1   General Introduction

1.1   The Mystery of Cognitive Control Processes

A person is capable of performing an immense variety of potentially complex behaviours or tasks at any given point in time. Yet, even seemingly simple tasks, such as catching a ball, require complex coordination and activation of intricate motor and cognitive processing systems. Vast amounts of knowledge have been accumulated regarding the structural and functional organisation of cognitive processes and their outcomes, such as memory retrieval capacities and face recognition abilities. However, the *control* of cognitive processes, that is what provides us with the ability to respond and adapt to constantly changing situational and contextual parameters based on short and long term goals, continues to remain a mystery. Recent research has thus been directed at investigating the nature of cognitive control processes.

The control of cognitive processes usually occurs efficiently and effectively facilitating purposeful behaviour. Consequently, the vital role played by cognitive control processes in human functioning is most evident when these processes fail. Temporary everyday failures are commonly experienced among normal healthy people, such as when habitual behaviours occur in inappropriate circumstances (Monsell, 1996). The importance of cognitive control processes in human functioning is also strikingly evident in the deficits exhibited by patients with prefrontal cortex lesions. Despite often achieving normal performance on many measures of neuropsychological functioning, frontal lobe patients demonstrate deficits in complex situations necessitating the organisation of multiple step tasks. These deficits result from an inability to organise, perform and switch between simple everyday tasks (e.g., Shallice & Burgess, 1991; Goldstein, Bernard, Fenwick, Burgess & McNeil, 1993; Levine et al., 1998; Burgess, 2000; Keele & Rafal, 2000). Prefrontal cortex dysfunction has also been associated with the decline in cognitive functioning associated with normal ageing (e.g., Williams et al., 1999) as well as with cognitive and behavioural problems evident in clinical conditions, including schizophrenia (e.g., Pantellis et al, 1997) and attention deficit hyperactivity disorder (e.g., Barkley, 1997).

Traditional theories of cognitive control are intertwined with the concept of prefrontal cortex functioning and tend to incorporate a unitary construct of executive function that is responsible for the control of cognitive processes, such as James's (1890) 'the will'. For example, Norman and Shallice's (1986) attention to action model features three main components including the supervisory attentional system. It is argued that this system is responsible for the organisation and performance of complex or novel behaviours through a top-down control process. Similarly, Duncan (1986) proposed a frontal lobe executive model, in which the frontal lobes are credited with facilitating the achievement of goals. Baddeley's (1986) working memory model also features an attentional controller, known as the central executive, which is responsible for supervising and coordinating lower systems and functions.

These models tend to perpetuate the myth that there is an intelligent 'little man', the homunculus, who resides in the prefrontal cortex and is responsible for directing and controlling subordinate cognitive functions (Monsell & Driver, 2000; Logan, 2003). While the conceptualisation of the homunculus and the attribution of control to a single ubiquitous executive was once a useful solution to easily explain the mystery of cognitive control processes, it fails to provide any tangible understanding about the nature of such processes. Over recent years, researchers have questioned the concept of an executive controller and have called for the homunculus to be 'banished' (Monsell & Driver) and 'exorcised' into non-existence (Hommel, Daum & Kluwe, 2004). This involves setting aside complex philosophical issues, such as debates over mind/body dualism and the existence of consciousness, and examining the nature of the processes that implement this control. Rather, than invoking the concept of a single control mechanism, it is possible that cognitive control may be exercised by multiple independently functioning systems without an identifiable single controller (Hommel, Ridderinkhof & Theeuwes, 2002; Monsell & Driver).

Current research efforts thus need to be directed towards the 'fractionation' of the homunculus (Monsell & Driver, 2000) by understanding how cognitive processes are controlled, what is doing this controlling and where in the brain this control stems from. Ideally,

converging evidence from different methodologies, including behavioural, psychophysiological, electrophysiological and neuroimaging, can contribute to the development of formal models of cognitive control that are testable and falsifiable. This is particularly important for understanding, and hopefully one day overcoming, the deficits in cognitive control processes evident in clinical conditions like schizophrenia (Hommel et al., 2002; Logan, 2003; Monsell, 1996; 2003; Monsell & Driver).

Early research on cognitive control processes used complicated multi-factorial tasks with a particular emphasis on testing patients with frontal lobe disorders (see Lezak, 1983; Stuss & Alexander, 2000). An example of such tasks is the Wisconsin Card Sorting Test (WCST; e.g., Heaton, Chelune, Talley, Kay, & Curtiss, 1993), a task designed to assess concept formulation, cognitive flexibility and abstract thinking abilities. Complex tasks like the WCST necessitate the involvement of 'higher-order' cognitive control processes *as well as* many 'lower-order' processes, such as those related to attention, memory and problem-solving (Monsell & Driver, 2000; MacDonald & Carter, 2002). When using such complex multi-faceted tasks, it is thus difficult to dissociate between deficits attributable to cognitive control processes and those due to impairments in subordinate mechanisms (Anderson, Damasio, Jones, Tranel, 1991).

To examine the nature of cognitive control processes, it is hence important that these processes are investigated using paradigms that permit isolation and differentiation of such control from any underlying components (Logan, 2003; Monsell & Driver, 2000). Recent research has tended to focus on identifying sub-components of cognitive control using very specific paradigms, such as the inhibition of responses in go/no-go and stop-signal paradigms (e.g., Logan, 1985; Rubia et al., 2001; van den Wildenberg, van der Molen & Logan, 2002) and switching attention between tasks in task-switching paradigms (e.g., Rogers & Monsell, 1995).

1.2   The Investigation of Cognitive Control using Task-switching Paradigms

Successful performance of any given task requires implementation of the specific configuration of cognitive processes that are necessary to perform the desired task. This configuration of the rules and procedures required for task completion is referred to as the

procedural 'schema' (Norman & Shallice, 1986) or 'task-set' (Monsell, 1996; 2003). In task-switching paradigms, participants are typically required to quickly alternate between multiple simple tasks throughout a block of trials. The time required to respond on any given trial is greater when the trial involves switching to a different task as compared to repeating the same task (e.g., reaction time to Task B is greater when it is preceded by the alternate Task A as compared to when it is preceded by the same Task B; Rogers & Monsell, 1995). This increase in reaction time (RT) for task switch trials is referred to as the RT switch cost, which is calculated by RT on task switch trials minus RT on task repeat trials. The nature of the processes that underlie this RT switch cost are very much under debate and will form a central element of discussion throughout this thesis. One formulation is that the RT switch cost indexes the execution of cognitive control processes involved in reconfiguring the currently active task-set to enable performance of Task B versus continued performance of Task A (Monsell, 1996; 2003; Rogers & Monsell, 1995).

Jersild's (1927; as cited in Spector & Biederman, 1976 and Rogers & Monsell, 1995) original task-switching paradigm compared RT to a block of trials on a single task with RT to a block of trials requiring alternating between two tasks. Participants were presented with written lists of digits. In the pure task condition, participants repeated the same task, such as subtracting three from every digit (e.g., Task AAAA). In the mixed task condition, participants alternated between two tasks, such as subtracting three from the first digit, then adding six to the next digit (e.g., Task ABABAB). Jersild calculated the cost of switching tasks by subtracting the average RT for completing the pure lists from the average RT for the mixed list. On average, the cost of switching tasks (i.e., the RT switch cost) was approximately one second per each item on the list. Spector and Biederman (1976) replicated Jersild's experiment presenting stimuli one at a time instead of altogether in a list to prevent cueing. They reported similar results, with a RT switch cost of approximately half a second per item (Experiment 3). This increase in RT for the mixed list of tasks was attributed by Spector and Biederman to processes involved in keeping

track of the outcomes of the previously performed task (e.g., if a participant had just subtracted three from the digit on the list, they had to remember to add three to the next digit).

These findings remained largely unnoticed until the early-to-mid 1990's when task-switching paradigms became a burgeoning field of research. While researchers were able to consistently replicate the finding of a RT switch cost, conflicting models were proposed to account for this effect. The early formulations of factors or components proposed to underlie the RT switch cost can be separated into two main models; the active reconfiguration of cognitive processes initiated by a control mechanism (Rogers & Monsell, 1995) versus automatically triggered effects that occur as a result of interference between multiple tasks. These interference effects are believed to passively dissipate over time and do not utilise any form of cognitive control process (Allport, Styles & Hsieh, 1994). Each of these models will be reviewed in turn.

1.3   Sources of RT Switch Cost: Active Task-set Reconfiguration

Early task-switching paradigms (Jersild, 1927; as cited in Spector & Biederman, 1976) have two main flaws restricting their ability to index any form of cognitive control. Firstly, as the mixed task condition requires continuous alternation between tasks (e.g., Task ABABAB), it can not be determined whether the switch cost is attributable to the need to alternate between task-sets on each trial or to the continuous activation of both task-sets throughout the run of trials. Secondly, performance on pure versus mixed task conditions may be differentially affected by motivation and arousal on the obviously more difficult mixed condition (Monsell, 1996). To overcome these problems, Rogers and Monsell (1995) developed the 'alternating runs paradigm' comparing performance on task switch and task repeat trials occurring within the same block of trials. Instead of having separate blocks of constantly switching tasks (e.g., Task ABA) or repeating the same task (e.g., Task AAA), their paradigm employed a predictable sequence of task-switching on every second trial (e.g., Task AABBAABB). This allowed task performance to be examined when the task was repeated (e.g., Task AA) versus when the task switched (e.g., Task AB).

To ensure predictability, participants were presented with a grid divided into four equal segments. Stimulus presentation rotated in a clockwise sequence around the four segments. As shown in Figure 1-1, participants were instructed to perform Task A (is the letter a vowel or a constant?) when the stimulus was presented in one of the top two segments and Task B (is the digit odd or even?) when the stimulus was displayed in one of the bottom two segments. Thus, for any given trial, the position of the stimulus validly indicated which task was to be performed on the current trial as well as which task would be required on the upcoming trial.
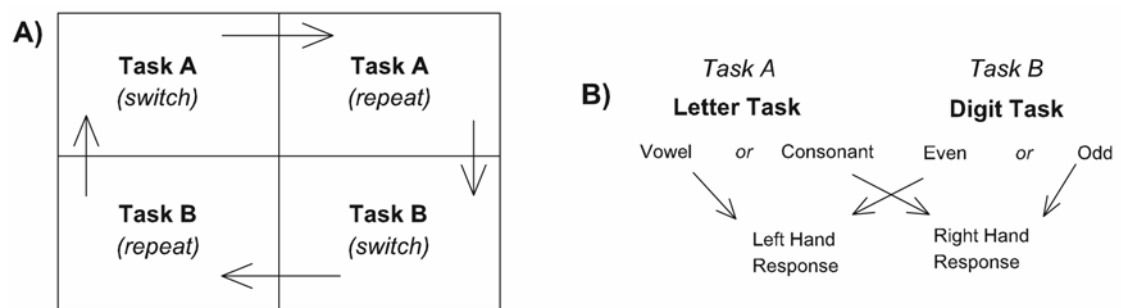

Figure 1-1. Rogers and Monsell's (1995) A) 2x2 grid showing predicable clockwise task alternation sequence and B) example task and stimulus-response mappings.

The results showed a large and reliable RT switch cost that remained robust despite extensive task practise, suggesting that switch cost effects can not be attributed to task learning. Rogers and Monsell (1995) argued that the switch cost reflects processes associated with or contributing to the process of 'task-set reconfiguration'. That is, switching from Task A to Task B is assumed to require the activation of cognitive control processes that oversee shifting from the set of task rules and procedures associated with Task A to the task-set of rules and procedures associated with Task B. The implementation of task-set reconfiguration is believed to underlie the increase in RT on switch trials.

To investigate this hypothesis, Rogers and Monsell (1995) varied the time interval between the response to the current stimulus and the onset of the next stimulus (response-stimulus interval; RSI) between 150 and 1200 ms. It was predicted that the longer RSI conditions, in combination with the predicable nature of the switch in task, would enable participants sufficient time to reconfigure the currently active task-set and be fully prepared for

the switch in task; thereby eradicating the RT switch cost. As shown in Figure 1-2 below, RT switch cost declined as the RSI increased from 150 to 600 ms across different blocks of trials. However, when the RSI increased from 600 to 1200 ms, only a slight further decline was detected and at this longest RSI of 1200 ms, a significant RT switch cost of 115 ms was still evident. Rogers and Monsell referred to this as the 'residual' switch cost.

Figure 1-2. Mean RT and RT switch cost from Rogers & Monsell (1995) Experiment 3.

Rogers and Monsell (1995) proposed that the process of task-set reconfiguration involves two separate components. Firstly, there is an active 'anticipatory' component that is evident in the sharply declining RT switch cost when the RSI increases to 600 ms. This anticipatory component is believed to involve the endogenous (i.e., internal) activation of cognitive control processes involved in preparing for the switch in task, such as the retrieval and transfer of the relevant task-set from long term memory into working memory. This anticipatory component of task-set reconfiguration can be initiated prior to stimulus onset when there is adequate opportunity (i.e., long RSI), leading to reduced RT switch cost. This endogenous process is argued to provide a valid index of a cognitive control process involved in switching between tasks. Secondly, there is a 'stimulus triggered' component that is exogenously (i.e., externally) activated by the stimulus itself. This process can not be activated in anticipation of the stimulus irrespective of the RSI and is reflected in the residual switch cost that remains even with an RSI of over one second.

De Jong (2000) proposed a different model to account for residual switch cost. De Jong largely replicated Rogers and Monsell's (1995) alternating runs paradigm using a predictable switch in task and also reported a residual switch cost at long RSIs. However, De Jong argues that residual switch costs do not reflect a separate component of task-switching as proposed by Rogers and Monsell, but rather occur as a result of a failure to engage in anticipatory task-set reconfiguration on some proportion of trials. As illustrated in Figure 1-3 below, the 'failure to

engage' hypothesis proposes that residual switch costs occur because, despite adequate foreknowledge and time, on some trials participants fail to engage in advance preparation.

De Jong (2000) argues that task-set reconfiguration is an optional single 'all-or-none' process. On some trials, participants may activate task-set reconfiguration in anticipation of an impending switch in task and on these trials there is no RT switch cost (see Figure 1-3, bottom left; compare first few percentiles for repeat / non-switch trials versus switch trials with a long RSI). On other trials however, task-set reconfiguration is delayed until after the presentation of the stimulus resulting in increased RT. This can occur due to a variety of factors, including time limitations, loss in concentration or a lack of motivation to prepare in anticipation of the stimulus. With a very short RSI, there is no opportunity for advance preparation on switch trials, and therefore the mean RT switch cost is high. With increasing RSI, task-set reconfiguration is engaged prior to stimulus onset on at least some proportion of trials, resulting in a reduction in the mean RT switch cost. However, as some trials remain unprepared even at the longest RSI due to failures to engage, a residual switch cost remains (i.e., there is a *mixture* of prepared and unprepared responses with a long RSI; see Figure 1-3, top right; compare last few percentiles for repeat / non-switch trials versus switch trials with a long RSI).

Figure 1-3. Cumulative distribution functions for task repeat and switch trials at short and long RSIs as reported by De Jong (2000, Figure 2). The model fit was produced by a mixture model with a probability of .51 that participants fully engage in advance preparation.

The failure to engage theory can thus account for residual switch cost without invoking the second stimulus-triggered component of task-set reconfiguration postulated by Rogers and Monsell (1995). Nieuwenhuis and Monsell (2002) tested De Jong's (2000) hypothesis by slightly modifying Rogers and Monsell's paradigm to include a payoff reward system for faster RTs (on both switch and repeat trials), extensive task feedback and a reduced number of trials in each block. It was hypothesised that this would increase motivation and assist in sustaining attention. This, in turn, was expected to maximise engagement in anticipatory task-set reconfiguration and minimise failures to engage. The results showed that despite the strong incentives and a decline in switch cost compared with Rogers and Monsell, a robust residual

switch cost was still evident. Thus, Nieuwenhuis and Monsell concluded that there is the need to retain the concept of a stimulus-triggered component in task-switching *in addition* to failures to engage in anticipatory task-set reconfiguration on some proportion of trials.

Brown, Lehmann and Poboka (2006) directly tested De Jong's (2000) RT mixture model of prepared versus unprepared responses with increasing RSI. Brown et al. argue that the simple mixture model predicts that RT distributions corresponding to different RSIs share a common 'fixed point'. However, replicating Rogers and Monsell's (1995) paradigm with RT distribution analysis, Brown et al. showed that there was no fixed point in the RT distribution, suggesting that the RT switch cost can not be accounted for by a single all-or-none process. Lien, Ruthruff, Remington and Johnston (2005) also concluded that task-set reconfiguration does not consist of a single all-or-none process. Their results suggest that preparation involves multiple components that can potentially be completed prior to stimulus onset depending on specific stimulus-response mappings. While these recent studies suggest that task-set reconfiguration is not a singular processes, as proposed by De Jong, failures to engage in anticipatory task-set reconfiguration on some proportion of trials can still partially account for the residual switch cost that remains even at a long RSI.

1.4   Sources of RT Switch Cost: Task-set Interference Effects

A completely different interpretation of the factors underlying the RT switch cost was proposed by Allport, Styles and Hseih (1994). These researchers used a variation of Jersild's original paradigm with Stroop-like stimuli presented on a predefined list of tasks. For example, Task A was to progressively read aloud through a list of colour words (e.g., red) that were printed in different coloured ink (e.g., 'red' written in blue ink); while Task B involved reading aloud lists of numerical values. The results showed that there was a RT cost associated with switching tasks. However, in contrast to Rogers and Monsell (1995), Allport et al. proposed that this RT switch cost results from 'task-set inertia'; the continued activation of the currently irrelevant task-set (i.e., positive priming) as well as the continued inhibition of the previously irrelevant, but now relevant task set (i.e., negative priming). This 'inertia' or interference then

slowly and passively dissipates over a period of time. For example, the information or 'task-set' required to complete the previous task remains active and only slowly fades away with time, regardless of any new information requiring processing.

However, as Rubinstein, Meyer and Evans (2001) argue, Allport et al.'s (1994) data provide only partial support for their hypothesis. In support of the task-set inertia hypothesis, Allport et al. report that the RT switch cost is smaller the larger the difference between the tasks (i.e., less overlap between the rules required to complete the different tasks reduces task-set interference effects, resulting in smaller RT switch cost). The RT switch cost is then greater when the task to be performed is in competition with a well practised, but now irrelevant task-set (i.e., when there is increased carryover inference from the irrelevant task-set, RT switch cost increases). Nevertheless, this is in conflict with Allport et al.'s finding that a RT switch cost was present when task-set inertia should be absent (e.g., long RSI), and that only minimal RT switch cost was found under conditions where task-set inertia should be present (e.g., short RSI, Rubinstein, Meyer & Evans).

To account for these discrepancies, Allport and Wylie (2000; see also Wylie & Allport, 2000; Waszak, Hommel & Allport, 2003) acknowledge that the RT switch cost can be marginally reduced by engaging in task preparation or task 'setting', as suggested by Fagot (1994). This process involves activating the goal to perform the alternate task and can potentially be initiated prior to stimulus onset. However, unlike Rogers and Monsell's (1995) anticipatory component of task-set reconfiguration, Allport and Wylie argue that this goal 'setting' does not necessitate the involvement of cognitive control processes, nor does it account for the significant reduction in RT switch cost with increasing RSI. Allport and Wylie argue that goal 'setting' to perform a specific task can be distinguished from the level of 'readiness' to perform the task (see also Fagot, 1994). It is the level of performance readiness that determines RT on any given trial (i.e., a higher level of readiness results in reduced RT switch cost). Readiness is affected by factors present at stimulus onset, including the amount of positive and

negative priming interference between task-sets. This task-set interference passively dissipates over time, leading to increased performance readiness, which results in reduced RT switch cost.

1.5   Cueing Task-Switching Paradigm

The models proposed by Allport & colleagues (e.g., Allport et al., 1994; Allport & Wylie, 2000) and Rogers and Monsell (1995) to account for the processes that underlie the RT switch cost, particularly the decline in RT switch cost with increasing RSI, have contradictory implications for the usefulness of task-switching paradigms in the study of cognitive control processes (Logan, 2003). If the decline in RT switch cost with increasing RSI is simply a consequence of declining levels of proactive interference from the previously active and currently irrelevant task-set, then task-switching paradigms can not help inform us about mechanisms of cognitive control (i.e., it is an entirely passive process being measured). However, if the decline in switch cost with increasing RSI reflects an endogenous process that actively modulates the level of activation of differing task-sets based on advance knowledge of which task will be relevant on the subsequent trial (i.e., Rogers & Monsell's anticipatory task-set reconfiguration component), task-switching paradigms may prove a powerful tool for studying the structure and function of cognitive control processes.

The paradigms used by Allport and colleagues (e.g., Allport et al., Allport & Wylie, 2000) and Rogers and Monsell (1995) do not enable differentiation between the relative contribution of passive dissipation of task-set interference and active preparation in anticipation of a predictable switch in task to the decline in RT switch cost with increasing RSI. In particular, in Rogers and Monsell's (1995) paradigm, since the sequence of tasks is fully predictable, preparation for a switch trial can begin any time after the decision is made to respond to the preceding stimulus. Hence, longer RSIs provide more time for *both* passive dissipation of the currently irrelevant task-set as well as greater opportunity to initiate active task-set reconfiguration of the currently relevant task-set.

In order to differentiate between the contribution of passive dissipation and active reconfiguration processes to the reduction in switch cost with increasing RSI, Meiran (1996)

used an explicit cueing paradigm. Rather than presenting switch and repeat trials in a predictable alternating sequence, the sequence of tasks was random and an explicit valid cue was presented within the RSI that indicated which task would be active on the subsequent trial. In Meiran's (1996) study, participants were presented with a two-by-two grid and the stimulus was a circle that could appear in any of the four squares. Task A required participants to identify whether the circle was located in either the left or right half of the screen (regardless of whether it was in the top or bottom square), while Task B required participants to identify whether the circle was located in either the top or bottom half of the screen (either left or right side). Alternation between tasks occurred unpredictably, with the task cued prior to stimulus onset by a pair of arrows appearing outside the grid. Task A was indicated by arrows appearing at the left and right of the grid and Task B was indicated by arrows at the top and bottom of the grid.

In order to dissociate the effects of anticipatory task-set reconfiguration processes from passive dissipation of the previous task set, Meiran (1996) manipulated the length of the RSI and the timing of the cue within the RSI. As illustrated in Figure 1-4 below, the period between the response on the previous trial and the timing of the instructional cue for the next trial (response-cue interval; RCI) was varied, with longer intervals leading to a longer overall RSI, providing increased opportunity for the passive dissipation of task-set interference. The period between cue onset and the onset of the next stimulus was also manipulated (cue-stimulus interval; CSI), with longer CSIs providing greater opportunity for the initiation of anticipatory task-set reconfiguration processes prior to stimulus onset.
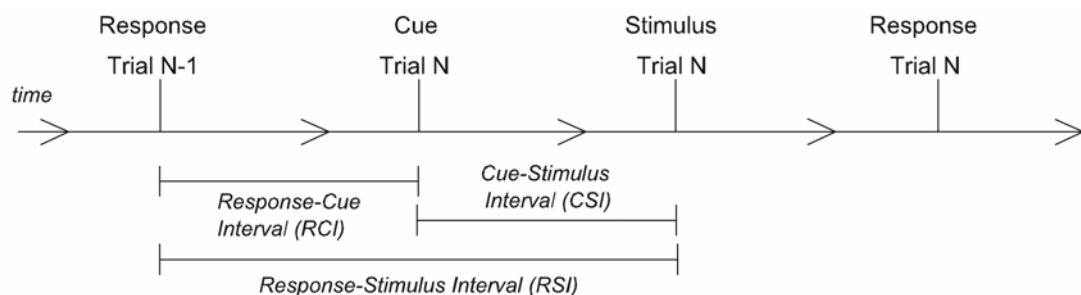

Figure 1-4. The timing of the displays used by Meiran (1996)

Using a constant RSI of 1848 ms and varying the CSI (132 versus 1632 ms), Meiran (1996) found that RT switch cost was significantly smaller in the long compared to the short CSI condition. Conversely, using a constant CSI of 117 ms and increasing the RSI (249 to 3139 ms), Meiran, Chorev and Sapir (2000) found that RT switch cost reduced significantly as RSI increased. The finding that RT switch cost reduced with increasing RSI *and* with increasing CSI suggest that both passive dissipation and active preparation processes contribute to RT switch cost. Additionally, that a residual switch cost remained, even with a CSI of almost two seconds (Meiran, 1996), supports the existence of a stimulus-triggered component of task-set reconfiguration that can not be completed until after stimulus onset. Meiran et al. (2000; see also Meiran, 2000a) thus proposed a three component model of task-switching, incorporating a passive 'waiting' component similar to that proposed by Allport et al. (1994), an active 'preparatory' component, corresponding to Rogers and Monsell's anticipatory task-set reconfiguration process and a stimulus-triggered 'residual' component, again similar to that of Rogers and Monsell.

Summary of Behavioural Task-Switching Findings

Task-switching paradigms have provided a method for specifically and empirically investigating the mystery of cognitive control processes. Across the varied paradigms (e.g., Rogers & Monsell, 1995; Allport et. al., 1994; Meiran et al., 2000) it has been demonstrated that RT is larger for trials where participants are required to switch tasks as opposed to repeating the same task. However, there is disagreement regarding the mechanisms that underlie this RT switch cost. Three main components appear to contribute to the RT switch cost; 1) an endogenously triggered process of anticipatory task-set reconfiguration that utilises cognitive control processes and may be initiated prior to stimulus onset if there is adequate opportunity and motivation, 2) task-set interference effects that passively dissipate over time and 3) stimulus-triggered processes that remain even with very long preparation intervals.

1.6   Event-Related Brain Potentials

While previous studies (e.g., Rogers & Monsell, 1995; Allport & Wylie, 2000; Meiran et al., 2000) suggest that switching between tasks involves a number of different processes, these studies are limited in their ability to differentiate between these processes as they rely solely on overt behavioural outcomes (e.g., RT and error data). As recent reviews highlight (e.g., Logan, 2003), converging evidence from different methodologies is an important step in furthering our understanding of the functional organisation and neural substrates of cognitive control processes. Considering the nature of the cognitive processes under investigation, brain activity measures appear to be a logical avenue for exploration, as they can provide information regarding the cognitive processes that lead up to an overt behavioural response. Analysis of event-related brain potentials (ERPs), in conjunction with behavioural data, can provide a unique vantage point from which to inform the debate over the number and type of components involved in task-switching and whether these components index a form of cognitive control.

ERPs are variations in brain electrical activity over time that are time-locked to specific events. ERPs are recorded from the scalp via surface electrodes and represent electrical fields associated with synchronously active populations of neurons (Rugg & Coles, 1995). The ERP reflects variations in voltage between two or more electrodes. Most commonly, ERPs are recorded between a selected array of electrodes connected to a single reference electrode that itself does not emit similar levels of electrical activity (e.g., the nose or mastoid bones). Electrode locations are traditionally described with reference to the 10-20 system, which details location in terms of brain region proximity (frontal, central, parietal, occipital or temporal) and lateral plane location (z for a midline location and an odd number for left or even number for right side location; Rugg & Coles).

ERPs are extracted from an ongoing electroencephalogram (EEG) through a process of signal averaging and filtering. This provides a method for identifying the occurrence of cognitive processing activities in the human brain with millisecond accuracy (Rugg & Coles, 1995; Picton et. al., 2000). ERPs for different stimulus types are derived by extracting time-

locked averages over repeated presentations of the same stimulus type. The assumption is that EEG activity not related to the process of interest (i.e., the background noise) will vary randomly across trials and will be removed by the averaging process. Therefore, the average ERP waveform will include only activity related to the process of interest. Averaged ERPs are sensitive to subtle changes in attention and other underlying cognitive functions. ERPs hence provide a method for testing and extending inferences made using other methods of data collection (e.g., behavioural measures) and can lead to further understanding of the brain mechanisms that underlie task performance (e.g., Callaway, 1975; Barrett, 1996).

ERPs are traditionally described in terms of components that are most commonly identified and quantified using amplitude (in μV) and latency (in ms) measures. Amplitude is usually measured in relation to a pre-stimulus baseline by deriving an averaged voltage level over a time period after stimulus onset. Latency is measured as the time between the onset of the stimulus and the onset or peak of the component of interest (Rugg & Coles, 1995). The exact definition and extraction of specific ERP components tends to be a somewhat contentious issue. However, a number of standard ERP components can be described that are reliably elicited under certain circumstances and may potentially be evident in ERPs recorded while performing a standard task-switching paradigm (e.g., the alternating runs paradigm of Rogers & Monsell, 1995). For example, in the interval between a warning stimulus and the onset of an imperative stimulus that requires a response, a large slowly building negative drift occurs in the ERP waveform that tends to peak around the time of the onset of the imperative stimulus. This component is known as the contingent negative variation (CNV) and is thought to reflect processes involved in preparation for the response to the imperative stimulus, including the orientating of attention and expectancy in readiness to respond (Walter, Cooper, Aldridge, McCallum & Winter, 1964; Loveless & Sanford, 1974).

Other ERP components have been closely associated with perceptual and attentional processes. The P300, or late positive component (LPC), is a positive peak in the ERP waveform occurring around 300-400 ms after stimulus presentation. Notably, the timing and size of this

component can vary widely, ranging anywhere between 250-900 ms and between 5 and 20 μV. The classic P300 is maximal over the central and parietal brain regions and is often referred to as the P3b (or parietal P3). This is in contrast with the P3a (or frontal P3), which tends to have a shorter latency and be more frontally distributed. The peak latency of the P3b component tends to vary based on RT and accuracy, with shorter P3b latencies associated with reduced RT and increased accuracy. It has hence been proposed that the P3b reflects processes involved in stimulus evaluation and the updating of memory context, with the relative speed of execution of these processes reflected by the P3b latency (McCarthy & Donchin, 1981; Donchin & Coles, 1988). In comparison, the frontal P3a has been associated with the involuntarily orientation of attention to a salient stimulus (Näätänen, 1990; Knight, 1991).

1.7   Task-switching and Event-Related Brain Potentials

Karayanidis, Coltheart, Michie and Murphy (2003) utilised Rogers and Monsell's (1995) alternating runs paradigm to identify ERP components associated with the anticipatory and stimulus-triggered processes of task-set reconfiguration. Given that the switch in task occurs in a predictable sequence, it was hypothesised that ERP components associated with anticipatory task-set reconfiguration would be identifiable in the ERP waveform after a response to the current trial and in anticipation of the subsequent switch trial (i.e., any effects associated with anticipatory preparation would be evident in the response-locked ERP waveforms that span across the RSI). Similarly, by definition, ERP components associated with the stimulus-triggered component of task-set reconfiguration should occur after the onset of a switch stimulus and thus be evident in the stimulus-locked ERP waveforms.

Karayanidis et al. (2003) replicated Rogers and Monsell's (1995) behavioural data, finding that as the RSI increased, RT switch cost tended to decline, although a residual switch cost remained even when the RSI was 1200 ms. In order to isolate ERP components associated with task-set reconfiguration from other ERP components reflecting common aspects of processing for both switch and repeat trials, ERP difference waveforms were constructed by

subtracting the ERP waveform for repeat trials from the ERP waveform for switch trials, thus extracting an ERP index comparable to the RT switch cost measure.

As shown below in Figure 1-5, response-locked ERP waveforms showed an increased positivity on switch as compared to repeat trials. This increased positivity occurring in anticipation of a switch trial began around 200-300 ms after the response to the previous trial. This switch-related differential positivity was termed D-Pos[2]. As the RSI increased, D-Pos peak latency remained stable at around 400 ms after the previous response. At short RSIs (i.e., 150, 300 ms), D-Pos began prior to stimulus onset, but peaked after stimulus onset, overlapping early ERP components associated with stimulus processing. At longer RSIs (i.e., 600, 1200 ms), D-Pos was superimposed on a CNV-like negativity and fully completed before stimulus onset. Karayanidis et al. (2003) interpreted the D-Pos as providing support for the endogenous anticipatory component of task-set reconfiguration. In the shorter RSI conditions, anticipatory task-set reconfiguration could not be activated or completed prior to the onset of the stimulus, thus leading to a larger RT switch cost. Conversely, in the longer RSI conditions (e.g., 600 ms; Figure 1-5), D-Pos peaked during the RSI, as the longer intervals provided adequate time to initiate and potentially complete anticipatory task-set reconfiguration prior to stimulus onset, leading to an optimal reduction in RT switch cost.

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[2]   As in Karayanidis et al. (2003), the terms D-Pos and D-Neg are used here as convenience labels / abbreviations to refer to the differential switch minus repeat positivity occurring prior to stimulus onset and the differential switch minus repeat negativity in stimulus-locked waveforms, respectively, without necessarily implying that each label represents a single ERP component, defines a new ERP component that is not evident in the original waveforms or reflects a single underlying cognitive process. Given that the identity, number and cortical source of ERP components differentially involved in task switching and the underlying cognitive processes are still being defined, there is no advantage to using existing ERP component labels to identify these effects until such correspondence has been empirically established. Therefore the terms D-Pos and D-Neg are merely labels that simply describe the pattern in the data.
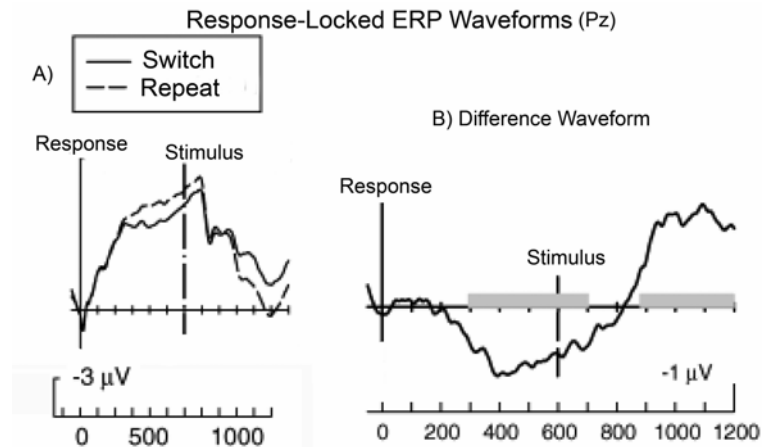
Figure 1-5. Response-locked A) switch versus repeat waveforms and B) difference waveforms (switch – repeat) at Pz with a 600 ms RSI (Karayanidis et al., 2003, extracts from Figures 6 and 7).

Stimulus-locked ERP waveforms showed a large posterior late positivity for both repeat and switch stimuli (Figure 1-6) that was reduced for switch trials. Karayanidis et al. (2003) interpreted this as reflecting a differential negativity for switch as compared to repeat trials (termed D-Neg). D-Neg was evident in all RSI conditions and emerged in some instances as early as 180 ms after stimulus onset. D-Neg tended to peak around 550 ms post-stimulus for short RSI conditions, but earlier (around 400 ms) for the longer RSI conditions. In the short RSIs, D-Neg emerged immediately following D-Pos, while in the longer RSIs, D-Pos was clearly differentiated from D-Neg. D-Neg was interpreted by Karayanidis et al. as reflecting the exogenous stimulus-triggered component of task-switching. The ERP data from Karayanidis et al. therefore supported Rogers and Monsell (1995) two component model of task switching, with the D-Pos in the RSI reflecting anticipatory task-set reconfiguration and the D-Neg after stimulus onset linked to stimulus-triggered processes.
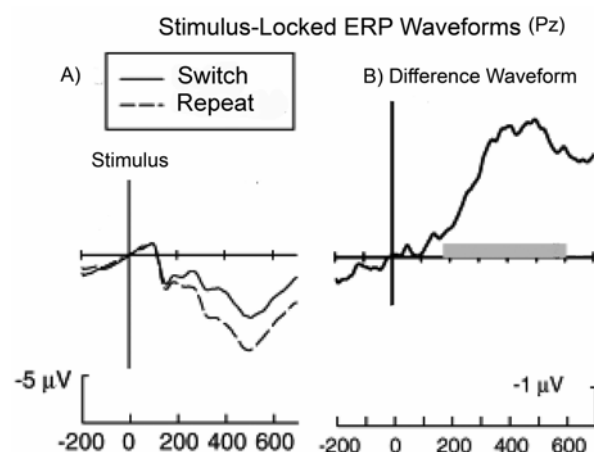
Figure 1-6. Stimulus-locked A) switch versus repeat waveforms and B) difference waveforms (switch – repeat) at Pz with a 600 ms RSI (Karayanidis et al., 2003, extracts from Figures 4 and 7).

A number of other studies have also used ERPs to examine the processes that underlie task-switching. However, relatively few studies have attempted to isolate cognitive control processes associated with anticipatory task-set reconfiguration, with most focusing on post-stimulus effects. Barceló, Perianez and Knight (2002; see also Barceló, Munoz-Cespedes, Pozo & Rubia, 2000) used a modified version of the WCST and recorded ERPs to feedback tones presented after every trial (CSI 1400 ms). These feedback tones indicated whether the response to the previous trial was correct and therefore whether to continue using the same classification rule (stay cue) or to change to one of the other two classification rules (switch cue; every 4-8 stay trials). ERPs to switch cues resulted in a large frontal positivity (350-400 ms) and a large later parietal positivity (550-600 ms) that reduced in amplitude for the first stay cue and was not evident in subsequent stay trials. Test cards also elicited a late parietal positivity that was smaller for switch feedback cues and increased over successive stay trials. These effects were interpreted as modulation of frontal P3a and parietal P3b components as a result of switching task-set and updating and/or implementing the new task-set, respectively. Note, however, that the feedback tones provided information not only as to whether to switch or stay task rule on the next trial, but also about whether the preceding response was correct.

Hsieh and Yu (2003) examined P300 and lateralised readiness potential (LRP) measures in a 2-choice switching task, which involved the reversal of stimulus-response mappings preceded by either an informative or non-informative cue. The LRP has been shown to reflect differential activation over the contralateral motor cortex in the lead up to an overt lateralised hand response. Stimulus-locked LRP is associated with pre-motor processes, such as response selection and activation, while the response-locked LRP is associated with response execution (Coles, 1989; Miller & Hackley, 1992). Hsieh and Yu found that RT and stimulus-locked LRP onset latency were larger for switch compared to repeat trials and for non-informative compared to informative cues, although there was no interaction between trial and cue type.

These results were replicated by Hsieh and Liu (2005) and Hsieh (2006) using a more complicated stimulus-mapping reversal task and letter (vowel or consonant) and digit (odd or even) tasks, respectively. Hsieh and Yu (2003) and Hsieh (2006) reported that the peak latency of the P300 and the onset latency of the response-locked LRP were not affected by either cue or trial type, while Hsieh and Liu found that P300 peak amplitude and latency were reduced for informative compared to the non-informative cues, but remained unaffected by task-switching. Hsieh and colleagues thus concluded that task-switching affects processes occurring after stimulus identification as none of the studies found any effect of trial type (switch or repeat) on the P300, while task cueing affects stimulus identification and response selection process that vary depending on the complexity of the task. Notably, despite the use of cueing manipulations (e.g., cued versus uncued trials) and a long CSI on cued trials (e.g., 1200 ms in Hsieh, 2006), none of the studies by Hsieh and colleagues examine ERPs at the onset of the cue, where any effects of anticipatory task-set reconfiguration may be expected to be evident.

A simple response-mapping switching paradigm was also used by Rushworth, Passingham and Nobre (2002). Participants were cued every 7-18 trials to either maintain or reverse stimulus-response mapping between two simple shapes and response hand. Their findings support a multi-component model of task-switching. With a 1200 ms CSI, cue-locked waveforms showed an early frontal switch-related positivity (360-520 ms) succeeded by a later posterior positivity (520-1040 ms), whereas stimulus-locked waveforms indicated greater early posterior negativity and later frontal positivity for switch compared to repeat trials. Rushworth Passingham and Nobre (2005) showed that switching attentional set (e.g., shifting between different stimulus dimensions) also produced large early modulation for switch compared to repeat waveforms. Cue-locked waveforms (CSI of 2000 ms) showed a right lateral frontal negativity and a left posterior positivity over 360-440 ms, followed by a later posterior central positivity spreading from 500 ms onwards. These effects were followed by a stimulus-locked negativity for switch compared to stay trials that persisted beyond the first few trials and occurred even on trials that did not require set implementation (i.e., no response).

Using the alternating runs paradigm of Rogers and Monsell (1995), Gladwin, Lindsen and De Jong (2006) also found that ERPs occurring in anticipation of a switch trial showed a differential parietal positivity for switch trials over approximately 250 to 600 ms after the previous response. Similarly, Wylie, Javitt and Foxe (2003) used a modified alternating runs paradigm with three run sequences (i.e., Task AAABBB). Stimulus-locked ERPs showed that, compared to repeat trials, pre-switch trials were associated with a large sustained posterior positivity emerging around 400 ms and a small anterior negativity. Wylie et al. concluded that the absence of a frontal anticipatory component argues against a reconfiguration process and interpreted the posterior sustained effect as reflecting a 'top-down' mechanism that adjusts the activation weights of the two task rules leading to increased competition between rules which, in turn, increase post-stimulus interference thus leading to RT switch costs. Note, however, that anticipatory processes were not examined in ERP waveforms time-locked to the likely onset of preparatory processes (e.g., readiness potential, response completion). Given trial-by-trial variability in RT, stimulus-locked waveforms are also likely to smear any ERP components time-locked to response onset.

Poulsen, Luu, Davey and Tucker (2005) used a cued version of the alternating runs paradigm (Rogers & Monsell, 1995) with a 450 ms CSI and overall RSI of 1150 ms. The ERP results showed that switch trials were more positive than repeat trials over centro-parietal sites beginning from around 350 ms after cue onset and extending until 300 ms after stimulus onset. Poulsen et al. found this effect to be larger during the first half of the experiment, which is consistent with Lorist et al. (2000), who found that increased fatigue from time on task is associated with reduced involvement of cognitive control processes in a task-switching paradigm. Miniussi, Marzi and Nobre (2005) used trial-by-trial cued switching (variable CSI of 500-900 ms) between verbal and spatial tasks that used distinct stimulus sets. Cue-locked switch waveforms showed an early anterior negativity followed by a posterior positivity spanning 440-600 ms after cue onset. These switch-related effects were larger on the more difficult verbal task. Most recently, Goffaux, Phillips, Sinai and Pushkar (2006) also report greater parietally

maximal positivity for switch relative to repeat trials during the CSI, although they refer to this as an increased negativity for repeat relative to switch trials, which remains even when RT on switch and repeat trials is equated.

Summary of Electrophysiological Task-Switching Findings

Behavioural task-switching studies show a RT cost associated with switching tasks that is presumed to arise at least partly as a result of processes involved in task-set reconfiguration. The analysis of this behavioural effect, in *conjunction* with the recording of ERPs, can provide greater understanding about the nature of task-set reconfiguration processes. A number of recent ERP task-switching studies provide strong evidence for differential processing of switch and repeat trials, both in anticipation of a switch in task and following presentation of the switch stimulus. In particular, a differential positivity has been identified that occurs in anticipation of a switch relative to a repeat in task that appears to be related to anticipatory task-set reconfiguration (e.g., Karayanidis et al., 2003, Rushworth et al., 2002; 2005), supporting the involvement of cognitive control processes in preparation for a switch in task. However, there is substantial variability within the somewhat ad hoc collection of current ERP task-switching studies regarding the number, distribution and range of differential switch versus repeat trial ERP effects. This variability, combined with an apparent lack of cohesion between behavioural and electrophysiological task-switching studies, limits the interpretation and application of ERP findings, particularly their ability to further understand the nature of the cognitive control processes involved in anticipatory task-set reconfiguration.

1.8   Overview of Experiments

The overall aim of this thesis was to investigate the behavioural and ERP correlates of processes involved in task-switching. Five experiments were conducted in a normative population that were designed to investigate the nature of task-set reconfiguration components. Specifically, the experiments aimed to expand previous findings suggesting an anticipatory component of task-set reconfiguration that indexes the active utilisation of cognitive control processes. It was expected that the combined analysis of behavioural and electrophysiological

measures would further inform the debate over the existence of, and the processes involved in, anticipatory task-set reconfiguration and contribute to models of cognitive control. The final experiment applied a task-switching paradigm to investigate deficits in cognitive control processes evident in clinical populations, in this case, individuals with schizophrenia.

Experiment 1: Karayanidis et al. (2003) reported that preparation for a switch in task is associated with increased parietal positivity for switch relative to repeat trials. However, due to the predictable nature of switch trials in alternating runs paradigms, the relative contribution of passive dissipation and active preparation processes occurring within the RSI can not be dissociated. Experiment 1 modified Rogers and Monsell's (1995) paradigm to incorporate an unpredictable task sequence with trial-by-trial cuing (e.g., Meiran, 1996). The CSI and RSI were independently manipulated to dissociate the effects of anticipatory preparation from the effects of passive dissipation of task-set interference. It was expected that RT switch cost would decline with increasing CSI *and* with increasing RSI, suggesting contribution from both active preparation and passive interference processes. If, as proposed by Karayanidis et al., the switch-related differential positivity reflects anticipatory task-set reconfiguration processes, this positivity would be evident in ERP waveforms time-locked to the onset of the cue and peak either before or after stimulus onset depending on the length of the CSI.

Experiment 2: Experiment 1 provided evidence that the switch-related differential positivity is associated with the anticipatory component of task-set reconfiguration. However, the mechanisms and processes underlying this component remain undefined. Experiment 2 was designed to investigate the intuitively most obvious mechanism contributing to anticipatory task-set reconfiguration: activation of the new task-set. This was examined by manipulating preparation for a switch in task using two types of switch cues. *Switch-to* cues signalled that the upcoming trial required a switch in task *and* identified the specific task to be performed. *Switch-away* cues also signalled a switch in task, but did not identify the specific task that would be relevant on the upcoming trial. This was not indicated until after stimulus onset for *switch-away* trials. If activation of the new task-set prior to stimulus onset is the crucial process of

anticipatory task-set reconfiguration that facilitates the reduction in RT switch cost with a longer preparation interval, increasing the CSI should facilitate a reduction in RT switch cost for *switch-to* trials *only* (i.e., a longer preparation interval would provide no benefit on *switch-away* trials). It was anticipated that if the switch-related differential positivity reflects anticipatory task-set reconfiguration, and more specifically, activation of the new task, this differential positivity should be evident following cue onset for *switch-to* trials, but be delayed until after stimulus onset for *switch-away* trials.

Experiment 3: An endogenous process of task-set reconfiguration is, by definition, under voluntary control. Participants may therefore fail to engage in anticipatory task-set reconfiguration even when there is a long CSI on at least some proportion of trials (De Jong, 2000). Experiment 3 aimed to develop a task-switching paradigm that encouraged engagement in anticipatory task-set reconfiguration on a maximal proportion of trials. Specifically, the cue was removed immediately prior to stimulus presentation and the stimulus itself carried no information about which task was currently relevant. Consequently, failure to process the cue prior to stimulus onset resulted in equivocation regarding which task was relevant on the current trial. RSI and CSI were manipulated as in Experiment 1. It was expected that if the current paradigm successfully encouraged engagement in anticipatory task-set reconfiguration on a greater proportion of trials, RT switch cost would be smaller in the long versus short CSI and that this difference would be greater than the equivalent reduction observed in Experiment 1 using the same RSI / CSI conditions.

Experiment 4: Logan and Bundesen (2003) suggested that the RT switch cost observed in cued task-switching experiments reflects a cue repetition benefit rather than an endogenous control process of task-set reconfiguration. Clearly this has ramifications regarding the usefulness of task-switching paradigms in the investigation of cognitive control processes. Experiment 4 was designed to investigate cue repetition benefits in task-switching paradigms using both behavioural and ERP measures. Two different types of cues were assigned to each task. These were based on either a colour or a shape (e.g., Task A = blue or circle cue; Task B =

orange or diamond cue). Task was cued 600 ms prior to stimulus onset. In addition to either a switch or repeat in task, there could also be a switch or repeat in the type of cue used (either colour or shape). It was expected that if the RT switch cost and differential ERP effects previously observed in Experiments 1-3 reflect task-set reconfiguration processes, a RT switch cost and cue-locked switch-related differential positivity should still be found for task switch relative to task repeat trials when controlling for a repeat or switch in cue category (colour or shape). Alternatively, if previously observed switch-related effects are attributable to a cue repetition benefit as suggested by Logan and Bundesen, a RT switch cost and cue-locked switch-related differential positivity should be evident when there is a switch relative to a repeat in cue category, irrespective of whether there is a switch or repeat in task.

Experiment 5: Differential ERP effects for task switch versus task repeat trials are consistently evident in Experiments 1-4, namely a switch-related differential positivity that emerges during the preparation interval. This differential positivity tends to be maximal over parietal electrodes, however little has been established regarding the topography and structure of this effect. Experiment 5 utilised independent component analysis (ICA) and low-resolution electromagnetic tomography analysis (LORETA) to investigate the underlying component and brain structures of the switch-related differential positivity. ICA was used to investigate the ERP component structure for switch and repeat waveforms during the CSI. It was expected that this may reveal an additional component occurring for switch trials only, which may be attributable to the differential positivity. LORETA was used to localise brain regions differentially activated on switch as compared to repeat trials during intervals within the CSI when the differential positivity was maximal. The LORETA findings were expected to be consistent with current studies using brain imaging techniques that suggest a prefrontal and parietal network of activation in preparation for a switch in task.

Experiment 6: People with schizophrenia tend to perform poorly on neuropsychological tasks requiring the use of cognitive control processes, such as the WCST. In order to identify the processes that underlie these cognitive deficits in schizophrenia, research needs to utilise

tasks that can specifically target and more closely isolate the use of cognitive control processes, such as the task-switching paradigm. In Experiment 6, the task-switching paradigm was applied to investigate whether schizophrenia is associated with a specific deficit in anticipatory task-set reconfiguration. Participants predictably switched between univalent tasks in an alternating runs paradigm (Rogers & Monsell, 1995) with blocked RSI manipulations. The alternating runs paradigm was selected to explore the effects of internally generated cues in schizophrenia (rather than explicit cueing as in Experiments 1-5). Schizophrenia was expected to be associated with impaired implementation of endogenously driven processes associated with anticipatory task-set reconfiguration, particularly under the current conditions that required internal generation of task cuing. This was expected to be manifested as a reduced benefit of increasing preparation interval (i.e., smaller reduction in RT switch cost with increasing RSI) and a reduction in ERP correlates of cognitive control processes (i.e., smaller switch-related differential positivity), for individuals with schizophrenia as compared with controls.

1.9   General Method

Participants

Participants in Experiments 1-5 were undergraduate students from the University of Newcastle, Australia, who participated in the experiments for course credit in an introductory psychology course. Participants had no prior exposure to the paradigm and all provided written informed consent. All procedures were approved by the University of Newcastle, Australia, Human Research Ethics Committee.

Stimuli and Tasks

Stimuli and tasks were presented on a computer screen viewed by participants from approximately 90 cm in a dimly lit room. Participants used their left and right index fingers to respond to buttons located on the arms of the chair in which they were seated. Stimuli were displayed on the screen until a response was generated or until 5000 ms elapsed. When an incorrect response was made, immediate auditory feedback (a single tone) was given and the onset of the next trial was delayed by 1000 ms. Participants pseudorandomly switched between multiple tasks, with the restriction that the same trial type (e.g., repeat or switch) could not be repeated on more than four successive trials.

Procedure

All participants attended two sessions, scheduled 2-14 days apart. The first session consisted solely of task practice. The second session involved another short practice session on the tasks followed by the testing session. Participants were randomly assigned to cue-task and stimulus-response mapping conditions, which were counterbalanced across participants. For each participant, the assigned cue-task and stimulus-response mappings were held constant across practice and testing sessions. During practice sessions, cue-task and stimulus-response mappings were continuously displayed underneath the computer monitor. Participants were instructed to respond as quickly as possible, while maintaining a high level of accuracy. At the start of each block of trials, participants were informed of the specific RSI and CSI being used and were always encouraged to use the CSI to prepare for the next trial. Following each run,

behavioural feedback (overall mean RT and percentage of trials correct) was displayed and participants were encouraged to monitor and improve their performance.

Data analysis

Initial 'warm-up' trials at the beginning of every run, trials associated with an incorrect response, trials immediately following an incorrect response and trials associated with a response occurring outside a 200 to 2000 ms window after stimulus onset were excluded from all behavioural and ERP analyses. The maximum RT window of 2000 ms was selected to prevent extensive drift in the ERP waveforms related to the very late onset of response processes on the small proportion of trials occurring beyond this RT range (on average across experiments, RT exceeded 2000 ms on only 1-2% of trials). RT and error switch cost were calculated by subtracting the value on switch trials from the value on repeat trials. Percentage error rates were arc sine transformed to normalise the distribution (Vasey & Thayer, 1987). EEG was recorded from scalp electrodes placed according to the 10/20 system. Vertical electro-oculogram (EOG) was recorded bipolarly from electrodes attached to the supra-orbital and infra-orbital ridges of the left eye. Horizontal EOG was recorded bipolarly from electrodes placed on the outer canthi of each eye. Vertical eye-blink artifact was corrected (Semlitsch, Anderer, Schuster & Presslich, 1986; as implemented in NeuroScan 4.3 software). Continuous EEG files were manually inspected offline and sections with movement or muscle artifact (+100 or -100 µV) or channel saturation were excluded from further analysis.

ERP difference waveforms were derived by subtracting the average ERP repeat waveform from the average ERP switch waveform for each participant. These were analysed using the Guthrie and Buchwald (1991) procedure. For both behavioural and ERP analysis of variance (ANOVAs), degrees of freedom for factors with more than 2 levels were adjusted using Greenhouse–Geisser correction for the violation of the assumption of sphericity (Vasey & Thayer, 1987). Where multiple simple effect contrasts were performed, significance levels were adjusted with Bonferroni correction. Standard error values were calculated using the method for within-subjects designs by Loftus and Masson (1994).

2   Experiment 1: ERP correlates of task-switching processes [3]

The RT switch cost is presumed to reflect, at least partially, processes associated with or contributing to task-set reconfiguration (Rogers & Monsell, 1995), a set of processes involved in shifting from a readiness to perform Task A to a readiness to perform Task B. In Rogers and Monsell's alternating runs task-switching paradigm, increasing the RSI from 150 to 1200 ms resulted in a significant decline in RT switch cost. Rogers and Monsell proposed that this reflects an active anticipatory component of task set reconfiguration that is endogenously triggered and that, given adequate foreknowledge and time, can be initiated prior to stimulus onset. This anticipatory component is thought to involve processes such as suppression of the previously active but now irrelevant task-set and activation of the previously inactive and currently relevant task-set. The reduction in RT switch cost with increasing RSI has also been attributed to passive dissipation processes associated with the relative level of activation of task-sets and stimulus-response interference (Allport et al., 1994; Allport & Wylie, 2000).

ERPs can inform the debate over the number and type of processes underlying the RT switch cost because they provide information regarding the timeline of processes leading up to the behavioural response. An increasing number of studies have used ERPs to examine the processes that underlie task-switching, however few have attempted to isolate processes associated with anticipatory task-set reconfiguration (e.g., Barceló, Perianez & Knight, 2002; Barceló, Munoz-Cespedes, Pozo & Rubia, 2000; Hsieh & Yu, 2003; Hsieh & Liu, 2005; Hsieh, 2006). An exception to this is Karayanidis et al. (2003), who used the alternating runs paradigm (Rogers & Monsell, 1995) to identify ERP components associated with anticipatory task-set reconfiguration in waveforms time-locked to the onset of the previous response in anticipation of the impending switch in task. Response-locked waveforms showed a large parietally-maximal differential positivity for switch compared to repeat trials (Figure 1-5). This differential positivity peaked either before or after stimulus onset depending on the length of the

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[3] Published as Nicholson, R., Karayanidis, F., Poboka, D., Heathcote, A., & Michie, P. (2005). Electrophysiological correlates of anticipatory task-switching processes. *Psychophysiology, 42(5), 540-554*. See Appendix.

RSI and was interpreted as reflecting processes involved in anticipatory task-set reconfiguration. Using a similar paradigm, Gladwin, Lindsen and de Jong (2006) found that ERPs occurring in anticipation of a switch trial showed a differential parietal positivity for switch trials over approximately 250 to 600 ms after the previous response. Wylie, Javitt and Foxe (2003) also reported that trials preceding a predictable switch in task were associated with a larger sustained posterior positivity compared to trials preceding a repeat in task.

The alternating runs paradigm used in the above three studies can not precisely locate the onset of an anticipatory task-set reconfiguration process. The predictable nature of the paradigm means that participants are aware of whether the next few trials will require a switch or repeat in task and anticipatory task-set reconfiguration can thus commence at any time. The paradigm also confounds processes associated with the execution of a response to trial *n* with the likely onset of anticipatory preparation for trial *n+1*. In addition, the alternating runs paradigm can not separately identify the effects of anticipatory task-set reconfiguration versus greater passive dissipation of task-set interference, with longer RSI conditions providing increased opportunity for both processes to occur. Meiran and colleagues (Meiran, 1996; Meiran et al., 2000) used trial-by-trial task cueing to examine the relative contribution of passive dissipation and anticipatory preparation to RT switch cost. Increasing RSI (Meiran et al., 2000) and increasing CSI (Meiran, 1996) both produced a significant reduction in RT switch cost, supporting the involvement of both active preparation and passive dissipation processes in task-switching.

A number of studies have now examined task-switching ERP effects using cued switching paradigms. Consistent with the ERP studies using predictable switching paradigms (e.g., Karayanidis et al., 2003), these studies have also reported a parietally maximal switch-related positivity that peaks at around 400-500 ms after onset of the cue, which appears to correspond with anticipatory task-set reconfiguration processes (e.g., Rushworth, Passingham & Nobre, 2002; 2005; Miniussi, Marzi & Nobre, 2005). However, none of these studies have systematically manipulated the duration of RSI and CSI. As a result, the long CSI confounds

effects of passive processes associated with task-set interference and active processes associated with task-set reconfiguration on RT and ERP measures.

Experiment 1 used a cued version of the alternating runs paradigm (Rogers & Monsell, 1995) in order to confirm the relationship between the differential switch-related positivity observed by Karayanidis et al. (2003) and task-set reconfiguration components. Specifically, this experiment was designed to dissociate and further investigate the behavioural and ERP effects of anticipatory task-set reconfiguration versus passive dissipation of task-set interference. Like Rogers and Monsell, stimuli were presented on a 2x2 grid and each quadrant on the grid was mapped to one of the two tasks (Figure 2-1). However, the sequence of tasks was random and each trial commenced with a cue that validly indicated the position of the next stimulus and hence the task to be completed (e.g., Meiran, 1996). Passive dissipation of the competing task-set was examined by varying the duration of the RSI (short: 750 ms versus long: 1200 ms) for fixed CSI in different blocks of trials. The opportunity for anticipatory preparation was manipulated by varying the duration of the CSI (short: 150 ms versus long: 600 ms) for a fixed value of RSI.

Based on earlier findings (Meiran, 1996; Meiran et al., 2000), it was expected that RT switch cost would be smaller for long as compared to short RSI conditions and for long as compared to short CSI conditions. If the differential switch-related positivity identified by Karayanidis et al (2003) reflects anticipatory task-set reconfiguration processes, it was expected to be closely time-locked to cue onset, regardless of the CSI.

With very short CSIs (e.g., 150 ms), it has been argued that cue processing may disrupt subsequent stimulus processing, resulting in artificial inflation of RT switch cost (e.g., Logan & Bundesen, 2003). Therefore, the current study included a no cue condition in which the stimulus location alone signalled the task to be completed on a given trial (i.e., there was no cue preceding stimulus onset). If, at short CSI, cue processing disrupts subsequent stimulus processing then, when controlling RSI, RT switch cost should be larger for the short CSI condition compared to the no-cue condition. Alternatively, even a short CSI of 150 ms may be

sufficient to elicit task-set reconfiguration processes, in which case, RT switch cost should be *smaller* for the short CSI condition as compared to the no cue condition. Earlier studies that manipulated RSI alone have suggested that 600 ms represents an optimal preparation period, with minimal reduction in RT switch cost with further increases in RSI (e.g., Rogers & Monsell, 1995). In order to examine whether 600 ms also represents an optimal value for CSI, RT switch cost was compared for two conditions that both had an RSI of 1200 ms and CSI of 600 ms and 1050 ms, respectively.

2.1   Method

Participants

Twenty-four undergraduate students (mean age 22.2 years, range 18 to 30; 15 women).

Stimuli and Tasks

A rectangular box (15 by 13.5cm) divided into four equal quadrants was continuously displayed. In the cued conditions, the cue was a brightening of the line defining one of the quadrants (from grey to white). A stimulus was displayed in the centre of the highlighted quadrant. Two adjoining quadrants were assigned to a letter task and the other two to a digit task (Figure 2-1a). The letter task was assigned to the top two quadrants for half of the participants, and to the right two quadrants for the other half of participants. Thus, the association between eye shifts (vertical versus horizontal) and trial type (switch versus repeat) was counterbalanced across participants.

For the letter task, stimuli were selected from a set of four vowels (A, E, I, U) or four consonants (G, K, M, R). For the digit task, stimuli were selected from a set of four odd (3, 5, 7, 9) or four even (2, 4, 6, 8) numbers. Participants used their left and right index fingers to respond vowel or consonant for the letter task and odd or even for the digit task (Figure 2-1b). The hand assigned to each response was counterbalanced across participants.
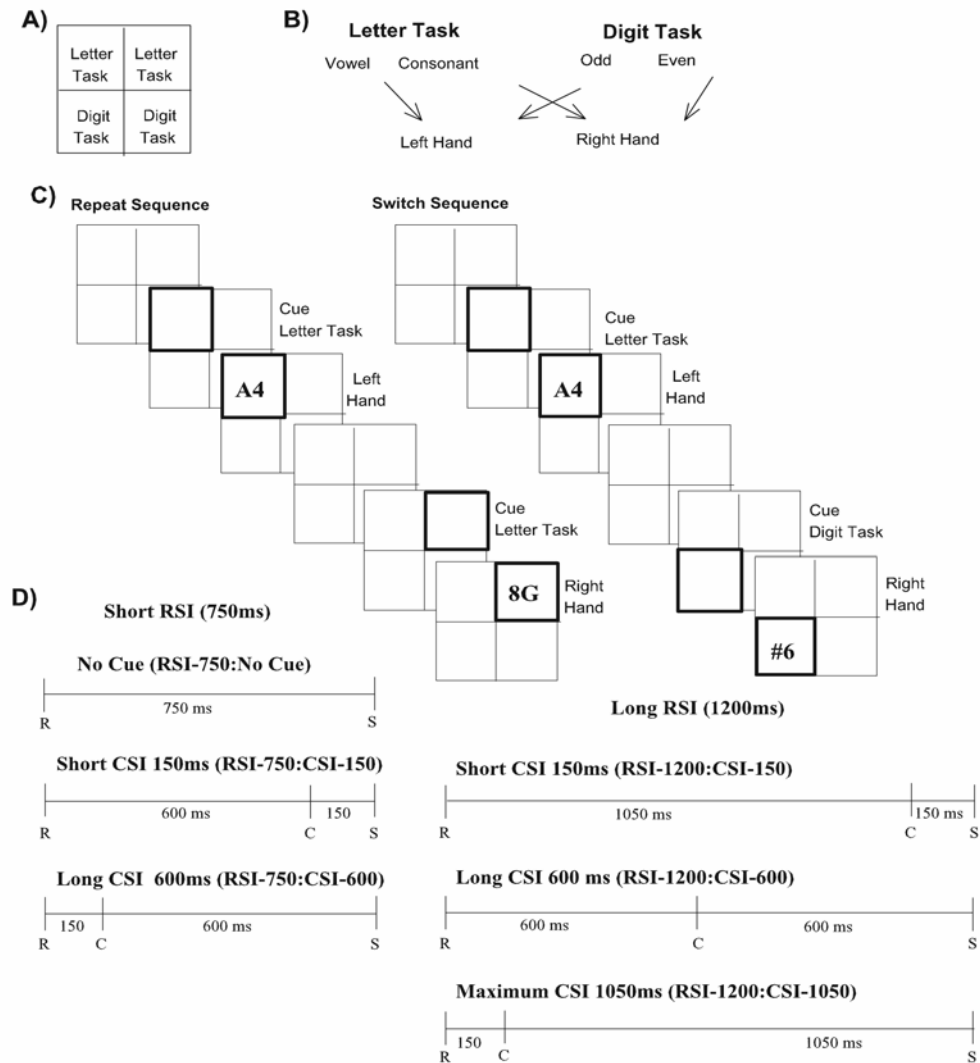
Figure 2-1. A) Stimulus display grid. Two adjoining positions were assigned to each task. B) Stimulus response mapping example. C) Examples of repeat and switch trial sequences. The cue was a highlight displayed around the specific box. D) Depiction of Short (left) and Long (right) RSI & CSI conditions.

Stimuli consisted of a pair of characters in Times New Roman font. One character was selected from the currently active task-set (e.g., letters for the letter task). The second character was selected from either a neutral set (non-alphanumeric characters: #, ?, *, %) or from the task-irrelevant set (e.g., digits for the letter task). The task-relevant character was accompanied by a non-alphanumeric task-irrelevant character on one third of the trials (neutral stimulus, e.g., A%). On another third of trials, the irrelevant character was mapped to a response on the opposite hand (incongruent stimulus; e.g., "A4" vowel–left hand, even–right hand), while for the remaining third, the irrelevant character was mapped to the same hand (congruent stimulus; e.g., "A3" vowel–left hand, odd–left hand). The order of the task-relevant and irrelevant

character was varied randomly across trials (e.g., M%, %M). Stimuli were randomly selected from the respective character set with the restriction that the same stimulus from any set could not appear on two successive trials. In cued conditions, the cue remained visible throughout the duration of the stimulus. After a response, the next cue could occur in either the horizontally or vertically adjacent quadrant, indicating the location of the next stimulus and hence the task to be performed (Figure 2-1c). Thus, on successive trials, the cue never repeated in the same location and never shifted to the diagonally opposite location.

Overall six conditions were included. Condition labels represent the duration of the RSI (e.g., RSI-750 = RSI of 750 ms) and CSI (e.g., CSI-150 = CSI of 150 ms). Four conditions orthogonally manipulated RSI and CSI (Figure 2-1d). RSI was manipulated across two levels: short (750 ms) and long (1200 ms). CSI manipulated across 2 levels: short (150 ms) and long (600 ms). A fifth condition included a long RSI (1200 ms) and a longer CSI of 1050 ms. This condition was compared to RSI-1200:CSI-600 condition to determine whether switch cost reduces further as CSI increases beyond 600 ms. Note that in all these conditions, stimulus position provided a redundant cue for task type. The final condition was the No-Cue condition with an RSI of 750 ms. Here, a stimulus appeared 750 ms after a response to the preceding stimulus and its position validly indicated which task was to be performed. The No-Cue condition was compared to the short CSI condition with the same RSI in order to examine whether such a short CSI presents any benefit.

Procedure

The first session included task training initially on each task alone and then in switching between tasks and practice with each of the six conditions. The second session included further practice followed by testing. Participants completed a total of 900 training and practice trials on the tasks before testing. Behavioural and continuous EEG were recorded during the testing session that consisted of six conditions presented in blocks of three 100-trial runs (conditions were order counterbalanced using Latin square design). The first four trials of every run were considered dummy \ warm-up trials and were discarded from analysis.

Data analysis

RT and error switch cost were calculated by subtracting the value on switch trials from the value on repeat trials. RT and arc sine transformed proportion error data were analysed initially using a 6 condition by 2 trial type (switch, repeat) by 2 task (letter, digit) repeated measures ANOVA. As task did not interact with any other factor, all further analyses were averaged across task.

The relative contribution of CSI and RSI manipulations on switch cost were examined using a 2 RSI (750, 1200 ms) by 2 CSI (150, 600 ms) repeated measures ANOVA. To examine whether, for a fixed value of RSI, RT switch cost declined further as CSI increased beyond 600 ms, CSIs of 600 and 1050 ms were compared at RSI 1200 ms. To examine whether a CSI of 150 ms facilitated or disrupted task-set reconfiguration compared to the No-Cue condition, these two conditions were compared at 750 ms RSI. Finally, a one-sample t-test was conducted for 1050 ms CSI condition to examine whether a significant residual RT switch cost remained at the long RSI with maximal cueing.

EEG recording and data analysis

EEG was recorded from 12 scalp electrodes according to the 10/20 system using an electrode cap (Electro-cap International) and linked mastoids reference. EEG and EOG were continuously sampled at 500Hz/channel using NeuroScan Inc. software. EOG and EEG were amplified (x 5000 for EOG and frontal channels; x 20 000 for other EEG channels) using a Grass Neurodata system (Model 12) with a bandpass of 0.01-30 Hz (-6 dB down).

Response-locked, cue-locked and stimulus-locked averages were created by extracting 1400 ms epochs around the onset of the response, cue or stimulus respectively, including a 200 ms pre-onset interval. Baseline was set to -50 to 50 ms around the onset of the response, cue, or stimulus. This short baseline was used because of relatively large pre-baseline shifts resulting from post-response negativity in short RCI conditions and build-up of CNV in long CSI conditions (Karayanidis et al. 2003).

Within each condition, ERP waveforms were averaged across task (letter/digit) and congruency (neutral/incongruent/congruent) in order to increase signal to noise ratio. Cue- and stimulus-locked epochs within each condition were averaged separately based on whether the current trial required a task switch or repeat. Ten cue-locked (5 cue conditions by 2 trial types) and twelve stimulus-locked (6 conditions by 2 trial types) ERP average waveforms were created for each participant at each electrode site. Response-locked epochs within each condition were averaged separately depending on whether the following cue (i.e., the cue on trial *n+1*) signalled a switch or repeat trial. This enabled direct comparison between response-locked, cue-locked and stimulus-locked data.

Difference waveforms were derived by subtracting the average ERP switch waveform from the average ERP repeat waveform for each participant. Thus, six response-locked, five cue-locked and six stimulus-locked difference waveforms were created for each participant at each of the twelve electrode sites. Response-, cue- and stimulus-locked difference waveforms were analysed using point-by-point t-tests over 0-700 ms to establish points of significant deviation from baseline. This analysis was only conducted at the midline sites (Fz, Cz, Pz and Oz) after visual inspection of grand averages indicated that the effects of switching were maximal at midline and did not show any discernible differences at lateral electrodes. The Guthrie and Buchwald (1991) procedure was used to control for Type 1 error at $\alpha= 0.05$ using an autocorrelation coefficient of 0.9. Only effects significant by these criteria are reported.

Based on the results of the above analyses, mean amplitude measures were extracted for the differential switch-related positivity over 350 to 400 ms after cue onset. Mean amplitude measures were taken and rescaled (McCarthy & Wood, 1985) at the four midline sites (Fz, Cz, Pz & Oz). Interactions between electrode site and other factors are only reported when they remained significant after rescaling. Where significant interactions between electrode and one of the other factors emerged, separate analyses were conducted at each midline site using Bonferroni family-wise correction. The effects of CSI and RSI manipulation on D-Pos amplitude were analysed using an electrode (Fz, Cz, Pz, Oz) by CSI (150, 600 ms) by RSI (750,

1200 ms) repeated measures ANOVA. The effects of increasing CSI beyond 600 ms were examined using an electrode by CSI (600, 1050 ms) repeated measures ANOVA. Short CSI and No-Cue conditions were compared using an electrode by CSI (No Cue, 150 ms) repeated measures ANOVA.

2.2 Results

Behavioural Data

RT switch cost ranged between 82 and 182 ms in different conditions (Figure 2-2). RT switch cost was significantly smaller for long (1200 ms) than short (750 ms) RSI conditions ($F_{(1,23)}=19.5$, $p<.001$) and for long (600 ms) than short (150 ms) CSI conditions ($F_{(1,23)}=23.4$, $p<.001$). Thus, RT switch cost reduced with increasing values of both RSI and CSIs. Although the effect of increasing CSI on RT switch cost tended to be greater for short than for long RSI (48 versus 35 ms), the interaction between RSI and CSI was not significant ($F<1$). For 1200 ms RSI, increasing CSI from 600 ms to 1050 ms resulted in no further reduction in RT switch cost ($F<1$, Figure 2-2) and a significant residual RT switch cost of 82 ms remained at a CSI of 1050 ms ($t(23)=7.53$, $p<.001$). At 750 ms RSI, RT switch cost was 25 ms smaller at short CSI (150 ms) compared to the No-Cue condition ($t(23)=2.9$, $p<.01$; Figure 2-2). Overall, accuracy levels were very high, with error switch cost ranging from 1% to 2.4% (Figure 2-2). There was no effect of RSI or CSI on error switch cost ($F<1$), no difference between no cue and short cue conditions or between 600 and 1050 ms CSI. However, error switch cost significantly differed from zero in the latter CSI condition ($t(23)=2.86$, $p<.01$).
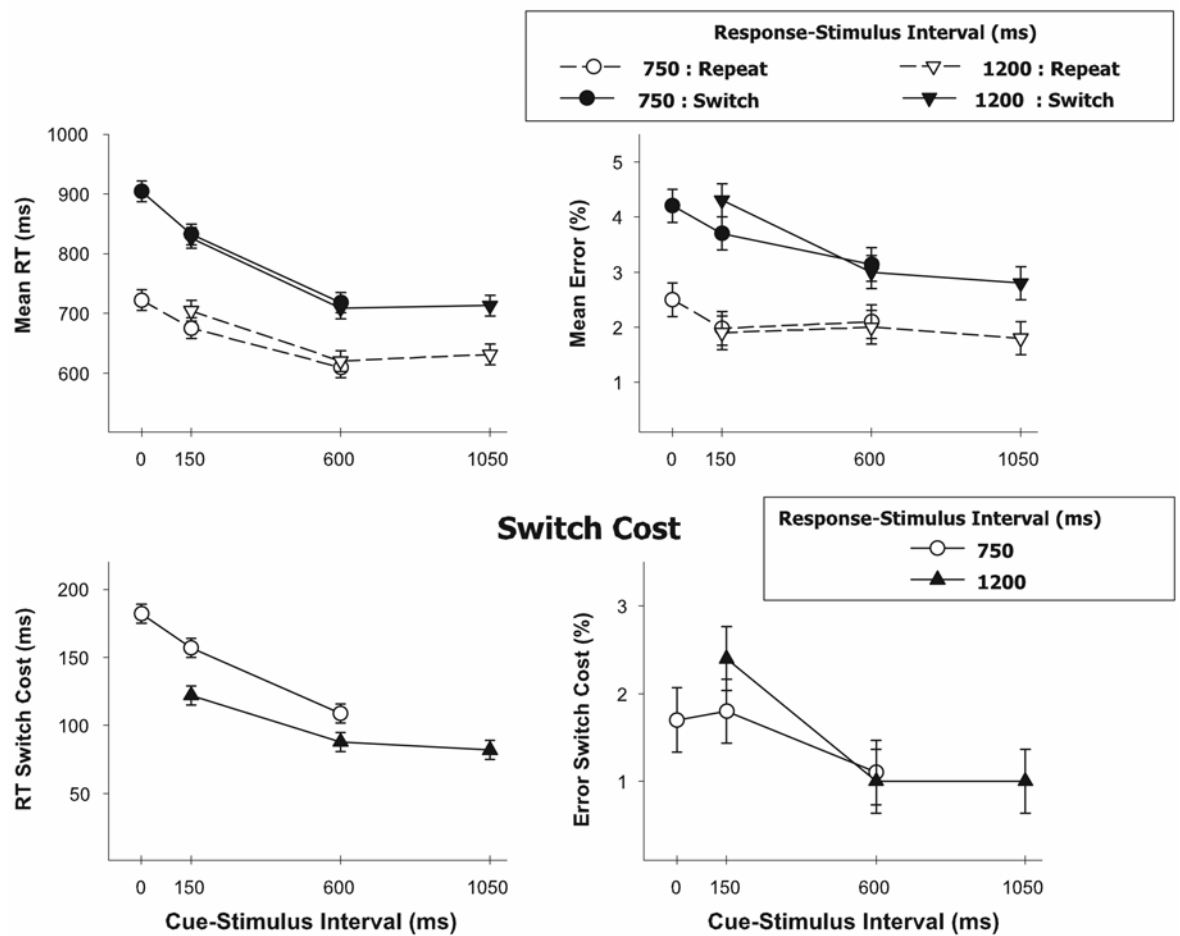
Figure 2-2. Top. Mean RT and percent error for each RSI and CSI condition. Bottom: RT and error switch cost. Standard error bars are shown.

ERP Data

Cue-locked waveforms

Cue-locked ERP average waveforms for switch and repeat trials are shown in Figure 2-3 for each condition at four midline sites. Early cue processing ERPs overlapped with a post-response negativity in conditions that have a very short interval between the response to the preceding stimulus and the onset of the next cue (i.e., RCI is 150 ms in the short RSI condition with a CSI of 600 ms and in the long RSI condition with a CSI of 1050 ms) and with stimulus-locked ERPs in conditions with short CSI (150 ms).
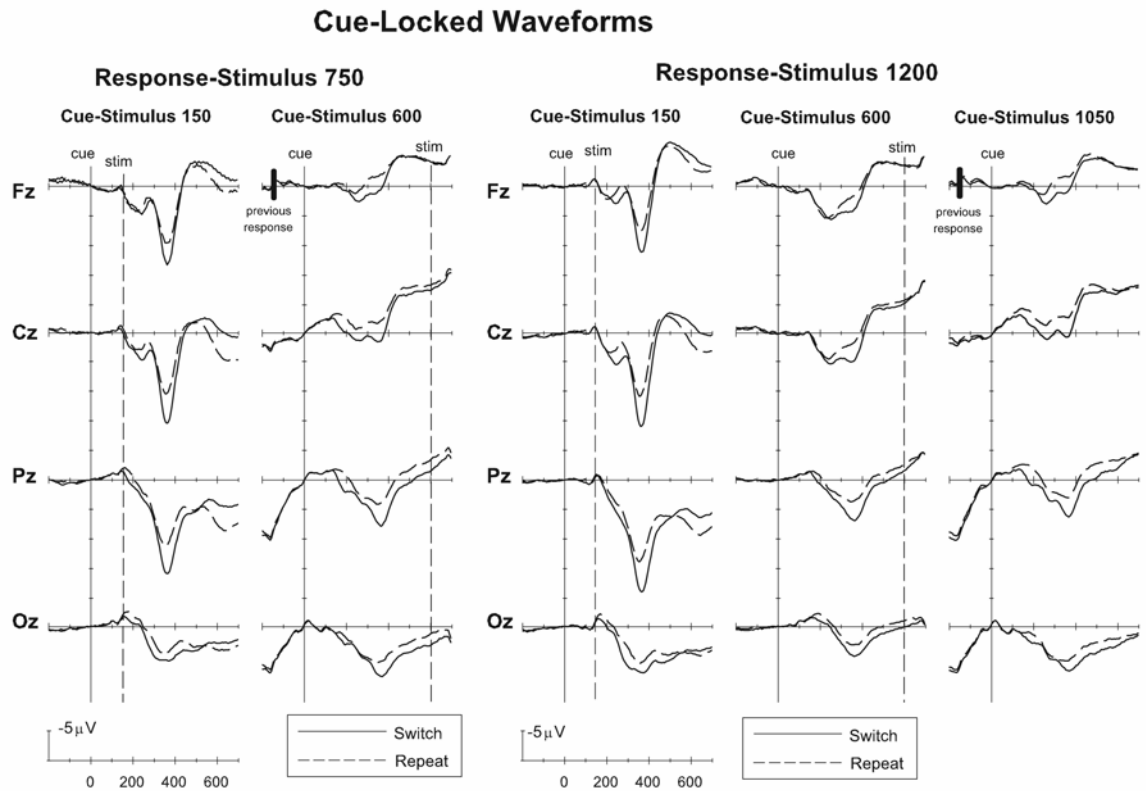
Cue-Locked Waveforms

Figure 2-3. Cue-locked waveforms for switch and repeat trials are depicted at four midline sites for each condition. Solid vertical line: cue onset; broken vertical line: stimulus onset. The preceding response is also displayed in conditions that had a short RCI of 150 ms. Negative is plotted up.

For all conditions, both switch and repeat waveforms were characterised by the emergence of a large positive component that was maximal 350-400 ms after cue onset. At both short and long RSI, the 600 ms CSI condition showed a diffuse positivity for both switch and repeat trials emerging around 150 ms anteriorly and extending beyond 400 ms posteriorly. This positivity was followed by a slower, sustained negative CNV-type shift extending beyond stimulus onset. These effects all emerged before stimulus onset and were also evident at CSI of 1050 ms. Short CSI conditions (150 ms) showed a sharper positivity that peaked after 350 ms and was preceded by a smaller centrally maximal positivity. These positivities peaked after stimulus onset and were followed by a fronto-centrally maximal negative component (see stimulus-locked averages, below).
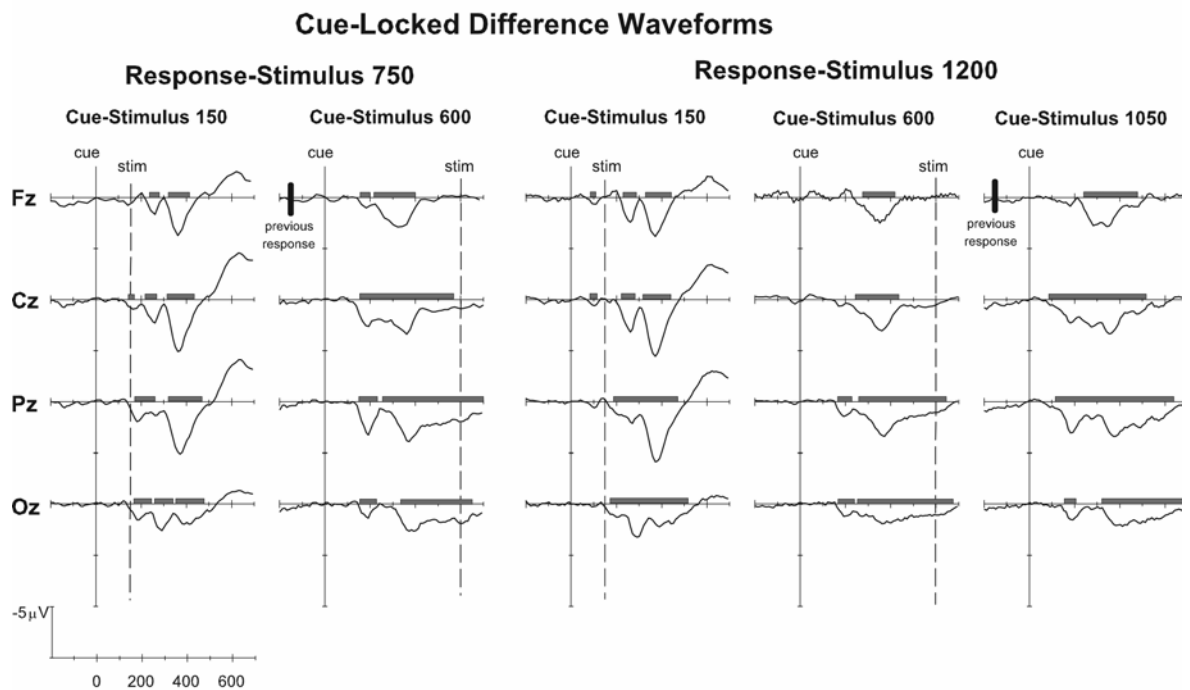
Figure 2-4. Cue-locked difference waveforms are depicted at four midline sites for each condition. Grey bars denote regions of significant deviation from baseline (see Table 2-1).

Cue-locked difference waveforms are depicted in Figure 2-4 above with areas of significant positive deviation from baseline indicated by grey bars on the time axis. The results of point-by-point waveform analyses are summarised in Table 2-1. All cued conditions showed large switch-related differential positive deflections that emerged as early as 80 ms post-cue and, in some cases, extended to 700 ms post-cue (Table 2-1). While a number of different areas of significant deviation were evident, the most consistent deviation from baseline extended over 300 to 400 ms after cue onset, was largest at parietal and central sites, and appears to correspond to the differential switch-related positivity identified by Karayanidis et al. (2003).

This component was most clearly defined in the long RSI condition with a 600 ms CSI, as this condition has no temporal overlap with either post-response or stimulus-locked components. In this condition, the D-Pos significantly deviated from baseline (i.e., was greater for switch compared to repeat waveforms) over 250-450 ms. At Pz and Oz, it was preceded by an earlier significant positive deviation over 160-240 ms. A similar pattern of findings was obtained in the other long CSI conditions (RSI-750:CSI-600 and RSI-1200:CSI-1050). However, note that in these latter conditions, the positive deflection extended centrally over

approximately 100-550 ms and the earlier positive deviation was much larger at posterior electrodes. Comparison of Figures 2-3 and 2-4 suggests that a large broad positive shift developed centrally for both trial types, but was largest for switch ERPs and that D-Pos overlapped the more posterior negativity and P3-like positivity. Note that these effects are fully contained within the CSI and could not have been affected by stimulus-locked processing.

In short CSI conditions (150 ms), a large differential positivity was most clearly defined centro-parietally deviating from baseline over approximately 300-400 ms post-cue (Table 2-1). Here, D-Pos was preceded by a smaller centrally maximal positivity that was significant over approximately 220-290 ms post-cue. Although Figure 2-3 shows that D-Pos overlapped a centroparietal P300 type component elicited post-stimulus, again the switch-related effect extended topographically across all midline sites and temporally across a wider time window.

Table 2-1

Results of point-by-point analysis of positivity in cue-locked and response-locked difference waveforms. Numbers represent the area (ms) over which the difference waveforms significantly differed from baseline according to Guthrie and Buchwald's (1991) criteria. Numbers in italics represent the number of consecutive points that were significantly deviate from baseline.

		Positivity in Cue-locked Difference Waveforms			
		Fz	Cz	Pz	Oz
RSI: 750 ms					
	No Cue*	210-384 *(87)*	196-384 *(94)*	170-400 *(115)*	126-192 *(33)* 224-420 *(98)*
CSI	150 ms	236-268 *(16)* 318-408 *(45)*	138-170 *(16)* 218-278 *(30)* 314-442 *(64)*	156-266 *(55)* 312-466 *(77)*	156-240 *(42)* 250-336 *(43)* 348-484 (68)
	600 ms	162-200 *(19)* 222-400 *(89)*	140-564 *(212)*	148-234 *(43)* 252-700 *(224)*	148-224 *(38)* 326-650 *(162)*
RSI: 1200 ms					
CSI	150 ms	84-116 *(16)* 226-290 *(32)* 322-436 *(57)*	84-114 *(13)* 218-294 *(38)* 310-446 *(68)*	190-478 *(144)*	160-518 *(179)*
	600 ms	262-416 *(77)*	250-430 *(90)*	166-224 *(29)* 254-646 *(196)*	172-240 *(34)* 246-676 *(215)*
	1050 ms	232-484 *(126)*	88-514 *(213)*	110-632 *(261)*	160-202 *(21)* 318-700 *(191)*
		Positivity in Response-locked Difference Waveforms			
RSI: 750 ms					
	No Cue	-	-	-	-
CSI	150 ms	-	-	-	-
	600 ms	334-364 *(15)* 390-556 *(83)*	314-586 *(136)* 626-656 *(15)*	324-396 *(36)* 476-700 *(112)*	338-366 *(14)* 500-700 *(100)*
RSI: 1200 ms					
CSI	150 ms	-	-	-	-
	600 ms	-	-	-	-
	1050 ms	410-560 *(75)*	326-574 *(124)*	332-400 *(34)* 488-700 *(106)*	338-384 *(23)* 506-700 *(97)*

* Although No Cue condition is really not a cue-locked waveform, it has been included here to show the areas of significant positive deviation after stimulus-onset when there was no opportunity to prepare in advance for a switch trial.

Mean amplitude analysis

Although the difference waveforms in Figure 2-4 suggest two or possibly three areas of differential positive deviation of switch compared to repeat waveforms, two of these positivities (frontocentrally maximal over 225-275 ms for short CSI conditions and parieto-occipitally maximal over 175-225ms especially for short RCI conditions), mean amplitude was only analysed for the differential positivity that closely corresponds to previously observed D-Pos (Karayanidis et al., 2003), which was measured over 350-400 ms in all conditions (Figure 2-5).
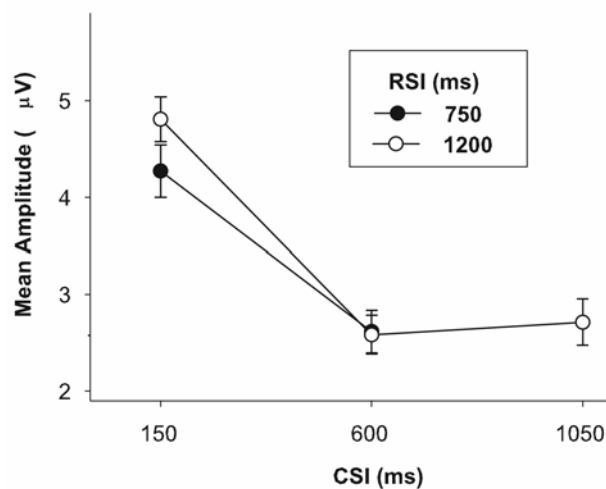

Figure 2-5. Mean amplitude of D-Pos measured 350-400 ms after cue onset at Cz.

D-Pos amplitude was larger for short than long CSI (150 versus 600 ms; $F_{(1,23)}=4.27$, $p<0.05$; Figure 2-5), and was not affected by RSI duration. A significant main effect of site ($F_{(3,69)}=14.43$, $p<0.001$) reflected that D-Pos was larger at central and parietal sites (3.6 and 4.0 uV, respectively). The interaction between electrode and CSI ($F_{(2,50)}=9.368$, $p<.001$) indicated that the decline in D-Pos amplitude with increasing CSI was only statistically significant at Cz (2.0 uV decline, $F_{(1,23)}=8.11$, $p<.01$). D-Pos amplitude did not decline further as CSI increased from 600 ms to 1050 ms (Figure 2-5).

Response-locked waveforms

Response-locked difference waveforms depicted in Figure 2-6 (left) show no systematic difference between switch and repeat trials until after cue onset (Table 2-1).

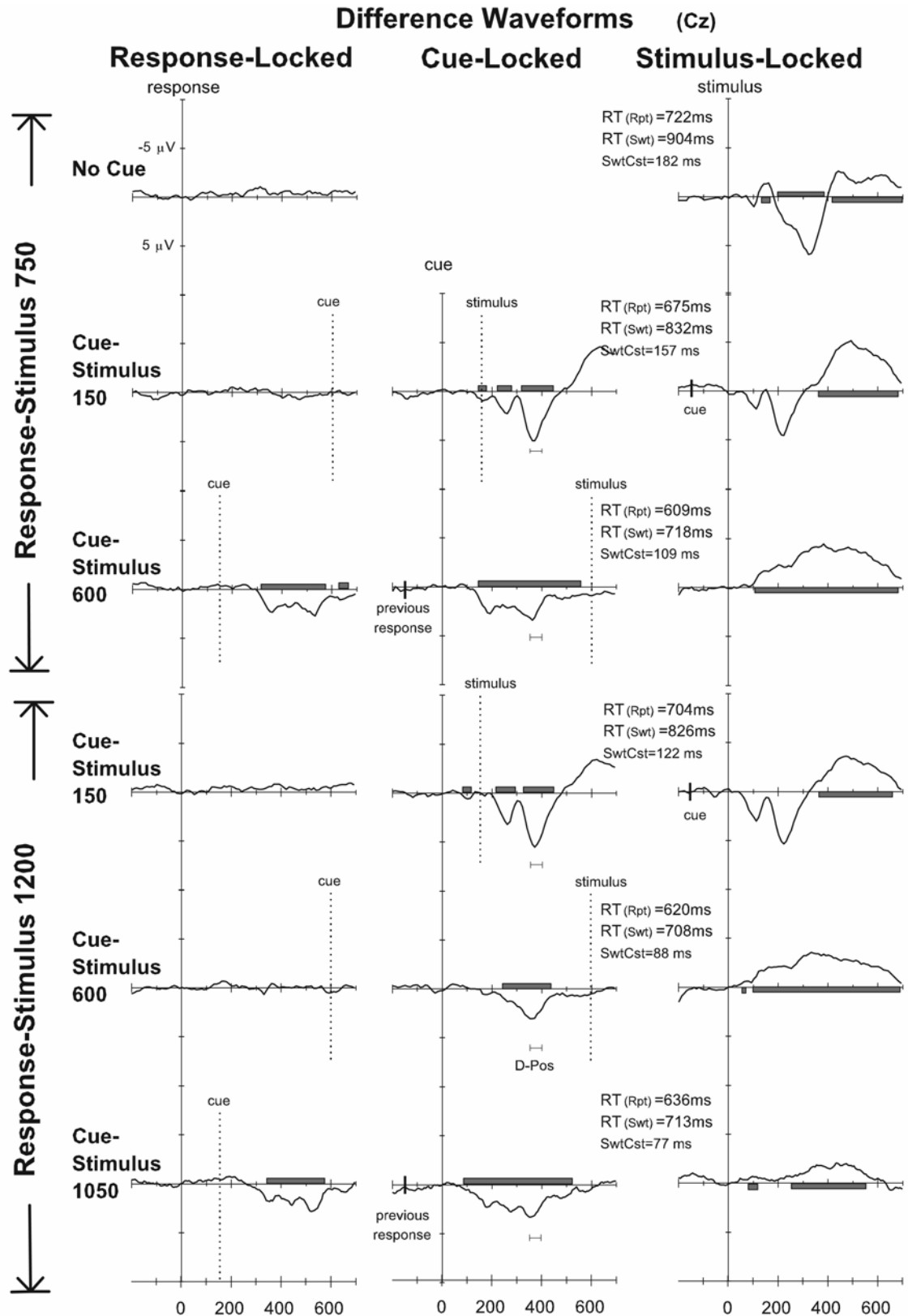**Figure 2-6.** Response-locked (left), cue-locked (middle) and stimulus-locked (right) difference waveforms at Cz. Grey bars denote regions of significant positive deviation from baseline in response- and cue-locked waveforms (Table 2-1) and negative deviation from baseline in stimulus-locked waveforms (Table 2-2). Note that stimulus-locked No Cue condition also depicts significant positive deviation.

Stimulus-locked waveforms

Stimulus-locked ERPs and difference waveforms are shown in Figure 2-7 and Figure 2-6 (right). Note that, in the no cue condition, stimulus location provided information about which task was active on that trial. Also note that despite considerable temporal overlap between the cue-locked and stimulus-locked waveforms at short CSIs, minor differences between the two conditions may emerge because of different baselines. Occipital P1, N1, P2 components and frontal N1, P2 components can be seen most clearly at longer CSIs that had no overlap between cue- and stimulus-locked waveforms. These early ERPs were followed by a broad negativity evident centrally over 200-400 ms and a parietal P3b-like positivity over 400-600 ms.
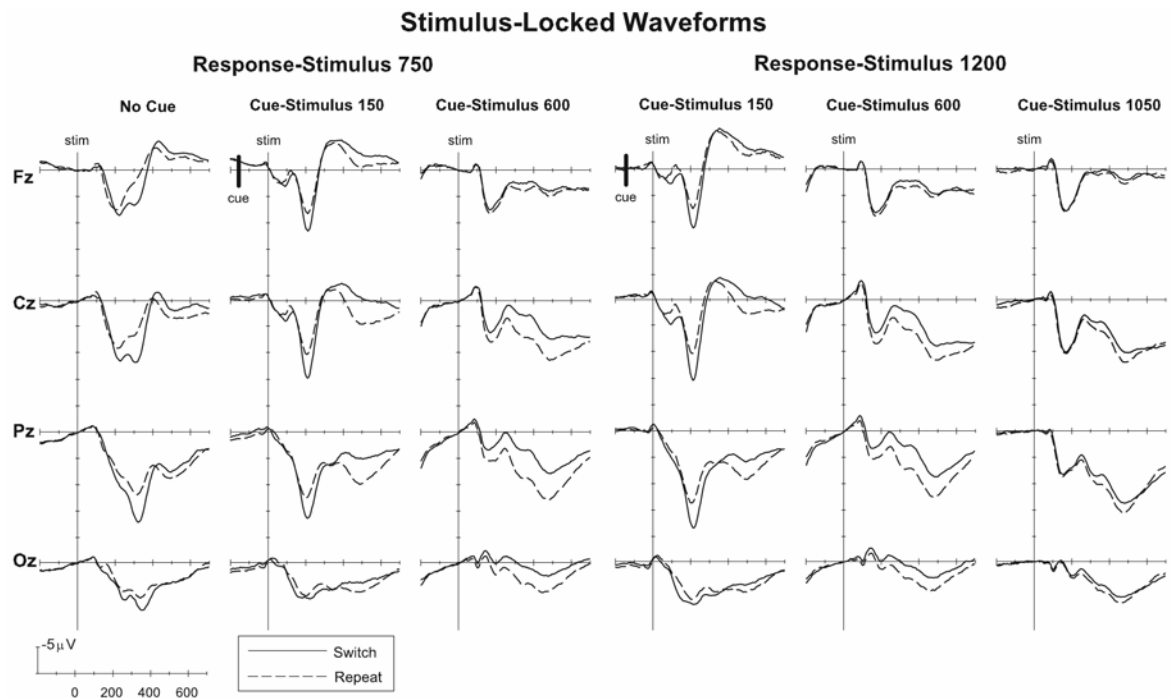
Figure 2-7. Stimulus-locked waveforms for switch and repeat trials. Solid vertical line indicates stimulus onset. Cue onset is also displayed in conditions with a short CSI (150 ms).

At 600 ms CSI, switch and repeat ERPs deviated as early as 40 ms at parietal and occipital sites and continued beyond 700 ms in many instances (Table 2-2). This negative difference between switch and repeat trials emerged earlier and was larger for 600 ms than 1050 ms CSIs (Figure 2-6 & 2-7). This component is consistent with the D-Neg component described by Karayanidis et al. (2003).

Table 2-2

Results of point-by-point analysis of negativity in stimulus-locked difference waveforms. Numbers represent the area over which the difference waveforms significantly differed from baseline according to Guthrie and Buchwald's (1991) criteria. Numbers in italics represent the number of consecutive points that were significantly deviate from baseline.

		Fz	Cz	Pz	Oz
		Negativity in Stimulus-locked Difference Waveforms			
RSI: 750 ms					
	No Cue	124-184 *(30)* 416-506 *(45)*	126-164 *(19)* 406-698 *(146)*	426-644 *(109)*	-
CSI	150 ms	378-650 *(136)*	364-688 *(162)*	368-664 *(148)*	390-608 *(109)*
	600 ms	166-234 *(34)* 282-398 *(58)* 468-498 *(15)*	102-684 *(291)*	44-700 *(328)*	38-700 *(331)*
RSI: 1200 ms					
CSI	150 ms	382-532 *(75)*	354-672 *(154)*	380-658 *(139)*	422-612 *(95)*
	600 ms	116-226 *(55)* 256-440 *(92)*	58-86 *(14)* 94-682 *(294)*	46-700 *(327)*	48-700 *(326)*
	1050 ms	418-448 *(15)* 456-486 *(15)*	88-114 *(13)* 262-552 *(145)*	86-148 *(31)* 224-528 *(152)*	100-148 *(24)* 222-514 *(146)*

For both short CSI (150 ms) conditions, there was substantial temporal overlap between cue and stimulus processing ERP components. The differential switch-related positivity, that for long CSIs was completed prior to stimulus onset, extended over the early P2-like component, resulting in significant positive deviation from baseline over 150-350 ms. This differential positivity in the short CSI conditions is believed to represent the same component seen in the cue-locked waveforms with a 150 ms shift to the left and a different baseline. This can be more clearly seen in Figure 2-6 which compares cue-locked (middle) and stimulus-locked (right) difference waveforms for each condition at Cz. For short CSI conditions, the same positivity was seen in cue-locked and stimulus-locked difference waveforms, whereas for long CSI conditions, it emerged only within the CSI. For short CSI conditions, D-Neg emerged much later (350 ms) than for the long CSI conditions.

No Cue versus 150 ms CSI

The No-Cue condition produced larger RT switch cost than the 150 ms CSI condition with the same RSI (750 ms). Comparison of stimulus-locked difference waveforms in these two conditions indicate that D-Pos was delayed in the No-Cue condition, peaking around 300-400 ms after stimulus onset. This latency coincides with the latency of D-Pos when measured relative to the onset of the preceding cue for the RSI-750:CSI-150 ms condition (Figure 2-6).

2.3   Discussion

Behavioural Effects of Switching Tasks

Across all conditions, switch trials were associated with larger RT and error rate compared to repeat trials (784 ms and 3.5% versus 660 ms and 2%, respectively). When averaged across CSI, RT switch cost significantly reduced as RSI increased from 750 to 1200 ms (29 ms decline). Similarly, when averaged across RSI, RT switch cost significantly reduced as CSI increased from 150 to 600 ms (50 ms decline). Increasing CSI from 600 ms to 1050 ms produced no further reduction in RT switch cost, and a significant RT and error switch cost was found at the longest CSI (82 ms and 1.0%, respectively).

These findings are compatible with multi-component models of task-switching. The reduction in RT switch cost with increasing RSI is compatible with a decline in passive interference processes associated with switching between different task-sets (Allport et al., 1994; Allport and Wylie, 2000; Meiran, 2000a), such as positive priming of the previously active task-set and negative priming of the previously irrelevant task-set (Allport & Wylie, 2000; Mayr & Keele, 2000). The reduction in RT switch cost with increasing CSI is compatible with active preparation processes (Goschke, 2000; Meiran, 2000a; Rogers & Monsell, 1995), such as cue encoding (Logan & Bundesen, 2003; Mayr & Kliegl, 2003; Monsell, Sumner & Waters, 2003), active inhibition of the irrelevant task-set (Mayr & Keele, 2000) and/or retrieval of the relevant task-set into working memory (Mayr & Kliegl, 2000). Although the reduction in RT switch cost with increasing CSI is also compatible with De Jong's (2000) intention-

activation model, this model can not readily account for the effect of RSI on RT switch cost. The significant residual switch cost at the longest CSI (1050 ms) is consistent with differential response interference for switch trials (Woodward, Meier, Tipper & Graf, 2003), even after maximal anticipatory preparation, as well as with an 'unprepared' state on some proportion of trials (De Jong, 2000). Interestingly, a CSI of only 150 ms resulted in smaller RT switch cost than the No-Cue condition (25 ms reduction)[4]. This finding suggests that anticipatory preparation processes may be initiated even with a short lead interval of 150 ms and questions the use of a 150 ms CSI as a 'no preparation' baseline (e.g., De Jong, 2000).

Electrophysiological Effects of Switching Tasks

Cue-locked ERP difference waveforms showed a differential positivity for switch compared to repeat trials. This differential switch-related positivity closely corresponds to the D-Pos component reported by Karayanidis et al. (2003) in an alternating runs paradigm. Despite large differences in paradigm, Rushworth et al (2002; 2005) also showed a switch-related positivity over the 350-500 ms range, albeit differing in scalp distribution and accompanied by different additional effects (see also Barceló et al. 2002). These findings are compatible with the existence of an active task-set reconfiguration process that can be initiated in anticipation of a predictable or cued switch in task. At a 600 ms CSI, D-Pos was fully contained within the CSI and there was maximal reduction in RT switch cost, indicating that anticipatory reconfiguration could be fully completed prior to stimulus onset. At shorter CSI (150 ms), D-Pos emerged as early as 88 ms after cue onset (Table 2-1), but still peaked around 350-400 ms after cue onset and both D-Pos and RT switch cost were larger than for the longer CSI condition. The no cue condition showed a further increase in RT switch cost and D-Pos was time-locked to stimulus onset, indicating firstly that CSIs as short as 150 ms can facilitate task switching and secondly that the process(es) reflected in D-Pos are necessary for task-set reconfiguration and may be

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[4] It is possible that overall RT may have increased in the No-Cue condition as participants were required to shift fixation to the location of the stimulus after stimulus presentation, whereas this was initiated at cue onset in all other conditions. In addition, stimulus location would have to be processed to determine which task was active on the current trial. However, an effect of shifting visual fixation or processing stimulus location would be expected to affect both switch and repeat trials equally and not differentially increase RT switch cost.

initiated after stimulus onset if no cue is present. The fact that increasing CSI from 600 to 1050 ms produced no further reduction in RT switch cost or D-Pos amplitude, despite a significant residual RT switch cost, indicates that 600 ms provides optimal anticipatory preparation and that additional post-stimulus processes contribute to RT switch cost. However, the degree to which this reconfiguration process is specifically and exclusively activated in anticipation of switch trials is questioned by the fact that, although D-Pos represents a greater positivity for switch compared to repeat stimuli, cue-locked ERP waveforms in Figure 2-3 indicate that both switch *and* repeat trials show a positive deflection within the timeframe of the D-Pos.

Comparing conditions C-600 and C-1200 in Figure 5 of Karayanidis et al. (2003) with 600 ms and 1050 ms CSI conditions in Figure 2-3 of the present study reveals differences in the expression of this differential positivity in predictable versus cued switching paradigms. In the alternating runs paradigm, D-Pos for switch trials was restricted posteriorly, was superimposed on a post-response negative shift, and there was no evidence of a positive shift in repeat waveforms (Figure 6 in Karayanidis et al.). In the cued paradigm, the condition that had no overlap between cue processing and either post-response or stimulus-triggered effects (i.e., RSI-1200:CSI-600) clearly showed a positivity emerging within a 200-400 ms window across all midline sites and for both switch and repeat waveforms (Figure 2-3). So, in the current study, cue-locked waveforms show a positivity for both trial types, which is significantly larger for switch trials. Rushworth et al (2002; 2005) showed a similar pattern of positivities to both switch and stay cues.

The evidence of a positivity for both switch and repeat cue-locked waveforms may reflect cue processing (see Experiment 4). Recent studies by Logan and Bundesen (2003) and Mayr and Kliegl (2003) suggested that, in cued switching paradigms, RT switch cost can be accounted for by cue processing, because switch trials are preceded by a change in cue whereas repeat trials are preceded by the same cue. While cue processing may account for the emergence of a positivity for repeat trials in the current cued switch paradigm that was not evident in the alternating runs paradigm, it is unlikely to account for the *differential* positivity in switch

compared to repeat trials. In the current study, the cue was a highlight of one of the four quadrants of the grid. However, the same quadrant was never highlighted on successive trials, so both switch and repeat trials were preceded by a change in cue position. Therefore, the cue provided valid information about the location of the next stimulus, and this also determined which task-set would be active on the next trial. Thus, on each trial, the cue position determined where to direct attention. This was equally relevant for switch and repeat trials, possibly accounting for the common positivity. In addition, the cue indicated whether to maintain the current task-set or activate the alternative task-set. This would be expected to result in differential processing for switch and repeat cues and could account for the differential positivity to switch cues. Recent behavioural (Monsell & Mizon, 2006) data also indicate that, in many instances, task switch costs can not be accounted for by differential cue processing for switch versus repeat trials.

Alternatively, the fact that both switch and repeat cue-locked waveforms show a positivity, albeit larger for switch trials, may indicate that the process of task-set reconfiguration can be activated on both switch and repeat trials, depending on task parameters, strategy formation and trial-by-trial variations in performance. Comparison between cue-locked ERPs on blocks with short versus long CSI (Figure 2-3) supports the contention that participants may implement different processing strategies depending on specific timing parameters. Firstly, the change in the morphology and amplitude of D-Pos with increasing CSI could reflect variations in the onset of task-set reconfiguration for switch trials resulting from differences in time pressure, particularly as the CSI was manipulated across blocks of trials. For example, when the CSI was short, onset of active preparation occurred, in the majority of trials, immediately following cue onset (as the stimulus appeared almost immediately after cue onset), resulting in little latency jitter and a sharp D-Pos. In comparison, when the CSI was long (i.e., 600 or 1050 ms), there was less time pressure to initiate preparation immediately following the cue. Hence, jitter in the onset of preparation may have resulted in jitter in D-Pos onset across individual trials producing a broader and smaller average D-Pos. Secondly, *repeat* cues on short CSI

conditions (150 ms) showed a sharp and large positivity around 300-400 ms, whereas repeat cues on long CSI conditions (600 ms) showed a much less prominent positivity. Like D-Pos, this positivity was clearly evident across all midline sites, but maximal centroparietally. RT to repeat trials was longer for short than for long CSI conditions (by 75 ms when averaged across RSI). Relative to repeat cues, switch cues showed a larger positivity than repeat cues at both short and long CSI conditions, measured here as the D-Pos over 350-400 ms, and a greater increase in RT for short as compared to long CSI conditions (by 116 ms averaged across RSI).

These findings suggest that participants may have adopted different processing strategies in short and long CSI blocks. Given the time constraints of the short CSI blocks, participants may have adopted a strategy of initiating task-set reconfiguration processes in parallel with cue processing, rather than awaiting the outcome of cue processing to determine whether a change in task-set reconfiguration would or would not be required. The centroparietal positivity in the cue-locked average waveforms for both repeat and switch trials suggests that cue processing, and possibly the onset of task-set reconfiguration, was initiated for both repeat and switch trials. That switch trials were associated with a further positivity, i.e., D-Pos, may indicate that these trials required additional processes or additional sub-components relative to repeat trials (i.e., in the slow paced long CSI conditions, active task-set reconfiguration processes were more selectively initiated for switch trials and their onset was contingent upon having processed a switch cue). Alternatively, it may indicate that task-set reconfiguration can be completed more rapidly and/or efficiently for repeat trials because the stimulus-response associations were already primed on the previous trial. The fact that the data analysed here were recorded after substantial task practice over two days and that CSI and RSI conditions were varied across blocks supports the proposition that participants may have adopted different strategies depending on the duration of the CSI. In Monsell and Mizon (2006), switch probability was inversely related to active reconfiguration on switch trials, whereas Brass and von Cramon (2004) argued that using equal probability of switch and repeat trials might encourage preparation to both types of trials, thereby reducing switch/repeat trial differences. The use of an

equal switch/repeat probability may have increased the probability of task-set reconfiguration on repeat trials, especially at short CSI. If the above interpretation is correct, it suggests that task-set reconfiguration processes are largely under voluntary control and may be activated on both switch and repeat trials, depending on task parameters and participant strategy.

Another possibility is that the parietal positivity in the repeat waveform represents a P3b component that is larger in amplitude for switch trials, reflecting updating and/or implementation of the new task-set (Barceló et al, 2002). However, this interpretation does not neatly fit the current results or previous data (Karayanidis et al. 2003). In Karayanidis et al., a centro-parietal differential positivity for switch trials was obtained in the interval leading up to a predictable switch trial, despite no evidence of a P3b to repeat trials. Although both repeat and switch trials here show a positivity in the long CSI, the difference waveforms show that the differentiation between switch and repeat ERP waveforms begins much earlier and extends beyond the latency range of the P3b. Even though the current analysis measured the differential positivity around 350-400 ms to capture the peak and be compatible with Karayanidis et al., the current data suggest that multiple ERP components extending across the measurement window are affected by whether the cue indicates an impending switch or repeat trial. Difference waveform analyses showed deviation between switch and repeat cue ERPs as early as 84 ms after cue onset and extending across the entire analysis epoch, in some instances. Figure 2-4 suggests that there is at least one earlier positivity for switch compared to repeat cues (see below). The present data can not conclusively confirm or reject the possibility that a P3b is elicited by repeat cues and increased for switch cues. However, even if the D-Pos over 350-400 represents partly a P3b modulation, this clearly can not fully account for the differential ERP signature of switch trials that extends across most of the recording epoch.

An earlier switch-related differential positivity was also observed that peaked around 175-225ms after cue onset and was maximal centrally and parietally. Although this earlier D-Pos was evident in all conditions, it was most distinct and largest for conditions with a very short RCI of 150 ms when the cue indicated a switch. That this early D-Pos is a differential

positivity for switch compared to repeat cues suggests that cue analysis has at least commenced if not been completed by 200 ms post-cue. The fact that the early D-Pos appears selectively enhanced in the short RCI conditions may indicate increased overall arousal and perceived speed of stimulus presentation resulting in earlier activation of cue processing and task-set reconfiguration processes. The early D-Pos may thus reflect early cue and cue-task association analysis occurring in all RSI and CSI conditions, such as processing the location of the cue within the grid displayed on the screen (or the stimulus in the no cue condition) in order to determine which task to perform (e.g. Logan & Bundesen, 2003; Mayr & Kliegl, 2003). These early processes are more cognitively demanding when the response to the previous task is very recent (i.e., short RCI of 150 ms) due to interference with post-response processes and/or task-set interference. Given that the present experiment made no specific hypotheses about these earlier effects and the rather restricted electrode montage used, no further analyses were conducted to differentiate the positivities seen in Figure 2-4.

The stimulus-locked difference waveforms showed a larger differential negativity for switch than repeat trials, similar to D-Neg reported by Karayanidis et al. (2003; see also Barceló et al., 2002; Rushworth et al. 2005). D-Neg emerged less than 50 ms after stimulus onset in long CSI conditions but more than 300 ms later in short CSI conditions, wherein it was preceded by a D-Pos. The delay in onset indicates either that the process(es) represented by D-Neg can not be initiated until completion of the processes reflected in the preceding D-Pos or, alternatively, that in short CSI conditions, D-Pos is superimposed on D-Neg, and D-Neg does not become visible until after D-Pos resolution. Even though D-Neg was larger centroparietally and peaked around 300-600 ms after stimulus onset, it is unlikely to reflect a reduction in P3b for switch relative to repeat trials (but see Barceló et al., 2002). Figure 2-6 shows a large single component spreading over more than 600 ms in some instances, suggesting a slow wave negativity superimposed on the switch trial ERPs (Karayanidis et al., 2003). This differential switch-related negativity, in combination with the residual RT and error switch cost, support the notion that anticipatory task-set reconfiguration processes do not completely account for behavioural switch costs.

Rather, it is suggested that switch and repeat stimuli may trigger different processes, depending on the task and sequence parameters (e.g., Gehring, Bryck, Jonides, Albin & Badre, 2003). These processes are likely to represent differential stimulus-response priming and/or response interference for switch versus repeat trials (e.g., Allport and Wylie, 2000; Waszak et al., 2003; Yeung & Monsell, 2003 a, b) and to contribute to the residual switch cost.

Summary

Experiment 1 provides strong evidence for differential processing in preparation for an anticipated switch and repeat trial (see also Barceló et al. 2002; Karayanidis et al., 2003; Rushworth et al. 2002; 2005). The data support the existence of an endogenous process of task preparation that is *differentially* activated for switch and repeat trials, such as anticipatory task-set reconfiguration (Rogers and Monsell, 1995), goal-shifting (Rubinstein, Meyer & Evans, 2001) or set initiation (Rushworth et al., 2005). The differential stimulus-locked negativity for switch compared to repeat trials also supports the role of stimulus-response priming and response interference in task-switching (e.g., Allport & Wylie, 2000). However, the decline in RT switch cost with increasing CSI and the differential positivity for switch versus repeat trials within the CSI provide strong evidence that stimulus- and response-locked interference processes can not fully account for the behavioural RT switching cost.

3   Experiment 1 (b): Effects on the LRP

Hsieh and Yu (2003) used P300 and LRP measures to examine the locus of task-switching and task-cueing effects using a 2-choice switching task that involved reversal of stimulus-response mapping with either informative or non-informative cueing. The P300 is part of a complex positive component that is affected by stimulus and task complexity and is believed to represent processes associated with stimulus evaluation and context updating (e.g., Rugg & Coles, 1995). The LRP represents differential activation over the contralateral motor cortex leading up to an overt lateralised hand response (Coles, 1989). The stimulus-locked LRP is associated with pre-motor processes (e.g., response selection and activation) whereas the response-locked LRP is associated with motor processes (e.g., response execution; Miller & Hackley, 1992). Hsieh and Yu (2003) found that RT and stimulus-locked LRP onset latency increased for switch compared to repeat trials and for non-informative compared to informative cues, with no interaction between trial and cue type. P300 peak latency and response-locked LRP onset latency were not affected by either manipulation. Using a more complex stimulus-response mapping reversal task with two stimuli mapped to two responses each, Hsieh and Liu (2005; see also Hsieh, 2006) replicated the effects of task switching and task cueing on RT and stimulus-locked LRP. In addition, the size of the switching effect on RT (127 versus 64 ms) and stimulus-locked LRP onset (83 versus 38 ms) was halved under informative cueing conditions, although the interaction was only significant for RT. P300 peak amplitude and latency were reduced for informative compared to non-informative cue blocks, but unaffected by task switching.

Hsieh and colleagues (Hsieh & Yu, 2003; Hsieh & Liu, 2005; Hsieh, 2006) conclude that task-switching affects processes that occur after stimulus identification (no effect on P300) and possibly involve prolongation of response selection, whereas cueing affects stimulus identification and/or response selection, depending on the complexity of task requirements. Importantly, they argue that the results do not support the involvement of a control process that is differentially activated for cued switch trials. Instead these studies provide strong evidence for

an effect of task-switching on response selection and activation processes. However, note that the task parameters do not encourage activation of anticipatory task-set reconfiguration. Switching was restricted to reversal of stimulus-response mapping rather than shifting between different task-sets. Additionally, since the stimulus carries all the information necessary for task completion, cue utilisation is not essential for successful task completion. More importantly, given the long CSI (1200 ms), it is likely that any effects of preparation in anticipation of a cued switch in task would have emerged before stimulus onset.

Previous studies (Karayanidis et al. 2003; Miniussi, Marzi & Nobre, 2005; Rushworth, Passingham & Nobre, 2002; 2005) have shown a centroparietal positivity for switch compared to repeat cues emerging 150-300 ms and peaking around 400-500 ms after cue onset. Using a cued task-switching paradigm, Experiment 1 showed that RT switch cost reduced with increasing RSI (750, 1200 ms) and with increasing CSI (150, 600 ms), but there was no interaction between the two factors. Cue-locked waveforms showed a large differential positivity for switch compared to repeat ERPs. In conditions that did not provide opportunity to activate anticipatory task-set reconfiguration (e.g., short CSI), this differential switch-related positivity peaked after stimulus onset. At long CSIs ($\geq$ 600 ms), this positivity was smaller and peaked before stimulus onset. This differential positivity was interpreted as reflecting processes involved in task-set reconfiguration that are activated before or after stimulus onset depending on task parameters. In stimulus-locked waveforms, a large broad negativity for switch compared to repeat trials emerged as early as 100 ms after stimulus onset for long CSIs but only after resolution of the differential positivity (i.e., at around 400 ms) for short CSIs.

The present chapter extends the analysis from Experiment 1 in order to examine whether task-switching modulates ERP components associated with stimulus processing and evaluation (reflected by the LPC), response selection and activation (in the stimulus-locked LRP) and response execution (in the response-locked LRP). Further, it is examined whether any effect of task-switching on these ERP components is modulated by independent manipulation of opportunity for anticipatory task-set reconfiguration (CSI manipulation) and passive dissipation

of interference (RSI manipulation). Experiment 1 showed that long CSIs encourage activation of anticipatory task-set reconfiguration, as indexed by reduced RT switch cost and the differential post-cue positivity. This differential level of advance preparation for switch trials at long compared to short CSIs would be expected to be associated with reduced effects of task switching on stimulus processing, response selection and response activation processes, as indexed by the LPC, stimulus-locked LRP and response-locked LRP, respectively. Passive effects that are associated with task-set inertia, stimulus-response priming or cross-talk interference are likely to be triggered by the stimulus itself and may also affect stimulus processing and/or response selection. Therefore, increasing RSI would be expected to modulate the effects of task switching on LPC and/or stimulus-locked LRP but not response-locked LRP.

3.1 Method

Participants

Of the twenty-four participants from Experiment 1, LRP data from four participants could not be analysed due to malfunction of the C3 electrode. Therefore all analyses reported in this chapter were conducted on the remaining twenty participants.

Behavioural and ERP data analysis

All analysis was conducted on only the four orthogonal RSI / CSI conditions from Experiment 1 (RSI-750:CSI-150; RSI-750:CSI-600; RSI-1200:CSI-150; RSI-1200:CSI-600). LRP waveforms were extracted from C3 and C4 electrodes using the averaging method according to Coles (1989). C4 minus C3 difference waveforms were derived for left hand responses and C3 minus C4 for right hand responses. These were averaged to create separate LRP waveforms for each condition and trial type. Stimulus-locked LRP waveforms were epoched over -200 to 1200 ms and were baseline corrected over the pre-stimulus interval (-200 to 0 ms). Response-locked LRP were epoched over -700 to 200 ms and were baseline corrected over -700 to -600 ms.

Stimulus processing was examined by measuring peak amplitude and latency of the stimulus-locked LPC at Pz over 400-600 ms. Stimulus-locked LRP peak amplitude was measured over 250-700 ms and response-locked LRP over -300 ms to response onset. Due to considerable individual variability in stimulus-locked LRP morphology, onset latency was measured using the jack-knife procedure (Ulrich & Miller, 2001). Response-locked LRP peak amplitude was not significantly affected by any of the experimental factors, so onset latency was measured using a 30% peak amplitude criterion.

Mean RT (with the reduced sample size of 20), LPC and LRP measures were analysed using a 2 RSI (750, 1200 ms) by 2 CSI (150, 600 ms) by 2 trial type (switch, repeat) repeated measures ANOVA. Significant interactions were examined using simple effect contrasts with Bonferroni correction.

3.2   Results

RT was larger for switch than repeat trials ($F(1,19)=72.4$, $p<.001$) and at short than long CSI ($F(1,19)=110.9$, $p<.001$). RT switch cost was larger at short than long CSI (142 ms versus 96 ms; $F(1,19)=22.3$, $p<.001$) and at short than long RSI (132 ms versus 106 ms; $F(1,19)=13.8$, $p<.001$), but there was no interaction between RSI and CSI.

Stimulus-locked ERPs at Pz and stimulus- and response-locked LRPs are shown below in Figure 3-1 for the four orthogonal RSI / CSI conditions from Experiment 1. LPC amplitude was smaller for switch than repeat trials (8.4 versus 12.3μV; $F(1,19)=90.9$, $p<.001$) and for short than long CSI (8.8 versus 11.9 μV; $F(1,19)=8.4$, $p<.01$; Figure 3-1). The effect of task switching was smaller at long as compared to short RSIs (RSI by trial type, $F(1,19)=10.4$, $p<.01$). LPC peaked later for switch than for repeat trials (504 versus 491 ms; $F(1,19)=5.2$, $p<.05$), but was not affected by RSI or CSI.
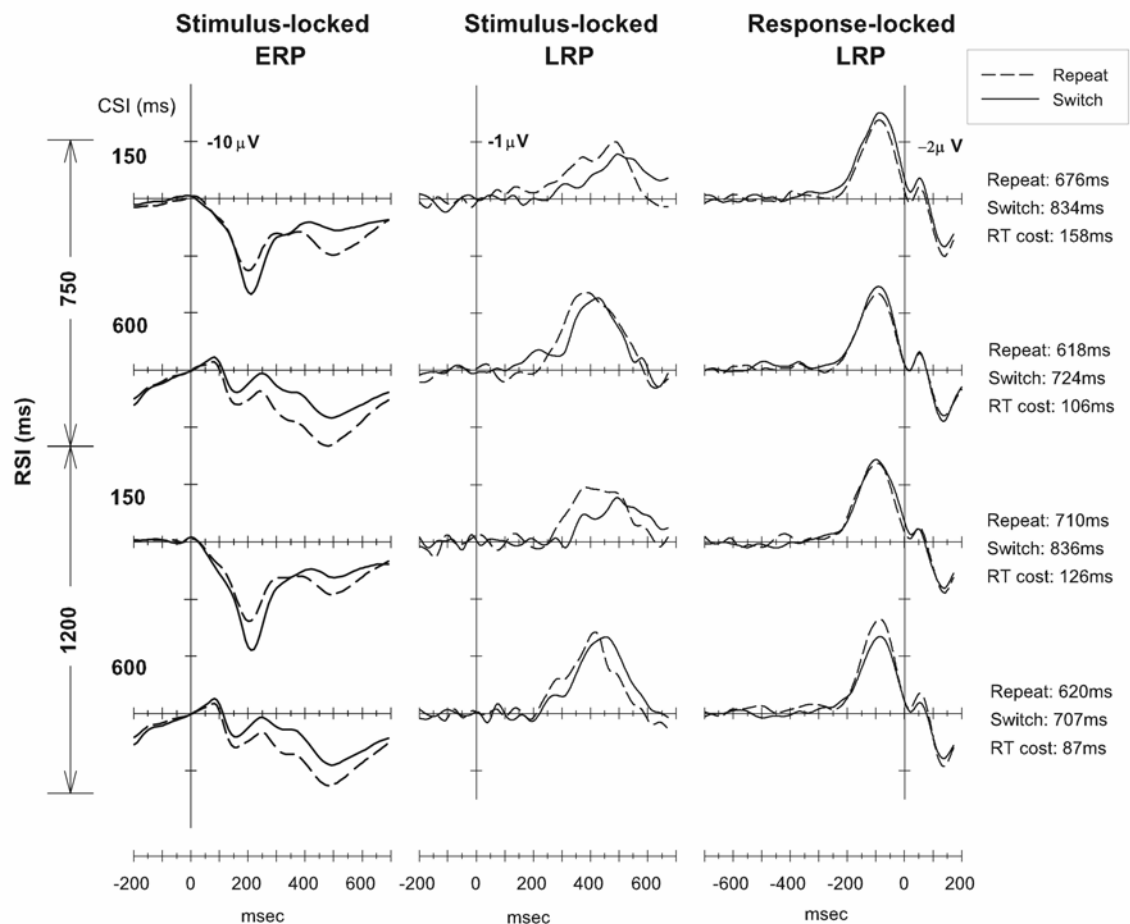
Figure 3-1. Stimulus ERPs at Pz (left), stimulus LRPs (middle) and response LRPs (right) are shown for each of the four conditions from Experiment 1.

As shown in Table 3-1, stimulus-locked LRPs emerged earlier at long than short CSI (286 versus 334 ms, respectively; $F(1,19)=6.81$, $p<.05$) and earlier for repeat than switch trials (272 versus 347 ms, respectively; $F(1,19)=13.63$, $p<.01$). No other main effect or interaction between CSI, RSI or trial type was significant. Response-locked LRPs emerged around 190 ms before response onset and peaked 100 ms later. Response-locked LRP onset was not significantly affected by trial type, CSI or RSI.

Table 3-1

Average peak amplitude and latency of the stimulus-locked ERP LPC (400-600 ms), as well as peak amplitude, peak latency and onset latency for stimulus- and response-locked LRPs for each of the four conditions. Standard error of the mean in italics.

LPC				Stimulus LRP						Response LRP					
Amp		Lat		Amp (-)		Lat		Onset		Amp (-)		Lat		Onset (-)	
Rpt	Swt	Rpt	Swt	Rpt	Swt	Rpt	Swt	Rpt	Swt	Rpt	Swt	Rpt	Swt	Rpt	Swt
RSI-750:CSI-150															
11	6.6	503	516	2.1	1.8	473	576	416	536	3.5	3.8	-93	-92	145	155
0.9	*0.9*	*9*	*13*	*0.1*	*0.2*	*16*	*29*	*20*	*30*	*0.4*	*0.3*	*6*	*9*	*7.5*	*10*
RSI-750:CSI-650															
14	9.6	477	496	2.4	2.1	390	427	339	390	3.4	3.6	103	-98	160	165
1.0	*1.2*	*10*	*9*	*0.3*	*0.2*	*17*	*16*	*13*	*16*	*0.4*	*0.3*	*10*	*10*	*7*	*11*
RSI-1200:CSI-150															
10	7.3	491	502	2.2	1.7	435	509	401	476	3.7	3.8	-98	100	151	153
1.2	*1.2*	*10*	*11*	*0.2*	*0.1*	*21*	*25*	*22*	*23*	*0.3*	*0.4*	*9*	*10*	*9*	*9*
RSI-1200:CSI-600															
13	10.2	491	501	2.2	2.2	428	473	380	423	4.0	3.5	-93	-84	149	140
1.0	*1.0*	*10*	*10*	*0.2*	*0.2*	*18*	*25*	*17*	*23*	*0.4*	*0.5*	*6*	*7*	*7*	*9*

3.3 Discussion

Together with earlier results reported in Experiment 1, these findings document the effects of task switching across the entire range of processing from cue onset to response execution. Experiment 1 showed that compared to repeat trials, switch trials were associated with slower and less accurate responding, a centroparietal cue-locked positivity and a large broad stimulus-locked negativity. Increasing CSI, thereby providing more opportunity for advance task-set reconfiguration, resulted in reduced RT switch cost, a smaller cue-locked switch-related positivity and earlier onset of the stimulus-locked differential negativity. Increasing RSI, thereby increasing the time available for passive dissipation of activation of the previously active task-set, resulted in reduced RT switch cost but did not affect the switch-related cue-locked positivity or stimulus-locked negativity. The current analyses extends these findings by examining switching effects on the LPC, a component associated with stimulus evaluation and context updating and the stimulus-locked LRP and response-locked LRP,

components associated with response selection and activation, and response execution, respectively. Switch trials were associated with a smaller and later LPC[5], and later onset of the stimulus-locked LRP, suggesting more difficult stimulus processing and later response activation. In contrast, increasing CSI resulted in a larger LPC and earlier stimulus-locked LRP. Increasing RSI reduced the effect of switching on LPC amplitude, but had no effect on LPC or stimulus-locked LRP latency. Response-locked LRP onset was not affected by trial type, CSI or RSI settings. Notably, that the response-locked LRP peaked 100 ms before response onset suggests that either triggering was inaccurate or that the response button required substantial force. As it was tested to ensure that triggering was accurate, the latter possibility is quite likely as the response buttons were selected so as to elicit a clear and large physical response. Therefore the lack of an effect of task parameters on response-locked LRP may reflect covert co-activation of the response at a muscular level.

In combination with the Experiment 1 findings presented in the previous chapter, these results show that the increased RT for switch versus repeat trials may reflect contributions from: 1) pre-stimulus processes associated with differential level of task-readiness, 2) increased stimulus-response interference at the post-stimulus level resulting in differential difficulty of stimulus processing for switch versus repeat trials, and 3) differential difficulty in activation of pre-response processes associated with response selection and activation due to differential stimulus-response interference for switch and repeat trials. The opportunity for anticipatory task-set reconfiguration at long CSIs, which has been shown to reduce the size of the RT switch cost, operated within the CSI reducing the amplitude but not the onset latency of the cue-locked differential switch-related positivity. The time available for passive dissipation of the previously active task-set, which also reduces RT switch cost, operated on the relative difficulty of

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[5] In Karayanidis et al. (2003) and experiment 1 a differential post-stimulus negativity for switch as compared to repeat trials was observed (see also Rushworth et al. 2002). This effect emerged much earlier and was more widespread than the LPC, leading Karayanidis et al. (2003) to argue that it represents a negativity superimposed on a number of stimulus-related ERP components. This issue has not yet been resolved. To increase comparability with Hsieh & Yu (2003) and Hsieh & Liu (2005), peak amplitude and latency of the LPC were also measured here. However, the amplitude measure is likely to be affected by any superimposed negativity. If this is the case, it is also likely to affect the LPC measured by Hsieh & Yu (2003) and Hsieh & Liu (2005).

stimulus processing for switch versus repeat stimuli. Neither active preparation of task-set reconfiguration nor passive dissipation of the previously active task-set affected the size of the switch effect on stimulus-locked LRP onset. Although stimulus-locked LRP emerged earlier at long than at short CSIs, this appears to represent an overall effect of response-readiness as it was not differentially expressed for switch and repeat trials. The finding that increasing CSI affects the amplitude of the cue-locked differential switch-related positivity and the size of the RT switch cost, but did not modify the effect of task-switching on LPC, stimulus-locked LRP and response-locked LRP appears to support cascade or parallel models rather than purely serial models of information processing. CSI and RSIs modulated the effect of task-switching on distinct ERP components, suggesting that active preparation and passive interference effects on task-switching operate at different levels of processing.

These findings partially complement the findings by Hsieh and Liu (2005). The CSI manipulation used here affected opportunity for anticipatory preparation, much like the cueing manipulation used by Hsieh and Liu. Both studies showed that increasing opportunity for anticipatory task-set reconfiguration reduces but does not eliminate RT switch cost. In Hsieh and Liu, informative cueing reduced the effects of switching on stimulus-locked LRP onset latency and on RT, although only the latter effect was statistically significant. In the present analyses, increasing CSI also reduced the effects of switching on RT but did not significantly affect stimulus-locked LRP latency. The fact that switch trials showed reduced LPC amplitude and increased LPC latency here but not in Hsieh and Liu, may reflect that, in Rushworth's terminology (Rushworth et al. 2002), the current paradigm involved switching both attentional (letter task versus digit task) and intentional (press left for odd versus press left for vowel) set, whereas Hsieh's paradigm involved switching intentional set only.

Summary

Analyses of the ERPs in the CSI from Experiment 1 suggest that, at least under attentional-set switching conditions, anticipatory task-set reconfiguration is activated prior to stimulus onset and differentially affects RT switch cost at short and long CSIs. Rushworth et al.

(2002; 2005) showed similar patterns of cue-locked ERPs under both intentional and attentional set switching conditions, suggesting that a differential switch-related positivity is likely to be found in the CSI in Hsieh et al's (2002; 2005) data as well. Like Hsieh et al., the present data also provide evidence for task-switching effects at later stages of processing. Specifically, task-switching effects on stimulus processing were modulated by passive interference processes reflected in the RSI manipulation, whereas task-switching effects on response selection and activation were not affected by either active preparation or passive dissipation processes. These findings suggest that anticipatory task-set reconfiguration processes affect task-set retrieval but not stimulus processing or response-related processes.

4   Experiment 2: Effects of 'switch-to' and 'switch-away' cues [6]

Experiment 1 provides strong evidence regarding the existence of a process of anticipatory task-set reconfiguration, however relatively little is known about what this process actually entails. For task-set reconfiguration to be activated prior to stimulus onset, it is necessary for participants to have foreknowledge that the next trial will require a switch in task, as is the case with alternating runs paradigms that use a predictable task sequence (e.g., Task AABB) and with task cueing paradigms that validly cue the relevant task prior to stimulus onset. Foreknowledge is only useful if the length of the preparation interval (e.g., the RSI in alternating runs paradigms or the CSI in cued task paradigms) is sufficient to allow activation of anticipatory task-set reconfiguration (Rogers & Monsell, 1995) *and* these processes are actively engaged prior to stimulus onset (De Jong, 2000). If these conditions are not met, task-set reconfiguration is initiated and/or completed after stimulus onset, resulting in longer switch trial RT and hence increased RT switch cost.

Anticipatory task-set reconfiguration can be affected by parameters that promote or impede active engagement in these processes. Goschke (2000) found that interrupting anticipatory task-set reconfiguration by requiring participants to recite irrelevant verbal material during a long RSI (1200 ms) resulted in RT switch cost equivalent to the short RSI (150 ms) condition. In contrast, when participants verbalised the task to be completed on the next trial, there was a significant reduction in RT switch cost compared to either of the above conditions and equivalent to that obtained with a long RSI when no verbalisation was required. This suggests that retrieval and application of the new task-set from long term into working memory is an important part of anticipatory task-set reconfiguration (Mayr & Kliegl, 2000).

Using cues that manipulate subjective expectancy of equiprobable switch and repeat trials, Dreisbach, Haider & Kluwe (2002) found equivalent effects of subjective expectancy on both switch and repeat trials, suggesting that task preparation may occur in anticipation of both

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[6] Published as Nicholson, R., Karayanidis, F., Davies, A., & Michie, P. (in revision). Components of Task-set Reconfiguration: Differential Effects of *'Switch-to'* and *'Switch-away'* Cues. *Brain Research.* See Appendix.

switch and repeat trials. Further, task preparation did not interact with task foreknowledge (see also Sohn & Carlson, 2000) suggesting that these manipulations affect independent processes and supporting a preparation readiness account of switch cost. Alternatively, Monsell and Mizon (2006) argue that these effects may be at least partly attributed to cue complexity, as complex cues may inadvertently introduce an additional task, resulting in task-set reconfiguration for both switch and repeat trials.

Inhibitory processes may also affect task-set reconfiguration. Mayr and Keele (2000) found that switching back to a recently abandoned task-set resulted in larger RT switch cost as compared to switching to a third task – a phenomenon they refer to as backward inhibition. Specifically, RT was larger on the third trial of a CB$\underline{C}$ task sequence as compared to an AB$\underline{C}$ sequence (see also Arbuthnott & Frank, 2000; Koch, Gade & Philipp, 2004). This suggests that the previously relevant, but now irrelevant, task-set (task C) was inhibited in the former task sequence thereby resulting in longer RT when this task-set was reactivated within a short period. Using a go/no-go paradigm, Schuch and Koch (2003) found that backward inhibition did not occur following no-go trials that required task-set preparation but no response execution, suggesting that selection or execution of the response triggers the inhibitory processes.

Mayr and Keele (2000) found that the amount of backward inhibition was not reduced with increasing CSI, suggesting that the inhibition process is not affected by the amount of time available for anticipatory task-set reconfiguration. In contrast, backward inhibition was reduced at longer RCI that facilitated greater passive dissipation of task-set interference (see also Koch et al., 2004). Furthermore, Gade and Koch (2005) showed that the opportunity for passive dissipation of interference across the interval between trial n and trial n-2 had a greater effect than the interval between n and n-1 (e.g., in task sequence ABA the amount of backward inhibition was affected more by the interval between the two Task A trials than between Task B and Task A trials). Dreisbach et al. (2002) reported that 'semi-specific' cues (i.e., cues that signal an impending switch trial without identifying which specific task to prepare) resulted in longer RT switch cost than 'specific' cues that indicated which task to switch to. Unlike specific

cues, semi-specific cues did not produce subjective expectancy effects, suggesting that knowledge that the task would change without specification of which task would be performed did not result in any differential response benefit. Hubner, Dreisbach, Haider and Kluwe (2003) showed that backward inhibition effects were comparable for an uncued switch in task and a cued switch in task with semi-specific cues.

Taken together, these findings suggest that task-set reconfiguration may involve not only activation of the currently active task-set but also inhibition of the previously active task-set. Further, it appears as if the inhibition process can not be initiated independently of activation of the currently active task-set. Mayr and Keele (2000) argue that inhibition may reflect a low-level control process, such as lateral inhibition of competing action schemas. Dreisbach et al. (2002) suggest that active engagement of the cued task-set triggers automatic inhibition of the previously relevant task-set when the response is executed. That is, they argue that inhibition of the irrelevant task-set is not under endogenous control and cannot occur independently of activation of the relevant task-set (see also Hubner et al., 2003).

Overall, there are still considerable gaps in our knowledge regarding the number and type of cognitive processes that underlie anticipatory task-set reconfiguration. Although there is evidence of a role for an inhibitory process, its timing and degree of dependence on other activation processes remain unclear. Further, the precise sets of operations that constitute activation of the relevant task-set in anticipation of a switch in task remain to be defined.

ERPs in task-switching experiments can help elucidate the cognitive processes that lead up to behavioural differences between switch and repeat trials in general, as well as those processes more specifically involved in task-set reconfiguration. Most ERP task-switching studies have focused on differences between ERPs to switch and repeat stimuli occurring after stimulus onset (e.g., Barceló, Munoz-Cespedes, Pozo & Rubia, 2000; Barceló, Perianez & Knight, 2002; Gehring, Bryck, Jonides, Albin & Badre, 2003; Hsieh & Yu, 2002; Hsieh & Liu, 2005; Poulsen, Luu, Davey & Tucker, 2005; Swainson et al., 2003). ERP differences between switch and repeat trials occurring after stimulus onset may reflect processing differences

occurring as a result of differential levels of proactive interference for switch compared to repeat stimuli, differential level of activation of the relevant task-set at stimulus onset, as well as differential stimulus-response interference elicited by the stimulus itself. Therefore, although anticipatory task-set reconfiguration may indirectly affect stimulus-locked ERPs (e.g., Barceló et al, 2000), it is difficult to isolate this effect from that of other passive interference or stimulus-elicited processes.

It is possible to isolate ERP effects associated with anticipatory task-set reconfiguration by examining either the interval preceding stimulus onset in an alternating runs paradigm or the interval following cue onset in a cued task-switching paradigm. Karayanidis et al. (2003) identified an increased positivity for switch as compared to repeat trials in the interval between the response to the previous trial and the onset of the next trial. Wylie, Javitt and Foxe (2003) found that trials preceding a predictable switch trial were associated with a larger late positivity over posterior scalp electrodes compared to trials preceding a repeat trial. Other studies found that ERP waveforms time-locked to cue presentation show a larger positivity for switch compared to repeat cues over parietal sites around 500 ms after cue onset (Miniussi, Marzi & Nobre, 2005; Rushworth, Passingham & Nobre, 2002; Rushworth, Passingham & Nobre, 2005). Using a cued task-switching paradigm, Experiment 1 demonstrated that the morphology of the parietal switch-related positivity was modified by manipulation of the CSI but not the RSI, indicating that it is affected by opportunity to engage in active task-set reconfiguration but not by the passive passage of time between the previous and the current trial.

In summary, anticipatory task-set reconfiguration is associated with increased positivity in anticipation of switch relative to repeat trials, particularly over parietal electrodes. At longer preparation intervals, this differential activity for switch trials can be completed prior to stimulus presentation and is associated with reduced RT switch cost. With short preparation intervals, which provide little or no opportunity for anticipatory task-set reconfiguration, these processes occur after stimulus onset and are associated with larger RT switch cost.

The current experiment investigates one component process of task-set reconfiguration, the activation of the currently relevant task-set. The aim was to examine whether the switch-related differential positivity is specifically associated with activation of the relevant task-set or is affected by other processes that may occur during preparation for a switch in task. A cued-trials task-switching paradigm was used. Participants randomly alternated between three tasks defined for the same stimulus set. Three types of cues were used to signal the requirements of the next trial. The first cue type signalled task repetition, the second cue type signalled a task switch and specified which task to switch to (*switch-to* or specific cues), whereas the third cue type signalled a task switch, but did *not* specify which of the two alternate tasks would be active (*switch-away* or semi-specific cues). With the latter cues, participants knew that they would not be repeating the same task as on the previous trial but had no information about which task-set would be relevant and had to await stimulus onset before the new task-set could be activated. Therefore, the use of *switch-to* and *switch-away* cues was designed to isolate processes associated with activation of the relevant task-set.

Switch-to trials were identical to the switch trials defined in previous ERP and behavioural studies (e.g., Experiment 1). Therefore, *switch-to* trials were expected to produce a large RT switch cost that reduced with increasing CSI and with increasing RSI, as well as a large switch-related positivity time-locked to cue onset and peaking before stimulus onset in the long CSI condition (Karayanidis et al., 2003; Experiment 1). Semi-specific or *switch-away* cues index that the current task-set will not be active upon stimulus onset, but do not specify which of the remaining two task-sets will be active. Since for *switch-away* cues, activation of the relevant task-set could not be completed until after stimulus onset regardless of preparation interval, it was expected that switch-away cues would have larger RT switch cost than *switch-to* cues, and that *switch-away* RT cost would not reduce with increasing CSI. However, as passive dissipation of task-set interference should not be affected by the information provided by the two switch cue types, increasing RSI for constant CSI was expected to reduce RT switch cost equally for *switch-to* and *switch-away* trials.

ERP waveforms for *switch-to* and *switch-away* trials were compared only at the long CSI (1000 ms) that affords the opportunity for activation of anticipatory task-set reconfiguration and provides temporal dissociation between cue and stimulus related processes. If the cue-locked differential switch-related positivity that peaks before stimulus onset with long CSIs for *switch-to* trials indexes activation of the relevant task-set in anticipation of a cued switch in task-set, then since this process can not be activated until after stimulus onset for switch-away trials, there should be no evidence of a cue-locked differential switch-related positivity for *switch-away* trials. Instead, for *switch-away* trials, this cue-locked differential switch-related positivity should emerge after stimulus onset just as it does when there is no advance cueing or when the CSI is very short (Experiment 1). If a differential switch-related positivity is still evident within the CSI for *switch-away* trials, then clearly it can not indicate activation of the relevant task-set, but presumably some other component of task-set reconfiguration that can be triggered by both *switch-to* and *switch-away* cues.

4.1   Method

Participants

Thirty-six undergraduate students (mean age 23 ± 6.8 years, 18 to 40 years; 29 female).

Stimuli and tasks

For each run of trials, a circle (230 pixels diameter) divided into 6 equal wedges was continuously displayed in the middle of a computer monitor at approximately 90 cm viewing distance. On each trial, a stimulus was displayed in the centre of one of the six wedges (Figure 4-1a). Pairs of adjacent wedges were grouped by thicker lines extending slightly beyond the perimeter of the circle thus demarcating three sections. Each of the three sections was assigned to one of three tasks. The assignment of task to section was counterbalanced across participants.

In the letter task, participants responded whether the letter presented was a vowel (A, E, I, U) or a consonant (G, K, M, R). In the digit task, participants responded whether the digit presented was odd (3, 5, 7, 9) or even (2, 4, 6, 8). In the colour task, participants responded

whether the colour of the stimulus was hot (red, pink, orange, burgundy) or cold (ocean blue, emerald green, sky blue, turquoise).

Stimuli consisted of a pair of characters in Times New Roman font (60 by 60 pixels). Characters could be a letter, a digit, or a non-alphanumeric character (#, ?, *, %) that was not mapped to a response (neutral). Stimuli were presented either in grey (neutral) or in one of eight colours listed above. Each stimulus therefore consisted of three dimensions; character 1, character 2 and colour. One dimension was selected from the currently relevant task-set (i.e., a digit for the digit task). The second dimension was selected from one of the two alternative task-sets (i.e., a letter or a colour). This second dimension was always incongruently mapped to the first dimension, whereas the third dimension was always neutral.

For example, assume that the digit task was relevant on the current trial, and that the number '3' was presented, thus requiring a left hand response. The second character could be either a letter or a neutral stimulus. If it was a letter, then it would have to be a consonant, so as to be mapped to an incongruent response (i.e., right hand). In this case, the third stimulus dimension (colour) would be neutral (i.e., grey). For example, the stimulus '3G' would be presented in grey and the correct response would be left. Alternatively, if the second character was neutral (e.g., #), then the stimulus would be presented in one of the cold colours, so that again it would be mapped to an incongruent response (right hand). For example, the stimulus '3#' would be presented in green. The combination of stimulus dimensions and the position of task-relevant and task-irrelevant characters (e.g. 4U, U4) were varied pseudorandomly across trials. Stimuli were selected pseudorandomly from their character set with the only restriction that the same stimulus could not appear on two successive trials.
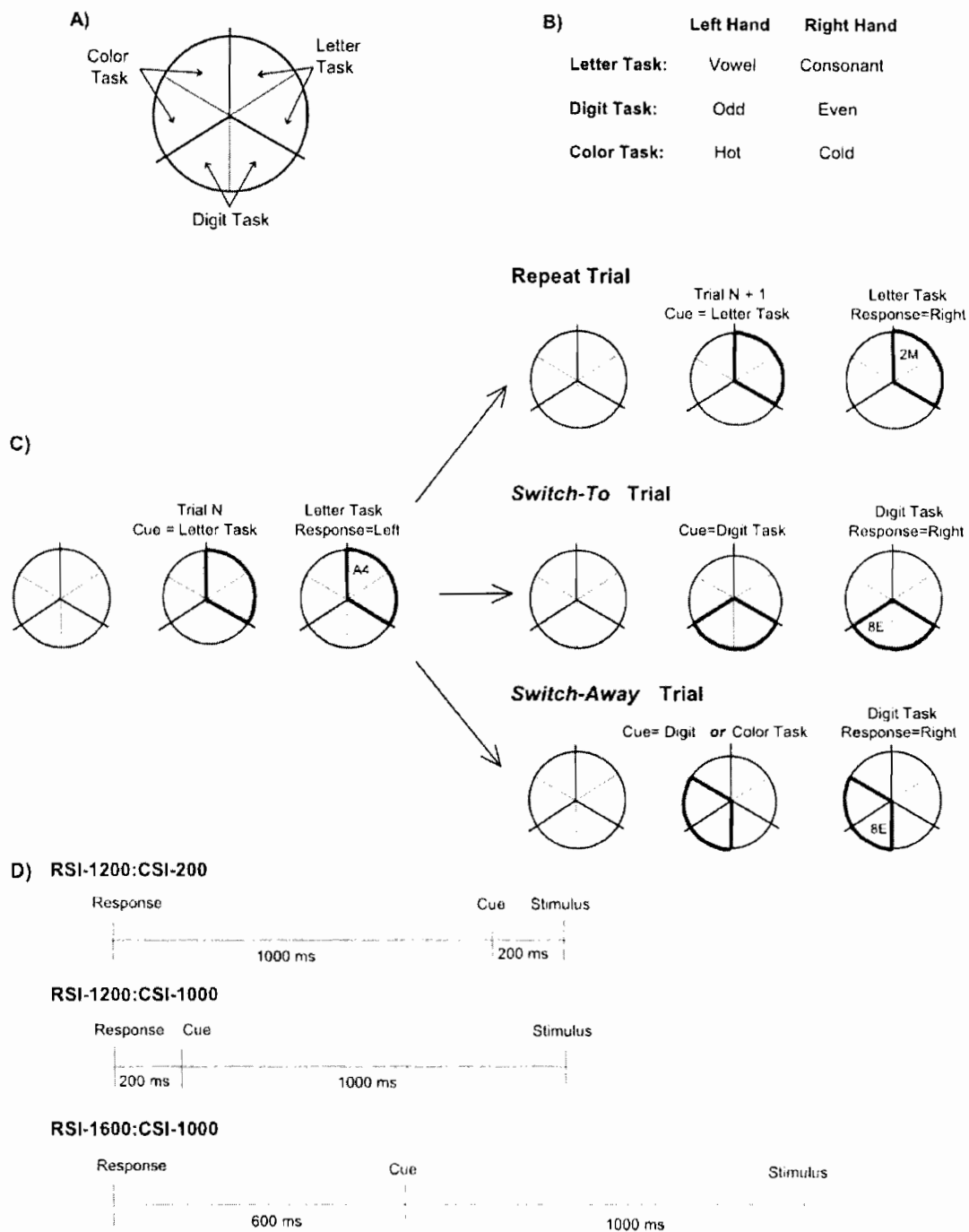
Figure 4-1. A) Circle fixation grid with three task sections B) Example stimulus-response mappings for the three tasks C) Circle grid showing unpredictable task alternation sequence with either repeat task cue (indicates the same task will be repeated on the next trial), *switch-to* task cue (indicates that the task will switch on the next trial and shows which task will be switched to) or *switch-away* task cue (indicates that the task will switch on the next trial but does not show which task will be switched to). The cue was a highlight displayed around the outline of the circle sections. D) The three RSI / CSI conditions used.

Each trial began with a cue that highlighted the border surrounding two of the six wedges (Figure 4-1c). Three different trial types were defined by the location of the cue and were

pseudorandomly selected with equal probability. The same trial type was never repeated more than 3 times. On repeat trials (1/3 of trials), the cue highlighted the section of the circle assigned to the same task as on the previous trial. Figure 4-1c (repeat sequence) shows that having completed a letter task trial, the next cue signals that the following trial will also be a letter task trial. On half of the repeat trials, the stimulus appeared in the same wedge as on the previous trial, while on the other half it appeared in the adjacent wedge within that task section. The other two types of cues indicated that the next trial would involve a switch in task, but provided different degrees of information regarding what the next task would be. S*witch-to* cues (1/3 of trials) highlighted a section assigned to one of the other two tasks, thereby validly cueing which task-set would be active on the upcoming trial. Figure 4-1c (*switch-to* sequence) shows that, having performed a letter task trial, the next cue indicates that the following trial will involve a *switch-to* the digit task.

Switch-away cues (1/3 of trials) transgressed task sections and highlighted wedges belonging to the two tasks that were irrelevant on the previous trial, thereby indicating that the current task would not be repeated, but not indicating which task-set would be active on the upcoming trial. As shown in Figure 4-1c (*switch-away* sequence), the cue highlighted two segments, one assigned to the digit task and one assigned to the colour task. Therefore, having completed a letter trial, the highlight indicated that the upcoming trial would require a *switch-away* from the letter task-set. The active task-set (digit or colour) is then determined by the position of the stimulus itself and thus the new task-set cannot be activated until after stimulus onset. The cue and the stimulus remained on the screen until a response was generated or 5000 ms had elapsed.

Three timing conditions were used to vary the CSI and RSI (Figure 4-1d). RSI was manipulated across two levels: short (1200 ms) and long (1600 ms). At the shorter RSI, CSI varied across two levels: short (200 ms) and long (1000 ms). Condition labels represent the duration of the RSI and CSI (e.g., RSI-1200:CSI-200 = RSI of 1200 ms and CSI of 200 ms).

Procedure

The first session provided substantial task practice. This began with two runs (48 trials/run) on each task alone. This was followed by two runs (72 trials/run) of repeat and *switch-to* trials and two runs of repeat and *switch-away* trials. Session 1 finished with 2 runs (228 trials/run) of combined repeat, *switch-to* and *switch-away* trials. Throughout practice, stimulus-response mapping (Figure 4-1b) and task location (Figure 4-1a) were displayed continuously at the bottom of the computer monitor and the CSI was a minimum of 600 ms. Second day practice included one run (48 trials/run) on each task alone, two runs (72 trials/run) with repeat and *switch-to*, and repeat and *switch-away* trials, respectively, and two runs (228 trials/run) of combined repeat, *switch-to* and *switch-away* trials (RSI-1200:CSI-1000 & RSI-1200:CSI-200, respectively). Participants thus completed a total of 1776 practice trials across the 2 practice sessions. The behavioural and ERP testing session consisted of the 3 timing conditions presented in blocks of 3 runs (228 trials/run). Each condition was presented in a separate block and the order of block presentation was counterbalanced across participants using a Latin square design. The first 12 trials of every run were consider 'warm-up' trials and were discarded from analysis.

Data analysis

Only data from digit and letter task trials were included in behavioural and ERP analyses. Data from colour task trials were excluded for two reasons: firstly, in order to enable direct comparison of these results to Experiment 1, and secondly, a task based on colour classification may activate slightly different processes compared to the classification of digits as odd or even and letters as vowels or consonants. This was manifested as significantly faster RT as well as a tendency towards greater negativity in the stimulus-locked ERPs for the colour task, relative to the digit and letter tasks, for all trial types. Colour task trials were thus excluded from all analysis in this experiment to remove this confound.

Behavioural data analysis

Error and RT switch cost for *switch-to* and *switch-away* trials was calculated by subtracting the mean value for repeat trials from the mean value on *switch-to* and *switch-away* trials, respectively (i.e., *Switch-to* cost = *switch-to* – repeat ; *Switch-away* cost = *switch-away* – repeat). RT and arc sine transformed proportion error data were first analysed using a 3 condition (RSI-1200:CSI-200, RSI-1200:CSI-1000, RSI-1600:CSI-1000) by 3 trial type (repeat, *switch-to, switch-away*) by 2 task (letter, digit) repeated-measures ANOVA. Given significant main effects of trial type and interactions between trial type and other factors, RT and error switch cost measures were then examined in a 3 condition (RSI-1200:CSI-200, RSI-1200:CSI-1000, RSI-1600:CSI-1000) by 2 switch cost type (*switch-to* switch cost, *switch-away* switch cost) by 2 task (letter, digit) repeated-measures ANOVA. The effects of condition on switch cost type were examined in two sets of planned comparisons that were run separately for *switch-to* and *switch-away* costs (averaged across task with alpha adjusted using the Bonferonni correction). The effect of increasing CSI was examined by comparing RSI-1200:CSI-200 and RSI-1200:CSI-1000. The effect of increasing RSI was examined by comparing RSI-1200:CSI-1000 and RSI-1600:CSI-1000.

EEG recording and data analysis

EEG was recorded continuously from 12 scalp electrodes according to the 10/20 system using an electrode cap (Electro-cap International) and linked mastoids reference. EEG and EOG were continuously sampled at 500Hz/channel using NeuroScan Inc. and amplified (x 5000 for EOG and frontal channels; x 20 000 for other EEG channels) using a Grass Neurodata system (Model 12) with a bandpass of 0.01-30 Hz (-6 dB down). Cue- and stimulus-locked averages were created by extracting 1400 ms epochs around the onset of the cue or stimulus, respectively, with a 200 ms pre-onset interval. Due to large pre-baseline shifts in some conditions, baseline correction was set -50 to 50 ms around the onset of the cue or stimulus.

Behavioural data indicated that, although there was an overall effect of task on RT, task did not interact with RT switch cost type or condition. Therefore, in order to maximise signal to

noise ratio, all ERP data were averaged over task (letter/digit). Cue-locked and stimulus-locked epochs were averaged separately for each condition and trial type. Nine cue- and nine stimulus-locked (3 timing conditions by 3 trial types) ERP average waveforms were created for each participant at each electrode site. Across all conditions and trial types there tended to be slow potential drift from the fronto-temporal sites that extended beyond the range of the epoch. This was mostly likely attributable to drift from the HEOG channel, which was consistent for all three trial types, as participants were required to make horizontal eye movements around the circle grid. All average files were thus linearly detrended across the entire interval in order to remove this eye drift artifact.

As with the behavioural switch cost data, *switch-to* and *switch-away* difference waveforms were calculated by subtracting the ERP repeat waveform from the ERP *switch-to* waveform and the ERP *switch-away* waveform, respectively. Six cue-locked and six stimulus-locked difference waveforms were thus created for each participant at each electrode site. Difference waveforms were analysed using point-by-point t-tests over 50 to 1000 ms to identify points of significant deviation of each waveform from baseline and points of significant deviation between the two waveforms (i.e., *switch-to* versus *switch-away* difference waveforms). This analysis was conducted at the midline sites (Fz, Cz, Pz and Oz). The Guthrie and Buchwald (1991) procedure was used to control for Type 1 error at $\alpha = 0.01$ using an autocorrelation coefficient of 0.9.

4.2 Results

Behavioural data

Mean RT and error rate for each timing condition, trial type and task are shown in Table 4-1. The main effects of condition, trial type and task ($F_{(2,70)}=36.2$, p<.001; $F_{(1,48)} =229.3$, p<.001; $F_{(1,35)}=22.2$, p<.001, respectively) and the condition by trial type and trial type by task interactions ($F_{(4,140)}=6.9$, p<.001; $F_{(2,58)}=8.5$, p<.005) were significant. Overall, RT was longer for the digit task compared to letter task, and this effect was larger for both types of switch trials compared to repeat trials (Table 4-1). RT was also longer for the short CSI (RSI-

1200:CSI-200) compared to the two long CSI conditions, and again this was larger for both type

of switch trials compared to the repeat trials.

Table 3-1

Mean reaction time (RT) and percentage error rate by condition, trial type and task (average over task also shown) Standard error in parentheses.

	RSI-1200:CSI-200			RSI-1200:CSI-1000			RSI-1600:CSI-1000		
	Repeat	Switch -to	Switch -away	Repeat	Switch -to	Switch -away	Repeat	Switch -to	Switch -away
Mean RT (ms)									
Letter Task									
	773	949	1008	703	843	955	701	840	942
	(14)	(9)	(12)	(13)	(10)	(12)	(13)	(13)	(11)
Digit Task									
	776	1021	1072	721	905	1007	740	918	1004
	(14)	(14)	(14)	(13)	(16)	(14)	(13)	(15)	(15)
Average									
	775	986	1040	713	875	982	721	880	973
	(12)	(9)	(10)	(11)	(10)	(9)	(11)	(11)	(9)
Error %									
Letter Task									
	2.1	3.9	4.1	1.4	3.4	2.9	1.3	4.3	3.5
	(0.6)	(0.4)	(0.5)	(0.4)	(0.3)	(0.3)	(0.5)	(0.6)	(0.4)
Digit Task									
	2.8	5.2	4.6	2.5	3.5	4.1	1.9	3.6	4.4
	(0.4)	(0.8)	(0.4)	(0.5)	(0.6)	(0.4)	(0.4)	(0.4)	(0.6)
Average									
	2.5	4.6	4.4	1.9	3.4	3.5	1.6	3.9	4.0
	(0.4)	(0.5)	(0.2)	(0.4)	(0.3)	(0.3)	(0.3)	(0.3)	(0.4)

These effects were further examined in the switch cost for *switch-to* and *switch-away* trials (Figure 4-2). RT switch cost was larger for the digit than for the letter task ($F(1,35=11.3$, $p<.005$), however task did not interact with switch type or condition. As shown in Figure 4-2, RT switch cost was larger for *switch-away* than for *switch-to* trials across all three conditions ($F(1,35)=139.8$, $p<.001$). Paired comparisons between conditions showed that, for *switch-to* cues, RT switch cost did not differ significantly between short (1200 ms) and long (1600 ms) RSI (162 ms and 159 ms, respectively), but it was significantly greater in the short (200) compared to the long (1000) CSI (210 ms and 162 ms, respectively, $F(1,35)=13.9$, $p<.005$). For *switch-away* cues, RT switch cost did not differ significantly between short and long RSI (269 ms and 252 ms, respectively) nor between short and long CSI (265 ms and 269 ms).
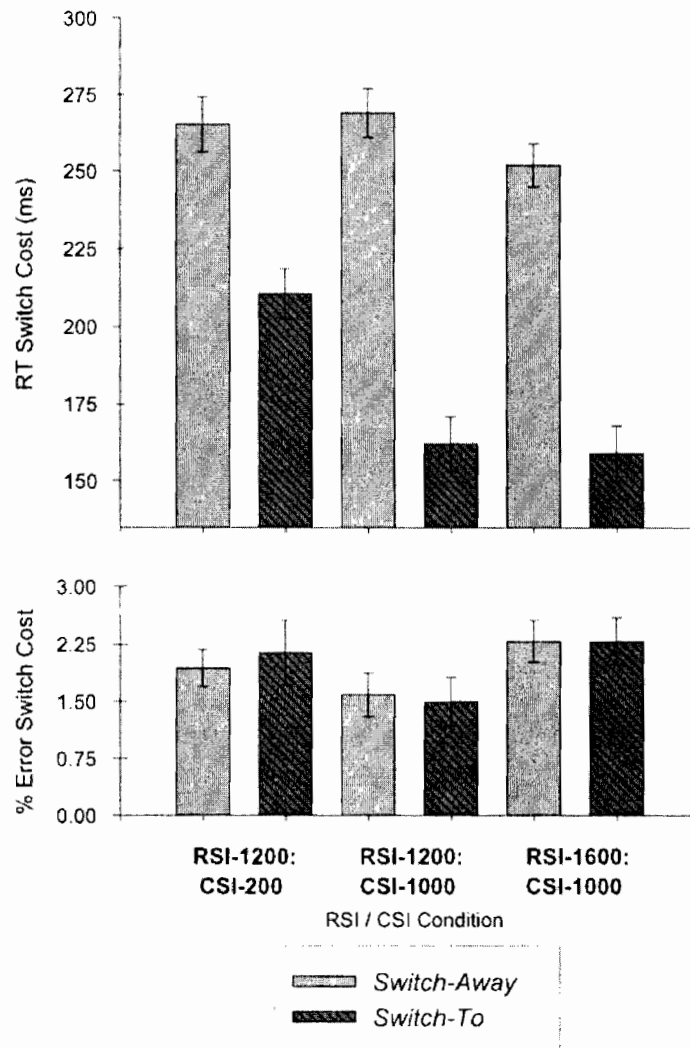
Figure 4-2. *Switch-away* Switch Cost (*switch-away* minus repeat) and *Switch-to* Switch Cost (*switch-to* minus repeat) for each condition averaged across task. Standard error bars are shown. Top: Mean reaction time (RT) switch cost. Bottom: % error switch cost.

The overall error rate was very low, ranging between 1.3 and 4.6% (Table 4-1). Transformed error scores showed a significant main effect of condition ($F(2,70)=6.5$, $p<.005$) reflecting slightly higher error rates in the short CSI (3.8%) compared to the long CSI conditions (3.0-3.2%). Both switch trial types produced more errors (3.9% for *switch-away* and 4% for *switch-to*) than repeat trials (2%, $F(2,68)=23.5$, $p<.001$). There were no further significant effects in the error data.

ERP data

Cue-locked effects of *switching-to* a task

Cue-locked waveforms averaged separately for repeat and *switch-to* trials for each timing condition at midline sites are shown in Figure 4-3A (top). Long CSI conditions (middle and right) show a broad centro-parietally maximal positivity beginning approximately 200 ms after cue onset at most midline sites. This positivity returned to baseline by 450 ms at frontal and central sites, but persisted to approximately 700 ms at parietal and occipital sites. Differences between repeat and *switch-to* cue-locked ERPs emerged as early as 100 ms occipitally and spread beyond 800 ms parietally. The variations in ERP morphology between these two long CSI conditions are likely to reflect differential resolution of post-response processes. Specifically, although CSI was constant at 1000 ms for both conditions, the RCI was only 200 ms for RSI-1200 but 600 ms for RSI-1600 ms. In the former condition, both switch and repeat trials may have included an overlap of post-response processes that had resolved in the longer RSI condition.

Cue-locked waveforms for the short CSI condition (left) differed more notably from the two long CSI conditions (middle, right) due to the partial temporal overlap of cue-locked and stimulus-locked ERPs. In this short CSI condition, frontal and central sites showed a series of positive and negative deflections that do not differentiate between repeat and *switch-to* trials as clearly as the long CSI conditions and are likely to reflect cue and stimulus processing. Central and parietal electrodes do, however, show a broad positive deflection extending from 150 ms to approximately 1000 ms after cue onset reflecting the temporal overlap of a post-cue positivity, similar to that seen in the long C-S conditions, and a LPC to stimulus onset.
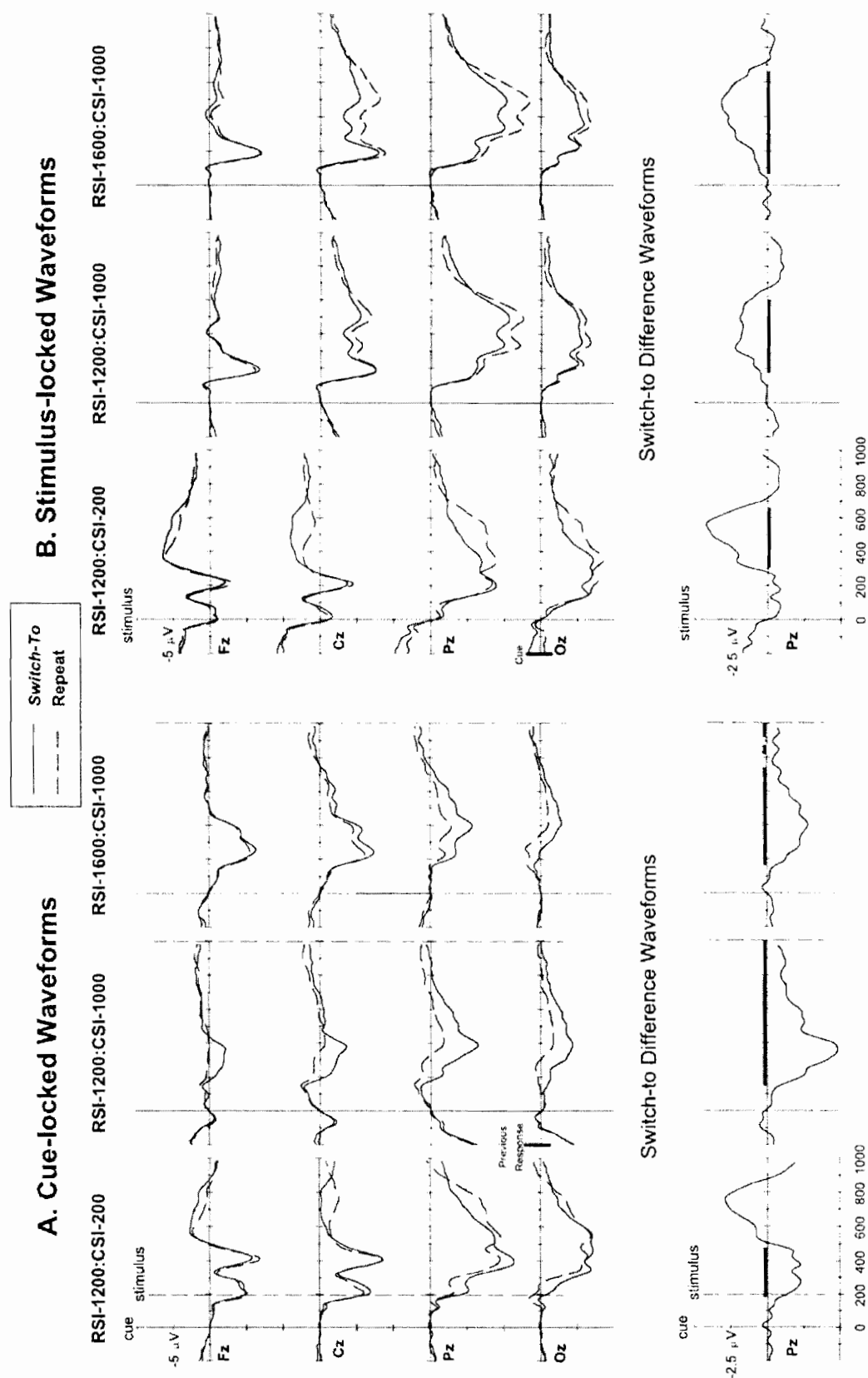
Figure 4-3. Top: A) Cue-locked and B) stimulus-locked ERP waveforms for *switch-to* and repeat trials Bottom: A) Cue-locked and B) stimulus-locked ERP *switch-to* difference waveforms (*switch-to* waveform minus repeat waveform) at Pz. Black bars indicate regions of significant deviation between the *switch-to* and repeat waveform (see Table 4-2 for exact values at the four midline sites).

Table 4-2

Results of point-by-point analysis of cue- and stimulus locked *switch-to* difference waveforms (*switch-to* minus repeat waveform). *Switch-to* positivity represents regions where the *switch-to* waveform was significantly more positive than the repeat waveform. *Switch-to* negativity represents regions where the *switch-to* waveform was significantly more negative than the repeat waveform.

	Cue-locked Waveforms			Stimulus-locked Waveforms		
	Switch-to Positivity			*Switch-to* Negativity		
	RSI-1200: CSI-200	RSI-1200: CSI-1000	RSI-1600: CSI-1000	RSI-1200: CSI-200	RSI-1200: CSI-1000	RSI-1600: CSI-1000
Fz	-	190-406	248-270	180-212 428-534 562-602	-	458-512
Cz	236-264	172-426 858-1000	224-316 508-532 837-862 924-960 982-1000	344-662	290-388 450-550	110-180 216-694
Pz	192-480	146-1000	176-734 824-874 920-1000	302-664	194-600	68-680
Oz	126-370 450-512	126-956	142-602 944-986	178-232 318-650	190-250 270-426 436-574	262-608

Cue-locked *switch-to* difference waveforms

Figure 4-3A (bottom) depicts *switch-to* cue-locked difference waveforms for the three timing conditions at Pz[7] where the effects were maximal. Positive deviations from baseline indicate areas where the *switch-to* waveform was more positive relative to the repeat waveform (see Table 4-2). *Switch-to* difference waveforms showed a broad positive deflection similar to that previously reported by Karayanidis et al (2003) and Experiment 1. This differential positivity emerged 150-190 ms after cue onset for all three conditions. In both long CSI conditions, D-Pos spread beyond 800 ms covering the entire interval until stimulus onset, whereas in the short CSI condition, it resolved around 500 ms post-cue.

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[7] Difference waveforms for the four midline sites (averaged over the two long CSI conditions) are shown in Figure 3-4B (left).

Stimulus-locked effects of *switching-to* a task

ERP waveforms time-locked to stimulus onset for repeat and *switch-to* trials are shown at midline sites in Figure 4-3B (top). Stimulus-locked waveforms tended to show a pattern of early occipital obligatory ERPs (P1, N1 and P2) followed by a broad LPC that spread beyond 700 ms and was maximal parietally. Frontally, a large P2-type component emerged around 200 ms but there was little evidence of further activity. These effects are most clearly evident in the long CSI conditions that had no temporal overlap with the cue-locked period. In comparison, the short CSI condition (RSI-1200:CSI-200) had a sharp shifting pre-stimulus baseline, especially at frontal to parietal sites, reflecting the partial temporal overlap between cue-locked and stimulus-locked ERPs. Overall, the stimulus-locked ERP morphology was very similar for repeat and *switch-to* waveforms; however differences emerged as a broad negative shift for *switch-to* relative to repeat waveforms.

Stimulus-locked *switch-to* difference waveforms

Figure 4-3B (bottom) depicts *switch-to* stimulus-locked difference waveforms at Pz. For long CSI conditions (middle, right), *switch-to* difference waveforms show the emergence of a broad parietally maximal negativity as early as 70 ms that extended beyond 600 ms (Table 4-2). This differential negativity is similar to D-Neg described by Karayanidis et al. (2003) and overlapped a number of ERP components at parietal and occipital sites. D-Neg was also evident in the short CSI condition (i.e., RSI-1200:CSI-200), but parietally, it did not significantly deviate from baseline until 300 ms after stimulus onset (Table 4-2).

ERP results for *switch-to* compared to repeat waveforms thus replicate earlier findings indicating a switch-related positivity in cue-locked waveforms and a switch-related negativity in stimulus-locked waveforms (Karayanidis et al., 2003; Experiment 1).

Comparison of *switch-to* versus *switch-away* ERP effects

Given that differences between *switch-to* and *switch-away* trials will be most clearly evident when there is a long preparation interval, these two switch types were only compared at

the long CSI conditions which also provide maximal temporal separation between cue- and stimulus-locked processes. Additionally, since there was no significant difference in RT switch cost between the two conditions with a long CSI and both conditions showed very similar patterns of effects in the cue- and stimulus-locked waveforms over parietal and occipital sites, ERPs differences between *switch-to* and *switch-away* trials were examined in long CSI waveforms averaged across RSI condition. Figure 4-4A shows cue-locked (left) and stimulus-locked (right) ERP waveforms for repeat, *switch-to* and *switch-away* trials at midline sites averaged over conditions RSI-1200:CSI-1000 and RSI-1600:CSI-1000. Figure 4-4B shows cue-locked (left) and stimulus-locked (right) difference waveforms for *switch-to* trials (*switch-to* minus repeat) and *switch-away* trials (*switch-away* minus repeat).

Table 4-3

Results of point-by-point analysis of cue- and stimulus-locked difference waveforms averaged over the two conditions with a 1000 ms CSI. *Switch-to* and *switch-away* positivity represents regions where the *switch-to* waveform and the *switch-away* waveform were significantly more positive than the repeat waveform, respectively. *Switch-to* and *switch-away* negativity represents regions where the *switch-to* waveform and the *switch-away* waveform were significantly more negative than the repeat waveform, respectively. The To/Away difference values represent regions where there was a significant difference between the two difference waveforms.

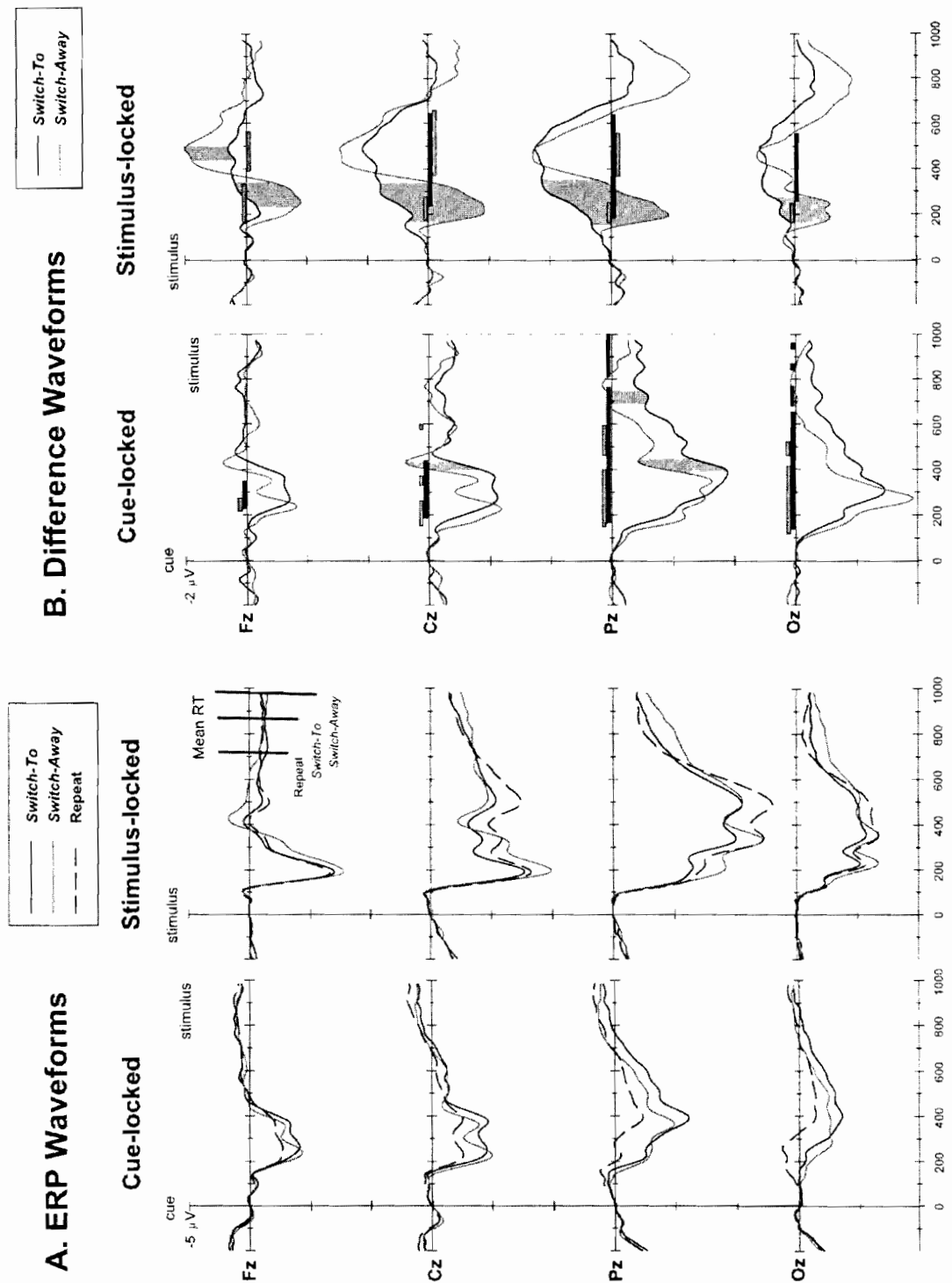|	Cue-locked Difference Waveforms			Stimulus-locked Difference Waveforms			
	Switch-away Positivity	*Switch-to* Positivity	To/Away Difference	*Switch-away* Positivity	*Switch-away* Negativity	*Switch-to* Negativity	To/Away Difference
Fz	202-264	226-388	-	172-332	392-556	-	222-332 432-500
Cz	150-278 324-374 576-602	194-420	392-424	172-276	370-654	232-640	162-336
Pz	140-400 470-594	162-766 810-1000	394-442 690-742	164-254	374-556	188-634	156-354
Oz	110-408 470-510	134-666 684-764 844-884 938-978	-	160-264	414-488	266-548	160-278

Figure 4-4. A) Cue- and stimulus-locked ERPs for *switch-to*, *switch-away* and repeat trials averaged over the two 1000 ms CSI conditions. B) Difference waveforms for *switch-to* (*switch-to* minus repeat) and *switch-away* (*switch-away* minus repeat). Black bars indicate regions of significant deviation between the *switch-to* and repeat waveform. Grey bars indicate regions of significant deviation between the *switch-away* and repeat waveform. Areas shaded grey indicate regions of significant difference between the two difference waveforms. See Table 4-3 for exact values.

Switch-to versus *switch-away* cues: cue-locked waveforms

Cue-locked waveforms for *switch-away* and *switch-to* trials were overall very similar and were characterised by a broad parietally maximal positivity (Figure 4-4A, left). Cue-locked difference waveforms (Figure 4-4B, left) show a large differential positivity emerging for both *switch-to* and *switch-away* cues approximately 100 ms after cue onset. However, this differential positivity was less widespread across the midline sites and smaller for *switch-away* compared to *switch-to* waveforms. At the parietal site, for the *switch-to* waveform, the positivity deviated from baseline over most of the CSI with a significant effect even at stimulus onset. However, the *switch-away* waveform showed no further positivity beyond 600 ms. The shaded grey areas in Figure 4-4B (left) show that this differential switch-related positivity was significantly smaller for *switch-away* compared to *switch-to* waveforms centroparietally over approximately 400-450 ms and 700-750 ms (Table 4-3). Thus, the differential positivity emerged almost concurrently for both *switch-to* and *switch-away* waveforms. While for *switch-to* cues, this positivity remained significant across the entire CSI, for *switch-away* cues it reduced in amplitude around 400 ms, and returned to baseline before stimulus onset.

Switch-to versus *switch-away* cues: stimulus-locked waveforms

The overall morphology of stimulus-locked ERP waveforms was similar for repeat, *switch-to* and *switch-away* trials (Figure 4-4A, right). However, *switch-away* and *switch-to* waveforms differed in their pattern of deviation from the repeat waveform. As shown earlier, *switch-to* trials showed an early and prolonged centro-parietally maximal negative shift compared to repeat waveforms. In contrast, *switch-away* waveforms show an early *positive* deviation emerging around 150 ms after stimulus onset. This can be most clearly seen in the difference waveforms (Figure 4-4B, right). *Switch-away* trials showed a large, sharp positive deviation from repeat trials approximately 150-300 ms after stimulus onset (Table 4-3). This positivity was spread across all midline sites, overlapping P2 anteriorly and P2 and early P3 posteriorly. This early positivity in the *switch-away* difference waveform was quickly succeeded by a differential negativity that differed from the *switch-to* negativity in that it began

much later (360 ms) and spread more broadly across the scalp. However, like the *switch-to* negativity, the negativity for *switch-away* trials also returned to baseline around 700 ms (Table 4-3). Direct point-by-point comparison of *switch-to* and *switch-away* difference waveforms resulted in significant differences over approximately 160-350 ms spanning across all midline sites (Table 4-3), but no further differences across the analysis epoch. This confirmed that *switch-away* trials showed a significant early differential positivity which was replaced by a differential negativity that began later than but resolved in line with the *switch-to* negativity.

Summary of ERP findings

Switch-to cues showed the expected pattern of a parietally-maximal broad differential cue-locked positivity emerging around 150 ms and extending across the entire CSI and a centro-parietal differential negativity emerging shortly after stimulus onset and extending beyond 600 ms. In cue-locked waveforms, a differential positivity also emerged around 150 ms for *switch-away* cues, but had a smaller amplitude and shorter duration than for *switch-to* cues. In stimulus-locked waveforms, *switch-away* trials showed an early differential positivity relative to repeat trials extending over 150-300 ms that was followed by a differential negativity that emerged much later and was more widespread than for *switch-to* trials.

4.3   Discussion

The present experiment used behavioural and ERP measures to dissociate components of anticipatory task-set reconfiguration. Specifically, it was investigated whether the differential positivity observed during preparation for a switch in task (Karayanidis et al., 2003; Experiment 1) can be shown to be associated with activation of the currently relevant task-set. The point at which the new task-set could be activated was manipulated by varying the amount of information provided by the task cue. Cues signalled either that the present task would be repeated (task *repeat* cue), that the next trial would require a switch in task and specified which task was to be performed (*switch-to* cue), or that the next trial would require a switch in task but did not specify which task was to be performed (*switch-away* cue).

Behavioural effects of *switching-to* versus *switching-away* from a task-set

The *switch-to* cues used here were identical to the switch cues used in most previous task-switching studies in that they specified both the need to shift away from the current task-set and identified which task-set would be relevant on the upcoming trial. RT on *switch-to* trials was much slower as compared to repeat trials and RT switch cost ranged from 159 to 211 ms, which is larger than that found in Experiment 1. A number of factors may have contributed to this inflated switch cost. Firstly, this experiment included only bivalent incongruent stimuli that have been shown to produce slower RT and greater switch cost (Rogers & Monsell, 19955; Woodward, Meier, Tipper & Graf, 2003). Secondly, the task involved a larger switch trial probability (two-thirds of all trials) compared to Experiment 1. Monsell and Mizon (2006) suggest that increasing the proportion of switch trials reduces participants' tendency to engage in anticipatory task-set reconfiguration, thus potentially leading to increased mean RT switch cost (De Jong, 2000). Thirdly, this experiment involved switching between three instead of two task-sets. This may have resulted in larger memory requirements and more stimulus-response mapping interference.

As found in previous studies (Meiran, 1996; Rogers & Monsell, 1995) and Experiment 1, increasing the preparation interval resulted in a reduction in *switch-to* RT cost (i.e., 48 ms decline as CSI increased from 200 to 1000 ms). However, contrary to previous studies (Meiran et al., 2000) and Experiment 1, increasing opportunity for passive dissipation of task-set interference (i.e., increasing RSI from 1200 to 1600 ms) had no further effect on *switch-to* RT cost. This may be attributable to the specific RSI values used in the current experiment. Although Experiment 1 found that switch cost significantly declined as the RSI increased from 750 to 1200 ms, Meiran et al. found no reduction in RT switch cost as the RSI increased from 1000 to 3000 ms. At the shortest RSI value used in the current experiment (1200 ms) passive dissipation of task-set interference may have already plateaued. Thus, the further increase to 1600 ms provided no additional benefit.

A large 'residual' switch cost (Rogers & Monsell, 1995) remained on *switch-to* trials, even with a preparation interval of one second, which is consistent with Experiment 1. This 'residual' switch cost may reflect failures to engage in anticipatory task-set reconfiguration on some proportion of *switch-to* trials, thereby resulting in an overall increase in mean *switch-to* RT (De Jong, 2000). Upon stimulus onset, the spatial location of the stimulus provided a redundant cue as to which task was relevant. Therefore, although participants were encouraged to use *switch-to* cues to prepare in anticipation, if they failed to do this on some trials, they could still respond successfully by initiating task-set reconfiguration after stimulus onset.

Overall, RT switch cost was significantly larger for *switch-away* (around 260 ms) compared to *switch-to* (around 180 ms) trials. In contrast to *switch-to* trials, increasing the preparation interval from 200 to 1000 ms did not have any effect on *switch-away* RT cost. This finding is compatible with the earlier findings by Dreisbach et al. (2002) and Hubner et al. (2003) that information about an impending switch trial without specific knowledge about which task to switch to does not provide any behavioural advantage and supports the suggestion by Dreisbach et al. that irrelevant task-set inhibition can not occur independently of relevant task-set activation. Interestingly, RT cost was larger for *switch-away* than *switch-to* cues even at the short (200 ms) preparation interval. Experiment 1 found that RT switch cost was smaller for 150 ms CSI compared to a no cue condition. These findings suggest that active task-set reconfiguration can at least be initiated prior to stimulus onset even with a very short CSI.

Electrophysiological effects of *switching to* versus *switching away* from a task-set

Cue-locked ERP waveforms for *switch-to* trials showed a significant differential positivity that began approximately 100 ms after cue onset, peaked around 350-400 ms and was largest parietally. At long preparation intervals, this differential switch-related positivity extended across most of the CSI but resolved prior to stimulus onset. At the short preparation interval (200 ms), the differential positivity peaked after stimulus onset and had a shorter duration. For all conditions, *switch-to* trials showed a large stimulus-locked differential negativity. This emerged earlier for long CSI conditions (around 150 ms) than for the short CSI

condition (around 300 ms) but peaked around 500 ms in all conditions. These findings are consistent with those of previous studies (Karayanidis et al., 2003; Miniussi et al., 2005; Rushworth et al., 2002; 2005) and Experiment 1, showing differential processing in anticipation of a switch trial and differential processing of switch and repeat stimuli; thereby supporting the contribution of both active task-set reconfiguration and stimulus-elicited interference processes on RT switch cost.

ERP differences between *switch-to* and *switch-away* trials were examined at the long preparation interval that provided opportunity for anticipatory task-set reconfiguration processes to be initiated prior to stimulus onset and temporally separated cue- and stimulus-locked processes. *Switch-away* difference waveforms showed a cue-locked differential positivity emerging approximately 150 ms after cue onset similar to that for *switch-to* difference waveforms (Figure 4-4B, left). However, while for *switch-to* trials this positivity remained significant centroparietally across the entire CSI, for *switch-away* trials it reduced in amplitude over 350-450 ms and returned to baseline by 600 ms. Specific point-by-point comparisons between *switch-to* and *switch-away* waveforms showed that the later portion of the positivity was significantly smaller centroparietally over 400-450 ms and parietally over 650-750 ms after cue onset for *switch-away* trials. So, a differential switch-related positivity emerged within the CSI for both *switch-to* and *switch-away* waveforms but had a smaller amplitude and shorter duration in the latter cue type. Additionally, *switch-away* difference waveforms showed the emergence of differential positivity *after* stimulus onset (Figure 4-4B, right). This post-stimulus differential positivity for *switch-away* trials was broadly distributed emerging around 150 ms and extending frontally beyond 300 ms. It was succeeded by a centroparietal differential negativity that peaked around 500 ms, similar to that obtained for *switch-to* trials.

Implications for models of task-switching

Experiment 1 suggested that the differential positivity to specific switch cues (i.e., cues that both signal an impending switch trial and specify which task will be active on the next trial) reflects task-set reconfiguration. The finding that, at long preparation intervals, this positivity is

restricted within the CSI suggests that at least some aspects of task-set reconfiguration can be completed in anticipation of stimulus onset (see current *switch-to* data, but also Karayanidis et al., 2003; Rushworth et al., 2002; Rushworth et al., 2005). However, the fact that a residual RT switch cost remains at even the longest preparation intervals combined with the evidence for differential post-stimulus processing of switch and repeat trials, suggests that this anticipatory component of task-set reconfiguration can not fully account for RT switch cost. Stimulus and/or response-interference, as well as passive dissipation of the previously activated task-set may account for the post-stimulus differential negativity and contribute to the RT switch cost. Additionally, at short preparation intervals and in no cue conditions, the positivity emerges or peaks after stimulus onset (see current *switch-to* data for short CSI, but also Karayanidis et al., 2003; Experiment 1) suggesting that task-set reconfiguration is a crucial process that is completed either before or after stimulus onset, depending on task parameters.

Within this framework, the current findings for *switch-away* trials suggest that the process of task-set reconfiguration consists of multiple sub components that can be temporally dissociated. One process appears to be reflected in the emergence of a cue-locked differential positivity for both *switch-to* and *switch-away* trials. This finding indicates that forewarning of an impending switch trial initiates differential processing between switch and repeat trials, even in the absence of information about which specific task will be active on the subsequent trial. This process can not relate to activation of the task-set that will be relevant for the next stimulus, because this information is not yet available for *switch-away* trials. A second process is reflected in the post-stimulus differential positivity for *switch-away* compared to repeat trials. This is believed to reflect the active engagement of the relevant task-set, which for *switch-away* trials is only possible after the stimulus has been presented and its position has indicated which task to perform.

Therefore, it is suggested that the late component of the cue-locked differential positivity for *switch-to* trials and the stimulus-locked differential positivity for *switch-away* trials both reflect activation of the relevant task-set. This interpretation is supported by the finding that

switch-away trials have a larger RT switch cost than *switch-to* trials, even at the short 200 ms CSI (i.e., even with a CSI of only 200 ms, participants were able to begin preparation for the new task-set following cue presentation on *switch-to* trials, resulting in reduced RT switch cost compared to *switch-away* trials). It is also supported by earlier findings that, at short preparation intervals (e.g., see short CSI condition in Figure 4-3A) and in no cue conditions (Experiment 1) the differential positivity emerges and/or peaks after stimulus onset.

The functional significance of the early cue-locked positivity for both switch-to and switch-away trials is more obscure and a number of possible interpretations will be examined. Given that the only common information provided by *switch-to* and *switch-away* cues is that the following trial will *not* be a repeat trial, it is possible that the common early differential positivity may reflect suppression of the previously active but now irrelevant task-set (e.g., having just completed a letter task, the letter task can be safely inhibited). As switch-away trials are associated with longer RT switch cost than switch-to trials and show no reduction in RT switch cost with increasing CSI, it would appear that, if such a suppression process exists, it has no effect on speed of responding. This, however, is not necessarily true. It is possible that any behavioural effect of this suppression or inhibition process would have reached a plateau by 200 ms and would only be evident when comparing performance on trials with a completely non-informative cue versus *switch-away* cues. This interpretation appears largely compatible with Barceló, Perianez and Knight's (2002) frontal P3a component that is elicited to feedback cues indicating a shift in task-set within the WCST and that can be differentiated from a later parietal component that Barceló et al suggest is a P3B, which reflects retrieval of task-set into working memory. Like the current *switch-away* cues, Barceló's 3D shift feedback cues indicate that the previous task-set is no longer relevant but do not specify which task-set will be relevant on the

subsequent trial[8]. However, this interpretation still contradicts the conclusion drawn on the basis of recent behavioural data that inhibition is not an independent process, but a by-product of activation of the relevant task-set (e.g., Dreisbach et al., 2002; Hubner et al., 2003) or is triggered upon response selection (Schuch & Koch, 2003). Clearly, there are differences in the type and timing of information provided by ERP and behavioural data and further research is necessary to reconcile these discrepancies.

An alternative possibility is that the early differential positivity for both *switch-away* and *switch-to* relative to repeat cues reflects differing amounts of information provided by the cue. Specifically, repeat cues may be said to provide no new information as the same task-set will be implemented again, *switch-away* cues provide information about an impending task change, whereas *switch-to* cues also indicate which task-set will need be implemented. Given the sensitivity of the P300 component to stimulus information value (e.g., Rugg & Coles, 1995), it is possible that the early portion of the differential positivity for *switch-to* and *switch-away* cues represents modulation of P300 by cue information value. Within this framework, given that the early differential positivity did not differ in amplitude between *switch-to* and *switch-away* cues, it would then appear to reflect general processes associated with preparing for a switch in task-set, whereas the prolonged differential positivity for *switch-to* cues would reflect processes more specifically associated with activation of the new task-set. Further work is needed to define what is encompassed by the general preparation processes that are evident for both *switch-to* and *switch-away* cues and to explain why this general preparation does not appear to contribute to behavioural performance (see earlier discussion).

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[8]   Although the current *switch-away* cues and Barceló's 3D shift feedback cues both indicate that the previously active task-set is no longer relevant, they convey different information about how to proceed. In the WCST, participants select one of the alternative task-sets, implement it upon stimulus onset and wait for the next feedback cue to determine whether it was correct. In the present task, the relevant task-set is defined upon stimulus onset and, as discussed below, there was no evidence that participants either prepared both task-sets or prepared one task-set based on subjective sequence expectancies. Despite these task differences, in both studies the late parietal positivity to shift cues behaved quite consistently; Barceló et al found that P3b amplitude reduced with increasing certainty about which task-set would be active upon stimulus onset (e.g., 3D shift versus 2D shift feedback cues) and the present data showed a larger late differential positivity for *switch-to* than for *switch-away* cues.

Another possibility is that *switch-away* cues elicit the activation of both possible task-sets and their maintenance in working memory. This could account for the overall longer RT cost on *switch-away* compared to *switch-to* trials and for the lack of a switch cost reduction with increasing CSI for *switch-away* trials, as activation and maintenance of two task-sets takes longer to be completed. However, if this were the case, then *switch-away* trials would be expected to show a larger and more prolonged differential positivity in the CSI than *switch-to* trials, reflecting greater activation of task-set reconfiguration processes. This was clearly not the case in the current data. Further, this interpretation can also not account for the additional post-stimulus positivity that occurred exclusively for *switch-away* trials.

A related possibility is that, on *switch-away* trials, participants activated one of the two possible task-sets basing their choice on subjective expectancies derived using local probabilities (e.g., if the digit task has not been presented recently, a participant may activate that task-set based on their assumption that there is an increased probability it will be presented on the next trial). In this case, on roughly half of the trials they would have successfully reconfigured the correct task-set, whereas on the other half they will have to reconfigure again after stimulus onset. This explanation can account for the overall larger RT switch cost for *switch-away* than *switch-to* trials, for the emergence of an early differential positivity for both types of switch trials and for the brief post-stimulus differential positivity on *switch-away* trials only. However, it is hard to reconcile with the reduced amplitude and duration of the cue-locked differential positivity for *switch-away* compared to *switch-to* trials as well as with the absence of any reduction in RT switch cost with increasing CSI for *switch-away* trials. Moreover, this scenario would predict a bimodal distribution for RT on *switch-away* trials (i.e., fast RT on correctly guessed trials versus very slow RT on incorrectly guessed trials) but none of the Kolmogorov-Smirnov tests of normality of the RT distribution were significant suggesting that the RT on all trial types, including *switch-away* trials, were normally distributed.

The differential early positivity for *switch-to* and *switch-away* trials could, alternatively, reflect differential processing of the cue on repeat compared to switch trials. That is, it may not

represent a process that is common to the two types of switch trials, but a process that occurs for repeat trials only. This differential positivity may then represent processes that contribute to a repetition benefit (Dreisbach et al., 2002; Logan & Bundesen, 2003; Mayr & Kliegl, 2003). This appears to be unlikely in the current data. The outline of the circle and the six wedges were continuously displayed and the cue involved highlighting two of the six wedges that were associated with particular tasks (Figure 4-1a). The cue itself was thus identical on all trials, only its spatial position across the circle differed. On the other hand, based on the argument by Dreisbach et al. (2002) that active preparation occurs for the least expected trial type and the fact that, overall, there were fewer repeat than switch trials in the current paradigm, it could be argued that task-set reconfiguration occurred here for repeat rather than switch trials. However, in that instance, one would expect that the switch-related differential positivity would occur for repeat trials and that no switch cost would be observed, which was clearly not the case.

Summary

The electrophysiological data are compatible with the construct of task-set reconfiguration as an active control process that is necessary for successful switching between tasks. These findings suggest that the process of task-set reconfiguration consists of multiple sub components; however it is the activation of the currently relevant task-set prior to stimulus onset that facilitates the reduction in RT switch cost previously observed with increasing preparation interval. With long preparation intervals and complete information about an upcoming switch trial, task-set reconfiguration can be completed before stimulus onset. However, if the preparation interval is insufficient or the information provided is inadequate, then all or part of this process will be completed after stimulus onset.