC = +53 ms). Congruency effects were larger in CSI 100 ms (+55 ms) than in CSI 900 ms (+21 ms). Trial transition interacted with Congruency, $t = 8.44, p < .001$. Switch costs were larger in incongruent trials (+85 ms) than in congruent trials (+75 ms). Gender differences in CSI 100 ms were more salient compared to CSI 900 ms, $t = 17.95, p < .001$. Females (712 ms) were faster than males (753 ms) in CSI 100 ms while females (572 ms) and males (588 ms) were similar in CSI 900 ms.

Gender differences in task-switch costs were small. Congruency effects were reduced in females, but this was limited to repeat trials, $t = 16.19, p < .001$. Females had a congruency effect of +20 ms and males had a congruency effect of +46 ms in task-repeat trials; the congruency effect was +44 ms in females and +43 ms in males in task-switch trials.

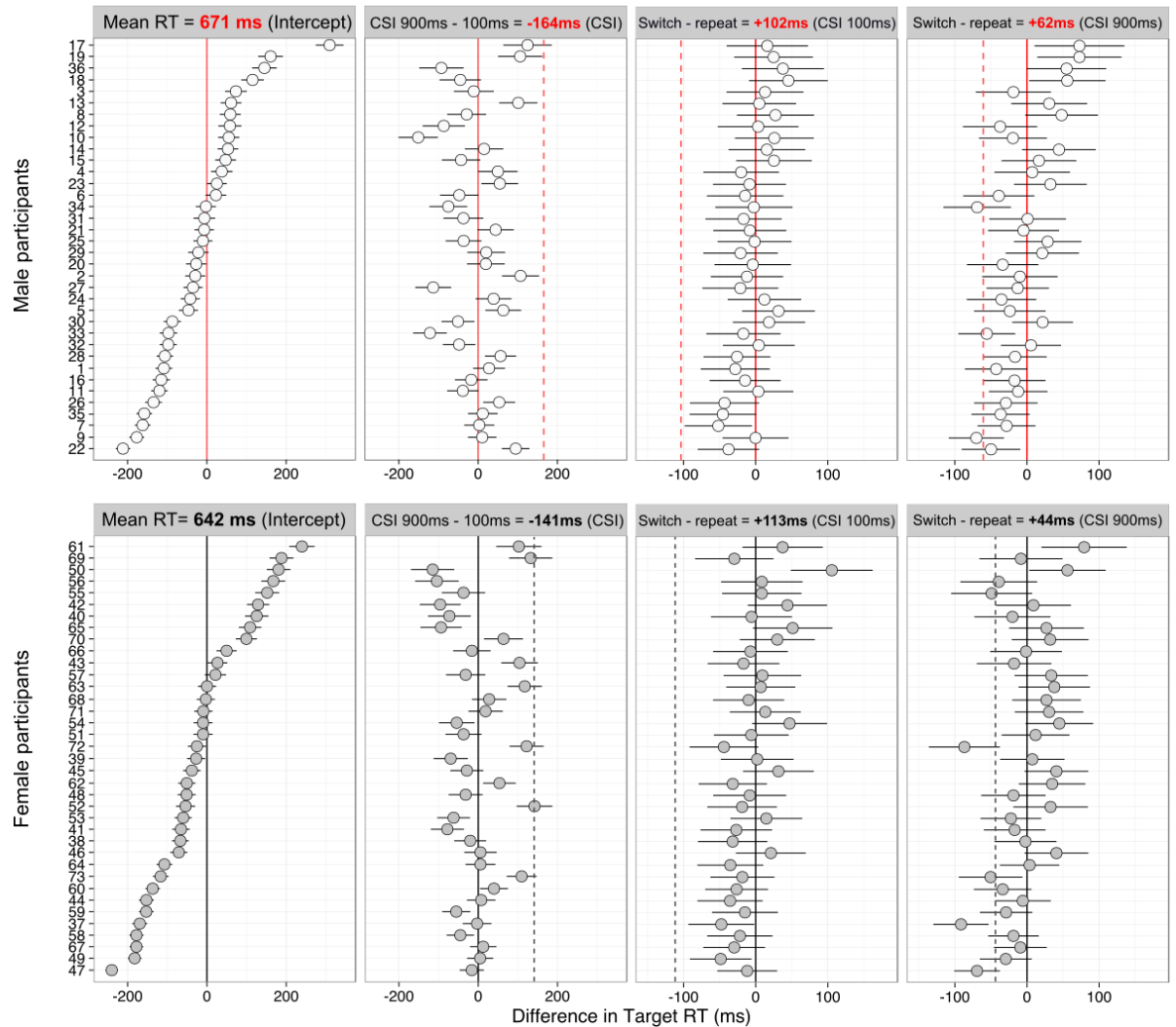


Figure 4.2. Experiment 3. Illustration of by-subject random effects for GLMM 3.3 on target RTs. Male participants are labelled with white dots shown in the top panel and female participants are labelled with grey dots shown in the bottom panel. The dotplots from left and right shows individual deviations (dots) and 95% confidence intervals (horizontal error bars) from conditional mean RTs (Intercept = grand mean RT of 671 ms for male participants and 642 ms for female participants, as indicated by the solid vertical red and black line centred on zero, respectively), conditional mean RT difference between CSI 900 ms and CSI 100 ms (-164 ms for males and -141 ms for females, as indicated by the vertical red and black line centred on zero, respectively), conditional mean switch costs in CSI 100 ms (+102 ms for males and +113 ms for females, as indicated by the solid vertical red and black line centred on zero, respectively) and in CSI 900 ms (+62 ms for males and +44 ms for females), respectively. The dashed vertical lines in the dotplots indicate zero differences between CSIs, and zero switch cost for each condition in each

gender. Please note that male and female participants have different intercept and fix effects. Please also note the different RT scales on the x -axis across plots.

The by-subject random effects explained considerable RT variance. Figure 4.2 shows individual differences in mean RTs, with both groups of participants showing significant deviations from the group mean RT. Sixteen males and 19 females responded faster than the grand average RT, while 12 males and 10 females showed slower responses than the grand average RT. Both groups showed large deviations between CSIs.

Figure 4.2 also shows that across CSIs, both genders showed significant deviations from the mean switch costs and zero switch costs. All participants showed significant switch costs in CSI 100 ms. However, when in trials with CSI 900 ms, there were two more females ($N = 20$) than males ($N = 18$) showing switch costs close to zero. In addition, three female participants, Participant 37, 47 and 72, showed a reversed switch cost of -48 ms, -25 ms and -43 ms, respectively, in CSI 900 ms. No male participants showed a clear reversed switch cost.

4.4 Experiment 3 Discussion

Experiment 3 studied gender differences in task-switching performance using two different CSIs. I found that in trials with CSI 100 ms female participants were on average faster compared to male participants whereas in this condition error rates were similar between males and females. For CSI 900 ms female participants made fewer errors and had smaller RT switch costs compared to males. In addition, males and females were different in the congruency effects in task-repeat trials. Congruency effects were more than halved and non-significant in female participants compared to male participants. These

results suggest that female participants were slightly better than males at task switching and interference control when in specific conditions.

Gender differences in task-switch costs

Comparing task-repeat with task-switch trials I found significant switch costs for RT and ER, consistent with previous task-switching results (e.g., Kiesel et al., 2010; Vandierendonck et al., 2010). The costs were reduced in the condition with a CSI of 900 ms compared to the condition with a CSI of 100 ms, in line with previous studies showing reduced switch costs when increasing preparation times (e.g., Kiesel et al., 2010; Vandierendonck et al., 2010).

I found gender differences in switch costs with longer preparation intervals. Compared to male participants, females showed reduced RT residual switch costs in CSI 900 ms, suggesting that females had a small advantage over males in task preparation. This result seems to support previous studies that showed that females were superior than males in task switching and cognitive performance using various tasks and paradigms (Friedman, 2016; Stoet et al., 2013; Van der Elst et al., 2006; Weiss et al., 2006). Researchers concluded that females were better at coping with complex conditions and that females had more efficient information processing.

I suggest that the advantage for females in task switching may be due to efficient task preparation. According to the *FTE* account of task-set reconfiguration (De Jong, 2000; Lindsen & De Jong, 2010), it is likely that females completed task-set reconfiguration within a cue-stimulus interval of 900 ms. Therefore, females had smaller switch costs compared to males in CSI 900 ms. This may be related to gender-specific memory network utilization. For example, Hill, Laird and Robinson (2014) conducted a meta-analysis using the BrainMap database which is based on 69 papers with a total of 901 participants. Studying the neural underpinning of working memory for males and females, Hill and

colleagues found that males and females employed different networks to solve complex problems. Males utilised more spatial processing related networks (i.e., parietal regions) than females, and females seemed to recruit more prefrontal regions. Research has shown that the prefrontal cortex plays a critical role in information maintenance (Prabhakaran, Narayanan, Zhao & Gabrieli, 2000) and top-down processing related to goal-directed behaviour (Miller & Cohen, 2001). In the present experiment, female participants might have used more top-down preparation strategies associated with more activated prefrontal networks compared to males.

The reduced switch costs in females in the present experiment contradicted previous studies suggesting a male advantage in task switching (Beeri et al., 2006; Reimers & Maylor, 2005; Tun & Lachman, 2008). For example, Tun and Lachman (2008) conducted a Switch and Go switching task with unlimited target-response intervals in five age groups ranging between 32 and 85 years. Researchers reported smaller switch costs in male participants. Importantly, researchers also reported an interaction between gender and age. Male participants performed better than females in groups with age above 45 whereas there was no difference between male and female participants below age 45. Their study suggested that the effect of gender on task switching may vary across lifespan. Similarly, Reimers and Maylor (2005) used a cue-stimulus interval of 1,000 ms showing that female adolescents had smaller RT switch costs whereas the gender difference tended to disappear and was even reversed as the age of the participants increased. Therefore, an important factor can be age differences of samples across studies. The participants in the present sample were young university students (aged between 18-32 years), and showed a small female advantage. However, I did not find gender differences in task switching performance in CSI 100 ms. Future studies may employ a larger sample to investigate whether gender interacts with preparation time in different age groups. For example, whether females would be better at task switching only when preparation time is long, and

whether such gender differences would disappear with increased age. Importantly, it is unclear whether there are gender-related individual differences in task preparation over adolescence, adulthood, and old age.

By analysing individual performance I found in CSI 900 ms that one female participant, Participant 37 showed significantly reversed switch costs, and that two other female participants, Participant 47 and 72, showed also reversed switch costs although not significantly different from zero. This is an unusual pattern as these participants responded more quickly in task-switch trials compared to task-repeat trials. Dreisbach and Haider (2006) reported similar results. In their study, participants decided either whether the digit was odd or even, or whether the digit was smaller or bigger than 5 based on the colour of the target digit. Participants were encouraged to use a specific probability cue for task preparation in each trial. As a result, participants showed slightly faster responses in switch trials when they were told to perform a task switch with 75% probability before every trial. In this condition, Dreisbach and Haider found that participants were able to adjust their cognitive control dynamically based on task expectancy and showed pronounced switch preparation. It is possible that if Participant 37, 47 and 72 had highly expected a task switch in each upcoming trial, a different task set would always be prepared. Then, responses can be faster for switch trials in the paradigm with both cue and target stimulus presented simultaneously. However, this is not the case in the present experiment because participants were informed about equal probability of tasks and a cue that specified the upcoming task was presented 900 ms before target onset. Participants can take the time to prepare a relevant task resulting in at least similar performance across trials.

Alternatively, a more plausible explanation would be that the participants with reversed switch costs had a different strategy in addition to high switch expectancy. In order to test this speculation, I conducted a post-hoc analysis for Participant 37. I found that in trials with congruent targets responses were significantly faster in task-switch trials

(351 ms) compared to task-repeat trials (426 ms) whereas no reliable differences were found in trials with incongruent targets (Mean switch RT = 397 ms; Mean repeat RT = 415 ms). This participant might have performed tasks using stimulus-response associations when the target stimulus was congruent, while the retrieval of associations was sometimes delayed in task-repeat trials due to high switch expectancy.

However, the post hoc analyses for the other two female participants, Participant 47 and 72, indicate an opposite pattern of results. These two participants showed much reversed switch costs in trials with incongruent targets. Specifically, with incongruent targets Participant 47 responded more quickly in switch trials (294 ms) compared to repeat trials (335 ms), while with congruent targets this participant responded equally fast in switch (317 ms) and repeat trials (318 ms). Similarly, Participant 72 showed significantly faster responses in switch trials (548 ms) compared to repeat trials (740 ms) only when the target stimulus was incongruent. There was no significant difference between switch (573 ms) and repeat trials (613 ms) when the target stimulus was congruent. It could be that when cue/task repeated these two female participants did not prepare until target onset. In addition, they might use stimulus-response associations in trials with a congruent target stimulus and apply task rules in trials with an incongruent target stimulus. The problem is that when in trials with an incongruent target participants need to prepare the relevant task rules before appropriate feature categorisation of the target stimulus. Unprepared repeat trials would then lead to delayed responses especially after incongruent target onset. In contrast, when cue/task changed these two female participants might always prepare so that they could apply the relevant task rule as soon as target onset, although they may still have associated a response with the congruent target directly.

Gender differences in congruency effects

The present experiment indicated gender differences in congruency effects. The difference was observed in task-repeat trials, where female participants showed a non-significant RT congruency effects whereas males showed significant congruency effects. The finding of reduced congruency effects in females is in line with previous results (Stoet et al., 2013; Van der Elst et al., 2006) that suggested that females were less affected by task-irrelevant information. For example, Van der Elst and colleagues (2006) asked participants to read words, name colours, and name the ink colour of printed words in a Stroop test. An interference measure was calculated by subtracting the average time needed to complete the first two tasks from the time needed to complete the third task. They found that female participants had lower (better) interference scores than male participants, suggesting better cognitive flexibility and executive control in females.

The present experiment employed bivalent stimuli. As noted in previous studies, a bivalent stimulus is not only associated with a competing task, but also affords a response to the competing task (Allport et al., 1994; Bugg & Braver, 2016; Kiesel et al, 2007; Yeung & Monsell, 2003). Half of the bivalent stimuli in the present experiment were incongruent and associated with conflicting responses in the colour and shape tasks. Thus, participants typically responded more slowly in incongruent trials than in congruent trials, showing a significant congruency effect. Studies suggest that the congruency effects are more pronounced in task-switch trials because there are increased between-task interferences and response conflicts. Interferences or conflicts are likely to occur due to carryover of previous task set and response mappings when a switch in task between trials (Allport et al., 1994; Bugg & Braver, 2016; Kiesel et al, 2007; Yeung & Monsell, 2003). In the present experiment, both males and females, showed congruency effects in task-switch trials, suggesting that both genders were influenced by the previous relevant but currently

irrelevant task information. They spent longer time to activate the relevant response when the task was changed and when there were large response conflicts.

In task-repeat trials, congruency effects were smaller because activation of the relevant task set persists from the previous trial (Allport et al., 1994; Bugg & Braver, 2016; Kiesel et al, 2007; Yeung & Monsell, 2003). I found that congruency effects were more than halved in female compared to male participants. It is possible that females were better at maintaining task information and therefore they re-activated the previous tasks-set in working memory more quickly. Consequently in task-repeat trials, females were less affected by distracting information from the other task and showed reduced congruency effects. This was supported by Guillem and Mogg (2005) that suggested that males and females may differ in their abilities to maintain information over interference: Males maintained less-specific information whereas females engaged in more detailed information leading to better performance in a memory task. Another explanation would be that female participants were more likely to employ a different strategy such as performing by cue-stimulus-response associations rather than applying task rules in task-repeat trials. Evidence for this strategy was provided by Li et al. (2019a), where participants showed reduced congruency effects in conditions that required to remember stimulus-response associations (+39 ms) compared to a condition where they applied task rules (+71 ms).

In sum, Experiment 3 revealed that females had small advantages in task switching, and a GLMM model comparison suggested that the distinction of gender significantly improved the prediction of response times. Studying individual performance I found that two more female than male participants made efficient task preparation and indicated no significant switch costs in CSI 900 ms (Figure 4.2). Three out of 37 female participants showed reversed switch costs for CSI 900 ms, suggesting that these participants might have used different switching strategies. For example, two of them may not prepare until target onset in repeat trials, in which they showed impaired performance with incongruent

target stimulus. In addition, the smaller congruency effects in females suggest better interference control of irrelevant task and/or a different strategy in task-repeat trials. For example, they may have performed different tasks by recalling cue-stimulus-response associations rather than applying task rules when in trials with a task repetition.

CHAPTER 5 General Discussion and Conclusion

5.1 Individual differences in task switching

In the past few years, researchers have reported striking individual differences in the performance of cognitive tasks and other related conditions. They suggested that a number of participants were considerably better than others, showing minimal performance decrements in task-switching trials (Lindsen & De Jong, 2010; Stoet & Snyder, 2003, 2007; Stoet et al., 2013), dual-task situations (Medeiros-Ward et al., 2014; Watson & Strayer, 2010, 2012), Stroop incongruent trials (Haff & Rouder, 2017, 2018), and other difficult tasks such as recognising unfamiliar faces (Robertson et al., 2016; Russell et al., 2009) and memorising long list of items (Mallow et al., 2015; Ramon et al., 2016). Other studies provided evidence for gender-related differences in task-switching, although the results were inconsistent in terms of task switching and interference control (Beeri et al., 2006; Christakou et al., 2009; Friedman, 2016; Stoet et al., 2013; Tun & Lachman, 2008; Van der Elst et al., 2006; Weiss et al., 2006). Accordingly, participants had variable performances and showed different effects in previous experiments. In task-switching paradigms participants may vary considerably in task-switch costs and few participants may have eliminated switch costs. In the present thesis I investigated individual differences in task-switching performance across tasks, conditions and paradigms using Generalised Linear Mixed-effect Models.

As predicted, I found that individuals differed significantly in both response times (RTs) and error rates (ERs) when performing in Experiment 1A and two follow-up studies. Using a novel method, in which participants were required to make no mistakes, I identified exceptionally performing participants who were able to switch between tasks without errors and switch costs. However, these participants varied in their task-switching performance and showed switch costs in the follow-up experiments when cue and target

stimulus were presented simultaneously. Their superior switching abilities were limited to conditions that allowed cue-based preparation. This is in line with the assumption made by Yehene and Meiran (2007) who suggested that switching costs in a short cue-stimulus interval do not indicate a general switching ability. Instead, the observation of residual switch costs for longer cue-stimulus intervals seems to represent a more general ability. De Jong and colleague's failure-to-engage (FTE) account (De Jong, 2000; Lindsen & De Jong, 2010) suggests that residual switch costs with long cue-target intervals are due to a proportion of trials in which participants failed to prepare the task. According to the FTE account, the proportion of prepared trials may reflect a general ability of advance preparation.

Similar to the FTE account (2000, 2010), where participants fail to prepare occasionally (see also Nieuwenhuis & Monsell, 2002; Poboka et al., 2014), other researchers have proposed the partial-mapping preparation (PMP) account. They suggested that task preparation is limited to a specific stimulus-response pair because focused attention is limited in capacity and it is therefore impossible to complete advance preparation in all trials (Lien et al., 2005; Monsell & Mizon, 2006). Note that Lien and colleagues described the stimulus-response pairs in the order of response-key position: left, middle, and right. They assumed that participants would learn the stimulus-response pairs, consistent with reading in English, from left to right, so that participants would prepare and assign priority to the stimulus-response pairs from left to right as well. As expected, Lien and colleagues only found complete preparation and no switch costs for the left, or high-priority stimulus-response pair. Participants consistently showed large and significant switch costs for the middle and right, or lower-priority stimulus-response pairs compared to the high-priority pairs on the left (Lien et al., 2005; Monsell & Mizon, 2006).

However, Lindsen and De Jong (2010) questioned the PMP account and compared individual cumulative response time distributions for all three stimulus-response pairs. The

results suggested that for some participants the probability of successful advance preparation appeared to be highest for the first stimulus-response pair (i.e., the leftmost/high-priority pair), consistent with the PMP hypothesis. Some participants showed similar probability of advance preparation for all three stimulus-response pairs, consistent with the FTE account. Moreover, they also observed that 7 participants (39% of all participants) showed a high degree of overlap between switch- and repeat-trial RT distributions for all stimulus-response pairs, corresponding to faster responses and smaller RT switch costs. This study suggested that participants prepared task sets differently and that a few participants appeared to have completed preparations for all tasks showing reduced switch costs. Thus, the question arises why some participants are better at task preparation and show smaller or even no switch costs compared to other participants.

5.2 Why some participants can eliminate switch costs

Better motivation

Based on the results of Experiment 1A I assumed that best performers might be more motivated by the zero-error policy. According to the FTE hypothesis (De Jong, 2000; Lindsen & De Jong, 2010), they may be engaged in the task preparation of each upcoming trial with a higher level of attention and motivation. Indeed, the results of post-experimental self-reports suggest that best performers had higher scores than most other participants on an intrinsic motivation scale (Deci & Ryan, 2011). Specifically, they reported to be more interested and felt more competent in the task-switching experiment. This is consistent with previous results indicating that motivation can modulate cognitive/attention flexibility, improve working memory performance and facilitate effective problem-solving strategies (Deci & Ryan, 2008; Krawczyk & D'Esposito, 2011; Nadler, 2013; Pessoa, 2009; Struthers et al., 2000; Wulf & Lewthwaite, 2016). However,

the finding of higher levels of motivation in best performers needs to be interpreted with caution because the participants completed the motivation scales after the experiment. As a result, those who finished the experiment early without an error would evaluate themselves as being highly motivated and more competent in the just completed task-switching experiment.

Superior executive control

Since best performers consistently performed well showing no switch costs in the task-switching conditions with a cue-stimulus interval of 650 ms, best performers might have superior executive control abilities, in line with the multi-tasking studies that showed that “supertaskers” had more efficient neural activity in attentional control networks when performing in the dual-tasks with better executive control functioning (Medeiros-Ward et al., 2014; Strayer & Watson, 2012; Watson & Strayer, 2010). This is also in line with previous studies on working memory showing that “superior memorisers” had more activation in executive-relevant brain areas (Mallow et al., 2015).

According to studies on executive control and related cognitive performance, higher cognitive control abilities were linked to improved abilities of switching back and forth between multiple tasks (*switching*) while inhibiting interference and task-irrelevant information (*inhibition*), along with a greater efficiency in continuous updating of working memory representations (Miyake et al., 2000; Zeidan et al., 2010). Best performers might have more efficient executive control, corresponding to improved switching, inhibition and updating when performing in the colour/shape task-switching trials. It is possible that as soon as a task cue appeared, best performers were faster than other participants in cue encoding, goal updating and task-set reconfiguration. Karayanidis et al. (2009) suggested

that greater preparation can optimise the encoding process after target onset, so best performers might also be better in target encoding and target-driven interference control.

Higher general intelligence

From the results of a Raven intelligence test in Experiment 1C, best performers had on average higher IQ scores compared to controls. Previous results also showed that higher IQ scores were related to better executive control, particularly in working memory updating (Benedek et al., 2014; Friedman et al., 2006). Task switching requires frequent updating of the task set in working memory, therefore a higher IQ score may correlate with a more efficient task-switching performance. However, it remains unclear whether superior intellectual abilities and better executive control are the result of learning or are genetic in origin. There are studies suggesting that the diversity of executive functions and intellectual abilities are primarily genetic in origin (Friedman et al., 2008; Friedman et al., 2016). However, other studies argued that executive functions such as working memory capacity can be entrained, and that training gains can translate into gains in general intelligence (Klingberg, 2010; Light et al., 2010). Nevertheless, the intelligence results in Experiment 1C suggest that differences in task-switching abilities may be linked to differences in executive control, and general intelligence.

Better self-control and lower impulsiveness

By using different psychological scales, I found that best performers had higher scores in trait self-control and lower scores in attentional and non-planning impulsivity. In Leshem (2015), participants switched attention between ears in a dichotic listening to word task with 4 target words. The target words appeared randomly in the attended ear. Leshem

(2015) found that participants with high self-reported impulsivity were associated with greater difficulty in inhibiting incorrect responses and resolving cognitive conflicts compared to low-impulsive individuals. Similarly, Enticott and colleagues (2006) reported that all subscales of the Barratt Impulsiveness Scale (BIS), the same impulsivity scale as in the present thesis, were significantly correlated with Stroop conflicts. Enticott et al. (2006) used a spatial Stroop task and required participants to overcome interference if a target arrow pointed in the opposite direction to the visual field in which the target was presented. They found that participants, who needed more time to solve the interference, scored higher in non-planning impulsivity, attentional impulsivity and other subscales of BIS. The researchers suggested that general impulsive behaviour in normal participants may be partially attributable to some forms of inhibitory dyscontrol, specifically, the difficulty of ignoring task-irrelevant information and suppressing inappropriate motor responses (Enticott et al., 2006). Moreover, other researchers showed that high-impulsive individuals had lower working memory capacity than low-impulsive individuals (Whitney et al., 2004). Participants need to retrieve or activate task-relevant information from their working memory while inhibiting interference in task switching (Kiesel et al., 2010; Vandierendonck et al., 2010). Accordingly, I suggest that best performers' superior switching performance is related to better self-control and lower levels of impulsiveness. Participants with these traits may be better at task preparation. In addition, they may also be more efficient in switch-related cognitive processing after target onset. As soon as a target stimulus is presented, best performers may direct attention effectively to the goal- or task-relevant features with reduced conflicts in response selection.

Gender-related individual differences

There are other possible factors that may account for why some participants can switch between tasks more efficiently than other participants. For example, some studies have found significant gender-related differences in task switching and switch-related cognitive abilities (Beeri et al., 2006; Friedman, 2011, 2016; Stoet et al., 2013; Tun & Lachman, 2008; Van der Elst et al., 2006; Weiss et al., 2006), while other researchers failed to find gender differences (Polunina et al., 2018; Reimers & Maylor, 2005; Weber et al., 2014). However, these studies neglected gender-related individual differences in task switching and in related cognitive tasks. In Experiment 3 I studied whether gender differences are present during the preparation phase of colour/shape task-switching by manipulating the cue-stimulus interval. I monitored group average and individual performance within each gender, using GLMMs. On average, I found that female participants were slightly better than males at task switching in trials with long preparation intervals. In addition, females had a small advantage in interference control when there was a task repetition. The individual analysis showed that for long preparation intervals two more female than male participants had switch costs close to zero while three more females had switch costs smaller than zero. However, the individual switch costs for female participants varied considerably as for male participants. These results were consistent with previous research reporting behavioural and neural-network advantages in female participants when performing in complex tasks and when solving complex problems (e.g., Hill et al., 2014; Stoet et al., 2013; Van der Elst et al., 2006; Weber et al., 2014; Weiss et al., 2006).

However, in Experiment 1 I found 6 females (13.6% of 44 female participants) and 3 males (21.4% of 14 male participants) among the best performers. This seems to suggest that males were more efficient in task switching, consistent with large-sample studies that observed a male advantage (e.g., Beeri et al., 2006; Tun & Lachman, 2008). Nevertheless,

a recent meta-analysis reported no consistent gender differences using task switching and related cognitive tasks (e.g., Polunina et al., 2018). Gender may be not very predictive when explaining switching performances across best performers and other individuals in Experiment 1A, 1B and 1C.

Accordingly, by exploring individual differences in task switching I found that a few exceptional individuals eliminated RT and ER switch costs in different conditions for a cue-stimulus interval of 650 ms. Although many factors seem to play a role in explaining their superior performance, future studies are needed in order to understand the nature of the differences between best performers and controls. For example, a future study may investigate best performers in task switching and the control participants using a variety of tasks, such as memory and perception tasks. Best performers may have advantage in sensory processing that allows them to capture the cue and target features more quickly, so that cue- and target-encoding can start earlier. Nevertheless, further evidence is needed to support this speculation. According to the current results in Experiment 1A, 1B and 1C, best performers consistently showed better advance preparation following a cue. Then, a follow-up question is whether I can encourage a typical participant to engage more efficiently in cue-based preparation to reduce switch costs.

5.3 Varying effects of cue type across participants

Participants can be encouraged to prepare the upcoming task if there is a cue-stimulus interval of over half of second, and importantly, if the cue informs about the upcoming task. The effect of cue type on task switching has been investigated in previous studies. It was found that, compared to non-transparent/non-informative task cues, transparent/informative task cues reduced task-switch costs, although switch costs were significant in both cue types (e.g., Arbuthnott & Woodward, 2002; Jamadar et al., 2010a,

2010b; Logan & Schneider, 2006; Mayr & Kliegl, 2000; Miyake et al., 2004; Nicholson et al., 2006; Schneider, 2016). From these studies it was concluded that transparent cues can help to retrieve relevant goal and task sets and therefore lead to faster task preparation.

In line with previous results, I showed in Experiment 2A, 2B and 2C that when participants were instructed with priming cues (i.e., transparent cues), participants had on average reduced and non-significant residual task-switch costs independent of cue-stimulus intervals. The priming cues were more similar to the iconic cues used in Grange and Houghton (2010). In their study iconic cues provided target feature, so that in trials with iconic cues participants can easily search for and respond to the location of a relevant target. According to Grange and Houghton (2010), the iconic feature cues, unlike word cues, can facilitate exogenous attention or directly stimulate the relevant working memory representations required to perform the task. If the task situation involves non-semantic categorisation, a specifically designed cue that primes features in the upcoming target would help to activate control process of task-set reconfiguration. The relevant task representation can be formed quickly in working memory.

Similarly, in Experiment 2A, 2B and 2C of the present thesis, when participants were presented with priming cues, a visual representation of the relevant task feature and the related target-response mappings were quickly activated, increasing the chances for making faster responses and fewer errors in task switching. In contrast, participants with non-priming cues need to activate or reconfigure the relevant task set, and this task-set reconfiguration requires high levels of cognitive control. In other words, the priming cues provide a shortcut for task-set reconfiguration and response retrieval from working memory, and thereby facilitate advance preparation.

Since in other studies it was argued that the task-switching process involves cue processing (Logan & Bundesen, 2003; Logan & Schneider, 2006), I also measured

response times to cues in Experiment 2A. I asked participants to respond to the cue by indicating which task needs to be performed before they respond to the target stimulus (c.f., Arrington et al. 2007). Only for priming cues participants showed no significant differences in response times between cue-repeat and cue-switch trials. This indicates that for priming cues the cue-encoding processes were equally fast for switch and repeat trials. A positive relationship between cue RT and target RT provides evidence that fast target encoding and fast response execution are related to fast cue processing and cue-based preparation. In line with the results in Grange and Houghton (2010), only for iconic feature cues participants performed the cue-switch trials as quickly as cue-repeat trials.

I found individual differences in task switching for two types of cues. With priming cues participants showed smaller deviations from group-average switch costs and many participants showed switch costs close to zero. In contrast, participants with non-priming cues deviated more from the mean switch costs. This may be because following a non-priming cue informing only the upcoming task participants can be rather different in their proportion of prepared trials due to different task-switching strategies and cognitive control abilities. However, priming cues activated relevant task representation and response mappings, leading to more efficient preparation in each trial.

In order to better understand the nature of the task preparation process for priming and non-priming cues, in Experiment 2C I measured cue-locked and target stimulus-locked ERPs as well as their brain topographies. I showed their ERPs for repeat and switch trials at four midline electrodes, and conducted ERP analysis at electrode Pz only. I found that participants with priming cues showed cue-locked switch positivity across different CSIs at Pz, whereas non-priming cues did not trigger a significant switch positivity in CSI 1100 ms. Previous studies indicated that switch positivity is associated with advance preparation (e.g., Karayanidis et al., 2009; for reviews see Jamadar et al., 2015; Karayanidis & Jamadar, 2014).

Karayanidis et al., (2009) suggested that advance preparation can optimise target encoding and decreases target-driven interference associated with reduced post-target negativity. In Experiment 2C post-target switch negativity was not significant for both cue types and in all CSI conditions. This may be the case because most participants in Experiment 2C were highly prepared, so that they had decreased target-driven interference associated with small RT switch costs. However, note that participants varied in their target-locked activity (Figure 3.11). At electrode Pz, some participants seemed to show larger than average switch negativity that peaked around 200 ms after target onset, consistent with previous results (e.g., Karayanidis et al., 2009). Participants with large post-target negativity might have delayed task-set reconfiguration and increased target-driven perceptual interference. Similarly, individual differences in target-locked activity were also found in trials with priming cues. It seems that even though priming cues should have facilitated task preparation and reduced ambiguity of feature categorisation when target onset, participants differed in their reactive control process. In other words, some participants seemed to have great difficulty to control target-driven interference, suggesting limited advantage of priming cues in these individuals. Indeed, there are many factors that may affect task-switching performance, such as how participants perceived the priming cues, whether each participant relied on the information provided by the cue, whether each individual had high motivation to engage in the cue-based preparation, and presumably other variables that were not controlled. In previous studies it has been suggested that individuals have different cognitive processing and task-switching performance because of context-based motivation, psychological development and population characteristics (e.g., Stoet & López, 2011; Tun & Lachman, 2008; Yee, Krug, Allen & Braver, 2016). In the next section, I will discuss other factors that may explain individual differences in task switching.

5.4 Other factors affecting individual differences in task switching

Induced emotion and incentive/motivational influence

It has been suggested that emotion and various incentives play a crucial role in directing human flexible behaviour (Dreisbach & Goschke, 2004; Nadler, 2013; Yee et al., 2016). For example, Dreisbach and Goschke (2004) studied how positive emotion affects goal maintenance and flexible switching of cognitive sets. In this study participants performed a letter/digit switching task. In each trial either two different digits or two different letters were presented simultaneously but in different colours. Participants were asked to respond to the target with the colour pre-specified by an instructional cue while ignoring the other target stimulus. Dreisbach and Goschke (2004) suggested that a positive mood enhanced performance and reduced switch costs when participants responded to the target with a new colour that was not previously presented while ignoring the non-target with a previously attended colour. However, the induced positive mood increased switch costs when participants had to respond to the target appearing in the previously ignored colour while ignoring the non-target that was presented in a new colour. They concluded that cognitive processing and behaviour control, are dynamic and context-dependent, and can be regulated by affective states (see also Nadler, 2013). Other researchers suggested similar effects of emotion on problem solving and decision making. As stated by Isen (2001, p75), “as long as the situation is one that is either interesting or important to the decision maker, positive affect facilitates systematic, careful, cognitive processing, tending to make it both more efficient and more thorough, as well as more flexible and innovative”.

Yee et al. (2016) studied the effect of various incentives on cognitive processing. In their study, participants were asked to perform in a pre-cued letter/number task-switching paradigm in order to receive monetary rewards. First, participants performed in a task-

switching baseline block without rewards, although dollar signs were presented in each trial. The purpose of the baseline block was to calculate individual reward criterion, i.e., 37.5th percentile of the correct response times. In the incentive condition, participants earned the monetary rewards when their response was accurate and faster compared to the reward criterion. In addition, dollar signs were presented in the beginning of each trial indicating the relative worth of that trial as low (\$), medium (\$\$), or high (\$\$\$\$). If participants earned the monetary rewards, they were served with appetitive, neutral or aversive liquid as secondary incentives. Each type of liquid appeared in one block. In total, there were three blocks in the incentive condition. Participants rated how much they liked the three types of liquids and reward trials after they completed the task-switching experiment.

Yee et al. (2016) found that participants had increased motivation and task-switching performance significantly improved when the amount of monetary reward was increased. Participants had the smallest switch costs when monetary reward was high. Using liquids as a second incentive, participants responded more quickly when they received an appetitive liquid, but more slowly when they received an aversive liquid, compared to a neutral liquid. However, switch costs were not affected by either appetitive or aversive liquid. Based on the self-report ratings after the experiment, Yee et al. (2016) found individual variability in the level of motivation. There was a wide spread of residuals of the motivation ratings in the aversive-liquid condition compared to conditions with neutral and appetitive incentives.

In their Experiment 2 researchers considered individual differences in perception to each liquid, rather than on the basis of the intrinsic properties of the liquids themselves. The preference ranking of liquid was derived by asking a new sample of participants to compare three juices with neutral liquid, before participants started the experiment. Moreover, participants evaluated each liquid based on its' pleasantness on a Likert scale.

This preference ranking procedure was important as researchers were able to control subjective motivational influence across liquid conditions. In addition, each participant can be truly motivated by appetitive liquids (i.e., juices). By doing so, Yee and colleagues found that while most participants preferred juices to neutral liquid, they showed different preferences to three types of juices. Surprisingly, two participants preferred the neutral liquid to all juices. Yee and colleagues found that juice did not produce any modulation of switch costs. Participants showed only reduced switch costs as the monetary rewards increased. Yee and colleagues (2016) explained the null effect of liquid incentives as satiation-related influences on motivational states and cognitive performance. The increased satiation may have reduced the value of appetitive liquid over the block of trials.

Aging

There is evidence suggesting that executive functions decline with age (Tun & Lachman, 2008; Reimers & Maylors, 2005; for a review see Kirova, Bays & Lagalwar, 2015). In contrast, two studies reported no age-related decline in key measures of attention and executive functioning (Grange & Becker, 2017; Wasylyshyn, Verhaeghen & Sliwinski, 2011) and one other study found smaller decrements in cognitive performance for older bilinguals than older monolinguals (Bialystok, Poarch, Luo & Craik, 2014).

For example, Reimers and Maylors (2005) recruited 5,271 participants between the age of 10 and 66 years to perform in an online task-switching experiment. They found U-shaped RT effect of age in the mixed task block: Children and older adults were slower than young adult participants. However, RT switch costs increased gradually with age only in participants over 18 years. There was no significant effect of age in switch costs in adolescents below 18 years. Reimers and Maylors (2005) study was based on 8 sets of 4 alternative-run trials. The null effect of age may be because the RT data was too small in

the group of adolescents. Additionally, a web-based experiment may result in a lot of random noise in young adolescents (e.g., distractions), so that it was difficult to detect an underlying age-related trend in cognitive control in this group of participants. The authors did acknowledge this limitation. In addition, Reimer and Maylor proposed that the switch costs measured within the mixed block may be less sensitive to neurologic changes across the lifespan.

Similarly, Tun and Lachman (2008) asked 3,616 participants aged between 32 and 85 years to perform in a Stop/Go Switch Task with a total of 29 trials. Saying “Go” for *Green* and “Stop” for *Red* were required in congruent trials whereas “Stop” for *Green* and “Go” for *Red* were required in incongruent trials. Participants alternated between congruent and incongruent trials based on the task cue. They found that participants responded more slowly in incongruent trials compared to congruent trials, indicating a significant congruency effect. Congruency effects were larger in older adults, participants with lower education, and female participants. Consistent with the results of Reimers and Maylors (2005), switch costs showed the same pattern as congruency effects, with larger switch costs as age increased, for lower education and female participants, even after controlling for differences in health status. In addition, Tun and Lachman (2008) found that after controlling for health status, there were no significant differences in response times between adults who received a college degree and less-educated participants who were 10 years younger in incongruent trials. Tun and Lachman (2008) concluded that formal education can moderate age differences in the more complex condition that involves executive control. This study provides a better understanding of age-related executive control processes in a multivariate design.

More recently, Grange and Becker (2017) conducted a meta-analysis of 16 task-switching studies and focused on response-time congruency effects. Their results showed no age-related decline in response-congruency effect on response times. However, it was

unclear whether a true effect of aging was present in accuracy. Although it was also unclear whether there were age-related deficits in the process of target-response-compound selections (*non-mediated route*; see Schneider, 2015) and/or target-feature categorisations (*mediated route*; see Schneider, 2015), Grange and Becker's (2017) results add to the evidence of a general lack of age-related deficits in task switching abilities. More generally, there may be no age-related decline in key measures of attention and executive functioning.

Typical and atypical populations in task switching

Since task-switching performance is often used as an important indicator of executive control functioning, in previous task-switching research typical and atypical populations were compared in order to understand how there are differences in cognitive behaviour and brain development (e.g., Belleville, Bherer, Lepage, Chertkow & Gauthier, 2008; Just, Cherkassky, Keller, Kana & Minshew, 2006; Stoet & López, 2011; for reviews see Keehn, Müller & Townsend, 2013; Kirova et al., 2015).

For example, Stoet and López (2011) studied 19 children with autism spectrum disorder (ASD) and 19 typical-developing controls, matched in age and IQ level, using a colour/shape task-switching paradigm. They found that when the relationship between stimulus and response was not clearly instructed by the cue (high-memory condition), children with ASD made more errors and had higher switch costs in error rates compared to a control group. When the stimulus-response mapping was made explicit (low-memory condition), researchers found no reliable difference in response times, error rates, and switch costs. In addition, they found that ASD children were less affected by task interference, showing similar response time congruency effects as the control children. Stoet and López (2011) suggested that children with ASD may have impaired cognitive

flexibility, but only in conditions with higher memory demand. However, the superior performance of the ASD children in terms of interference control may be because these children developed cue-target-response associations that helped them to be less affected by task-irrelevant information. Therefore, the critical difference between ASD children and typical children in task switching may be related to how they establish task representations and how they apply task rules. According to Just and colleagues (2006), executive dysfunction in ASD may result from poor coordination between brain regions that are necessary to complete complex cognitive tasks (for a review see Keehn et al., 2013).

Other atypical populations such as people with Alzheimer's disease (AD) showed poor selective and divided attention, failed inhibition of interference, and poor manipulation skills (Belleville et al., 2008; Kirova et al., 2015). Using a conceptual/spatial task-switching paradigm with pre-cueing, Belleville and colleagues (2008) compared the switching performance between AD patients and matched healthy controls. They found that AD patients had longer response times and made more errors, compared to controls. Moreover, AD patients showed larger switch costs in response times compared to healthy controls, suggesting that AD patients had difficulties in task-set reconfiguration. Practice failed to reduce the task-switching costs in AD patients. A further detailed task analysis showed that only when switching to the spatial task (i.e., identify the left-right location of a digit), AD patients needed at least two trials to recover to a pre-switch level, compared to one trial in the control participants, suggesting a specific deficit in spatial switching and attentional control in AD patients.

To sum up, according to previous studies on individual differences in task switching performance and various factors (e.g., Stoet & López, 2011; Tun & Lachman, 2008; Yee et al., 2016), it seems difficult to establish the nature of the different switching performance between induced emotions/motivations, typical and atypical participants, and across ages. In the present experiments it is therefore more difficult to reveal individual

differences in samples of typical university-student participants. For example, although in Experiment 1A I identified best performers and participants who performed relatively poor in task switching, they shared similar characteristics in their mean response times. They were also similar in response time switch costs in the cue-stimulus composite conditions. It is therefore unclear what specific factors contributed to their performances and whether they had different task-switching abilities, strategies, or just showed random variability.

5.5 Limitations and future directions

Studying individual differences in task switching is a complex topic because there are many factors that can affect individual differences, such as gender, age, educational background, personality, trait/state motivation, intelligence, and so on, that need to be considered when making comparisons between individuals. Participants showed considerably different task-switching performance, and when the same participants were studied in follow-ups and other conditions they also varied significantly in task-switching strategies and performance. Therefore, studying averaged-group performance in task-switching and the related cognitive tasks ignores individual variability. For example, it seems unlikely that every participant had the same task-switching effects and used the same strategy in an experiment.

This points to a limitation in the present thesis because in all experiments I did not try to control the strategy of participants but *assumed* that they have been motivated to engage in every cue-based preparation. Nevertheless, I demonstrated in Experiment 1A that when using a demanding experimental task a few participants did fully engage in advance preparation following task-cueing. I speculate that best performers, who showed no errors and no switch costs, efficiently prepared each upcoming task consistent with FTE account. The other participants, who made frequent errors, showed switch costs or both

occasionally fail to prepare. Alternatively, these participants might have used other strategies such as two-stage of reconfiguration which means they activated task rules after target onset leading to impaired switching performance. When employing more conventional task-switching paradigms and with different conditions in Experiment 1B and 1C, I also identified large individual differences in the mean response times and RT task-switch costs. Variations in task-switching performance may be due to different strategies across individuals.

A recent study indicated that participants can perform by associations, apply task rules, or both (Li et al., 2019a). In addition, participants may develop their own conjunctive rules, such as a “target-first” strategy as proposed by Li, Li, Liu, Lages and Stoet (2019b). In this study, non-Chinese participants were able to eliminate switch costs when they responded to Chinese characters. This is because they applied a target-first strategy which means that they processed the target stimulus before the cue in order to decide whether to apply task rules or use target-response associations. Participants can have even more complicated strategies when task switching. For example, three female participants in my Experiment 3 responded more quickly than the group average and showed switch costs that were smaller than zero. However, they may still have used different strategies between conditions because one of them showed reversed switch costs only in congruent trials while the other two showed reversed switch costs only in incongruent trials. Future research on cognitive tasks, such as task-switching studies should take individual variability into consideration in order to improve model fits and hypothesis testing and to make results more replicable.

Previous studies have identified supertaskers who demonstrated no decrements in dual task performance (Medeiros-Ward et al., 2014; Strayer & Watson, 2012; Watson & Strayer, 2010), “super-recognisers” who showed higher scores in facial recognition tests (Robertson et al., 2016; Russell et al., 2009), and “superior memorisers” who were

extraordinary when memorising long lists of items (Mallow et al., 2015; Ramon et al., 2016). Similarly, in the experiments of Chapter 2 I identified 9 best performers, to some extent conditional-based “super-switchers”, who showed high accuracy and consistently eliminated switch costs in conditions with preparation intervals across experiments. Based on Yehene and Meiran (2007) who argued that people may have a general switching ability, it is unclear whether people may also have a general cognitive ability that can be generalised to various cognitive and other related tasks. This is possible because performing in task switching, multitasking, and memory tasks require high level of executive functioning and some of cognitive or perceptual processes are shared between these tasks, such as interference control, task-set maintaining and task planning (for an editorial review see Strobach, Wendt & Janczyk, 2018). Future studies may investigate whether individuals would perform exceptionally in different complex task situation, and their distinct neural mechanisms.

5.6 Conclusions

The present thesis studied individual differences using different task-switching paradigms. By employing Generalised Linear Mixed-effects Models on single-trial response times, I found in all experiments that participants varied considerably in their mean response times and switch costs. A few participants were consistently better at task switching than others showing high accuracy and no switch costs across experiments and conditions. However, switch costs emerged when both cue and target stimulus were presented simultaneously. Therefore, I suggest that the superior switching performance may be due to efficient preparation following a task cue, associated with better cognitive control. In addition, better switching may be linked to higher general intelligence, intrinsic motivation, self-control, and lower levels of impulsivity. Although gender may play a less

important role when explaining superior performances, using a larger sample in Experiment 3 I found that female participants were slightly better than males at task switching in trials with longer preparation intervals. Females also showed a small advantage in interference control when the task was repeated in successive trials.

I also studied individual difference in trials with different cue types. In order to encourage typical participants to prepare efficiently, in Experiment 2A, 2B and 2C I designed priming cues that help to activate the relevant target features and response mappings in an upcoming trial. I found that compared to non-priming cues, RT switch costs were reduced in trials with a priming cue. Moreover, GLMM analyses suggest that with priming cues participants showed smaller deviations from the mean switch costs. ERP analyses suggest that in trials with priming cues efficient preparation was associated with cue-locked switch positivity at electrode Pz, independent of cue-stimulus intervals. I propose that priming cues may facilitate advance preparation but this may not be the case for all participants because individual differences in task-switching performance were observed for priming and non-priming cues. Participants may have different task-switching abilities in terms of cognitive control and motivation to engage in each upcoming trial but the variability in performance may also suggest the presence of idiosyncratic strategies to cope with task-switching demands.

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Appendix A. Experiment 2A target RTs and ERs following cue responses and without following cue responses

Mean target RTs and ERs following cue responses (yes; cue-response condition) and without following cue responses (no; standard condition) were analysed using an analysis of variance (ANOVA) with between-subjects factor Cue type (priming, non-priming) and within-subject factors Cue response (yes, no), Task (colour, shape), Trial transition (repeat, switch), and CSI (1100 ms, 1700 ms).

RTs

Task-switch trials (544 ms) were more slowly compared to task-repeat trials (507 ms), as indicated by a significant main effect of Trial transition, $F(1, 40) = 134.15, p < .001, \eta^2_p = .77$. Shape-task trials were more slowly (530 ms) compared to colour-task trials (521 ms), as indicated by a significant main effect of Task, $F(1, 40) = 5.25, p = .027, \eta^2_p = .12$. However, the main effects of Cue response ($F < 1$), CSI, $F(1, 40) = 2.79, p = .103, \eta^2_p = .01$, and Cue type, $F(1, 40) = 3.06, p = .088, \eta^2_p = .07$, were not statistically significant.

Trial transition significantly interacted with CSI, $F(1, 40) = 7.86, p = .008, \eta^2_p = .16$, suggesting that task-switch costs were larger in conditions with a CSI of 1100 ms (+43 ms) compared to conditions with a CSI of 1700 ms (+31 ms). Trial transition significantly interacted with Cue type, $F(1, 40) = 29.52, p < .001, \eta^2_p = .42$, suggesting that task-switch costs were larger in non-priming cues (+54 ms) than in priming cues (+19 ms). Moreover, Cue response significantly interacted with CSI, $F(1, 40) = 6.02, p = .019, \eta^2_p = .13$. A post hoc analysis suggested that target RTs were significantly longer in standard condition compared to cue-response condition in CSI 1700 ms (standard - cue-response =

22 ms, $p = .002$), whereas the difference was not significant in CSI 1100 ms (standard - cue-response = -9 ms, $p = .243$). There were no other significant effects for target RT.

ERs

For ERs, there were three significant main effects: Trial transition, $F(1, 40) = 49.09$, $p < .001$, $\eta^2_p = .55$, CSI, $F(1, 40) = 7.88$, $p = .008$, $\eta^2_p = .16$, and Cue response, $F(1, 40) = 90.92$, $p < .001$, $\eta^2_p = .69$, while there was no significant main effect of Cue type, $F(1, 40) = 1.03$, $p = .315$, $\eta^2_p = .03$, and Task, $F(1, 40) = 2.09$, $p = .156$, $\eta^2_p = .05$. I found that ERs were higher in task-switch trials (9.84%) compared to task-repeat trials (7.17%); and were higher in CSI 1100 ms (9.23%) compared to CSI 1700 ms (7.77%); finally, ERs were higher in cue-response condition (11.26%) compared to standard condition (5.74%).

In addition, Cue response significantly interacted with CSI, $F(1, 40) = 4.72$, $p = .036$, $\eta^2_p = .11$. ERs were higher in cue-response condition compared to standard condition in CSI 1100 ms (6.30%), relative to in CSI 1700 ms (4.75%). There were also significant three-way interactions between CSI, Cue response and Trial transition, $F(1, 40) = 5.40$, $p = .025$, $\eta^2_p = .12$, and between Task, Cue type and Cue response, $F(1, 40) = 7.27$, $p = .010$, $\eta^2_p = .15$. Moreover, there were significant four-way interactions between CSI, Task, Trial transition and Cue type, $F(1, 40) = 7.84$, $p = .009$, $\eta^2_p = .16$, and between CSI, Task, Cue type and Cue response, $F(1, 40) = 6.29$, $p = .016$, $\eta^2_p = .14$. No other interactions reached statistical significance.