5   Experiment 3: Engagement in anticipatory reconfiguration

The conceptualisation of anticipatory task-set reconfiguration as an endogenous process implies that, by definition, this process is under a participant's voluntary control and therefore requires active, conscious effort to initiate. As De Jong (2000) highlighted, a participant may therefore fail to engage in anticipatory task-set reconfiguration on at least some proportion of trials. This failure to engage can occur due to a variety of factors. For example, participants may be simply unmotivated or unwilling to actively initiate any cognitive control process unless it is crucial for task performance. In most cued task-switching experiments, information identifying which task is relevant on the current trial (i.e., the cue) remains visible after the stimulus is presented (e.g., Meiran et al., 2000) or the stimulus itself also identifies which task is relevant on the current trial (e.g., Experiments 1 and 2). Consequently, engaging in anticipatory task-set reconfiguration is an entirely optional process.

In Experiments 1 and 2, the location of the stimulus in the fixation grid identified the task relevant on the current trial. Task was cued prior to stimulus onset by identifying the location where the stimulus would appear on the upcoming trial. Participants could thus process the location of the cue and, when there was a long CSI (i.e., ≥ 600 ms), initiate anticipatory task-set reconfiguration prior to stimulus onset. However, participants could still accurately perform the task without necessarily having to use the cue or engage in anticipatory task-set reconfiguration. That is, they could simply wait until the stimulus was presented, identify that it required a switch in task and then initiate task-set reconfiguration processes, leading to increased switch trial RT with a long CSI that is comparable to RT on switch trials that afforded no preparation interval (i.e., short 150 ms CSI). Therefore, as suggested by De Jong (2000), the residual switch cost that remains with a long CSI can be at least partially attributed to failures to engage in anticipatory task-set reconfiguration on some proportion of trials.

Numerous other factors, such as fatigue, can also affect whether participants engage in anticipatory task-set reconfiguration. Lorist et al. (2000) found that overall RT and error rate were higher with longer time on task. Further, ERP differences between switch and repeat trials,

which were thought to be related to task preparation, reduced with increasing time on task. Lorist et al. thus proposed that fatigue associated with increasing time on task is associated with a reduction in the use of demanding cognitive control processes. In addition, complex or unclear task parameters can be a factor, such as task cues that are difficult to interpret or performance feedback that is ambiguous is likely to discourage participants from initiating anticipatory task-set reconfiguration (Monsell & Mizon, 2006). These factors lead to highly undesirable variability within participants on a trial-by trial basis as well as between participants overall.

The current experiment therefore aimed to design a paradigm that would reduce this inconsistency by maximising the proportion of trials on which participants actively engaged in anticipatory task-set reconfiguration. Simple visual cues were mapped to each task and participants received extensive training and practice to ensure a high level of association between cue-task and stimulus-response mappings. Immediate error feedback was provided after each incorrect response, general behavioural feedback was presented at the end of every run and participants were encouraged to monitor and improve upon their performance (e.g., Nieuwenhuis & Monsell, 2002). Participants randomly switched between two tasks based on a single digit stimulus and the stimulus itself carried no information about which task was currently relevant. In order to increase the probability that participants would use the cue to reconfigure their task-set in anticipation of a switch trial, the cue was removed immediately prior to stimulus presentation. As the stimulus itself carried no information about which task was relevant on any particular trial, it was expected that removing the cue prior to stimulus onset would increase the motivation for participants to engage in advance preparation when there is a long CSI of 600 ms. This would be manifest in a low error rate and a low RT switch cost. Alternatively, failure to process the cue would be expected to result in equivocation regarding which task was relevant on the current trial, which would be expected to lead to increased error rate and /or large RT switch cost as participants attempt to retrieve the cue from their working memory trace and initiate task-set reconfiguration after stimulus onset.

Poboka, Heathcote, Karayanidis and Nicholson (2005) found that anticipatory task-set reconfiguration and passive dissipation of task-set interference differentially affect the RT switch cost for faster (i.e., prepared) as compared to slower (i.e., unprepared) trials. Poboka et al. calculated cumulative distribution functions (e.g., De Jong, 2000, Figure 1-3) for RT switch cost for the five cued conditions from Experiment 1. As shown below in Figure 5-1, analysis at the leading edge (i.e., the first decile that represents the fastest or most prepared responses) replicated mean RT switch cost findings in that the longer CSI conditions had significantly lower RT switch cost (compare Figure 5-1, bottom left, the three fastest conditions have CSI $\geq$ 600 ms). Analysis at the right tail (i.e., the last decile that represents the most unprepared responses) showed RT switch cost was significantly lower for long versus short RSI, however increasing the CSI did not significantly affect the switch cost (compare Figure 5-1, top right, the three fastest conditions have RSI of 1200 ms). This effect is most clearly evident when looking at condition RSI-750:CSI-600 (indicated by red triangles in Figure 5-1), which has a long CSI and is thus quicker than the short CSI conditions at the fastest prepared responses (p= 0.1), but then because it has a short RSI, is slower than the long RSI conditions at the unprepared end of the distribution (p= 0.9).
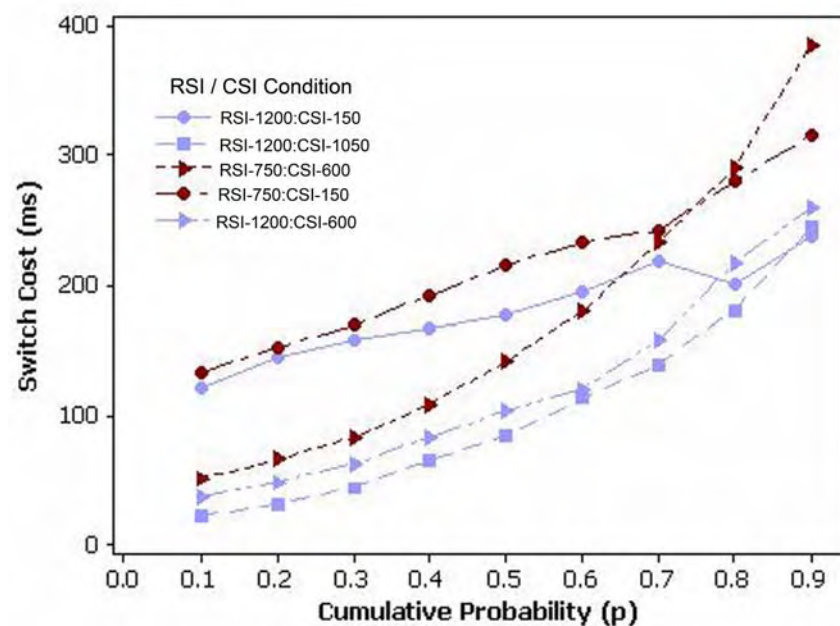

Figure 5-1. Cumulative distribution functions of RT switch cost for the five cued RSI / CSI conditions from Experiment 1 (Poboka et al., 2005).

The findings from Poboka et al. (2005) suggest that at the fast prepared end of the distribution a long CSI reduces RT switch cost as participants actively use the longer preparatory interval to engage in anticipatory task-set reconfiguration. Increased time for passive dissipation of task-set interference (i.e., longer RSI) appears to have little effect when participants are in this prepared state. In comparison, on slow unprepared trials there has been no anticipatory task-set reconfiguration either due to a short CSI or due to a failure to engage in anticipatory task-set reconfiguration. On these unprepared trials, increasing the RSI significantly reduces RT switch cost, irrespective of the CSI, due to the greater passive dissipation of task-set interference.

In order to examine the relative contribution of anticipatory task-set reconfiguration and passive dissipation processes to the behavioural and brain correlates of task-switching in the current experiment, while enabling direct comparison with the results from Experiment 1, RSI and CSI were manipulated across short and long intervals (750 versus 1200 ms and 150 versus 600 ms, respectively). RT switch cost was expected to be significantly reduced in the long compared to the short CSI, as the longer CSI should provide greater opportunity for participants to engage in anticipatory task-set reconfiguration. RT switch cost was also expected to be smaller for the long compared to the short RSI, reflecting greater passive dissipation of task-set interference across the long RSI condition. However, this effect was expected to be reduced in the current paradigm as the results from Poboka et al. (2005) suggest that the longer RSI is most beneficial when participants have not actively engaged in anticipatory task-set reconfiguration. Therefore, if the current experiment is successful in increasing the proportion of trials on which participants actively engage in anticipatory task-set reconfiguration, there should be a reduced benefit of passive dissipation of task-set interference. Likewise, it was expected that if participants are engaging in anticipatory task-set reconfiguration on an increased proportion of trials, the conditions with a CSI of 600 ms should have reduced mean RT switch cost relative to the same timing conditions used in Experiment 1. ERPs were analysed time-locked to the onset of the cue and to the onset of the stimulus for trials requiring a switch as compared to a repeat in

task. If participants actively engage in anticipatory task-set reconfiguration following cue presentation, then cue-locked ERPs should closely replicate the findings of Experiment 1. Specifically, it was expected that a parietally maximal differential positivity would be evident for switch relative to repeat trials after presentation of the cue, which peaks prior to stimulus onset when there is a long CSI.

5.1   Method

Participants

Twenty-four undergraduate students (mean age 23.5, range 17 to 40; 17 female).

Stimuli and Tasks

A square box outlined in grey (120 by 120 pixels) was presented against a dark background and was continuously displayed in the centre of the computer monitor (approximately 90 cm viewing distance). A single digit stimulus (1-4 and 6-9) was presented in the centre of the box. Participants randomly switched between performing two tasks. In the parity task, participants responded whether the digit was odd or even. In the magnitude task, participants responded whether the digit was less or greater than 5. On half of the trials participants repeated the same task they had just performed and on the other half of trials they switched to the alternate task. This sequence was random with the exception that the same trial type (e.g., switch) could not occur on more than four successive trials. As shown in Figure 5-2, a cue was presented prior to stimulus presentation that informed participants which task to perform on the next trial. This cue was a change in the colour of the box outline from grey to either blue or orange (e.g., blue = parity task; orange = magnitude task; Figure 5-2b). The cue remained on for the duration of the CSI, but was removed prior to stimulus presentation (i.e., the colour returned to grey immediately before the stimulus was presented). The stimulus-response mapping and task-colour associations remained constant for each participant throughout the experiment and were counterbalanced across participants. All stimuli were mapped to a response on both tasks (bivalent) and 75% of stimuli were incongruently mapped

(i.e., mapped to opposite hands). The remaining 25% of stimuli were congruent and were included to ensure that participants did not combine the two tasks into a single stimulus-response reversal task (e.g., blue: even = left response; orange: even = right response).

Three different timing conditions were used to vary the RSI and CSI (Figure 5-1c). With a constant CSI of 600 ms, RSI was manipulated across two levels; short (750 ms) and long (1200 ms). CSI was also manipulated across two levels (within a 750 ms RSI); short (150 ms) and long (600 ms). The conditions were labelled to reflect these intervals, such as in condition RSI-750:CSI-600 the RSI was 750 ms and the CSI was 600 ms. The RSI and CSI remained constant across a block of trials Two blocks were conducted for each timing RSI / CSI condition, with each block consisting of 3 runs of 68 trials.
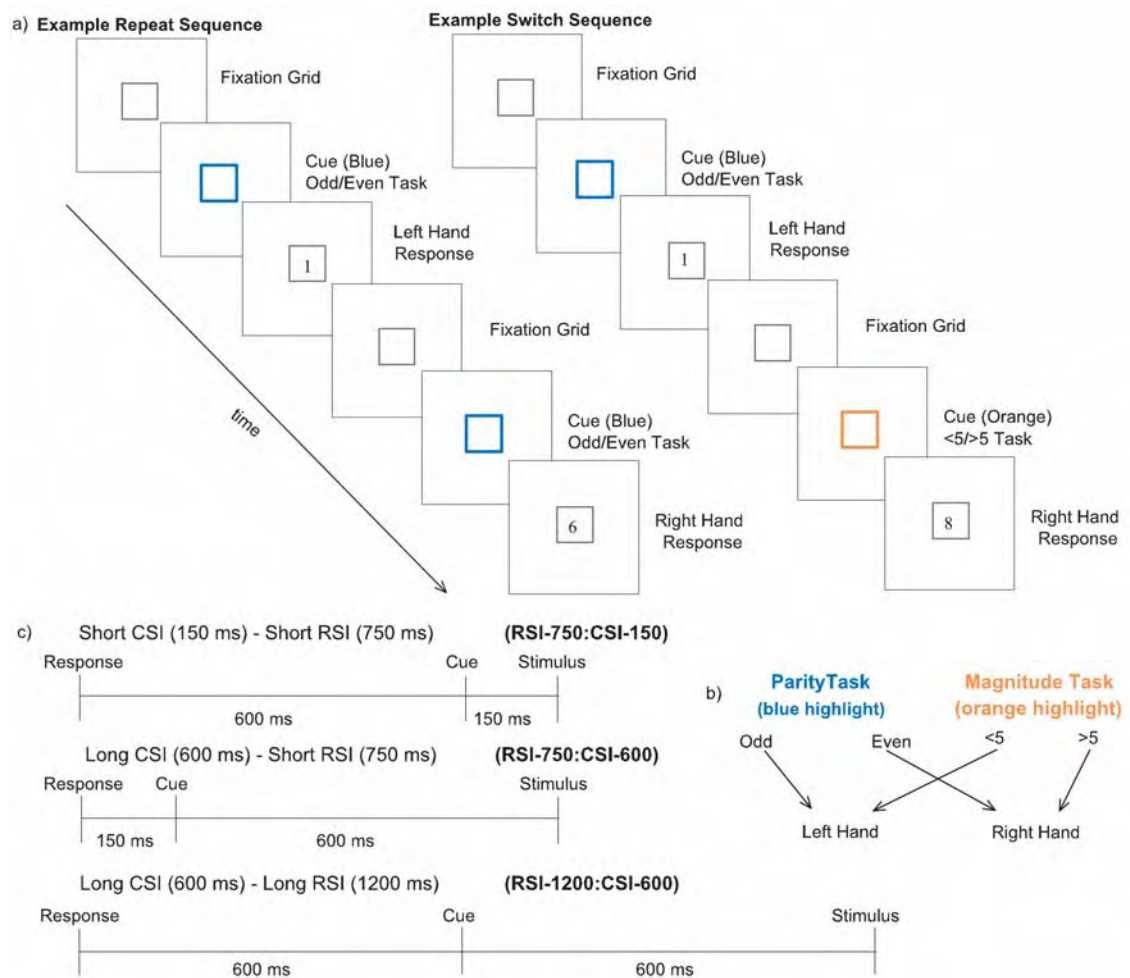

Figure 5-2. a) Example sequence of non-switch and switch trials. A small square was presented in the middle of the screen. The colour of the square changed colour to validly cue the task to be performed on the next trail. b) Each task was mapped to one cue colour and each hand was mapped to one response option for each of the two tasks. c) The three RSI \ CSI timing intervals used.

Procedure

Participants completed task practice during the first session, including 100 trials on each task alone and 4 runs of 64 trials of randomly switching between the two tasks. Participants also received further practice at the start of the second session, totalling 748 trials of practice. Behavioural and EEG data were recorded during the testing session, which consisted of the 2 blocks of 3 runs of 68 trials at each of the three timing conditions. The order of block presentation was counterbalanced between participants using a Latin square design. 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

The first four trials of every run were considered warm-up practice trials and were not included in any analysis. The 25% of trials with congruent stimuli (i.e., mapped to the same hand) were also discarded because even if a participant responded correctly on a congruent trial, there is no way to tell if they had actually applied the correct task-set rule (e.g., a left hand response to the number '2' is correct whether responding 'less than 5' or 'odd'). Correct responses occurring earlier than 200 ms (0.03% trials) or later than 2000 ms (1.5% trials) were also excluded. Trials associated with an incorrect response and trials immediately following an incorrect response were excluded from RT and ERP analysis.

RT and arc sine transformed error rates were analysed using a 3 Condition (RSI-750:CSI-150, RSI-750:CSI-600, RSI-1200:CSI-600) by 2 Trial Type (Switch, Repeat) by 2 Task (Parity, Magnitude) repeated-measures ANOVA. RT and error switch cost were calculated by subtracting the value on repeat trials from the value on switch trials. The effects of the RSI and CSI manipulations were examined in a series of planned simple effects comparisons on RT and error switch cost. The effect of increasing RSI was examined by comparing conditions with

short (750 ms) versus long (1200 ms) RSI, while the CSI remained constant (RSI-750:CSI-600 versus RSI-1200:CSI-600). The effect of increasing CSI was examined by comparing conditions with short (150 ms) versus long (600 ms) CSI, while the RSI remained constant (RSI-750:CSI-150 versus RSI-750:CSI-600). Finally, a one-sample t-test was conducted for the RSI-1200:CSI-600 condition to examine whether a significant residual switch cost remained.

RT and error data from the three Experiment 1 RSI / CSI timing conditions that were replicated in the current experiment were directly compared with the current results. Both experiments had 24 undergraduate student participants and 228 trials per condition included in the analysis (prior to removal of errors, post errors and responses outside the RT window). It was first verified there were no differences between experiments in the overall RT or error data in a 2 Trial Type (switch, repeat) by between-subjects factor of experiment (current, Experiment 1) ANOVA. Notably, various task parameters have been modified in the current experiment (e.g., the removal of information identifying the currently relevant task before stimulus onset), however, these changes were *specifically designed* to encourage participants to engage in anticipatory task-set reconfiguration on an increased proportion of trials. To investigate whether these task modifications were successful in achieving this aim, a between-subjects ANOVA was performed on the RT and error switch cost data comparing the 3 RSI / CSI conditions (RSI-750:CSI-150, RSI-750:CSI-600, RSI-1200:CSI-600) by between-subjects factor of experiment (current, Experiment 1).

Mean RT effects in the current experiment were further extrapolated by calculating cumulative distribution functions. RTs for each trial type in each condition (averaged over task) were separated in decile bins (10% bins) and mean RT was calculated within each decile (e.g., Poboka et al., 2005; De Jong, 2000)[9]. RT switch cost measures were then calculated (switch – repeat) separately for each decile. The cumulative distributions of the RT switch cost were then

---

[9] The RT distribution analysis reported by Poboka et al. (2005) was conducted over a RT window of up to 5000 ms. However, all analysis reported here are within a RT window of only 2000 ms to restrict excessive drift in the ERP waveforms. In the current study this resulted in the exclusion of 288 trials (approximately of 1.5% of trials) that had a RT between 2000 and 5000 ms.

analysed at the first and last deciles using the same paired t-test comparisons described above for the mean RT data.

EEG recording and data analysis

EEG was recorded using an electrode cap from 12 scalp electrodes positioned according to the 10/20 system referenced to linked mastoids. 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).

Cue-locked 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. Baseline correction was set to -50 to 50 ms around the onset of the cue or stimulus due to a shifting pre-stimulus baseline (see Karayanidis et al., 2003). As there were no significant RT effects of task (parity versus magnitude), ERP waveforms were averaged across task in order to increase signal to noise ratio. For each of the three timing conditions, cue- and stimulus-locked epochs were averaged separately depending on whether the current trial required a repeat or switch in task. Difference waveforms were then calculated by subtracting the average repeat waveform from the average switch waveform. Point-by-point t-tests were conducted up to 800 ms at the midline sites (Fz, Cz, Pz and Oz) for each difference waveform to identify areas of significant deviation from baseline. The Guthrie and Buchwald (1991) procedure was used to control for Type 1 error at $\alpha = 0.05$ using an autocorrelation coefficient of .9.

5.2 Results

Behavioural Data

Mean RT and percentage error rates are shown in Table 5-1 for each timing condition by task (parity or magnitude) and by trial type (repeat or switch). For RT, the effects of condition ($F_{(2,41)}=95.5$, $p<.001$), trial type ($F_{(1,23)}=34.6$, $p<.001$) and their interaction ($F_{(2,46)}=52$, $p<.001$), were significant reflecting the larger RT for switch trials, particularly in the short CSI

condition. Although RT tended to be slightly larger on the parity task, there was no main effect of task or interaction between task and trial type. Overall accuracy was very high with errors on only 4.2% of trials. Significantly more errors were made on switch compared to repeat trials (5.3 % compared to 3% respectively, $F(1,23)=14.8$, $p<.001$), which significantly interacted with condition ($F(2,45),=5.2$, $p<.05$). A significant main effect of task emerged in the error data ($F(1,23)=4.9$, $p<.05$), with more errors made on the parity (5.1%) compared with the magnitude task (3.3%), however this did not interact with condition or trial type.

Table 5- 1

Mean RT and % error rates across condition, trial type and task. Standard error in parentheses.

	RSI-750:CSI-150		RSI-750:CSI-600		RSI-1200:CSI-600	
	Repeat	Switch	Repeat	Switch	Repeat	Switch
Mean RT (ms)						
Parity	658 (11)	806 (17)	584 (9)	660 (15)	566 (12)	648 (19)
Magnitude	650 (13)	821 (16)	570 (18)	641 (11)	560 (11)	606 (9)
Average	654 (10)	814 (13)	577 (12)	650 (10)	563 (8)	627 (11)
Mean % Error						
Parity	3.0 (0.6)	7.6 (1.0)	3.5 (0.7)	5.6 (0.6)	4.4 (0.8)	6.4 (1.3)
Magnitude	2.6 (0.6)	5.2 (0.8)	2.6 (0.5)	4.1 (0.6)	2.0 (0.6)	3.0 (0.6)
Average	2.8 (0.5)	6.5 (0.6)	3.0 (0.3)	4.8 (0.4)	3.2 (0.4)	4.7 (0.5)

The significant effects of condition and trial type were further examined in the switch cost measures (averaged over task). As Figure 5-3 illustrates, as the CSI increased from 150 to 600 ms with the RSI held constant (compare conditions RSI-750:CSI-150 to RSI-750:CSI-600), RT switch cost significantly declined from 160 ms to 73 ms ($F(1,23)=68.2$, $p<.001$) and error switch cost significantly declined from 3.7% to 1.8% ($F(1,23)=8.0$, $p<.01$). Comparing conditions RSI-750:CSI-600 and RSI-1200:CSI-600 shows that increasing the RSI from 750 to 1200 ms with the CSI held constant, tended to slightly reduce the RT and error switch cost, however this did not reach significance. In the long CSI and long RSI condition (RSI-1200:CSI-600), a significant residual RT switch cost of 64 ms remained ($t(23)=3.7$, $p<.005$).

Analysis of the RT and error data from the current experiment compared with the same timing conditions used in Experiment 1 showed that overall RT was slightly faster in the current experiment (648 ms) compared with Experiment 1 (694 ms). However, this was not significant (p=.165) and neither was the interaction with trial type for both RT and error data (all F < 1), showing that overall switch and repeat trial RT and error rate was similar between the two experiments. The effects of the RSI / CSI manipulations were examined in the switch cost measures, which showed significant differences in RT switch cost between experiments. As shown in Figure 5-2, there was a strong effect of condition across both experiments (F(2,87)=69.4, p<.001), with the greatest switch cost in the short CSI, short RSI condition. Most interestingly, the interaction of experiment by condition was significant (F(2,87)=3.4, p<.05). As Figure 5-3 illustrates, this reflects that in the short CSI condition, there was no RT switch cost difference between the two experiments (157 ms in Experiment 1 versus 160 ms in the current experiment). However, as the CSI increased up to 600 ms (for constant RSI of 750 ms), switch cost declined by 48 ms in Experiment 1 compared with 87 ms in the current experiment. As the RSI increased up to 1200 ms (for constant CSI of 600 ms) switch cost declined by a further 21 ms in Experiment 1 compared with only 9 ms in the current experiment. There was no significant effect of the experimental comparisons in any of the error data.
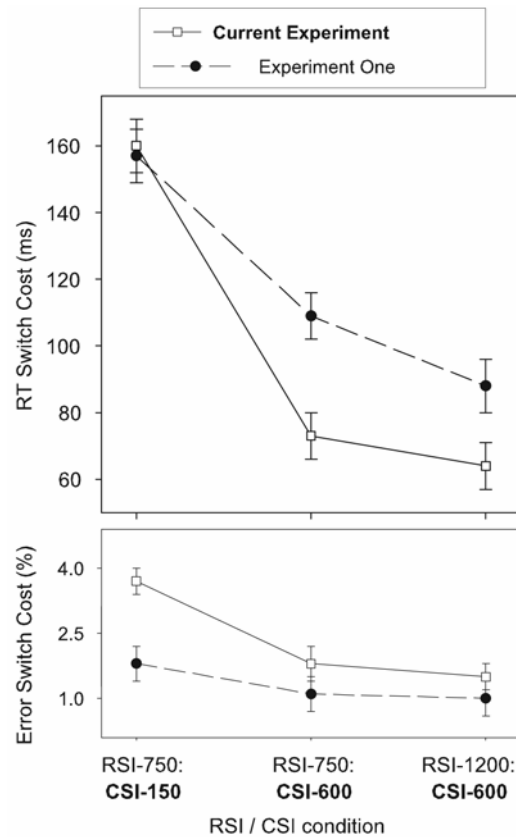
Figure 5- 3. Mean RT (top) and error (bottom) switch cost for each condition averaged across task with standard error bars shown. Shown for the current experiment versus the same three timing conditions from Experiment 1.

The RT distribution of the switch cost for the three timing conditions in the current experiment is shown below in Figure 5-4. At both the first (i.e., most prepared) and the last deciles (i.e., most unprepared), increasing the RSI (for constant CSI of 600 ms) did not significantly affect the RT switch cost (p=0.18 and p=0.78, respectively). This is clearly evident in the almost direct overlap of conditions RSI-1200:CSI-600 (red line) and RSI-750:CSI-600 (black line) in Figure 5-4. In comparison, when comparing the long CSI condition RSI-750:CSI-600 (black line) with the short 150 ms CSI condition (green line, same RSI of 750 ms), it can be seen that across the entire RT distribution, a longer CSI tends reduces RT switch cost. This was significant at the first decile (t(23)=-10.4, p<.001), however an artificial reduction in switch cost (due to increased repeat trial RT rather than a decline in switch trial RT) towards the end of the distribution for the short CSI condition resulted in no significant difference between conditions RSI-750:CSI-600 and RSI-750:CSI-150 at the last decile (p=0.17).
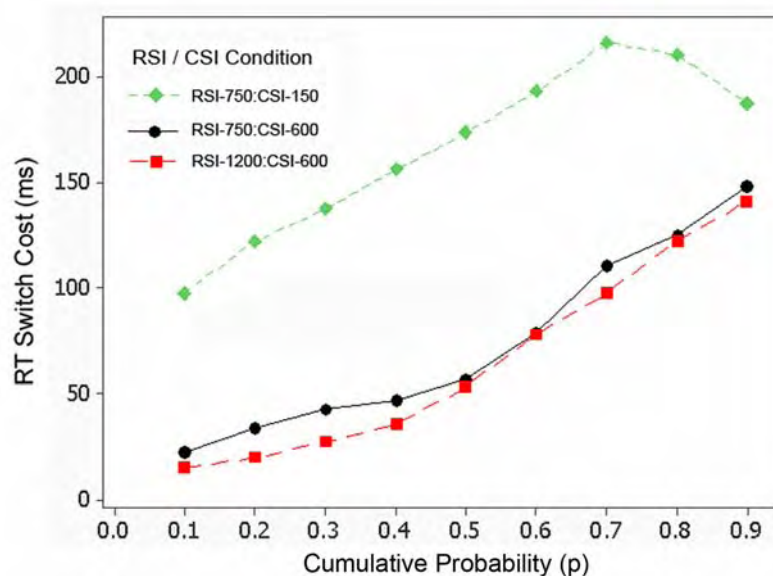
Figure 5-4. Cumulative distribution functions of RT switch cost for the three RSI / CSI conditions

Cue-locked ERP waveforms

Cue-locked waveforms for each condition are shown in Figure 5-5 (top) at four midline sites for task repeat as compared to task switch trials. Both task switch and task repeat waveforms showed a large posterior post-response negative shift that peaked shortly after cue onset in the RSI-750:CSI-600 condition that had a very brief RCI of only 150 ms (Figure 5-5, middle). Immediately after cue presentation, the early visual evoked potentials of P1, N1 and P2 can be seen for both trial types in all three conditions. The cue-locked ERP waveforms for the short CSI condition (Figure 5-5, left) showed a sharp positivity for switch and repeat trials that peaked slightly before 400 ms. However, it is important to note that, in this condition, there was considerable overlap between cue- and stimulus-related processes with stimulus onset occurring at 150 ms after cue onset (see stimulus-locked waveforms, below). In comparison, in the two conditions with a 600 ms CSI, early ERP components were succeeded by a sustained CNV shift that was clearly evident fronto-centrally and that extended until approximately 700 ms after cue onset (i.e., 100 ms after stimulus onset).
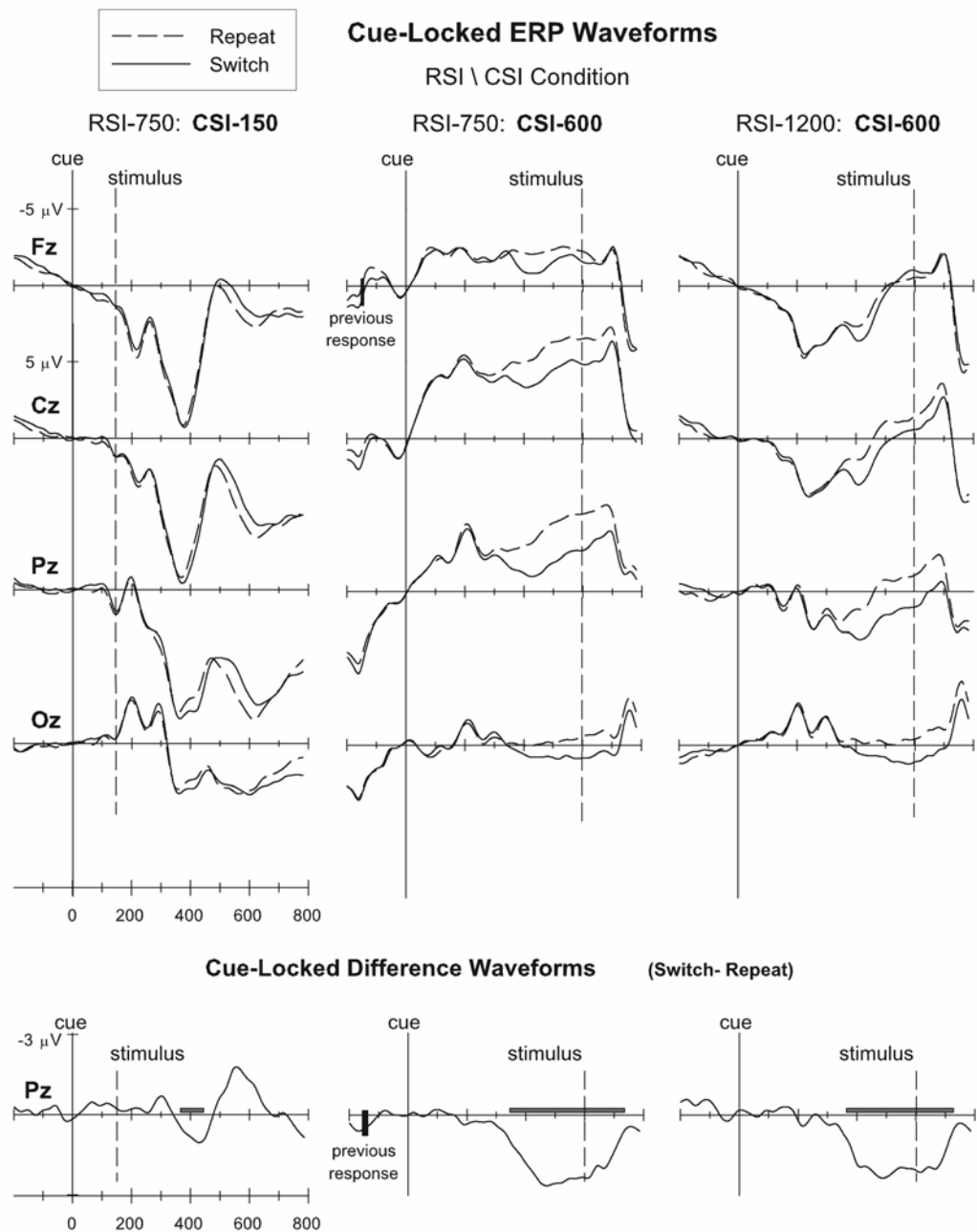
Figure 5-5. Cue-locked ERP waveforms for switch and repeat trials compared at four midline sites for each condition (top) and switch-repeat difference waveforms (bottom). Solid vertical line indicates the onset of the cue. Dotted vertical line indicates the onset of the stimulus Timing of the previous response is also displayed in the condition that had a short RCI of 150 ms (RSI-750:CSI-600). Grey bars indicate regions of significant deviation from baseline (see Table 5- 2).

In the long CSI conditions, task switch trials showed a broad positive shift compared to task repeat trials over approximately 300-700 ms after cue onset, peaking at around 450-500 ms. This is illustrated in the cue-locked difference waveforms shown in Figure 5-5 (bottom) at Pz, where the differential positivity was maximal. This differential positivity was noticeably smaller in the short CSI condition relative to the other conditions and was only significant occipital-

parietally across approximately 380-440 ms after cue onset (Table 5-2). In comparison, in the two long CSI conditions, the differential positivity was significant over 370-470 ms frontally and extended to 700 ms at other midline sites (Table 5-2).

Table 5- 2

Results of point-by-point analysis of positivity in cue-locked difference waveforms and negativity in stimulus-locked waveforms. Numbers in italics represent the number of consecutive points that were significantly deviate from baseline.

	Positivity in Cue-Locked Difference Waveforms		
	RSI-750:CSI-150	RSI-750:CSI-600	RSI-1200:CSI-600
Fz	-	366-504 (69)	388-472 (42)
Cz	-	344-694 (175) 774-800 (13)	370-562 (96) 588-694 (53)
Pz	384-450 (33)	338-720 (191)	362-714 (176)
Oz	384-436 (26) 654-800 (73)	412-800 (194)	378-800 (211)
	Negativity in Stimulus-Locked Waveforms		
Fz	-	106-170 (32) 314-416 (51)	296-352 (28)
Cz	368-436 (34)	114-174 (30) 246-674 (214)	124-166 (21) 228-696 (234) 774-800 (12)
Pz	368-460 (46)	90-800 (355)	92-800 (354)
Oz	-	204-496 (146) 570-800 (115)	182-800 (309)

Stimulus-locked ERP waveforms

As the stimulus-locked waveforms in Figure 5-6 (top) show, N1, P2, N2 components are evident for both trial types in all conditions, although this is overlapping cue related processes in the short CSI condition. In the long CSI conditions, these early ERPs were followed by a broad parietal LPC over 300-700 ms. As the stimulus-locked difference waveforms in Figure 5-6 (bottom) show, a negative deviation is evident for switch relative to repeat trials that begins as early as 150 ms after stimulus onset and continues until approximately 700 ms (Table 5-2). This post-stimulus switch-related differential negativity tended to be maximal centro-parietally and peaked at around 400 ms after stimulus onset.
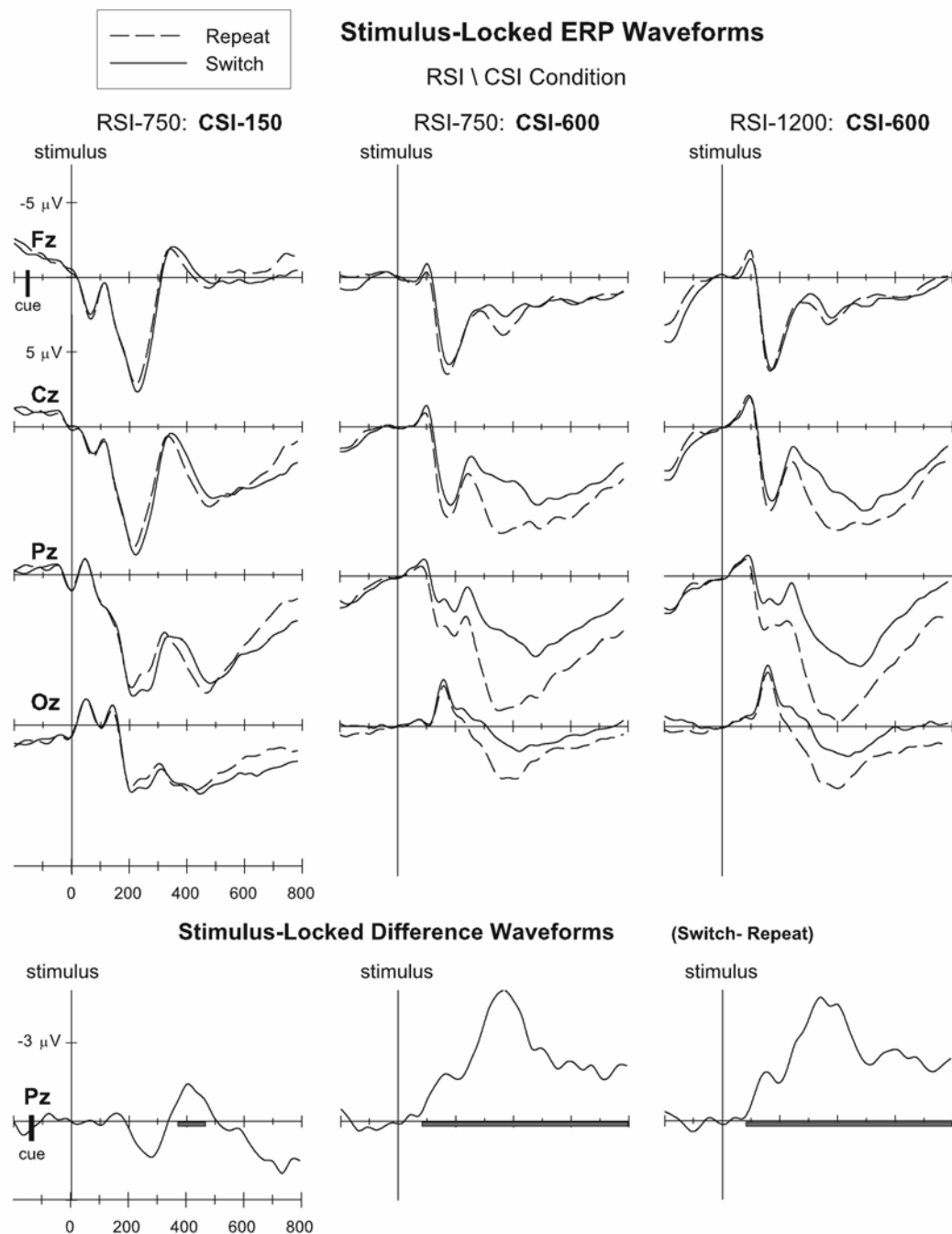
Figure 5-6. Stimulus-locked ERP waveforms for switch and repeat trials compared at four midline sites for each condition (top) and switch-repeat difference waveforms (bottom). Solid vertical line indicates the onset of the stimulus. Timing of the cue is also displayed in the condition with a short CSI of 150 ms (RSI-750:CSI-150). Grey bars indicated regions of significant deviation from baseline (see Table 5- 2).

5.3   Discussion

Behavioural effects of switching tasks

A cued task-switching paradigm was designed to maximise the proportion of trials on which participants actively engage in anticipatory task-set reconfiguration. The results showed

accuracy was very high (over 95%), suggesting that participants were utilising the cue to prepare for the upcoming trial. Mean RT and error switch cost significantly declined as the CSI increased from 150 to 600 ms. In contrast, there was no reduction in switch cost as the overall RSI increased from 750 to 1200 ms, either in mean RT or when examined across the cumulative RT distribution. These findings suggest that, on switch trials, participants effectively used the 600 ms CSI to actively initiate anticipatory task-set reconfiguration processes prior to the onset of the stimulus (e.g., Meiran, 1996; Rogers & Monsell, 1995). As Figure 5-3 illustrates, the CSI effect on RT switch cost was greater in the current paradigm relative to the same timing conditions used in Experiment 1. This suggests that, in the current experiment, participants were more effectively engaging in anticipatory task-set reconfiguration. Further, the effect of increasing RSI, which presumably increases the time available for passive dissipation of task-set interference (e.g., Allport et al, 1994), was reduced in the current experiment compared to Experiment 1. Based on the finding that passive processes reflected in RSI manipulations are more influential on unprepared rather than prepared trials (Poboka et al., 2005), this suggests that participants were more likely to be in a prepared state (i.e., had engaged in anticipatory task-set reconfiguration) on any given trial in the current experiment compared to Experiment 1.

What is being suggested here is not that in the current paradigm participants engaged in anticipatory task-set reconfiguration on *all* trials with a long CSI, but that they engaged on a *greater proportion* of trials relative to previous cued task-switching studies (e.g., Meiran, 1996; Experiment 1). For example, in the current experiment on a certain proportion of trials, participants may have been able to maintain a working memory trace of the colour of the cue, thereby enabling them to initiate task-set reconfiguration after stimulus onset. However, this strategy would seem impractical for the bulk of trials and would more likely occur very rarely on trials where loss of concentration or distraction prevented anticipatory preparation.

Other task parameters can also be manipulated to further encourage anticipatory task-set reconfiguration. Monsell and Mizon (2006) suggest that a lower proportion of switch relative to repeat trials (e.g., only one third switch) encourages participants to engage in anticipatory task-

set reconfiguration only when a switch in task is required and to reliably initiate such processes more often because they are a novel occurrence. In addition to the short runs of trials and behavioural feedback, as replicated in the current experiment, Nieuwenhuis and Monsell (2002) used a monetary reward type system to encourage increasingly accurate and faster responses. Lien, Ruthruff, Remington and Johnston (2005) imposed a restricted time deadline for accurate responses with immediate feedback ('too slow') for responses not within the deadline. Interestingly, Experiment 5 of this thesis uses an almost identical paradigm as the current experiment but restricts the interval for accurate responses to between 1400-1900 ms, which was equal to mean RT in the current experiment plus three standard deviations. This interval was jittered randomly on a trial-by-trial basis with a mean time to respond of 1650 ms. The CSI was fixed at 600 ms and feedback was provided as per an incorrect response if participants did not correctly respond within this timeframe. Overall mean RT declined to only 476 ms compared to 648 ms in the current experiment and although a significant RT switch cost was still evident, it was reduced to only 32 ms (see Experiment 5).

These findings demonstrate that if task-switching paradigms are to provide a useful tool in the investigation of cognitive control processes, experimental parameters must be designed to encourage active implementation of such control. Alternatively, inferences drawn could merely reflect failures to engage rather than actual effects. For example, Altmann (2004) did not find a reduction in RT switch cost with increasing CSI when the interval was manipulated between participants. This suggests that participants may need to experience a range of CSIs (i.e., short and long) to realise the benefit presented by a longer CSI. Alternatively, as the task cue remained on the screen with the stimulus, participants may have failed to use the long CSI to engage in anticipatory task-set reconfiguration, delaying reconfiguration until after stimulus onset, resulting in a RT switch cost comparable for short and long CSIs.

Electrophysiological effects of switching tasks

The ERP results clearly replicated previous studies (e.g., Karayanidis et al., 2003; Miniussi et al., 2005; Rushworth et al., 2002; 2005) and Experiments 1 and 2, with an increased

cue-locked positivity in anticipation of switch relative to repeat trials that was maximal over parietal sites. As suggested in Experiment 1, the differential positivity appears to reflect processes involved in anticipatory task-set reconfiguration as it peaks prior to stimulus onset when there is a long CSI, but after stimulus onset when there is a short CSI. A switch-related differential negativity was also observed after stimulus onset, which appears to reflect additional processes occurring after stimulus onset for switch trials. This may include the resolution of response interference, particularly considering the analysis was conducted on incongruent stimuli only, and may be related to the residual RT switch cost (Rogers & Monsell, 1995), which remained even in the long RSI, long CSI condition.

In the current experiment the differential positivity peaked around 100 ms later than in Karayanidis et al. (2003) and Experiment 1. This may be due to the increased demand required in the current experiment of actually having to use and process the cue on a greater proportion of trials, leading to a delay in the onset of task-set reconfiguration processes. It may also be due to decreased latency jitter in the current experiment as participants initiated anticipatory task-set reconfiguration processes within a more consistent and tighter timeframe (i.e., immediately following cue onset). Interestingly, the differential positivity in the short CSI condition was considerably smaller than in the long CSI conditions. As with the RT switch cost, the ERP effect refers to a differential increase for switch versus repeat trials. The difference may thus be reduced by either a decrease on the switch trial or an increase in the repeat trial. On some proportion of repeat trials, participants may accidentally engage in task-set reconfiguration, either because they misinterpret the cue or because of a temporary loss of concentration. The decreased differential positivity in the short CSI condition may thus reflect an increase in positivity on task repeat trials, as participants accidentally initiate task-set reconfiguration processes on some proportion of trials.

The current findings may partly reflect cue repetition benefits as a switch in task was confounded with a physical change in cue properties (Logan & Bundesen, 2003; Mayr & Kliegl, 2003). However, Monsell and Mizon (2006) demonstrated that task-switching effects can not be

fully accounted for by a cue repetition benefit. Moreover, Experiment 4 uses multiple cues per task in a similar paradigm to the current experiment and finds a significant RT task switch cost irrespective of whether the cue category repeated or switched as well as no RT effect of a switch in cue for both task repeat and task switch trials. The ERP data also show that cue processing effects are restricted to the first 300 ms after cue onset and do not affect the differential switch-related positivity.

Summary

The current experiment replicates previously observed ERP correlates of task-switching (e.g., Karayanidis et al., 2003; Experiments 1 & 2), further supporting the suggestion that the switch-related differential positivity reflects processes involved in anticipatory task-set reconfiguration. Anticipatory task-set reconfiguration is an active process that is time-locked to the onset of information regarding an impending switch in task. This process can be completed prior to stimulus onset when there is a long CSI facilitating a reduction in RT switch cost. Alternatively, it is completed after stimulus onset when the CSI is short, resulting in a larger RT switch cost. Moreover, the present experiment demonstrates that if task-switching paradigms are to be useful in informing us about the nature and function of cognitive control processes, it is important to manipulate task parameters so as to maximise the employment of these voluntary active preparation processes.

6　　Experiment 4: Effects of switching task-sets versus task-cues [10]

Experiments 1-3 suggest that in cued task-switching paradigms, changes in RT switch cost and the switch-related differential positivity with increasing CSI provide a useful measure of cognitive control processes involved in task-set reconfiguration. However, this has been challenged by a number of recent studies (e.g., Logan, 2003; Altmann, 2003). It is argued that the RT switch cost found with cued task-switching paradigms does not necessarily reflect the cost of task-set reconfiguration occurring as a result of the need to change task-set. Rather, it is contended that cued task-switching paradigms confound a switch in task with a switch in cue (Logan & Bundesen, 2003). Repeat trials involve a repetition of both cue and task type, whereas switch trials involve a change in cue as well as a change in task. Any RT increase associated with switching task may thus actually reflect cue processing on a task switch trial, rather than task-set reconfiguration.

Two recent studies (Logan & Bundesen, 2003; Mayr & Kliegl, 2003) attempted to dissociate the effect of cue processing from any effect of task-set reconfiguration on RT by mapping each task to more than one cue. In addition to the typical repeat trials where both cue and task repeat and the typical switch trials where both cue and task switch, mapping two cues to each task permitted a third type of trial where the task is repeated but the cue switches. Cue processing effects were isolated by comparing RT on trials where both task and cue repeated with trials where the task repeated but the cue switched. Task-set reconfiguration effects were measured by comparing RT on trials where both task and cue switched with trials where cue switched but task repeated, thereby equating for cue change. Logan and Bundesen (2003) found no RT cost associated with switching task when controlling for cue switch. Instead, they found a large RT cost associated with switching cue, even when repeating task type.

Mayr and Kliegl (2003) found significant RT costs associated with switching cue for the same task as well as with switching task type when controlling for cue switch. While RT cue

---

[10] Published as Nicholson, R., Karayanidis, F., Bumak, E., Poboka, D., & Michie, P. (2006). ERPs dissociate the effects of switching task-sets and task-cues. *Brain Research, 1095,* 107-123. See Appendix.

switch cost reduced with increasing CSI and task practice, RT task switch cost was only affected by response priming. Mayr and Kliegl argue that cue switch costs reflect task-set retrieval from long term memory, whereas task switch costs act upon a later stage of task-set application. Logan and Bundesen (2003) proposed that, with practice, the cue and the stimulus come to form a single compound cue-stimulus association that triggers a set response.

This cue-stimulus association is quickly retrieved from working memory on trials where both cue and task are repeated. However, on cue switch trials, the cue-stimulus association must be retrieved from long term memory resulting in increased RT. Therefore, the RT difference between cue repeat and cue switch trials represent a cue repetition benefit rather than a cue switch cost. Logan and Bundesen (2003) argue that, in single cue task-switching paradigms, it is this cue repetition benefit that underlies RT switch cost. Therefore, the RT switch cost observed in cued task-switching paradigms does not reflect an endogenous control process of task-set reconfiguration and, consequently, these paradigms do not measure any form of cognitive control. Rather, each cue activates all possible cue-stimulus associations and, upon stimulus onset, the correct response is automatically triggered. Increasing practice strengthens the cue-stimulus associations, thereby reducing RT cue switch cost.

According to this account of switch costs, it would be expected that a change in stimulus set, would result in an abrupt increase in RT switch cost in the short term, as these cue-stimulus associations would need to be re-established. Rogers and Monsell (1995) tested whether compound cue-stimulus associations are developed after considerable task practice. After eight blocks of trials, the set of four consonants used in the letter task were replaced with a different set of consonants for the last two blocks of trials (Rogers & Monsell, Experiment 1). In contrast to the predictions of the compound stimulus model, this change in stimulus set did not have any effect on RT or RT switch cost. Using a dual cue paradigm, Arrington and Logan (2004b) manipulated the number of stimuli within each stimulus set (8, 16, 32 or 640 stimuli) across different participants. Although overall RT was larger with the 640 stimulus set, the size of both the RT cue switch cost and the RT task switch cost were unaffected by stimulus set size,

arguing against a set of compound stimuli created in episodic memory. As the stimuli used were words, Arrington and Logan argue that the compound cue-stimulus associations may instead be retrieved from semantic memory.

Monsell and Mizon (2006) reported a series of task-switching experiments using dual cues. In their first experiment, Monsell and Mizon replicated the findings of Logan and Bundesen (2003) with no RT effects of switching task when controlling for a switch in cue, but a large cue switch cost that sharply declined as the CSI increased beyond 150 ms. However, across their later experiments, Monsell and Mizon were able to demonstrate a reliable RT cost associated with switching tasks that declined as the CSI increased. A switch in cue still tended to result in increased RT relative to task and cue repeat trials, however, this was smaller than the task switch cost and did not interact with the length of the CSI.

Monsell and Mizon's (2006) findings suggest that a number of parameters affect whether or not a task switch cost is found when controlling for a cue switch. One parameter is the proportion of switch relative to repeat trials. Logan and Bundesen used an equal proportion of the three trial types. Thus, cue and task repeated on only one third of trials, whereas participants switched either task and/or cue on two-thirds of trials. When Monsell and Mizon replicated this proportion of switch trials in their experiments, they also failed to find any RT task switch cost. In comparison, when Monsell and Mizon reduced the proportion of switch trials to only one-third they found a large RT task switch cost that reduced with increasing CSI.

Another parameter that can affect the relative effect of task switch and cue switch on RT cost is cue complexity (Monsell & Mizon, 2006). Monsell and Mizon argue that the use of complex, arbitrary cues that are difficult to interpret may inadvertently introduce an additional processing step that may itself be defined as an additional task. The effect of cue type is illustrated by the results of Logan and Bundesen (2004). In a dual cue paradigm, Logan and Bundesen used either the word cues from their earlier study (Logan & Bundesen, 2003) or the letter cues used by Mayr and Kliegl (2003). Participants completed the first half of the experiment using one cue category (e.g., letters) and then completed the second half of the

experiment using the other cue category (e.g., words). A RT cue switch cost was found in all conditions. Additionally, an RT task switch cost was found with the letter cues, *but only* when the letter cues were presented first. The RT task switch cost was eliminated when the word cues were used or when the letter cues were presented in the second half of the experiment.

A dual cue task-switching paradigm was used in the current experiment to dissociate the contribution of cue processing and task-set reconfiguration processes to behavioural and ERP indices of task-switching. The current paradigm was designed to maximise engagement in anticipatory task-set reconfiguration while controlling for the effects of cue change. The paradigm from Experiment 3 was largely replicated and simple visual cues were used that could be easily mapped to each task. A single long CSI of 600 ms was used, as this has been shown to be optimal for the engagement of anticipatory task-set reconfiguration processes (Rogers & Monsell, 1995; Experiment 1). In addition, as in all current experiments, participants received extensive training and task practice to ensure a high level of association between cue and task.

Two cue categories were defined: shape (circle or diamond) and colour (blue or orange). Of the two possibilities within each cue category, one was mapped to each task (Figure 6-1a). Instead of the three trial types used in previous dual cue experiments (e.g., Logan & Bundesen, 2003; 2004; Mayr & Kliegl, 2003; Monsell & Mizon, 2006), four trial types were presented in the current experiment with equal probability. These four trial types resulted from the combination of two task types (task repeat, task switch) and two cue types (cue category repeat, cue category switch). Hence, in addition to the three trial types used in previous two-cue studies (task repeat and cue repeat, task repeat and cue switch, task switch and cue switch), on 25% of trials, the cue category remained the same (e.g., colour), but the specific cue from this category changed (e.g., blue to orange), signalling a switch in task (see Figure 6-1c, trial 2). It is important to note that on cue category repeat / task repeat trials, the cue was physically identical to that presented on the previous trial (e.g., blue) whereas on cue category repeat / task switch trials, the cue belonged to the same category (colour) but was not physically identical (e.g., blue to orange). Therefore, cue category repeat / task repeat and cue category repeat / task switch

trials here were identical to task repeat and task switch trials in single cue paradigms (e.g., Experiment 3).

The inclusion of task switch and cue category repeat trials enabled orthogonal investigation of switch costs associated with task and cue switching. Task switch cost (task switch – task repeat) was calculated separately for trials that were cued within the same cue category (cue category repeat) and trials that were cued by the other cue category (cue category switch). Likewise, cue switch cost (cue category switch – cue category repeat) was calculated separately for trials that involved a repeat versus a switch in task. Task switch cost on cue category repeat trials should thus be comparable to the switch cost observed in single cue experiments. This could be directly tested in this experiment, as all participants completed both single cue and dual cue versions of the tasks, in separate counterbalanced blocks.

In the single cue condition, the results were expected to closely replicate the findings of Experiments 1-3, with task switch trials resulting in larger RT and increased parietal positivity in the CSI as compared to repeat trials. In the dual cue condition, it was expected that, for trials where cue category repeated (e.g., blue to orange, blue to blue), the effects of task switching on RT and the parietal positivity would be comparable to those obtained in the single cue condition and Experiment 3 (with the 600 ms CSI).

In the dual cue condition, effects of cue processing (e.g., Logan & Bundesen, 2003) were expected to emerge in the comparison between cue category switch and cue category repeat trials, irrespective of whether task switched or repeated. If RT switch cost and the differential switch-related positivity reflect processes involved in task-set reconfiguration (e.g., Rogers & Monsell, 1995; Karayanidis et al., 2003), a RT switch cost and differential positivity should be evident for task switch relative to task repeat trials in the dual cue condition, irrespective of whether cue category switches or repeats. Alternatively, if as suggested by Logan and Bundesen (2003), RT switch cost results from the fact that single cue task switching paradigms frequently confound task switching and cue switching, cue switch trials should result in an increase in RT relative to cue repeat trials, irrespective of whether task switches or repeats. In this case, all or

part of the differential positivity in the CSI should be associated with a switch in cue rather than a switch in task.

In order to examine whether the relative effects of cue processing and task switching effects differed across the RT range in the dual cue condition, RT effects were extrapolated across the entire RT distribution by calculating cumulative distribution functions in decile bins (De Jong, 2000). Poboka et al. (2005) reported that active task-set reconfiguration and passive dissipation of activation processes differentially affect RT switch cost for faster (prepared) and slower (unprepared) trials, respectively. Any cue repetition benefit may therefore also be expected to have a greater effect on the slower, unprepared range of the RT distribution.

6.1 Method

Participants

Thirty-two undergraduate students (mean age 23 ± 7, range 18 to 46; 20 female).

Stimuli and Tasks

A square box outlined in grey (120 by 120 pixels) presented against a dark background was continuously displayed in the centre of the computer monitor that was viewed from approximately 90 cm. A single digit stimulus (1-4 and 6-9) was presented in the centre of the box. Participants randomly switched between performing two tasks. In the parity task, participants responded whether the digit was odd or even. In the magnitude task, participants responded whether the digit was less or greater than 5. As shown in Figure 6-1, a cue was presented 150 ms after a response to the preceding trial (RCI of 150 ms) and validly cued the task to be performed on the next stimulus (CSI of 600 ms).
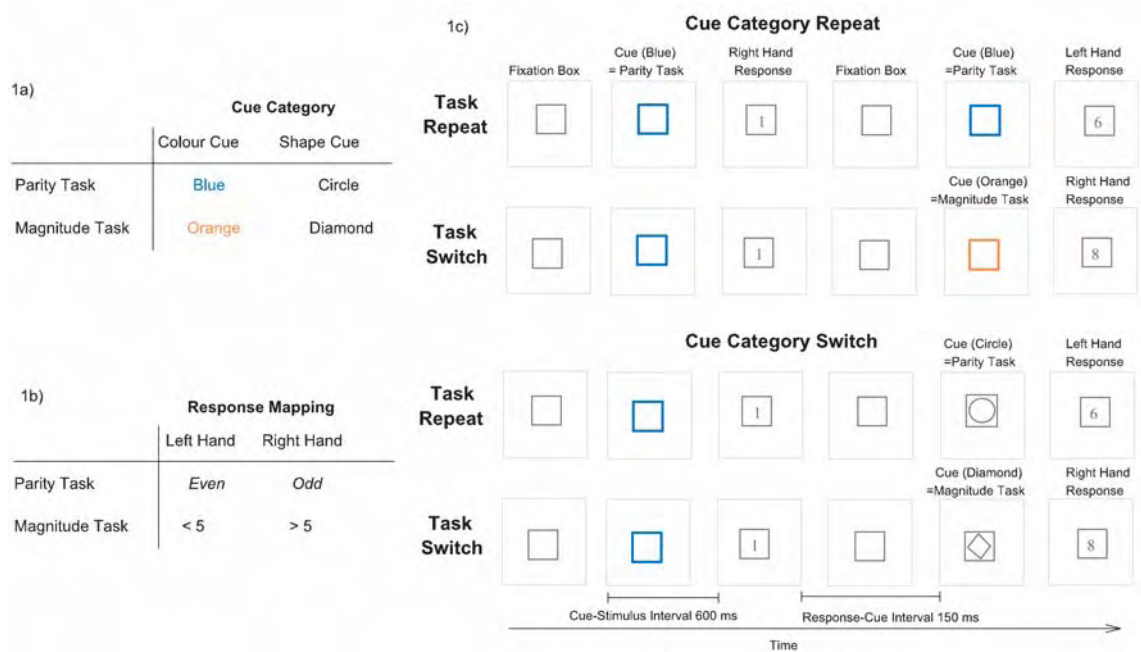
Figure 6-1. A: Example of cue-to-task mapping: one colour cue and one shape cue was assigned to each task. B: Example of stimulus-to-response mapping: each hand was mapped to one response option for each task. C: Example of trial sequences are shown for task repeat and cue repeat, task switch and cue repeat, task repeat and cue switch and task switch cue and switch trials (top to bottom).

Two cue categories were used. As shown in Figure 6-1a, colour cues involved a change in the colour of the box outline from grey to either blue or orange (e.g., blue = parity task; orange = magnitude task). Shape cues involved the outline of a grey circle or a grey diamond presented in the centre of the box (e.g., circle = parity task; diamond = magnitude task). The cue remained on for the duration of the CSI, but was removed immediately prior to stimulus onset (i.e., the colour returned to grey or the shape was removed). Participants responded with either their left or right index finger (Figure 6-1b). Stimuli were congruent (e.g., '2'; Figure 6-1b) between the two tasks on 25% of trials and incongruent (e.g., '3'; Figure 6-1b) on all remaining trials. A switch in task was required on 50% of trials.

The experiment was divided into two conditions, each consisting of 10 runs of 68 trials. In the single cue condition, only one cue category was presented within each run of trials. Participants completed 5 consecutive runs with the colour cue only and 5 consecutive runs with the shape cue only. The order of cue category presentation was counterbalanced across participants. In the dual cue condition, colour and shape cues were randomly intermixed within each run. On 50% of trials, the cue category was repeated and, on the remaining 50% of trials,

the cue category switched (Figure 6-1c). Four types of trials were possible and were presented pseudorandomly with equal probability: task repeat and cue category repeat (25% trials), task repeat and cue category switch (25% trials), task switch and cue category repeat (25% trials) and task switch and cue category switch (25% trials). Half of the participants completed the single cue condition of the experiment first while the other half completed the dual cue condition first.

Procedure

At the first session participants completed task practice, beginning with 50 trials of the parity task alone, followed by 50 trials of the magnitude task alone and 64 trials of switching between the two tasks using the colour cues only. This was repeated using the shape cues only. Participants then completed 64 trials of switching between the two tasks using only the colour cues and another 64 trials using only the shape cues. This was followed by 2 runs of 64 trials of pseudorandomly switching between the two tasks and the two cue categories. At the start of the second session participants received further task practice with 64 trials on each task alone (with dual cues) and 2 runs of 64 trials of pseudorandomly switching between the two tasks and the two cue categories. Participants thus completed a total of 840 practice trials. Testing consisted of 10 runs of 68 trials on both the single and the dual cue conditions. The firs four trials of every run were considered warm-up practice trials and were discarded from analysis.

Data Analysis

Error and RT task switch cost (task switch – task repeat) were calculated for the single cue condition and separately for cue category repeat and cue category switch trials in the dual cue condition. In the dual cue condition, error and RT cue switch cost (cue category switch – cue category repeat) were also calculated, separately for task repeat and task switch trials. In the single cue condition, error and RT data were analysed using a 2 Cue Category (colour, shape) by 2 Trial Type (task repeat, task switch) by 2 Task (parity, magnitude) repeated-measures ANOVA. In the dual cue condition, error and RT data were analysed using a 2 Cue Type (cue category repeat, cue category switch) by 2 Trial Type (task repeat, task switch) by 2 Task

(parity, magnitude) repeated-measures ANOVA. RT and error scores were also compared between the single cue condition and cue category repeat trials in the dual cue condition using a 2 Cue Condition (single cue, cue category repeat) by 2 Trial Type (task repeat, task switch) repeated-measures ANOVA. All the above analyses were initially run with an additional Condition Order between subjects factor (singe cue first, dual cue first). As condition order produced no main effect or any interaction with other factors, all analyses were re-run as repeated measures only.

In the dual cue condition, mean RT effects were extrapolated by calculating cumulative distribution functions. RTs for each trial type were separated in decile bins (10% bins) and mean RT was calculated within each decile (e.g., De Jong, 2000). The cumulative distributions were analysed at the first and last deciles using a 2 Trial Type (task repeat, task switch) by 2 Cue Type (cue category repeat, cue category switch) repeated-measures ANOVA. RT cue and task switch cost measures were also calculated as described above separately for each decile.

EEG recording and data analysis

EEG was recorded using an electrode cap from 30 scalp electrodes positioned according to the 10/20 system referenced to the left mastoid. EEG and EOG were continuously sampled at 1000Hz/channel using NeuroScan Inc. software from a NeuroScan Inc. Synamps 2 system with a bandpass of 0.01-30 Hz. Continuous EEG files were re-referenced offline to the average of the left and right mastoids to be consistent with the previous experiments.

Cue- and stimulus-locked averages were created by extracting 1400 ms epochs around the onset of the cue or stimulus, respectively (200 ms pre-onset interval). Baseline correction was set to -50 to 50 ms around the onset of the cue or stimulus due to a shifting pre-stimulus interval. As there were no significant effects of task or cue category on RT, ERP waveforms were averaged across task and cue category in order to increase signal to noise ratio. Cue- and stimulus-locked epochs were averaged separately for task switch and task repeat trials for both single and dual cue conditions and also for cue category switch and cue category repeat trials in the dual cue condition.

Consistent with the behavioural switch cost measures, ERP difference waveforms were calculated by subtracting the average repeat waveform from the average switch waveform. Task switch – task repeat difference waveforms were calculated for the single cue condition and separately for cue category repeat and cue category switch trials in the dual cue condition. Cue category switch – cue category repeat difference waveforms were also calculated for the dual cue condition, separately for task repeat and task switch trials. Point-by-point t-tests were conducted over 50-800 ms for difference waveforms at midline sites (Fz, Cz, Pz & Oz) to identify areas of significant deviation. The Guthrie and Buchwald (1991) procedure was used to control for Type 1 error at $\alpha = .01$ using an autocorrelation coefficient of .9.

These results were used to determine windows of interest for mean amplitude analysis. In order to directly compare the effects of task switching and cue switching, two mean amplitude windows were defined based on areas of significant deviation from baseline of the difference waveforms (Table 6-2). For cue-locked waveforms, one window was defined over 150-250 ms to capture the effect of cue category type on early ERPs and the early portion of the differential task-switch positivity defined in the single cue condition and a second window was defined over 450-600 ms to capture the later differential task-switch positivity evident for both single and dual cue conditions. For stimulus-locked waveforms, the effects of cue condition on the onset and maximal amplitude of switch-related negativity were examined using two mean amplitude windows, one over 150-250 ms to capture onset of task-switch versus task-repeat differentiation and another over 300-500 ms to capture the area of maximal differentiation.

Mean amplitude within these windows was compared between the single cue condition and cue category repeat trials in the dual cue condition using a 2 Cue Condition (single cue, cue category repeat) by 2 Trial Type (task repeat, task switch) by 4 Electrode (Fz, Cz, Pz, Oz) repeated-measures ANOVA. Effects of switching cue category and switching task in the dual cue condition were examined using a 2 Cue Type (cue category repeat, cue category switch) by 2 Trial Type (task repeat, task switch) by 4 Electrode (Fz, Cz, Pz, Oz) repeated-measures

ANOVA. Any significant interactions of cue type or task type with electrode are only reported if they remained significant after rescaling (McCarthy & Wood, 1985).

6.2   Results

Behavioural Data

Overall, participants responded very accurately with errors on less than 5% of trials. There were no significant effects of task (parity or magnitude) in the RT data. Although there were overall more errors on the parity (5.5%) compared to the magnitude task (4%) in the dual cue condition ($F(1,31)=7.4$, $p<.05$), task did not interact with any other factor. Therefore, mean RT and error were averaged over task in all remaining analyses (Table 6-1).

Table 6-1

Mean RT (ms) and % error for task switch and task repeat trials in the single cue condition (shown separately for the colour and shape cue categories) compared to the dual cue condition (shown separately for cue category repeat and cue category switch trials). Task switch cost (Task switch – task repeat) and cue switch cost (cue category switch – cue category repeat in the dual cue condition) are shown. Standard error shown in italics.

	Single Cue Condition		**Dual Cue Condition**		
	Colour Cue	Shape Cue	Cue Category Repeat	Cue Category Switch	*Cue Switch Cost*
Mean RT (ms)					
Task Repeat	659 *(12)*	662 *(14)*	702 *(13)*	697 *(13)*	*-5 (16)*
Task Switch	709 *(12)*	714 *(13)*	760 *(12)*	758 *(15)*	*-2 (16)*
Task Switch Cost	*50 (12)*	*52 (14)*	*58 (10)*	*61 (9)*	
% Error					
Task Repeat	3.3 *(0.4)*	3.4 *(0.3)*	3.6 *(0.3)*	4.5 *(0.5)*	*0.9 (0.6)*
Task Switch	4.9 *(0.4)*	5.8 *(0.4)*	4.9 *(0.3)*	6.1 *(0.5)*	*1.2 (0.5)*
Task Switch Cost	*1.6 (0.6)*	*2.4 (0.6)*	*1.3 (0.4)*	*1.6 (0.8)*	

Single cue condition: In the single cue condition, there was no significant difference in RT or error rate between colour and shape cues, nor any significant interaction between cue category and trial type. As shown in Table 6-1, task switch trials were associated with longer RT and more errors (711 ms, 5.4%) than task repeat trials (660 ms, 3.3%; $F(1,31)=17.9$, $p<.001$, $F(1,31)=21.5$ $p<.001$, respectively).

Dual cue condition: In the dual cue condition, task switch trials were again associated with a significant increase in RT compared to task repeat trials (59 ms task switch cost, $F(1,31)=45.4$, $p<.001$). This RT task switch cost was unaffected by whether cue category repeated (58 ms) or switched (61 ms). As Table 6-1 illustrates, switching cue category had no effect on RT (all $F<1$). However, the number of errors did significantly increase from 4.2% on cue category repeat trials to 5.3% on cue category switch trials ($F(1,31)=6.2$, $p<.05$). Error rate was also significantly larger for task switch than task repeat trials (1.5% task switch cost, $F(1,31)=8.3$, $p<.01$). There was no significant interaction between cue category type and trial type in either RT or error data.

Single cue versus cue category repeat trials: Cue category repeat trials in the dual cue condition were technically identical to trials in the single cue condition when averaging over runs of colour and shape cue. However, alternation between the two cue categories within a run of trials resulted in a significant increase in overall RT. RT for cue category repeat trials in the dual cue condition was 35 ms slower than RT in the single cue condition (731 versus 686 ms, $F(1,31)=5.5$, $p<.05$, Table 6-1). This effect of cue condition did not interact with trial type ($F<1$), indicating that the extra cost of alternating between cue categories did not differentially affect RT task switch cost. Task switch cost was consistently around 50-60 ms irrespective of the cue category in the single cue condition (colour or shape), cue condition (single cue or cue category repeat), and cue category type in the dual cue condition (cue category repeat or switch). There was no difference in error scores between single and dual cue conditions.

RT cumulative distribution functions: To investigate the effects of switching task and/or cue across the entire distribution of RT scores, cumulative distribution functions were calculated across deciles in the dual cue condition. The RT distribution for the four trial types are shown in Figure 6-2 (left) and the associated RT switch cost measures are shown in Figure 6-2 (right). Across the entire distribution of RT scores, task switch trials were clearly slower than task repeat trials, irrespective of whether cue category repeated or switched. The effect of task switching appears to increase at the slower end of the RT distribution. In contrast, there is little

differentiation between the RT distribution of cue category switch and cue category repeat trials for either task switch or task repeat conditions.
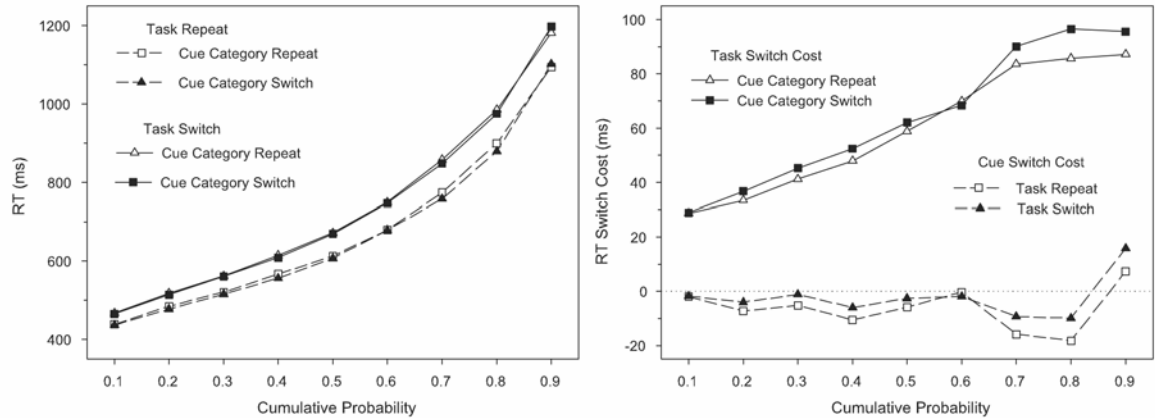

Figure 6-2. Left: Cumulative RT distributions are shown for the four trial types in the dual cue condition. Right: Cumulative RT switch cost distributions are shown for task switch – task repeat (separately for cue category repeat and cue category switch trials) and for cue category switch – cue category repeat (separately for task repeat versus task switch trials).

A significant effect of task type was obtained at both the fastest (first decile) and the slowest (last decile) end of the RT distribution ($F(1,31)=18.6$, $p<.001$; $F(1,31)=27.7$, $p<.001$, respectively). RT task switch cost was 29 ms in the first decile and 92 ms in the last decile. There were no significant effects of cue type or interactions between cue type and task type at either the first or the last decile (both $F<1$). In fact, cue category switch trials actually tended to be slightly *faster* than cue category repeat trials across most of the RT distribution with the cue switch cost distribution showing small *negative* cue switch costs at most deciles (Figure 6-2, right). At the last decile, cue category switch trials were 12 ms slower than cue category repeat trials (1149 ms versus 1137 ms respectively), however this cue switch effect was again not significant ($F<1$).

ERP Data

In the single cue condition, colour and shape cues did not differ in RT or in overall ERP morphology. ERP waveforms were therefore averaged over cue category so as to simplify the data and enable direct comparison between the single and dual cue conditions. In both conditions, the colour cue was presented on half the trials and the shape cue presented on the other half of trials. However, by definition, in the single cue condition, colour and shape cues

were presented in separate runs of trials, whereas in the dual cue condition, they were intermixed within each run of trials.
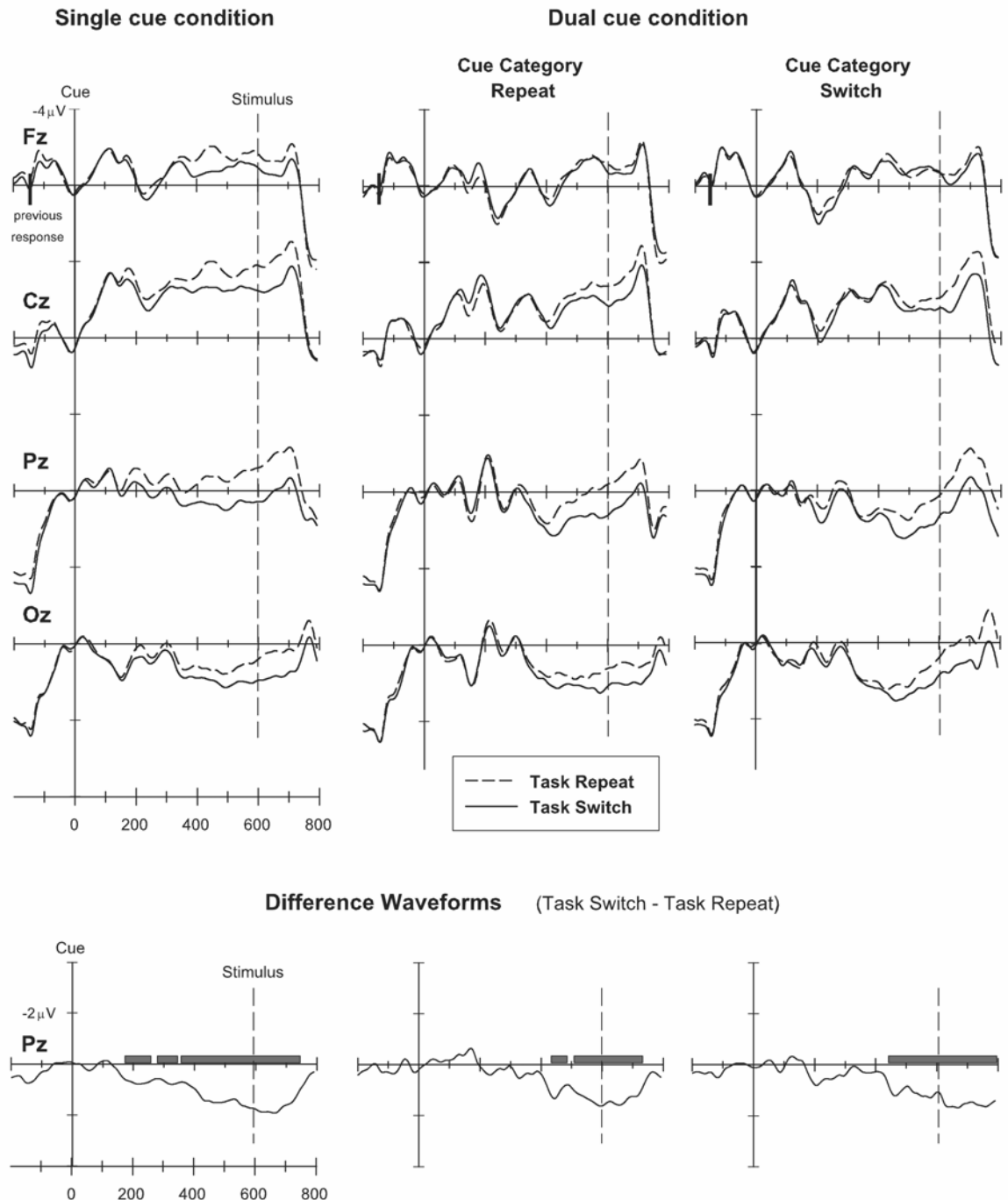

Figure 6-3. Top: Cue-locked ERP waveforms at four midline sites are superimposed for task switch and task repeat trials in the single cue condition (left) and for cue category repeat (middle) and cue category switch (right) in the dual cue condition. Negative is plotted up. The solid vertical line indicates the onset of the cue and the dotted vertical line indicates the onset of the stimulus. Bottom: Task switch difference waveforms (task switch – task repeat) for the above waveforms at Pz. Grey bars represent areas of significant differential positivity for task switch relative to task repeat trials. See Table 6-2 for exact values at all four midline sites.

Cue-locked ERPs

Cue-locked ERP waveforms for task repeat and task switch trials are superimposed in Figure 6-3 (top) for the single cue condition (left) and separately for cue category repeat and cue category switch trials (middle and right) in the dual cue condition.

Single cue condition: In the single cue condition, both task switch and task repeat waveforms showed a large posterior post-response negative shift leading up to cue onset which was followed by early ERPs associated with cue processing. Frontocentrally, there was a broad sustained negativity throughout most of the CSI that peaked shortly after stimulus onset. Task switch trials showed a broad centro-parietally maximal positive shift compared to task repeat trials. This positive shift for switch trials is most clearly evident in the task switch - task repeat difference waveform, shown here at Pz where the effects were maximal (Figure 6-3, bottom). This differential task-switch positivity emerged around 190 ms after cue onset at parietal and occipital sites and extended across the entire CSI deviating significantly from baseline over approximately 350-700 ms at all midline sites (Table 6-2).

Table 6-2

Regions of significant deviation from baseline in cue-locked difference waveforms with number of consecutive significant points shown in italics. Task-switch positivity refers to regions where the task switch waveform was significantly more positive than the task repeat waveform. Cue-switch positivity refers to regions where the cue category switch waveform was significantly more positive than the cue category repeat waveform.

| | **Task-switch Positivity** | | | **Cue-switch Positivity** | |
| | | Dual Cue Condition | | Dual Cue Condition | |
	Single Cue Condition	Cue Category Repeat	Cue Category Switch	Task Repeat	Task Switch
Fz	371-493 *(122)* 583-641 *(58)* 652-726 *(72)*	-	-	173-203 *(30)*	164-213 *(49)*
Cz	232-254 *(22)* 374-509 *(135)* 547-736 *(189)*	598-615 *(17)* 647-692 *(45)*	624-798 *(174)*	179-217 *(38)*	169-224 *(55)*
Pz	183-263 *(80)* 289-343 *(54)* 355-748 *(393)*	423-457 *(34)* 500-726 *(226)*	443-800 *(357)*	187-233 *(46)* 502-514 *(12)*	182-234 *(52)* 474-506 *(32)*
Oz	197-228 *(31)* 383-405 *(22)* 423-787 *(364)*	550-615 *(65)* 624-697 *(73)*	444-472 *(28)* 516-800 *(284)*	202-242 *(40)* 300-333 *(33)* 413-440 *(27)*	199-242 *(43)* 292-327 *(35)* 447-483 *(36)*

Dual cue condition: Like the single cue condition, cue category repeat and cue category switch trials (Figure 6-3, middle and right, respectively) in the dual cue condition showed a post-response posterior negative shift and large early ERPs associated with cue processing. However, the sustained frontocentral negativity appeared later for both task repeat and task switch trials. Irrespective of whether cue category repeated or switched, task switch trials showed a large centro-parietal positive shift relative to repeat trials over 350-700 ms after cue onset. This differential task-switch positivity (Figure 6-3, bottom) was significant parietally over approximately 400-700 ms for both cue category repeat and cue category switch trial types (Table 6-2) and is similar to that seen in the single cue condition. However, note that the earlier posterior section of this differential positivity that was significant over 190-250 ms in the single cue difference waveform was not significant in either dual cue condition.

Cue type effects: The effects of switching cue category can be seen more clearly in Figure 6-4 where cue category repeat and cue category switch waveforms are superimposed at Pz. For both task repeat and task switch trials, ERP differences between cue category repeat and cue category switch trials were largely restricted to around 150-250 ms after cue onset. Early ERP components, particularly N1, P2 and N2, were more distinct and larger in amplitude for cue category repeat as compared to cue category switch trials. These differences are emphasised in the cue category (switch – repeat) difference waveforms (Figure 6-4, bottom), with the large N2 for cue category repeat trials resulting in a sharp cue category switch positivity that was significant centro-parietally over approximately 180-220 ms for both task repeat and task switch trials (Table 6-2). Interestingly, after 450 ms, a later differential positivity emerged within the same timeframe as the task-switch positivity discussed above. However, this cue-switch positivity had a shorter duration (e.g., 502-514 ms on task repeat trials and 474-506 ms on task switch trials at Pz) and was restricted to posterior sites only (Table 6-2).
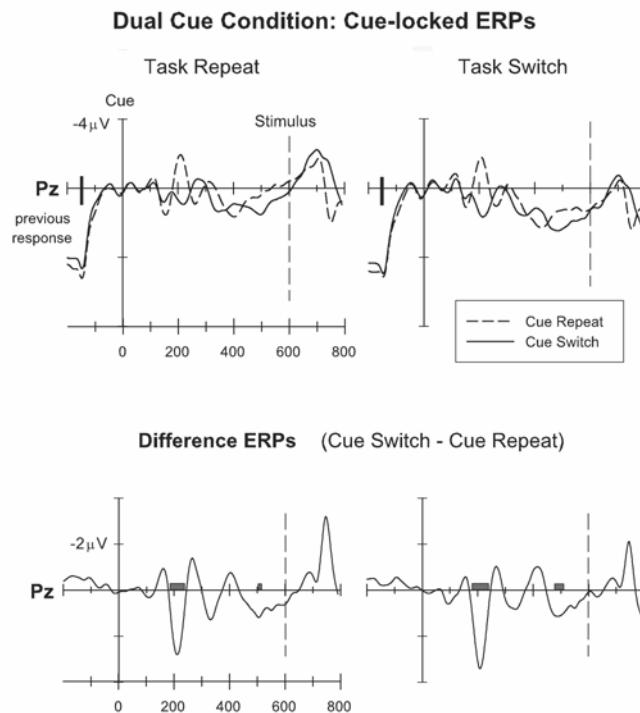
Figure 6-4. Top: Cue-locked waveforms at Pz are superimposed for cue category repeat and cue category switch trials in the dual cue condition for task repeat (left) and task switch (right) trials. Note that these are the same waveforms presented at Pz in Figure 6-3, however they have been rearranged emphasise any cue category switching effects. Bottom: Cue switch difference waveforms (cue category switch – cue category repeat) for the above waveforms at Pz. Grey bars represent regions of significant deviation between cue category switch and cue category repeat trials. See Table 6-2 for exact values at all four midline sites.

Cue-locked mean amplitude measures

Mean amplitude measures over 150-250 ms and 450-600 ms are shown in Figure 6-5 (left and right, respectively).

Single cue versus cue category repeat trials: The comparison between single cue and cue category repeat trials from the dual cue condition resulted in a significant interaction between cue type and trial type over 150-250 ms ($F(1,31)=8.2$, $p<.01$), indicating that task switch trials resulted in significantly larger positivity over this interval than task repeat trials (-.53 µV versus -.97 µV, respectively), but only in the single cue condition, with this task-switch positivity being larger parietally (trial type by electrode; $F(2,49)=5.5$, $p<.05$). Over the later interval (450-600 ms), a large, parietally maximal task-switch positivity was evident for both the single cue condition and the cue category repeat condition ($F(1,31)=19.3$, $p<.001$; $F(2,60)=11.2$, $p<.001$).
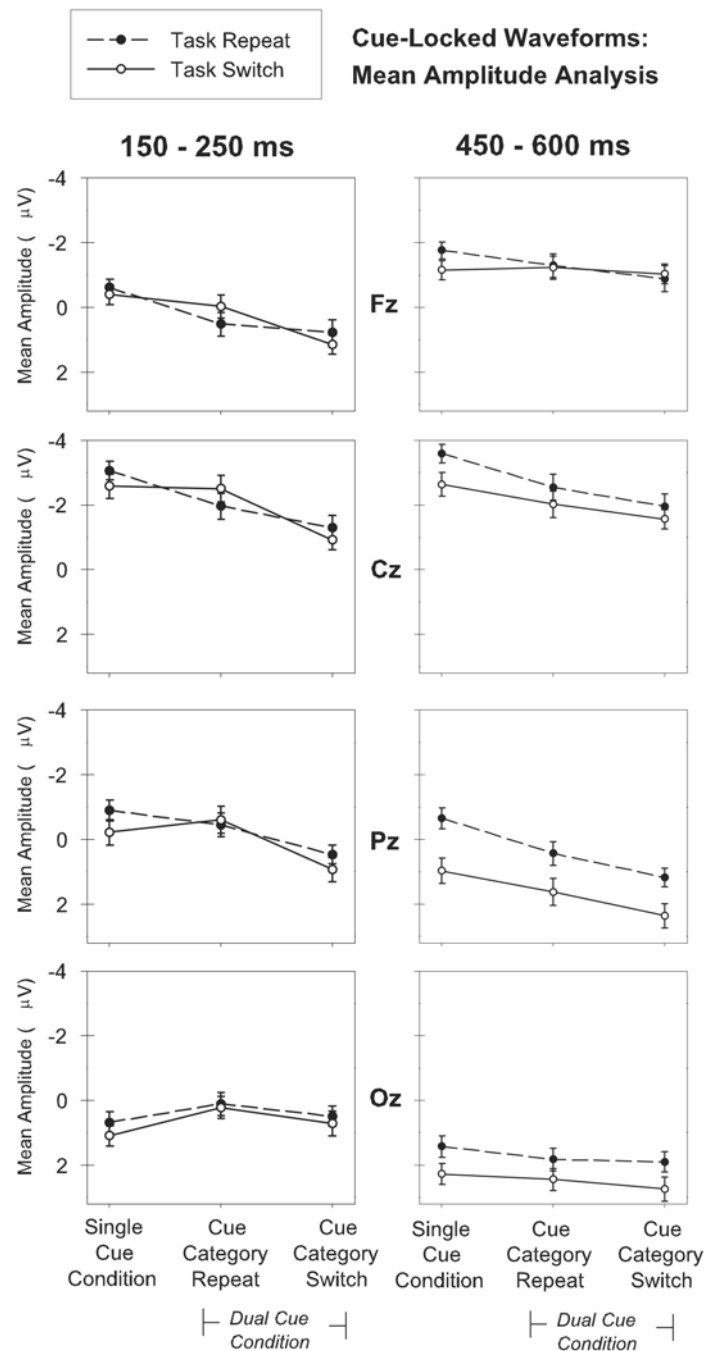
Figure 6-5. Mean amplitude measures at the four midline sites in cue-locked waveforms over 150-250 ms (Left) and over 450-600 ms (Right).

Cue category repeat versus switch trials: The larger N2 for cue category repeat than cue category switch trials from the dual cue condition was reflected in the significant main effect of cue type over 150-250 ms (-.59 and .29µV, respectively, F(1,31)=14.7, p<.001). While there was no effect of trial type over 150-250 ms, significant main effects of trial type and trial type by electrode interactions were obtained over 450-600 ms (F(1,31)=8.6, p<.01; F(2,51)=9.1,

p<.001) but no interactions between trial type and cue type. Thus, in the dual cue condition, the task-switch related positivity emerged after 400 ms and was equally evident for both cue category repeat and cue category switch trials.

Stimulus-locked ERPs

Stimulus-locked waveforms for task switch and task repeat trials are superimposed in Figure 6-6 (top) separately for the single cue condition and for cue category repeat and cue category switch trials in the dual cue condition. All cue conditions and both trial types show an N1 emerging first frontally, followed by a large fronto-central P2 and more posterior N2. A LPC was evident parietally and more pronounced for task repeat trials. For all cue conditions, the switch trial ERP waveform showed a large negative shift relative to the repeat waveform (Figure 6-6, bottom). This switch-related negativity was evident across all midline electrodes in the single cue condition, emerging as early as 135 ms after stimulus onset (Table 6-3) and extending to approximately 400 ms frontocentrally, but across the entire analysis epoch parieto-occipitally. In the cue category repeat condition, this switch-related negativity also emerged very early, but was reduced in duration and was smaller frontally, whereas in the cue category switch condition, it did not emerge until after 300 ms post-stimulus (Table 6-3).

Table 6-3

Regions of significant deviation from baseline in stimulus-locked difference waveforms with number of consecutive significant points shown in italics. Task-switch negativity refers to regions where the task switch waveform was significantly more negative than the task repeat waveform.

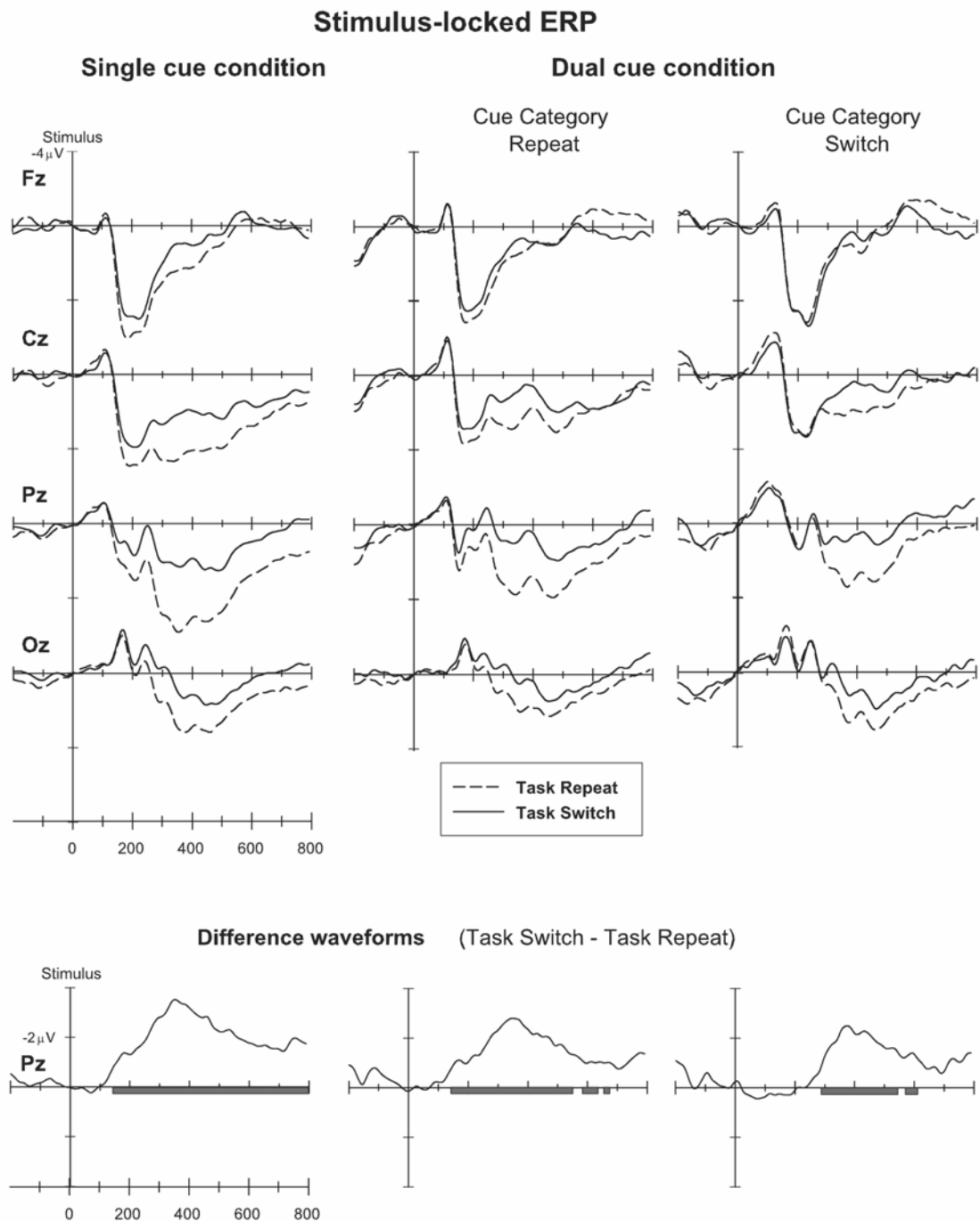|	**Task-switch Negativity**		
		Dual Cue Condition	
	Single Cue Condition	Cue Category Repeat	Cue Category Switch
Fz	142-215 *(73)* 236-262*(26)* 268-392*(124)*	-	-
Cz	141-598 *(457)*	232-386 *(154)*	335-458 *(123)* 517-543 *(26)*
Pz	135-800 *(665)*	139-584 *(45)* 594-620 *(26)* 666-683 *(17)*	293-562 *(269)* 574-606 *(32)*
Oz	202-800 *(598)*	213-419 *(206)* 429-441 *(12)* 474-520 *(46)*	300-533 *(233)* 583-607 *(24)* 710-747 *(37)*

Figure 6-6. Top: Stimulus-locked ERP waveforms at four midline sites are superimposed for task switch and task repeat trials in the single cue condition (left) and for cue category repeat (middle) and cue category switch (right) in the dual cue condition. Negative is plotted up. The solid vertical line indicates the onset of the stimulus. Mean RT is also depicted for each trial type. Bottom: Task switch difference waveforms (task switch – task repeat) for the above waveforms at Pz. Grey bars represent regions of significant differential negativity for task switch relative to task repeat trials. See Table 6-3 for values.

Stimulus-locked mean amplitude measures

Single cue versus cue category repeat trials: The single cue trials resulted in significantly larger positivity than the cue category repeat trials over both 150-250 and 300-500

ms windows (F(1,31)=17.4, p<.001; F(1,31)=10.9, p<.005), the former effect being larger centro-parietally (F(2,48)=6.1, p<.01). For both intervals, task switch trials had a smaller mean amplitude than task repeat trials (F(1,31)=33.4, p<.001; F(1,31)=44.1, p<.001), the former effect again being larger centro-parietally (F(2,48)=5.6, p<.05). While the early portion of the task-switching negativity did not differ significantly between the two cue conditions, it was significantly larger for the single cue condition than for the cue category repeat condition over 300-500 ms (F(1,31)=5.4, p<.05). Thus onset of differential processing of task switch and task repeat stimuli comparable in single cue and cue category repeat conditions.

Cue category repeat versus switch trials: At 150-250 ms, there was a significant interaction between cue type and trial type (F(1,31)=9.7, p<.005), whereas at 300-500 ms, only the effect of trial type was significant (F(1,31)=29.1, p<.001). As shown in Figure 6-6 (bottom), although the task-switch related negativity emerged later for cue category switch compared to cue category repeat trials, maximum amplitude was not affected by cue type.

6.3   Discussion

The current experiment utilised both behavioural and electrophysiological measures to dissociate between the effects of cue switching and task switching within cued task-switching paradigms.

Behavioural Effects of Switching Cues and Tasks

RT on both task repeat and task switch trials was not affected by a switch or a repeat in cue category, whereas a significant RT switch cost was obtained regardless of whether cue category repeated or switched. This RT task switch cost was consistently around 50-60 ms for the single condition and for both cue category repeat and cue category switch trials in the dual cue condition. Furthermore, the interaction between cue category type and task type in the dual cue condition did not approach statistical significance. The current experiment also directly compared RT switch cost under single cue and dual cue conditions within participants. Interestingly, even though RT task switch cost was not significantly affected by the use of

single or dual cues, the dual cue condition resulted in an overall increase in RT compared to the single cue condition, possibly reflecting increased working memory load under dual cues.

These findings clearly contrast with earlier findings indicating that RT task switch cost can be fully (Logan & Bundesen, 2003; 2004), or largely (Mayr & Kliegl, 2003), attributed to a confound between a switch in task and a switch in cue in cued task switching paradigms. The present results suggest that the RT switch cost previously observed in cued task-switching experiments (e.g., Hahn, Anderson & Kramer, 2003; Koch, 2001; Meiran, 1996; 2000; Meiran et al., 2000; Schuch & Koch, 2003; Tornay & Milan, 2001; Experiments 1-3) do not necessarily result from a cue repetition benefit on task repeat trials as proposed by Logan and Bundesen (2003; 2004) but may be attributed to task-set reconfiguration processes (see also Monsell & Mizon, 2006). In fact, the current results suggest that, at least under some circumstances, cue identity repetition, that is repetition of exactly the same cue on successive trials as is the case for cue category repeat / task repeat trials, offers *no* RT benefit over cue category switch / task repeat trials. The complete absence of any cue repetition benefit on RT in the current experiment is somewhat puzzling. The following section examines differences in methodology between previous studies, which have shown a cue repetition benefit and little or no RT cost associated specifically with task-switching, as compared to the current experiment that shows no cue repetition benefit but a large task-switch specific RT cost.

One possible account for the discrepancy between the results of the current experiment and previous work lies in the type of cues used. Logan and Bundesen (2003) used explicit verbal cues (the words 'parity' and 'odd/even' mapped to one task; 'magnitude' and 'high/low' mapped to the other), whereas Mayr and Kliegl (2003) used arbitrary consonants (e.g., G, S mapped to one task, B, W mapped to the other). In the current experiment, one cue category was the colour of the fixation box (blue or orange) and the other was the outline of a shape (circle or diamond) presented within the fixation box. In the single cue condition, there was no difference in RT or RT task switch cost for colour or shape cues, suggesting that the two cue categories were broadly equated for level of processing. Compared to the cues used in previous studies

(e.g., Logan & Bundesen, 2003; Mayr & Kliegl, 2003), these visual cues required little processing and were more readily associated with the two tasks in a structured way. Monsell and Mizon (2006) show that easy to interpret cues are less likely to result in large cue switch effects on RT. It should also be noted that the colour and shape cues used in the current experiment were categorically discrete and it would seem unlikely that the lack of a RT cue switching cost could be attributed to participants collapsing across the cue categories to form a single cue-task association (Monsell & Mizon, 2006; Logan & Schneider, in press).

Another possible account for the discrepancy may lie with differences in the strength of the cue-task association. Mayr and Kliegl (2003) reported a decline in the RT cue switch cost with increasing time on task, suggesting that increasing the strength of the cue-task association reduces the effect of cue switching. In the current experiment, participants received over 800 trials of single cue and dual cue task practice across two testing sessions prior to undertaking either the single cue or the dual cue switching task. Logan and Bundesen (2003, Experiments 3 & 4) used less than 1000 trials overall with little pre-task practice, whereas Mayr and Kliegl (2003) offered a total of 270 practice trials only a third of these with dual cue conditions. It is therefore likely that the strength of the cue-task association would be greater in the current experiment. The fact that dual cue condition RT and RT cue switch cost did not differ significantly between subjects completing the dual cue condition before or after the single cue condition despite the latter having received an extra 1280 trials, suggests that strong and stable cue-task associations had been established in the current experiment by the task practice alone. The importance of the cue-task association strength is highlighted by the finding that data from the dual cue practice runs on the first training session showed no RT cue switch cost on task repeat trials (2 ms), but a sizeable RT cue switch cost of 37 ms on task switch trials[11]. These observations suggest a cue repetition benefit in the initial stages of task learning when cue-task associations are being formed.

---

[11] This was not statistically analysed due to the small number of trials.

Although there was no RT cost associated with switching cues in the actual testing session, significantly more errors were made on cue category switch compared to cue category repeat trials. This could reflect a speed-accuracy trade-off, with participants responding just as fast on cue category switch as on cue category repeat trials, but then making more errors on cue switch trials. The number of errors made was also significantly greater on task switch compared to task repeat trials. This error task switch cost is a consistent finding and is thought to reflect the increased cognitive demands associated with task-set reconfiguration on task switch trials (e.g., Rogers & Monsell, 1995). The error cue switch cost may also thus reflect that it is more difficult to execute the tasks successfully when the cue switches.

Another factor that may affect the relative advantage of cue identity repetition trials is the degree to which across task interference is inherent in the stimulus sets. While all recent studies using a dual cue task-switching paradigm have used bivalent stimuli (Logan & Bundesen, 2003; Mayr & Kliegl, 2003; Monsell & Mizon, 2006), in the current experiment, 75% of stimuli were incongruently mapped to response hand. As in Experiment 3, the remaining 25% of stimuli were congruent and were included to ensure that participants did not combine the two tasks into a single stimulus-response reversal task (e.g., blue cue: even = left hand response; orange cue: even = right hand response). However, these congruent trials were not included in any analyses because even if a participant responded correctly on a congruent trial, there is no way to tell if they had actually applied the correct task-set rule (e.g., a left hand response to the number '2' is correct whether responding 'less than 5' or 'odd'). RT tends to be longer on bivalent compared to univalent stimuli and on incongruent compared to congruent stimuli (e.g., Rogers & Monsell, 1995; Meiran, 2000; Woodward, Meier, Tipper & Graf, 2003). If, as Logan and Bundesen (2003) propose, participants develop a single compound cue-stimulus association, this association would be stronger for univalent stimuli or for congruent stimulus-response mappings of bivalent stimuli. The use of bivalent incongruent stimuli in the current experiment would have restricted the effectiveness of a compound cue-stimulus strategy, thereby reducing the repetition benefit associated with cue repeat trials.

Finally, if task-set reconfiguration is a voluntary process, then it may be differentially activated upon cue onset depending on task parameters. In most cued task-switching experiments, the cue remains visible after stimulus onset. Consequently, there is no necessity to process the cue or initiate task-set reconfiguration until after stimulus onset. This is likely to lead to greater within-and between-subject variability in RT switch cost, as the engagement of anticipatory task-set reconfiguration would depend on factors such as motivation and vigilance (De Jong, 2000; see Experiment 3). In the current experiment, engagement of anticipatory task-set reconfiguration was maximised by using an optimal CSI of 600 ms (Rogers & Monsell, 1995; Experiment 1), using short runs of trials and providing regular behavioural feedback (Nieuwenhuis & Monsell, 2002), and by removing the cue prior to stimulus presentation[12]. Given that the bivalent stimuli carried no information about which task was relevant (e.g., '3' is both less than 5 and odd), this increased the likelihood that participants would process the cue prior to stimulus onset which, in turn, would increase the probability that task-set reconfiguration would be engaged in anticipation of a task-switch trial (see Experiment 3). On trials where the cue was not processed within the CSI, participants would rely on retrieval and processing of the cue after stimulus onset, and this would be expected to result in slower RT and increased error rate. The very high level of accuracy (over 95%) and overall quite fast mean RT suggest that participants processed the cue prior to stimulus onset on the majority of trials. Further, mean RT task switch cost in the current experiment (around 60 ms) is slightly faster than the comparable timing condition in Experiment 3 (RSI-750:CSI-600), which had a mean RT switch cost of 73 ms, suggesting that participants were engaging in anticipatory task-set reconfiguration on the majority of trials in the current experiment.

If maximisation of anticipatory task-set reconfiguration can account for the lack of a RT cue switch cost in the current paradigm, a cue switch cost should be evident for trials on which participants have failed to engage in anticipatory task-set reconfiguration. RT distribution analysis showed a significant RT task switch cost for both cue repeat and cue switch trials at all

---

[12] Although Monsell and Mizon (2006) suggest lower proportions of switch trials are preferable, they acknowledge that an equal proportion of switch and repeat trials, as used in the current experiments 1 and 3-5, should still result in reduced RT switch cost with a long CSI.

RT decile bins (Figure 6-2). There was no evidence of an RT cue switch cost except at the last RT decile bin that showed a very small and not statistically significant cue switch cost (<12 ms). This RT cue switch cost also tended to be larger for task switch than for task repeat trials, suggesting that cue and task switching effects operate on independent processes. Therefore, a small but non-significant RT cue switch cost could be seen for unprepared trials only.

In summary, a number of task parameters may have contributed to the absence of a cue repetition benefit in the current experiment and the small or absent task switching cost in Logan and Bundesen (2003) and Mayr and Kliegl (2003). Overall, these studies and Monsell and Mizon (2006) show that both cue repetition benefit and task-switching cost contribute to the RT differential between task switch and task repeat trials and point to the importance of considering these parameters when intending to employ task-switching paradigms to study cognitive control processes. These findings converge with recent evidence by Forstmann, Brass and Koch (in press) who used transition (switch/repeat) rather than task (A or B) cues and found independent effects of cue repetition and task switching.

Electrophysiological Effects of Switching Cues and Tasks

ERP data also showed independent effects of cue switching and task switching in both cue-locked and stimulus-locked waveforms. Consistent with previous studies (e.g., Karayanidis et al., 2003; Rushworth et al., 2002; 2005; Experiments 1-3), after cue onset task switch trials resulted in significantly larger positivity than task repeat trials, particularly over the parietal site. In the single cue condition, this differential switch-related positivity emerged parietally as early as 180 ms after cue onset and spread across all midline sites, extending beyond stimulus onset. This finding supports the previous interpretation that the differential switch-related positivity reflects processes involved in anticipatory task-set reconfiguration, such as initiating the new task-set. A similar switch-related positivity was evident in the dual cue condition for both cue category repeat and cue category switch waveforms (Figure 6-3, bottom). However, here this positivity emerged much later than in the single cue condition (423 versus 183 ms) and was

largely restricted to the parietal site. Nevertheless, over 450-600 ms this differential switch-related positivity did not differ in amplitude between single cue and dual cue conditions.

The effects of cue processing were manifested more clearly in early ERP components (Figure 6-4). Specifically, cue category repeat trials showed a larger N2 than cue category switch trials, resulting in a sharp positive peak in cue category (switch – repeat) difference waveforms (Figure 6-4, bottom) over 180-240 ms. Unlike the early switch-related positivity, this cue switch effect did not evolve into a later positivity and was significant across all midline sites. A small cue-switch positivity emerged around 450-500 ms after cue onset and showed brief periods of significant deviation from baseline, however, mean amplitude measures over 450-600 ms showed no effect of cue category switching and no interaction between cue category and task switching. These findings corroborate behavioural effects discussed earlier suggesting that cue switching and task switching operate at different levels of processing.

The use of dual cues delayed the onset of the differential switch-related positivity, resulting in a 50 ms increase in overall RT and a 10 ms increase in RT switch cost. The inclusion of dual cues appeared to result in modulation of early ERP components. Cue category repetition resulted in sharper and larger early ERPs and especially N2 as compared to cue category switch trials, but also surprisingly as compared to the single cue condition. Given that the only difference between cue category repeat and single cue trials was that the former but not the latter were intermixed with cue category switch trials, this difference in early ERPs associated with cue processing is puzzling and will require replication before any meaningful interpretation can be offered. The small late differential positivity for cue category switch versus cue category repeat trials that was evident for both task repeat and task switch trials (Figure 6-4, bottom) suggests that the differential positivity previously observed, particularly in Experiment 3, may partially reflect cue switch processing. Alternatively, it is possible that a change in cue may result in activation of anticipatory task-set reconfiguration on some proportion of trials, even when task is being repeated. That is, on some trials, participants may *accidentally* interpret the switch in cue as a switch in task and initiate task-set reconfiguration regardless of whether it

is necessary or not, leading to increased positivity on those trials. However, this would be expected to reduce the RT task switch cost at the slower end of the RT distribution, which is not the case in Figure 6-2.

Consistent with earlier experiments, a differential negativity emerged for task switch relative to task repeat trials after stimulus onset. In the single cue condition, this switch-related negativity emerged around 130 ms after stimulus onset across frontal to parietal sites, but frontally it resolved by 400 ms whereas parietally it continued to be significant beyond response onset. This differential negativity is believed to be associated with residual RT switch cost and to reflect differential post-stimulus processing of task switch versus repeat trials, occurring as a result of differences in stimulus-response priming and stimulus-triggered response interference associated with the previously relevant task-set. Although it was not possible to examine changes in RT switch cost across different values of CSI in the current experiment, a *residual* RT task switch cost is suggested by the 29 ms difference between switch and repeat trials at the fastest RT bin of the cumulative distribution. Thus even with an optimal preparation interval of 600 ms, even the most prepared switch trials were slower than the fastest repeat trials.

This switch-related post-stimulus negativity was also affected by cue condition. For cue category repeat trials, the onset of this switch-related negativity was similar to that for the single cue condition. However, this negativity was restricted more posteriorly and had smaller amplitude for cue category repeat than for single cue trials. This may have at least partly resulted from an overall reduction in LPC amplitude under dual cue conditions reflecting increased task complexity (e.g., Isreal, Wickens & Donchin, 1979). However, the absence of significant deviation from baseline at frontal sites in the cue category repeat conditions compared to the single cue condition can not be accounted for by LPC modulation. The post-stimulus negativity was further modulated for cue category switch trials in the dual cue condition. Here, the differential switch-related negativity emerged much later than (>300 ms after stimulus onset), but did not differ in maximal amplitude from the cue category repeat trials. Delayed onset of the differential negativity has been previously obtained with short RSIs

or CSIs (Karayanidis et al., 2003; Experiments 1-3), where it was interpreted as the result of post-stimulus completion of task-set reconfiguration processes that, in turn, delayed the onset of stimulus-response interference effects on task-switch trials. In the current context, this would suggest that completion of task-set reconfiguration is delayed for switch trials in the cue category switch condition, resulting in later onset of stimulus-triggered interference. This interpretation is supported by the prolonged differential positivity for the cue category switch condition in the cue-locked waveforms. As shown in Figure 6-3, while task switch and task repeat ERPs converge soon after stimulus onset for single cue and cue category repeat trials, a large positive differential remained beyond 750 ms for cue category switch trials.

Summary

The current pattern of data suggests that single and dual cue conditions differed in task difficulty and degree of stimulus-response interference. This implies that direct extrapolations from differences between cue category repeat / task repeat and cue category switch / task switch trials in single cue and dual cue paradigms should be interpreted with caution. In the current experiment, despite only very small increase in RT task switch cost from single to dual cue conditions, a number of other behavioural and ERP differences emerged. Overall RT was substantially larger, the cue-locked differential positivity emerged later and the stimulus locked differential negativity was smaller for cue category repeat trials in the dual cue condition compared to the single cue condition.

The main differences between cue category repeat and cue category switch trials were a reduction in the amplitude of the switch-related positivity and a delay in the onset of the switch-related negativity. However, switch-related differences in RT cost, cue-locked positivity and stimulus-locked negativity occurred regardless of whether cue category repeated or switched. More importantly, there was no evidence that cue repeat / task repeat trials showed a quantitatively or qualitatively different pattern of behavioural or ERP findings, as predicted by a cue repetition benefit account of RT switch costs.

Together with recent behavioural findings by Monsell and Mizon (2006), the current findings show that, cued task-switching paradigms do involve a process of task-set reconfiguration that can be activated in anticipation of a switch stimulus and therefore these paradigms provide a useful measure of one index of cognitive control processes. While cue repetition effects, stimulus-response priming and stimulus-response interference also affect the size of RT switch cost, it is possible to manipulate task parameters so as to minimise the effects of repetition benefits and interference processes while maximising the employment of voluntary active preparation processes.

7 Experiment 5: Localisation of reconfiguration processes[13]

Experiments 1-4 provide strong evidence for differential processing in anticipation of a switch versus repeat in task and support the existence of an endogenous task-set reconfiguration process. However, the positivity that is assumed to reflect this process is measured as a differential in the ERP waveforms for switch versus repeat trials. Therefore, it may reflect either a component that is exclusively activated for switch trials or a component that is activated for both switch and repeat trials, but has relatively greater activation for the former. These alternatives have different implications for models of task-switching, with the latter suggesting that the process of task-set reconfiguration is not exclusively activated on switch trials but may also occur on repeat trials, depending on task parameters and trial by trial variability. Certainly this possibility is not implausible, as ERP waveforms contributing to the difference waveform in previous studies tend to show a small positive shift occurring for repeat waveforms within the same time range as the differential positivity.

The current experiment aimed to examine the relative component structure of switch and repeat waveforms using independent component analysis (ICA; Jutten & Herault, 1991) and to identify areas of differential brain activation for switch as compared to repeat trials using low-resolution electromagnetic tomography (LORETA; Pascual-Marqui, 1999; Pascual-Marqui, Michel, Lehmann, 1994). The cued task-switching paradigm used in Experiments 3 and 4 was replicated with slight modification. Even though Experiment 4 demonstrates that cue repetition benefits do not affect the RT switch cost or differential positivity in this paradigm, in the current experiment the cue changed on every trial to avoid ever presenting the confound of a cue and task repeat trial. The cue was a change in the colour of the fixation box and multiple colours were assigned to each task so that even if the task repeated, the cue always changed. The second modification is that the response window (i.e., the time available for a response prior to the onset of the next cue) was restricted to an average of 1650 ms to impose a deadline for accurate

---

[13] Published as Nicholson, R., Karayanidis, F., Fulham, R. & Michie, P. (in revision). Organization of anticipatory task-switching processes using low-resolution electromagnetic tomography (LORETA). *International Journal of Psychophysiology*. See Appendix.

performance and encourage consistently faster responses (e.g., Lien, Ruthruff, Remington & Johnston, 2005). In previous experiments the stimuli remained on the screen until a response was made or up to 5000 ms after stimulus onset, although any responses occurring after 2000 ms were rejected from analysis. A fixed long CSI of 600 ms was used as this has been shown to be optimal for the engagement of anticipatory task-set reconfiguration processes (Rogers & Monsell, 1995; Experiment 1) and provides good temporal dissociation between cue- and stimulus-related processes.

ICA (Jutten & Herault, 1991) identifies statistically independent and non-gaussian factors occurring within a dataset and has been used to discern components underlying EEG recordings (for review see Hyvärinen, Karhunen & Oja, 2001; Makeig, Debener, Onton & Delorme, 2004; Vigario, Särelä, Jousmäki, Hämäläinen & Oja, 2000). The current experiment examines whether switch and repeat trials demonstrate a different underlying component structure of brain activity by performing ICA separately for switch and repeat trials over the CSI. If anticipatory task-set reconfiguration represents a process that occurs exclusively on switch trials and that is represented by the differential positivity, then an ICA component within the latency range of the differential positivity is expected to occur for switch trials only. Alternatively, if anticipatory task-set reconfiguration represents a process that is activated on a large proportion of switch trials but may also occur on a certain proportion of repeat trials, then a similar ICA component is expected to occur within the latency range of the differential positivity for both switch and repeat trials. As ICA can not differentiate the relative strength of activation of this component on switch and repeat trials, the ICA component structure would be expected to be relatively similar for both trial types.

The consistent finding of a switch-related positivity suggests differential brain activity on switch relative to repeat trials. This may reflect that, on switch trials, there is either activation of additional brain regions or different level of activation of the same brain regions relative to repeat trials. The current experiment attempts to localise these brain regions differentially activated in anticipation of a switch trial using EEG tomography analysis. Tomography analysis

was used rather than dipole fitting because the former does not require predetermined assumptions about the number of source regions. LORETA was selected from the available tomography analysis methods (e.g., Minimum Norm, Hämäläinen & Illmonemi, 1994) because it has been shown to have low localisation error rates, it provides a single solution to the inverse problem of source localisation (i.e., how to use surface data to identify sources) by searching for the 'smoothest' possible solution using only the assumption that neighbouring voxels have maximally similar electrical activity (Pascual-Marqui, 1999; Pascual-Marqui, Esslen, Kochi & Lehmann, 2002) and has successfully been used to localise brain regions involved in cognitive tasks (e.g., Fallgatter, Bartsch & Herrmann, 2002; Herrmann & Fallgatter, 2004; Kounios, Smith, Yang, Bachman & D'Esposito, 2001).

LORETAs were calculated separately for switch and repeat trials over two time windows within the CSI that maximally differentiated switch from repeat trial ERPs. Switch minus repeat difference tomography maps were created to identify regions of greater activation for switch trials. Based on the largely parietal distribution of the differential positivity it was expected that there would be significantly greater activity for switch trials in the parietal lobe. Recent functional magnetic resonance imaging (fMRI) studies have suggested that a switch in task is associated with greater activation in frontal areas including the inferior frontal gyrus and middle frontal gyrus (e.g., Brass & von Cramon 2002; 2004; Dreher, Koechlin, Ali & Grafman, 2002; Sohn, Ursu, Anderson, Stenger & Carter, 2000) and parietal areas including the superior parietal lobule and intraparietal sulcus (e.g., Barber & Carter, 2005; Dove et al., 2000; Erickson et al., 2006; Kimberg et al., 2000; Ruge et al., 2005). Brass, Derrfuss, Forstmann and von Cramon (2005) reviewed recent studies pointing to a specific role of the inferior frontal junction area in cognitive control processes. However, in many fMRI studies (e.g., Brass & von Cramon 2002; 2004; Ruge et al., 2005), activation differences between switch and repeat trials are found for short but not long CSI conditions, indicating that these differences may not reflect differential anticipatory processing for switch trials at long preparation intervals. Given that fMRI data provides excellent spatial resolution but relatively low temporal resolution, the high temporal

resolution of ERP data could complement the fMRI findings. Specifically, LORETA analyses will be used to examine whether the pattern of differential activation of switch and repeat trials *within* the CSI is similar to that suggested by fMRI studies. It was therefore expected that LORETA analyses would reveal that switch trials are associated with differential activation in similar frontal and parietal regions as those reported for fMRI data.

7.1 Method

Participants

Sixteen right-handed undergraduate students (mean age 25 ± 6.5 years; 10 female).

Stimuli and Tasks

A square box outlined in grey (120 by 120 pixels) was continuously displayed in the centre of a computer monitor (viewed from approximately 90 cm). The stimulus was a single digit (1-4 and 6-9, 60 by 60 pixels) presented in the centre of the box (Figure 7-1a). In the parity task, participants responded whether the digit was odd or even. In the magnitude task, participants responded whether the digit was less than or greater than 5. Prior to stimulus onset, the outline of the box changed from grey to one of eight colours (Figure 7-1b) and provided a valid cue as to the task to be performed on the subsequent stimulus. A task switch occurred on 50% of trials. Four 'cold' colours (ocean blue, emerald green, sky blue, turquoise) were mapped to one task and four 'hot' colours (red, pink, orange, burgundy) were mapped to the other task. Cue colour was never repeated on successive trials in order to eliminate any potential confound from cue repeat and task repeat trials (e.g., task repeat trial on trial N + 1, where trial N = red cue and therefore trial N + 1 = pink, orange or burgundy cue). The colour cue remained on for the duration of the CSI, but was removed immediately prior to stimulus onset (i.e., the outline colour of the box returned to grey). Stimulus-response mapping was congruent for the two tasks on 20% of trials and incongruent on all remaining trials. Incorrect responses resulted in auditory feedback and the onset of the next trial was delayed by 1000 ms.
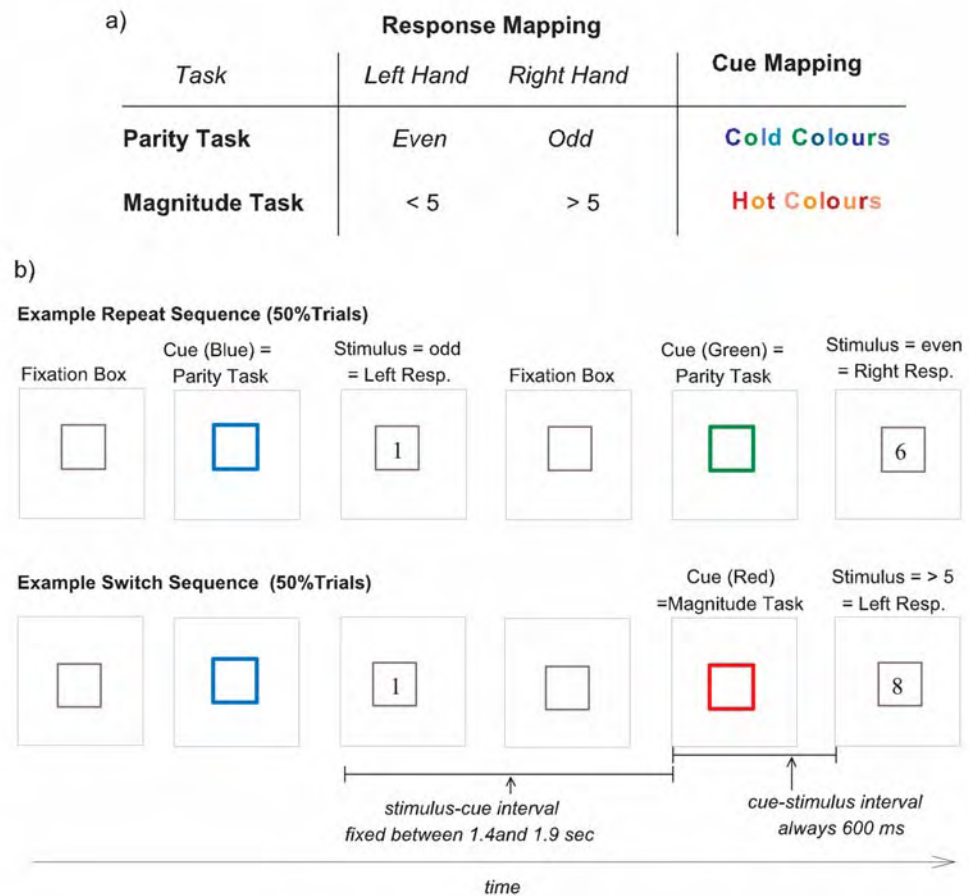
Figure 7-1. A) Example task-response and task-cue mappings. B) Example trial sequence.

The CSI was fixed at 600 ms. To provide a fixed interval for responses, the interval between the onset of the stimulus on trial N and the onset of the cue for trial N+1 was always between 1400 and 1900 ms, with an average of 1650 ms. The average interval of 1650 ms was selected based on mean RT plus 3 standard deviations from Experiment 3 (averaged across the two conditions with a 600 ms CSI). The RCI thus varied on a trial-by-trial basis depending on RT (range between 313 and 1567 ms, mean 1150 ms ± 230 ms). The stimulus was removed upon response onset or 100 ms prior to the onset of the next cue. In the latter case, the trial was classified as a 'missed' response and auditory feedback as per an error trial was given.

Procedure

Practice included 80 trials on each task alone and 300 trials of cued switching between the two tasks in the first session and 40 trials on each task alone and 200 trials of task switching tasks in the second session. Behavioural and EEG data were recorded after task practice on the

second day. Testing consisted of 936 trials in 6 equal blocks (50% switch trials). Participants were encouraged to maintain a high level of accuracy while responding as quickly as possible.

Data Analysis

The first two trials of every block, correct responses with RT less than 200 ms and all congruent trials were discarded from analysis[14]. Trials associated with incorrect or missed responses and trials immediately following an incorrect or missed response were also excluded from RT and EEG analysis. Transformed error rates and RT data were analysed using a 2 Task (Parity, Magnitude) by 2 Trial Type (Repeat, Switch) repeated-measures ANOVA.

EEG recording and data analysis

EEG was recorded using a Quik-cap (NeuroScan) from 62 scalp electrodes referenced to the nose electrode. Electrode positions were determined with a Fasttrack 3D Digitiser (Polhemus). EEG and EOG were continuously sampled at 500Hz/channel on a Synamps 1 system (NeuroScan) with a bandpass of 0.01-30 Hz.

To be consistent with the previous experiments, continuous EEG files were re-referenced offline to the average of the left and right mastoids. Cue-locked 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. The stimulus-locked ERP averages were baseline corrected over -50 to 50 ms due to a shifting pre-stimulus baseline. Cue-locked ERP averages were baseline corrected over -200 to 0 ms as there was no pre-cue baseline shift. As there were no significant effects of task on RT, ERPs were averaged across task in order to increase signal to noise ratio. Cue- and stimulus-locked epochs were averaged separately for switch and repeat trials and switch-repeat difference waveforms were calculated. Point-by-point t-tests were conducted on the difference waveforms up to 800 ms to identify areas of significant deviation between switch and repeat waveforms. 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.

---

[14] In previous experiments, responses occurring more than 2000 ms after stimulus onset were also excluded. This was not necessary in the current experiment as no RTs extended beyond 1500 ms.

ICA and LORETA

EEG data were re-referenced to the common average for ICA and LORETA analysis to remove any reference bias in the topography of the waveforms. This resulted in overall reduction in the amplitude of the ERP waveforms compared to the mastoid referenced data, however the relative difference between switch and repeat waveforms was not affected[15]. ICA was conducted separately for switch and repeat trials over 0 to 700 ms after cue onset[16]. The fixed-point FastICA algorithm (Hyvärinen, 1999; Hyvärinen & Oja, 1997; 2000; as implemented in the NeuroScan 4.3 ICA toolbox) was applied to concatenated data from all subjects, totalling over 5000 trials for each trial type (approximately 320 switch and 320 repeat trials per subject). Only components that accounted for more than 5% of the variance and had a signal-to-noise ratio greater than 1 were selected.

LORETA-KEY software was used for all LORETA analysis (Pascual-Marqui, 1999). A total of 2394 voxels were calculated for each subject separately for switch and repeat trials. LORETA analysis was conducted over two separate time windows: 350 to 450 ms and 450 to 550 ms after cue onset. These windows were selected because they were associated with significant deviation between switch and repeat trials in the difference waveform analyses. For each voxel, current density was calculated based on the linear, weighted sum of the scalp electric potentials (Pascual-Marqui et al., 1994). A three-shell spherical head model registered to the Talairach human brain atlas was used (Montreal Neurologic Institute, MNI, 305, Brain Imaging Centre; Talairach & Tournoux, 1988). The solution space within the head model was restricted to cortical grey matter and to the hippocampus in the Talairach atlas (Pascual-Marqui, 1999). Two-tailed paired t-tests were used to identify regions of differential activation for switch versus repeat trials (corresponding to the statistical non-parametric mapping method, e.g., Nichols & Holmes, 2002). Voxel-by-voxel comparisons were made (corrected for multiple

---

[15] This was determined by comparison of the Guthrie and Buchwald (1991) difference waveform analysis for mastoid versus common referenced data.

[16] Although the CSI was 600 ms, ICA was performed over 0 to 700 ms after cue onset based on visual inspection of the cue-locked ERPs. As Figure 7-2 shows, a CNV type component is building over approximately 400 to 700 ms. Restricting the ICA to 0 to 600 ms would have thus affected the inclusion of this component in the analysis.

comparisons) on the LORETAs averaged over 350 to 450 ms and over 450 to 550 ms based on the log transformed power of the estimated electric current density (Pascual-Marqui, 1999).

7.2   Results

Behavioural Data

Overall accuracy was very high (> 98%). Only 0.03% of trials were discarded for RT less than 200 ms and 0.4% for missed responses. RT was significantly larger for switch (493 ms) than repeat trials (461 ms, $F(1,15)=12.9$, $p<.005$; Table 7-1). There was no effect of switching on error rate. Neither RT nor error rate was affected by task (parity / magnitude).

Table 7-1

Mean RT and error rates for repeat and switch trials shown separately for parity and magnitude tasks. Average over task also shown. Standard error in parentheses.

	RT (ms)			**% Error**		
	Parity	Magnitude	Average	Parity	Magnitude	Average
Repeat	462 (5.4)	458 (5.3)	461 (4.3)	1.5 (0.2)	1.6 (0.3)	1.5 (0.1)
Switch	492 (7.4)	494 (5.5)	493 (4.3)	1.2 (0.2)	2.3 (0.3)	1.7 (0.1)
Switch Cost	*30 (10.4)*	*36 (7.8)*	*32 (8.6)*	*-0.3 (0.3)*	*0.7 (0.5)*	*0.2 (0.3)*

Cue-locked ERPs

Cue-locked ERP waveforms for task repeat as compared to task switch trials are shown in Figure 7-2. The cue elicited standard early visual evoked potentials (P1, N1 and P2) for both trial types. Both switch and repeat waveforms showed a large parietal positive component that was maximal around 400 ms after cue onset and a sustained CNV type shift that was most clearly evident fronto-centrally and extended until approximately 700 ms after cue onset (i.e., 100 ms after stimulus onset). As Figure 7-2 illustrates, a broadly distributed positive shift was evident for switch relative to repeat trials over approximately 350-700 ms after cue onset. This switch-related differential positivity was maximal over central and parietal sites and tended to be greater over the left hemisphere.
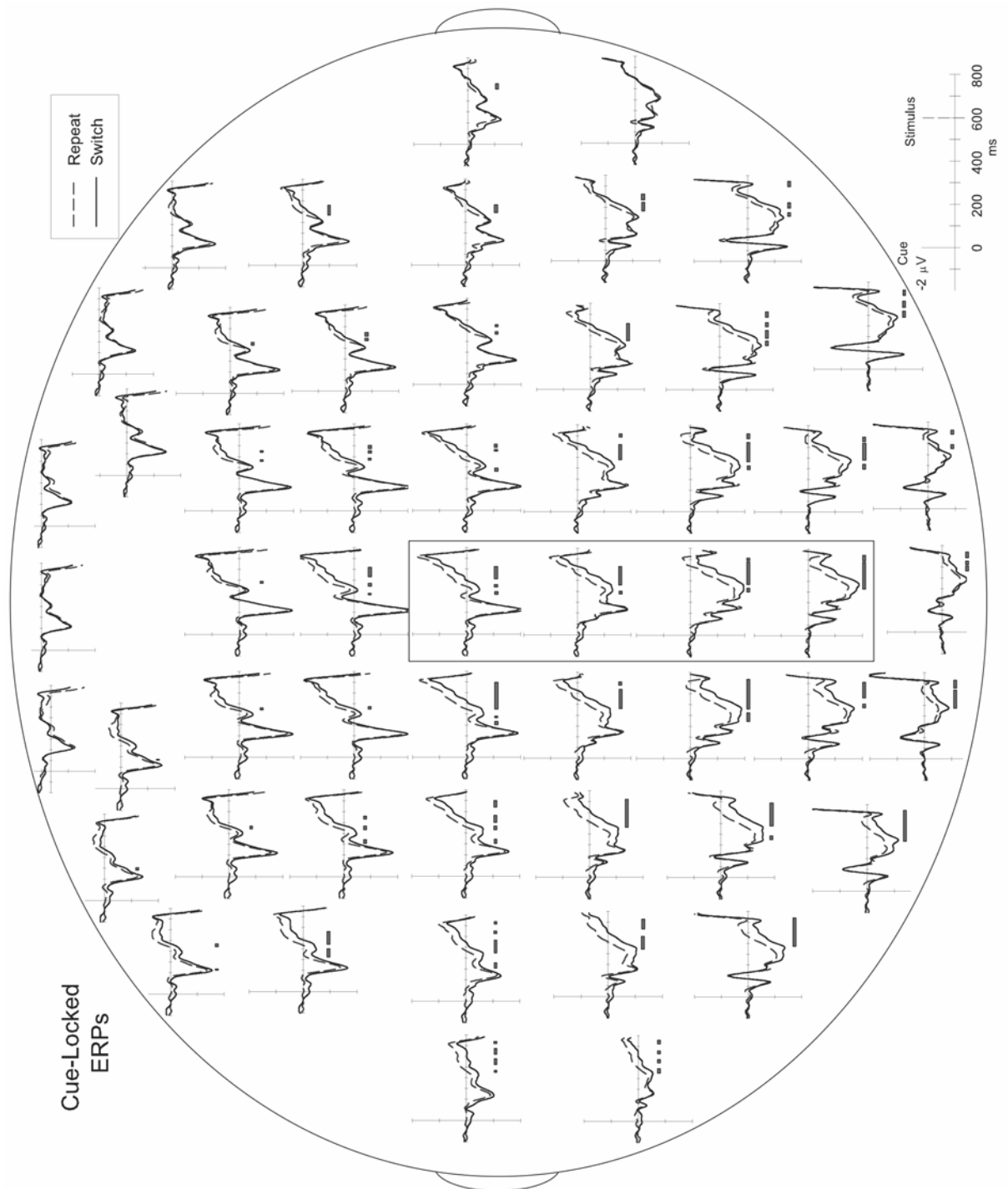
Figure 7-2. Cue-locked ERP waveforms for repeat and switch trials based on average mastoid reference. Bars indicate regions of significantly greater positivity for switch trials. Negative is plotted up. Solid vertical line indicates onset of the cue.

Figure 7-3 shows the cue-locked difference waveforms corresponding to the central and parietal sites highlighted in Figure 7-2. At these centro-parietal sites, switch trials were significantly more positive than repeat trials over approximately 360-410 ms and from 440 ms until after stimulus onset (Figure 7-3). These intervals were used to determine the timeframes over which the LORETA analysis was conducted. Specifically, LORETAs were calculated over 350-450 ms to investigate processes reflected by the 360-410 ms differential positivity and over 450-550 ms to capture the later effect from around 440 ms onwards. LORETA analysis was not conducted beyond 550 ms to ensure temporal dissociation from stimulus related processes related to stimulus onset at 600 ms.
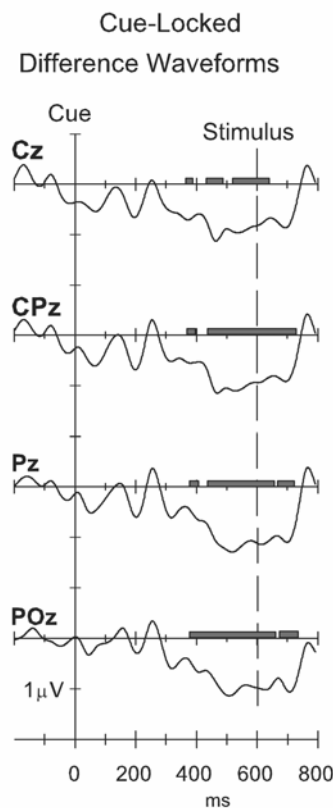

Figure 7-3. Cue-locked difference waveforms (switch – repeat) corresponding to the four midline sites highlighted in Figure 7-2. Bars indicate regions of significantly greater positivity for switch trials.

Stimulus-locked ERPs

Stimulus-locked ERP waveforms are shown in Figure 7-4 with N1 / P2 components evident for both trial types. These early ERPs were followed by a broad negativity evident

fronto-centrally over 150-400 ms and a parietal LPC over 300-600 ms. A negative deviation was evident for switch relative to repeat trials that began as early as 150 ms after stimulus onset and continued until approximately 700 ms. This post-stimulus differential negativity tended to be maximal centro-parietally and peaked at around 400 ms after stimulus onset.
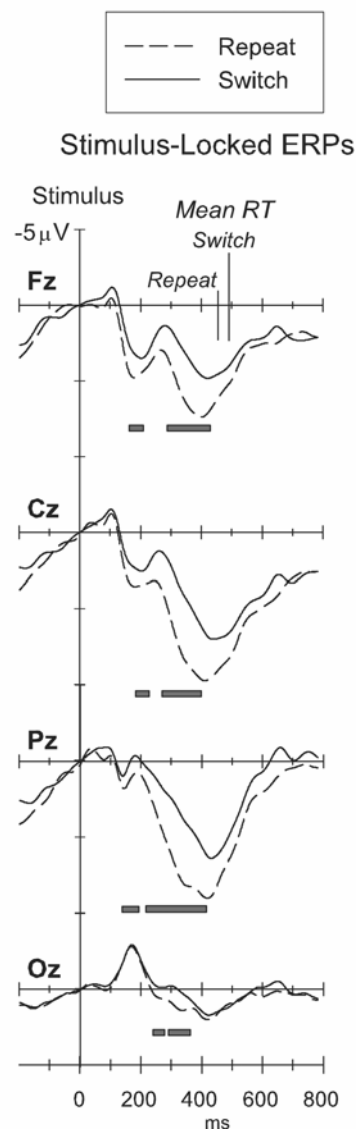

Figure 7-4. Stimulus-locked ERP waveforms at midline sites for repeat and switch trials. Bars indicate regions of significantly greater negativity for switch trials. Solid vertical line indicates onset of the stimulus. Mean RTs indicated for switch and repeat trials.

ICA

As Figure 7-5 illustrates, the ICA over 0-700 ms after cue onset identified three reliable components for repeat trials. Three similar components were also found for switch trials. In total across the averaged ERP data, the three components accounted for 77.1% of the variance for repeat trials and 77.8% for switch trials. The first component accounted for the largest

proportion of the variance for both trial types and showed a broad parietally-based positive shift that began around 250 ms after cue onset and extended until 700 ms. This component appears to correspond to the late positive shift evident in the cue-locked ERPs over 300-700 ms (Figure 7-2). The second component showed a large frontally distributed positive peak occurring approximately 210 ms after cue onset and can be mapped onto the frontal P2. The third component showed early activity that was slightly more positive for repeat trials and that was compatible with the parietal P1, N2, P2 pattern. The later portion of the third component shows a negative drift beginning around 400 ms after cue onset that corresponds closely with the CNV drift evident in the lead up to stimulus onset.
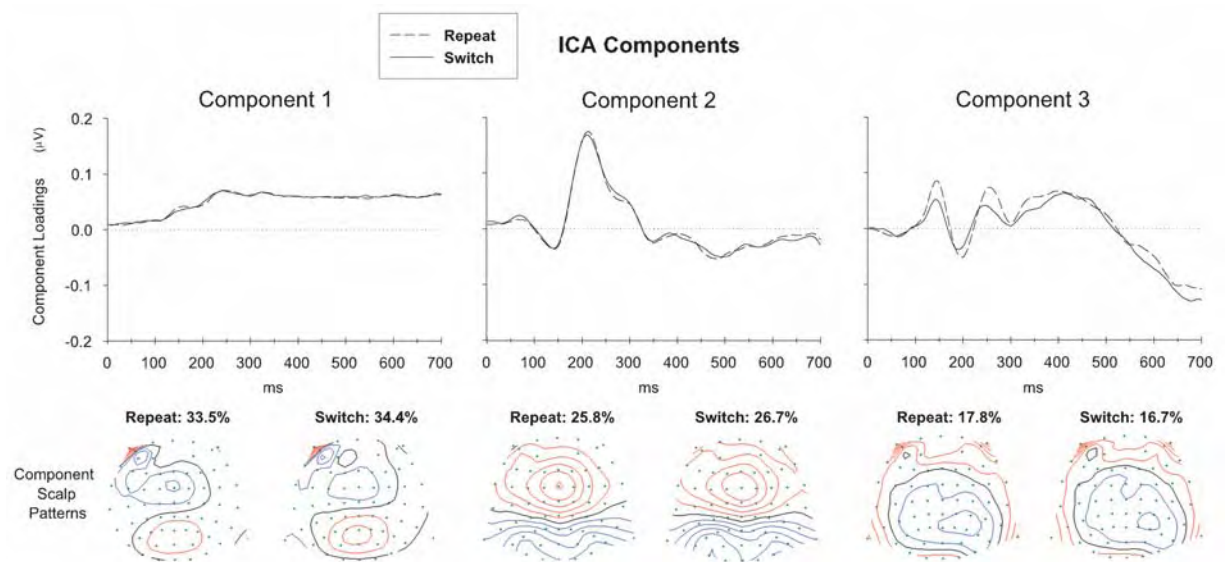

Figure 7-5. Top: Loadings of the independent components over 0 to 700 ms after cue onset for switch and repeat trials. Bottom: Scalp patterns for each of the components for each trial type and the amount of variance explained by the component. Patterns show the scalp distribution of the component loadings. Blue contour lines show the negative values and red contours show the positive values distribution.

LORETA

Multiple brain regions were significantly more active on switch as compared to repeat trials, with the strength and location of these differences varying over the two time intervals examined (Figure 7-6). Over 350-450 ms after cue onset, switch trials were associated with greater activation in the frontal, temporal and parietal lobes. Significant differences in activation between switch and repeat activation areas were more extensively evident in frontal regions, including the inferior, middle and superior frontal gyri (Table 7-2), where it tended to be greater

over the left hemisphere (Figure 7-6). Significantly larger activation for switch trials was also found in the superior temporal gyrus and the precuneus. Over 450-550 ms, there was less extensive switch-related activation over frontal regions, with significant differences restricted more anteriorly in the superior frontal gyrus. In this later window, there was more extensive switch activation in the parietal lobe (Table 7-2), more specifically in the superior parietal lobule and precuneus, which showed greater activation in the left hemisphere (Figure 7-6).
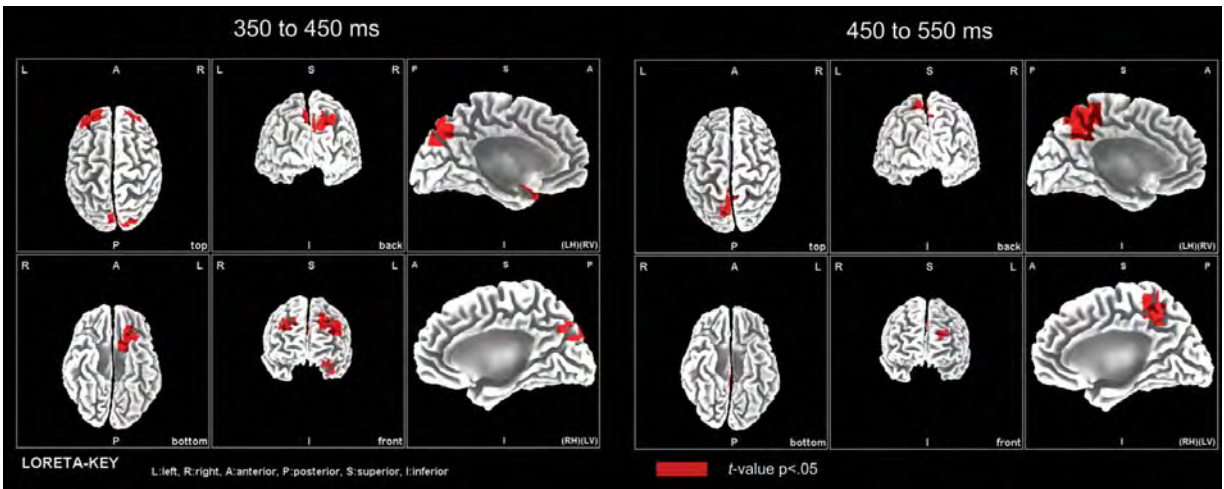

Figure 7-6. 3D cortical surface maps illustrating areas of significantly greater activation for switch compared to repeat trials over 350 to 450 ms and 450 to 550 ms after cue onset. See Table 2.

Table 7-2

Local maxima of areas with significantly greater activation for switch as compared to repeat trials.

		BA	X	Y	Z	t-value
350 to 450 ms after cue onset						
Frontal Lobe	Inferior Frontal Gyrus (L)	47	-24	17	-20	5.64
	Middle Frontal Gyrus (L)	9	-24	38	29	5.19
	Superior Frontal Gyrus (R)	9	18	52	36	5.19
Temporal Lobe	Superior Temporal Gyrus (R)	22	67	-39	22	3.87
Parietal Lobe	Precuneus (R)	19	18	-88	36	4.71
	Precuneus (L)	7	-3	-74	43	4.31
450 to 550 ms after cue onset						
Frontal Lobe	Superior Frontal Gyrus (L)	10	-24	59	22	3.63
Parietal Lobe	Precuneus (L)	7	-10	-46	50	5.03
	Precuneus (L)	7	-10	-60	57	4.01
	Precuneus (L)	7	-10	-60	36	4.01
	Superior Parietal Lobule (L)	7	-10	-67	57	4.30

Notes: Left (L) or right (R) hemisphere indicated. X, Y, Z co-ordinates in Talairach space in mm: X refers to the left - right, Y to the anterior – posterior and Z to the cranial – caudal dimension. BA = Brodman Area. t-value = value of the statistical comparison with p<.05 for values over 3.58 for the 350-450 ms window and over 3.46 for the 450-550 ms window.

7.3 Discussion

The current experiment aimed to extend previous findings that preparation for a switch in task is associated with increased parietal positivity. A cued task-switching paradigm was used with parameters that strongly encouraged the use of the CSI to engage in anticipatory task-set reconfiguration. Relative to the previous two experiments that used a similar paradigm, overall RT (477 ms) was very fast and accuracy was exceptionally high (> 98%). RT was significantly greater on switch as compared to repeat trials. In Experiment 3, in the short 150 ms CSI the RT switch cost was 160 ms compared with 64 ms in the longer 600 ms CSI, reflecting participants' ability to engage in anticipatory task-set reconfiguration when there was the longer CSI. In the current experiment the RT switch cost was only 32 ms, suggesting that participants were using the 600 ms CSI to actively prepare for the upcoming switch in task on the majority of trials. Indeed, it appears that restricting the time available for participants to respond encouraged them to prepare on an even greater proportion of trials relative to Experiment 3, leading to an even smaller mean RT switch cost. Participants may have still failed to engage in anticipatory task-set reconfiguration on some proportion of trials due to factors such as loss of concentration and fatigue, which may partially account for the 32 ms switch cost (De Jong, 2000). The switch cost may also reflect a 'residual' component of task-switching that cannot be triggered until after stimulus onset (Rogers & Monsell, 1995) or passive interference processes elicited by the stimulus itself (e.g., Allport & Wylie, 2000).

Electrophysiological effects of switching tasks

Cue-locked ERPs replicated previous findings (Karayanidis et al., 2003; Miniussi et al., 2005; Rushworth et al., 2002; 2005) and earlier experiments with switch trials showing a significantly larger positivity than repeat trials over 350-700 ms. This switch-related differential positivity was maximal over central and parietal sites and tended to be larger over the left hemisphere. This differential positivity is thought to reflect cognitive control processes involved in initiating task-set reconfiguration following presentation of the switch cue. These may include processes involved in inhibiting the task-set that has just been utilised and is now

irrelevant, as well as activating the alternative task-set that will be implemented following stimulus presentation. Stimulus-locked ERPs also demonstrated a familiar pattern with a parietally maximal differential negativity emerging for switch trials from around 200 ms after stimulus onset. This differential negativity has been previously interpreted as reflecting processes occurring after stimulus onset for switch trials, such as the resolution of response interference, and may be related to the 'residual' RT switch cost (Rogers & Monsell, 1995).

ICA was conducted on cue-locked ERPs to identify whether a unique component could be identified for switch as compared to repeat ERPs. However, this was clearly not the case. Three almost identical components were identified for both trial types over 700 ms following cue onset suggesting that switch and repeat trials have a similar underlying structure of ERP components. Components 2 and 3 appeared to map to early ERP components associated with perceptual processing of the cue and late components associated with anticipatory attention. The first component which accounted for the largest amount of variance emerged around 150 ms and was sustained across the entire processing interval of 700 ms. This component was strikingly similar for both trial types although there is some variation in the component scalp patterns, with a slightly more positive distribution parietally for switch trials. This component was consistent with the time course and scalp distribution of the differential positivity. These data therefore suggest that the differential positivity represents a component that is evident to some degree for both switch and repeat trials. This is consistent with previous fMRI studies that have not found any brain regions exclusively activated for switch trials, which suggests that many of the processes involved in task preparation are common to both switch and repeat trials (Brass & von Cramon, 2002; Braver, Reynolds, & Donaldson, 2003; Dove et al, 2000; Luks, Simpson, Feiwell, & Miller, 2002; Ruge et al., 2005).

These findings appear at first incompatible with the consistent finding of a switch-related differential positivity. However, closer inspection of Figure 7-2 reveals that the ICA results are not that surprising. Despite a significantly larger positivity for switch trials beginning as early as 300 ms after cue onset over central sites, the overall morphology and scalp distribution of repeat

and switch trials were very similar. Both trial types show a slow positive wave emerging at parietal electrodes around 150 ms, and the differential positivity appears to be a relative modulation of the late section of this broad positivity from 350 ms onwards. The first ICA component appears to capture this slow positive wave for both trial types (Figure 7-5). However, given that ICA was conducted separately on switch and repeat trials, the resulting components are unlikely to reflect ERP amplitude differences between switch and repeat trials. In summary, the ICA results suggest that the process of task-set reconfiguration is not necessarily exclusively activated on switch trials, but may occur on repeat trials as well. This is likely to occur on a certain proportion of repeat trials if the cues are ambiguous or difficult to interpret or if the participant has had a momentary lapse of concentration.

EEG topography analysis (LORETA) is better suited to capturing difference in amplitude between switch and repeat trials that presumably reflect difference in level of activation of underlying brain regions. This analysis was targeted at the two segments of the CSI that produced maximal differentiation between switch and repeat trials: 350-450 ms and 450-550 ms after cue onset (Figure 7-3). LORETA produced multiple areas of differential activation on switch as compared to repeat trials, with the pattern of differential activation varying across the two time intervals.

Over the early interval of the differential positivity (350-450 ms after cue onset), differential activation on switch as compared to repeat trials was evident in the prefrontal cortex, encompassing the inferior, middle and superior frontal gyrus, especially in the left hemisphere. Activation in the superior frontal gyrus was sustained over 450-550 ms, but had a more anterior focus. Increased activation for switch trials in prefrontal cortical areas is consistent with the view that task-set reconfiguration involves a cognitive control processes (Monsell, 2003; Rogers & Monsell, 1995). Despite limitations in spatial resolution (see below), these results are compatible with recent fMRI studies showing large prefrontal cortex activation for switch trials (e.g., Brass & von Cramon, 2002; 2004; Brass et al., 2003; Braver et al., 2003; Dreher et al., 2002; Sohn et al., 2000).

The early interval (350-450 ms) also showed a significant increase in activation for switch versus repeat trials in the superior temporal gyrus. The superior temporal gyrus is thought to be involved in semantic processing (e.g., Hart & Gordon, 1990; Hodges, Patterson, Oxbury & Funnell, 1992) and greater activation on switch trials may be related to cue verbalisation (i.e., participants process that a blue cue has been presented followed by verbalisation that blue equals switch to the 'odd or even' task, see Goschke, 2000 for role of verbalisation in task-switching).

LORETA analysis also revealed a parietal network of activation involved in anticipatory task-set reconfiguration. Over 350-450 ms after cue onset, there was significantly greater activation for switch versus repeat trials in the precuneus with the strength of this parietal activation increasing over 450-550 ms and extending more anteriorly as well as into the superior parietal lobule. This is consistent with many previous fMRI studies that have found increased parietal activation associated with a switch in task (Barber & Carter, 2005; Brass & von Cramon, 2004; Braver et al., 2003; Dove et al., 2000; Dreher & Grafman, 2003; Dreher et al., 2002; Erickson et al., 2006; Kimberg et al., 2000; Ruge et al., 2005; Rushworth, Paus & Sipila., 2001; Sohn et al., 2000). This parietal activation may reflect processes involved in the orienting and shifting of attention as well as the interpretation of stimulus features that may facilitate the application of stimulus-response mappings (e.g., odd = left hand response; even = right hand response; Brass & von Cramon, 2004; Barber & Carter, 2005).

These results complement fMRI findings by indicating the involvement of prefrontal and parietal networks in cognitive control. In addition, given that the LORETA findings reflect differential ERP activity associated with preparing for an impending switch trial and temporally restricted within the CSI, these findings provide evidence for differential activation of anticipatory task-set reconfiguration on switch trials. Changes in the pattern of activation across the two analysis windows suggest preparation for a switch in task recruits processes in the prefrontal cortex that may be related to identifying the broadly relevant task goals and that, in turn, signal posterior regions to implement more specific task goals, such as organisation of the

appropriate stimulus–response mappings required for the upcoming trial (e.g., Brass & von Cramon, 2002; Dreher & Grafman, 2003). Despite substantial differences in task-switching paradigm and pattern of ERP results, the conclusion that frontal and parietal networks follow a different timeframe and have a different role in cognitive control processes is highly compatible with that drawn in a recent ERP dipole analysis study by Brass, Ullsperger, Knoesche, von Cramon & Phillips (2005).

These findings, although highly consistent with fMRI evidence, are restricted by some limitations in methodology. LORETA analysis was conducted using the MNI 305 average brain rather than individual participant's structural MRIs and this may have resulted in more widespread activation within frontal and parietal areas. Furthermore, it has been suggested that LORETA may 'over-smooth' the data, resulting in blur across the two hemispheres or different lobes (Fuchs, Wagner, Kohler & Wischmann, 1999; Grave de Peralta & Gonzalez, 2000; Trujillo-Barreto, Aubert-Vazquez & Valdes-Sosa, 2004). These issues are likely to impact on the spatial resolution of the LORETA findings. Nevertheless, the differential yet consistent pattern of significant activations across the two time intervals suggests that areas within both frontal and parietal regions are selectively activated in preparation for a switch in task.

Future task-switching research would benefit from applying paradigms such as the one used here to maximise anticipatory task-set reconfiguration and combining behavioural, ERP, EEG topography and fMRI analyses to enable integration across a number of methodologies with the aim of identifying brain regions involved in task-set reconfiguration, both in anticipation of a switch in task and after stimulus onset. While the current findings indicate frontal and anterior network involvement in anticipatory task-set reconfiguration, different brain regions may be differentially activated for switch versus repeat trials after stimulus onset. For example, after stimulus onset, there may be greater activation in the posterior medial frontal cortex associated with monitoring performance outcomes, such as verifying that an error was not made (Ridderinkhof, Ullsperger, Crone & Nieuwenhuis, 2004; Ridderinkhof, van den Wildenberg, Segalowitz & Carter, 2004). The anterior cingulate cortex may also be activated

during the detection of response conflict, particularly when bivalent incongruent stimuli are presented (Badre & Wagner, 2004; Dreher & Berman, 2004; MacDonald, Cohen, Stenger & Carter, 2000). Detection of such conflict may then be followed by the initiation of inhibitory processes, which are associated with activation in the right inferior frontal cortex (Aron, Robbins & Poldrack, 2004; Aron, Monsell, Sahakian & Robbins, 2004). Further investigation of preparatory versus post-stimulus effects of task-switching may also help to clarify why some fMRI task-switching studies have not reported any brain regions differentially activated for switch compared to repeat trials (e.g., Brass & von Cramon, 2002; Braver, Reynolds, & Donaldson, 2003; Dove et al, 2000; Luks, Simpson, Feiwell, & Miller, 2002; Ruge et al., 2005).

Summary

The differential switch-related positivity occurring in anticipation of a switch in task was replicated again. This positivity has previously been suggested to reflect anticipatory task-set reconfiguration. ICA showed that the differential positivity cannot be attributed to a separate additional component occurring on switch trials only, as switch and repeat trials had an identical ERP component structure. LORETA analysis over the timeframe of the differential positivity identified greater activation for switch than repeat trials, first emerging largely in prefrontal cortex regions (350-450 ms post-cue) and later being most predominant in parietal regions (450-550 ms post-cue). These findings are consistent with the interpretation of the differential positivity as reflecting processes associated with anticipatory task-set reconfiguration. The findings are also consistent with fMRI studies implicating both frontal and parietal networks in anticipatory task-set reconfiguration processes.

8 Experiment 6: Example Clinical Applications[17]

The first five experiments reported in this thesis were conducted in a normative population in an attempt to fractionate the cognitive control processes involved in anticipatory task-set reconfiguration. In the current and final experiment, these findings are applied to demonstrate how task-switching paradigms can be used to enable further understanding of the deficits in cognitive control processes evident in clinical conditions such as schizophrenia. The complex pattern of behavioural and cognitive deficits observed in schizophrenia has been associated with disruption of a network of interconnected brain areas (e.g., Andreasen, Paradiso & O'Leary, 1998; Goldman-Rakic, 1994). One cortical region that has been consistently shown to be affected in schizophrenia is the prefrontal cortex. As previously discussed, this region plays a vital role in cognitive control processes, such as the setting of goals, planning, monitoring and modifying ongoing behaviour based on feedback and coordinating behaviour, particularly under novel situations (e.g., Stuss & Benson, 1986; Goldman-Rakic, 1987).

People with schizophrenia tend to perform poorly on neuropsychological tasks that tap into functions related to the prefrontal cortex, such as the WCST and the Trail Making task (e.g., Gold, Carpenter, Randolph, Goldberg & Weinberger, 1997, Goldberg & Weinberger, 1994), working memory tasks (Conklin et al., 2005) and the Tower of London task (e.g., Andreasen et al., 1992; Schall et al., 1998). Poor performance on such tasks has been associated with reduced or aberrant activation in prefrontal cortex networks in patients with schizophrenia (e.g., Andreasen et al. 1992; Liddle, Friston, Frith & Frackowiak, 1992; Perlstein, Carter, Noll & Cohen, 2005, Rasser et al., 2005). While these data strongly support the disruption of prefrontal cortex function in schizophrenia, they are limited in terms of their ability to define the nature of the underlying deficit(s).

---

[17] A portion of the behavioural data *only* from this experiment was reported as part of the Psychology Clinical Masters thesis by Lydia Meem (co-supervised by Frini Karayanidis and Ulrich Schall) in 2004 (titled 'task switching in schizophrenia: anticipatory and stimulus-driven components of task set reconfiguration processes associated with a predictable task switch', unpublished Masters thesis, the University of Newcastle, Australia). Published as Karayanidis, F., Nicholson, R., Schall, U., Meem, L., Fulham, R., & Michie, P. (in press). Switching between univalent task-sets in schizophrenia: ERP evidence of an anticipatory task-set reconfiguration deficit. *Clinical Neurophysiology*. See Appendix.

This is due to at least two limitations. Firstly, the tasks are very complex and successful performance depends on a number of different processes related to attention, memory and problem-solving (MacDonald & Carter, 2002). Secondly, despite being widely recognised as tests of prefrontal cortex function, there is evidence that damage in other cortical areas can also produce similar patterns of performance disruption (e.g., Anderson, Damasio, Jones & Tranel, 1991). In order to identify the processes that underlie cognitive decline in schizophrenia and how this relates to specific symptoms or symptom patterns, it is necessary to design tasks that tap into the cognitive processes that underlie performance on these complex neuropsychological tasks. Braver, Barch and Cohen (1999) classified cognitive decline in schizophrenia into four broad areas involving selective attention, maintenance and manipulation in working memory, context-specific use of cues in memory, and updating and switching internally represented information. They argue that these deficits may all result from disruption of a common mechanism that underlies cognitive control.

Although poor performance on many tasks that are associated with frontal cortex function is frequently attributed, at least partly, to deficits in set-shifting or task-switching (e.g., Braver et al., 1999), few studies have specifically examined task-switching performance in schizophrenia. Smith et al. (1998) developed a set of visual attention tasks to assess different types of attention using a common set of stimuli equated for discrimination difficulty. Selective attention performance was largely intact. The divided attention task and the attention switching task both required concurrently maintaining target pattern and target colour attributes in working memory. However, in the divided attention task, participants were instructed to respond to stimuli that matched the target for either pattern or colour, whereas on the attention switching task, they were instructed to alternate between responding to stimuli that matched the target for pattern and stimuli that matched the target for colour. The tasks were matched for difficulty in controls. Although there were no differences in RT or error rate between schizophrenia and control groups on the divided attention task, the schizophrenia group was both slower and less accurate than controls on the attention switching task.

These findings are unlikely to reflect a differential deficit in memory requirements, as both divided attention and attention switching tasks required maintaining colour and pattern target attributes in working memory. Likewise, both tasks involved similar sustained attention requirements and non-specific factors, such as fatigue or motivation. These tasks differed only in the requirement to update target attributes using internally driven cues so as to alternate between the two target attributes (e.g., 'now colour then pattern', rather than 'either colour or pattern'). The only other task to produce increased RT and reduced accuracy in schizophrenia compared to control groups involved alternating between different pattern targets and therefore also required updating target attributes throughout a block of trials. Therefore, these effects appear to reflect a specific deficit in the use of internally generated cues to track task context and update the active task-set in working memory so as to efficiently alternate between different attributes of the same target. Elliott, McKenna, Robbins and Sahakian (1998) showed that high functioning patients with schizophrenia exhibited more perseverative errors than learned irrelevance errors when shifting across distinct dimensions (extradimensional shift). These findings suggest that patients with schizophrenia show a greater difficulty in shifting away from the currently active attribute than shifting to a previously irrelevant attribute and fit well with the frequently reported increase in perseverative errors on WCST (e.g., Gold et al., 1997, Goldberg & Weinberger, 1994).

Meiran, Levine, Meiran and Henik (2000) examined task-switching in schizophrenia using the cued task-switching paradigm of Meiran (1996; 2000). In their first experiment, CSI was randomly varied across 132-3032 ms with a fixed RCI of 1532 ms. Both groups showed increased RT and error rate for switch compared to repeat trials and reduction in switch cost with increasing CSI. Overall, the schizophrenia group made more errors and were slower at responding than controls. Patients also showed larger RT switch cost than controls, and this difference was largest at the shortest CSI (132 ms). However, RT switch cost differences were eliminated when corrected for overall RT slowing (i.e., proportional switch cost), indicating that generalised response slowing in the schizophrenia group could account for increased RT switch

cost at all except the shortest CSI. In their second experiment, CSI was held constant at 132 ms and RSI was varied over 448-3148 ms, thus manipulating opportunity for passive interference processes while minimising any active preparation. Patients showed overall slower RT as well as larger RT switch cost that could not be accounted by a generalised RT slowing. Surprisingly, patients, but not controls, showed a reduction in RT switch cost with increasing RSI.

These results suggest that, when controlling for generalised response slowing, schizophrenia patients can actively reconfigure stimulus-response mappings as well as control participants, but show increased passive interference from the previously active stimulus-response mapping, at least on unprepared trials (i.e., short CSI). However, the finding of reduced RT switch cost with increasing RSI in patients but not in controls seems to suggest that patients can more effectively use the RSI to disengage from the previously active stimulus-response mapping. These findings of intact anticipatory activation and more efficient stimulus-response mapping disengagement appear incompatible with previous reports of perseveration, even on un-timed tasks such as WCST. Meiran et al. argue that their findings do not support a switch-specific deficit in schizophrenia but are compatible with impairment in working memory such that patients are more likely to forget task context on a trial-by-trial basis (e.g., Cohen et al., 1999). Note, however that the schizophrenia group consisted of long-term in-patients and over 30% of the 40 patients initially judged capable of completing the task did not do so.

Meiran, Levine, Meiran and Henik's (2000) cued-switching paradigm involves trial-by-trial external cueing. Brown and Marsden (1988) suggest that different processes underlie performance of tasks requiring switching under internal versus external cueing. External cueing requires less internal monitoring of task contingencies and therefore less reliance on cognitive control processes. Using a cued serial RT paradigm, Williams et al. (2000) found larger schizophrenia deficits in movement initiation time in no cue compared to cued conditions, suggesting a specific difficulty in the use of internally generated cues. A differential task-switching deficit in schizophrenia compared to controls may be more likely to emerge in tasks that rely more on internal cueing. Cools, Brouwer, De Jong and Slooff (2000) used an

alternating runs paradigm that relies more heavily on internal cueing, as the active task alternates in a predictable sequence and also found that patients with schizophrenia did not show a switch-specific deficit. However, patients had a high error rate on both switch and repeat trials and did not show the typical delay in RT. Like Meiran, Levine, Meiran and Henik (2000), this experiment used bivalent stimulus sets, so each trial contained elements that were mapped to a response on both tasks. Cools et al. suggest that patients may have been distracted by the presence of the irrelevant stimulus dimension and have applied the same task-set on all trials regardless of whether it was relevant or irrelevant.

In summary, there appear to be substantial discrepancies between the relatively few studies that have attempted to identify whether schizophrenia is associated with a deficit in switching attention between different target attributes or task-sets. Tasks that depend on the use of feedback or internal cueing to update task-set and alternate between target attributes have generally resulted in significantly poorer performance in schizophrenia relative to controls (e.g., Smith et al., 1998; Elliott et al., 1998, but see Cools et al., 2000). Within recent theoretical models of task-switching, these findings would be consistent with a deficit in anticipatory task-set reconfiguration. However, using an explicit task-cueing paradigm, Meiran, Levine, Meiran and Henik (2000) found no evidence for less reduction in corrected RT switch cost with increasing CSI in patients as compared to control. Similarly, using cued switching between prosaccade and antisaccade tasks, Manoach et al. (2002) found that schizophrenia patients did not differ from controls in task-switching performance despite significantly poorer inhibition on the antisaccade task. Differences between the tasks in stimulus complexity, type of cueing, preparation interval and patient parameters may account for these discrepancies. In addition, RT and error measures provide a window only at the end-point of processing and appear, at least in this case, to be unable to differentiate between different processes that lead up to the response.

The present experiment examined anticipatory, stimulus-driven and response-related contributions to task-switching performance in schizophrenia using behavioural and ERP measures. The alternating runs paradigm with a predictable AABB task sequence was used

(Rogers & Monsell, 1995; Karayanidis et al., 2003) rather than the explicit cueing paradigms used in experiments 1-5 to specifically investigate the effects of internally generated cues in schizophrenia (see below). Distinct non-overlapping stimulus sets were defined for each task and, on each trial, an exemplar of only one of the two stimulus sets was presented (univalent task-sets). In addition, each task was mapped to distinct spatial positions. Thus, on any given trial, after stimulus onset there was no ambiguity about which task was relevant. RSI was manipulated across 150-1200 ms in different blocks to examine the activation of anticipatory task-set reconfiguration. There was no external cueing with regard to either the position of the next stimulus or the task that would be relevant on the next trial during the interval between a response to one trial and the onset of the next stimulus.

Therefore, given the predictable and alternating task sequence, any differential processing in anticipation of switch or repeat trials within the RSI can only result from internal cueing about the identity of the next trial. The schizophrenia group included high functioning people with a lifetime diagnosis of schizophrenia who were on long-term medication and were living in the community independently or with minimal assistance. It was predicted that if schizophrenia involves a deficit in updating and switching internally represented information, patients will show larger RT switch cost than controls across all RSIs. Further, a deficit specifically related to the activation of task-set reconfiguration in anticipation of a switch trial or to the maintenance of context-specific information in working memory will be indicated by a slower decline in RT switch cost with increasing RSI in the schizophrenia as compared to the control group.

ERPs allow greater precision in the timing of any processing deficits. Therefore, if schizophrenia is associated with deficits in internally generated cueing and in preparation for an impending switch trial, patients will show reduced switch-related positivity especially at longer RSI. On the other hand, if deficits are related to differential processing of switch and repeat stimuli or external task-cueing, then ERP differences between patients and controls will be identified after stimulus onset at all RSIs. Finally, if deficits occur primarily because of

response selection or response activation, then group differences will emerge in stimulus-locked or response-locked LRP waveforms.

8.1 Method

Participants

Twenty-eight members of the Australian Neuroscience Institute of Schizophrenia and Allied Disorders Research Register responded to a letter of invitation to participate in the experiment. Six individuals were excluded because they met diagnostic criteria for schizoaffective disorder, affective disorders, substance abuse or neurological conditions. Three individuals withdrew after the practice session. The remaining 19 people with schizophrenia (Table 8-1) were clinically assessed using the Diagnostic Interview for Psychoses (Jablensky et al., 1999) based on the Operational Criteria diagnostic system (OPCRIT, McGuffi et al., 1991) by a psychiatrist and an intern psychologist. Current symptoms of schizophrenia were assessed using the Schedule for the Assessment of Negative Symptoms (SANS) (Andreasen, 1984a) and the Schedule for the Assessment of Positive Symptoms (SAPS) (Andreasen, 1984b). All patients were currently on antipsychotic medication (Table 8-1). Controls were recruited through posters on community notice boards. Twenty-two volunteers were selected following an initial screening interview to exclude a diagnosis of schizophrenia or mood disorders, or a family history of schizophrenia (Table 8-1). One control subject withdrew after the practice session. In order to eliminate differences between groups in gender, age and estimated IQ, two female control participants were excluded. This resulted in two groups that did not differ significantly for age, years of education, premorbid Full-Scale IQ or verbal ability estimated using the National Adult Reading Test (NART; Nelson, 1982), handedness (Edinburgh Handedness Inventory; Oldfield, 1971) or gender ratio.

Table 8-1

Demographic data, IQ estimates, symptom ratings and medication. Standard deviation in parentheses. Note that some patients were on more than one type of medication.

	Schizophrenia Group	Control Group
n	19 (10 men)	19 (10 men)
Age	43.05 *(12.9)*	39.95 *(13.2)*
Years of education	12.53 *(3.3)*	12.05 *(2.5)*
NART Full Scale IQ	99.7 *(12.7)*	105.3 *(9.75)*
NART Verbal IQ	98.74 *(11.8)*	103.95 *(9.0)*
Right/Mixed Hand Dominance	14/4	18/1
Age at Illness Onset	23.1 years	
Duration of Illness	20.2 years	
Diagnosis		
ICD-10: paranoid schizophrenia; DSM-III-R: schizophrenia:	n = 14	
ICD-10: undifferentiated schizophrenia; DSM-III-R: schizophrenia:	n = 3	
ICD-10: paranoid schizophrenia; DSM-III-R: atypical psychosis:	n = 2	
SAPS		
Hallucinations	1.79 *(1.93)*	
Delusions	2.42 *(1.68)*	
Bizarre Behaviour	0.63 *(1.30)*	
Thought Disorder	0.89 *(1.20)*	
SANS		
Affect	1.79 *(1.27)*	
Alogia	0.68 *(0.88)*	
Avolition	2.26 *(1.41)*	
Anhedonia	2.74 *(1.37)*	
Attention	1.42 *(1.46)*	
Medication		
Atypical antipsychotics		
Olanzapine	7	
Risperidone	5	
Quetiapine	3	
Clozapine	1	
Standard antipsychotics		
Depot injections	4	
Chlorpromazine	1	
Antidepressants	6	
Mood stabilisers	2	
Sleeping tablets	2	

Stimuli and Tasks

Two univalent stimulus sets were developed by Karayanidis, Jenkins and Fox (2001) for testing with young children and consisted of 16 stimuli (Figure 8-1). The picture task included line drawings of four animals and four plants drawn in black on a white background. The line task included line drawings with either straight lines or curved lines drawn in white on a purple background. On each trial, a single exemplar from the relevant task was displayed in one of four boxes of a 2x2 matrix that was continuously displayed on the screen. Two adjoining boxes were assigned to each task. For half the participants, the two upper boxes were assigned to the picture task and the two lower boxes were assigned to the line task. For the remaining participants, the two boxes on the right were assigned to the picture task and the two boxes on the left were assigned to the line task. This ensured that, for half the participants, switch trials occurred on a vertical eye shift, whereas for the other half, switch trials occurred on a horizontal eye shift. As the display proceeded in a predictable clockwise manner, the position of the current stimulus provided a valid cue as to the task active on the current trial as well as a valid task cue for the next trial (Figure 8-1). The task changed predictably every second trial (Task AABB).
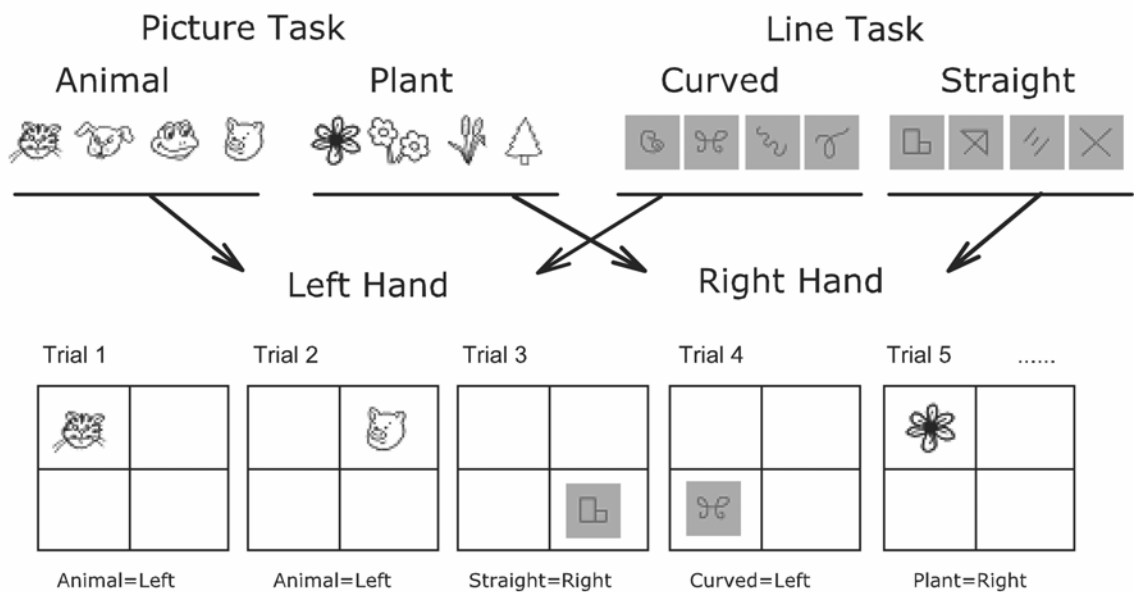

Figure 8-1. Top: Task-sets used for Picture and Line tasks are shown with an example of one of the stimulus-response mapping conditions. Bottom: A sequence of five trials of the alternating runs paradigm are depicted.

On the picture task, participants responded whether the picture was an animal or a plant using their left or right index finger. On the line task, participants classified the line(s) as straight or curved using the same response buttons. One button was mapped to animal and straight decisions and the other button to plant and curved decisions (Figure 8-1). Each incorrect response was followed by immediate auditory feedback and the subsequent stimulus was delayed by 1500 ms. After each run (100 trials per run), performance feedback was given, including mean RT and number of errors.

Procedure

Participants attended two sessions scheduled about one week apart. The first session included clinical assessments, psychometric tests and the first training session. The first training session consisted of training on each task alone (one run per task, 100 trials per run), followed by four runs of task-switching, one at each at RSI (150, 300, 600, and 1200 ms). Although a specific performance criterion was not used, all participants completed first day training performing well above chance level and showed clear understanding of task requirements. The second training session consisted of one run of each task alone and one run of task-switching (600 ms RSI). Stimulus-response and response-hand mappings were continuously displayed during training, but were removed during testing. Behavioural and ERP data were collected over three consecutive runs at each of the four RSI values (150, 300, 600, 1200 ms). The order of RSI presentation was counterbalanced across subjects using a Latin-square design. Participants were instructed to respond as quickly as possible while maintaining a high level of accuracy. Prior to each RSI block, participants were informed whether the stimuli would be presented slowly (RSIs of 600 ms or 1200 ms) or quickly (RSIs of 150 ms or 300 ms) and were encouraged to use the RSI to prepare for the next trial. They were also encouraged to use performance feedback at the end of each run to improve their performance. At the beginning of testing and between each run, participants were shown a grid of twelve coloured blocks representing the twelve runs. At the end of each run, a block was removed to reveal a simple

motivational cartoon (i.e., a stick man jumping for joy with the caption "one run to go!"). This was used to help participants track their progress through the twelve runs.

Behavioural Data Analysis

The first four trials of each run, trials associated with an incorrect response or following an incorrect response, and trials associated with a response outside a 200-2000 ms time window were excluded from behavioural and ERP analyses. RT and arc-sine transformed proportion error data were analysed using Group (schizophrenia, control) and three within subjects factors: Task (picture, line), Trial Type (switch, repeat), and RSI (150, 300, 600, 1200 ms). Significant RSI main effects and interactions were broken down using simple contrasts between successive RSIs. Significant interactions between Group and Type were examined using simple effects for group and type. Group differences in residual switch cost were examined with a Group by Task by Trial Type ANOVA at the 1200 ms RSI.

EEG Recording and Analysis

EEG was recorded from 12 scalp electrodes according to the 10/20 system using an electrode cap (Electro-cap International) as well as electrodes attached to the left and right mastoids. All channels were recorded to a nose reference and were re-referenced offline to the average of the left and right mastoids. EEG and EOG were continuously sampled at 500Hz/channel using NeuroScan Synamps 1 (x 20000) with a bandpass of 0.01-30 Hz (-6 dB down). Response-locked and stimulus-locked ERP epochs (1400 ms around response/stimulus onset; 200 ms pre-onset interval) were averaged separately for switch and repeat trials, resulting in 8 response-locked and 8 stimulus-locked ERP average waveforms (4 conditions by 2 trial type) for each participant at each site. Response-locked epochs within each condition were averaged separately depending on whether the following stimulus (i.e., trial *n+1*) would require a switch or repeat trial. Baseline was corrected over -50 to 50 ms to avoid effects of large pre-baseline shifts in some conditions, especially when anticipation of stimulus onset produced CNV build-up. For both response- and stimulus-locked waveforms, mean amplitude was measured at the four midline sites using 50 ms windows over 50-700 ms after response or

stimulus, respectively (i.e., 13 by 50 ms windows). When effects were significant across a number of consecutive time windows, statistical results are reported as the range of F values within that time range. Interactions between site and other factors are only reported if they remained significant after rescaling (McCarthy & Wood, 1985).

Response-locked ERPs: Given that these waveforms were quite broad with effects mainly focussed on trial type, analyses targeted switch and repeat differences. Switch minus repeat difference waveforms were created at each midline site for each RSI condition and were compared to baseline using point by point t-tests over 50-700 ms to establish areas of significant deviation between switch and repeat waveforms. In addition, difference waveforms for patients and controls were compared using point-by-point t-tests over 50-700 ms to establish points of significant deviation[18]. The Guthrie and Buchwald (1991) procedure was used to control Type 1 error at α= 0.05 using an autocorrelation coefficient of 0.9.

Stimulus-locked ERPs: Stimulus-locked ERPs showed a more complex pattern of early and late ERP components. Due to substantial variability between conditions and, for the schizophrenia group, reduced amplitude of most components, peak amplitude or latency measures of ERP components resulted in missing values for many cases (with the exception of LPC measures in controls, see Results below). Further, given the close temporal proximity of response and stimulus onset for RSI-150, there was considerable overlap between response- and stimulus-locked waveforms and the shift in baseline had little effect on the difference between switch and repeat trial ERPs and therefore, this condition was not included in the stimulus-locked ERP analysis. In order to target group differences in stimulus-triggered ERP components as well as in switch-related processing, stimulus-locked ERPs were analysed using 50 ms mean amplitude over 50-700 ms using a (3 RSI by 2 trial type by 4 midline sites) ANOVA[19]. Despite overall similarities in morphology, stimulus-locked ERP components were considerably

---

[18] Mean amplitude was also analysed in 50 ms windows spanning over 50-700 ms using a 2 group by (4 RSI by 2 trial type by 4 sites) ANOVA. This analysis produced a set of results that was highly compatible with the difference waveform analyses reported here, but were more complicated in presentation.

[19] Analyses were re-run including RSI-150 in the RSI factor. Results were overall identical, but produced additional interactions with RSI reflecting differences in overall morphology and trial type effects between RSI-150 and the other three levels.

affected by group. To examine the effects of RSI and trial type on stimulus-locked ERP components in this modified version of the alternating runs paradigm, the control group data was first analysed alone using a (3 RSI by 2 trial type by 4 sites) ANOVA. Group differences were then examined in baseline performance by comparing control and schizophrenia groups on repeat waveforms alone (Group by 3 RSI by 4 sites). Finally, differential effects of trial type in control and schizophrenia groups were identified by focusing on group by trial type interactions in a 2 Group by (3 RSI by 2 trial type by 4 sites). Stimulus-locked difference waveforms were derived and analysed as defined above for response-locked difference waveforms.

LRP waveforms

C4-C3 difference waveforms were extracted for left hand responses and C3-C4 difference waveforms were extracted for right hand responses for each condition, trial type and participant. These difference files were then averaged to derive LRP waveforms (Coles, 1989). Stimulus-locked LRPs were derived using a 900 ms epoch with -200 ms pre-stimulus baseline. Response-locked LRPs were derived over a 900 ms epoch with a -700 to -500 ms baseline and a 200 ms post-response interval. Peak amplitude, peak latency and onset latency of the LRP were measured after smoothing waveforms using a 50 point moving average. LRP onset latency was measured as the latency at which 25% of peak amplitude was achieved[20]. For each measure, an individual participant's measure was excluded from analysis if it resulted in outliers across the majority of conditions. This resulted in one patient's data being excluded from peak amplitude analyses and one control's data being excluded from stimulus-locked LRP onset analyses. Peak amplitude, peak latency and onset latency for stimulus-locked LRP and response-locked LRP were analysed separately using a 2 group by (4 RSI by 4 trial type) ANOVA.

---

[20] LRP onset latency was compared using three methods: segmented regression method with one and four degrees of freedom and quarter peak latency (QPL; Mordkoff & Gianaros, 2000). For stimulus-locked LRP onset, all three measures produced identical outcomes, but QPL resulted in larger effect sizes and is reported here. Response-locked LRP onset could be reliably measured across all 8 waveforms in only 9 patients using 1df and 4 patients using 4df, but 15 patients using QPL, so this is reported here.

8.2   Results

Behavioural Data

Figure 8-2 shows proportion error and mean RT for the picture and line tasks separately. Error rate was very low, ranging between 1 and 4%. The significant main effect of RSI $(F_{(3,108)}=4.78,\ p<.01)$ reflected a small decline in proportion error from 600 to 1200 ms $(F_{(1,36)}=17.36,\ p<.001)$. The picture task produced marginally more errors than the line task $(F_{(1,36)}=4.47,\ p<.05)$ and switch trials resulted in more errors than repeat trials $(F_{(1,36)}=10.20,\ p<.005)$. Overall error rate did not differ between the two groups. The interaction between group, task and trial type was significant $(F_{(1,36)}=4.21,\ p<.05)$. As shown in Figure 8-3, the control group showed no cost of switching in the line task, but an increase in error rate for switch compared to repeat trials in the picture task (task by trial type interaction, $F_{(1,36)}=5.40$, $p<.05$). Error rate in the schizophrenia group was not differentially affected by task. Neither the schizophrenia nor the control group had any residual error switch cost at the 1200 ms RSI.
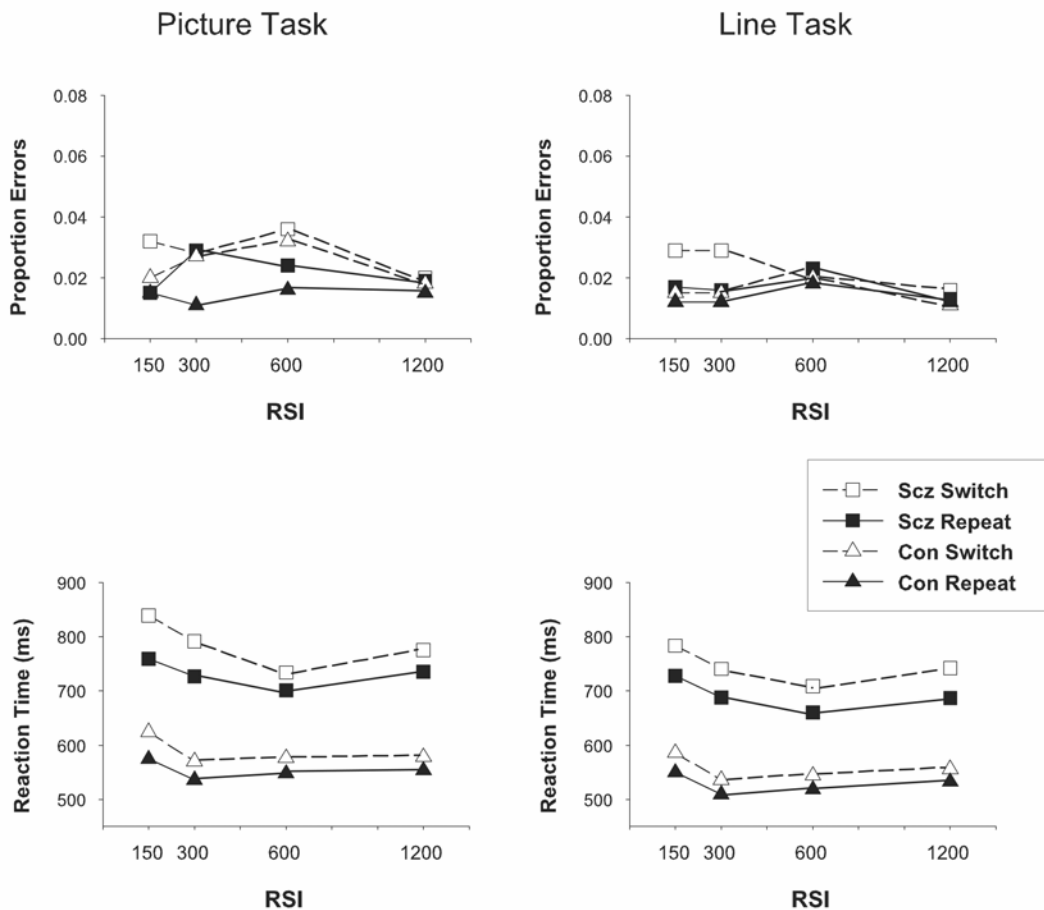

Figure 8-2. Proportion errors (top) and RT (bottom) for Picture and Line tasks.

Both groups responded more slowly to switch trials than repeat trials ($F_{(1,36)}=75.15$, $p<.001$), and to the picture task than the line task ($F_{(1,36)}=90.20$, $p<.001$). The significant effect of RSI ($F_{(3,108)}=14.49$, $p<.001$) reflected a reduction in RT (43 ms) as RSI increased from 150 ms to 300 ms ($F_{(1,36)}=31.42$, $p<.001$), and an *increase* in RT (21 ms) as RSI increased from 600 ms to 1200 ms ($F_{(1,36)}=8.23$, $p<.01$). Significant interactions were obtained between RSI and trial type ($F_{(3,108)}=8.73$, $p<.001$) and between RSI, trial type and task ($F_{(3,108)}=4.67$, $p<.005$). The interaction between RSI and trial type was significant for the picture task ($F_{(3,108)}=11.91$, $p<.001$), but not the line task ($F<1$). For the picture task, RT switch cost declined as RSI increased from 150 to 300 ms ($F_{(1,36)}=5.57$, $p<.05$) and from 300 to 600 ms ($F_{(1,36)}=8.53$, $p<.01$), with no further reduction at 1200 ms, whereas RT switch cost remained unaffected by RSI for the line task (Figure 8-3).

The schizophrenia group was approximately 180 ms slower in responding than controls ($F_{(1,36)}=21.06$, $p<.001$; Figure 8-2). RT switch cost was also larger for the schizophrenia than the control group (group by trial type interaction, $F_{(1,36)}=5.28$, $p<.05$), but there was no three-way interaction between group, trial type and RSI or between group, trial type and task (both $F<1$). This effect was not significant when analysing proportional switch cost scores[21] to correct for overall group differences in RT ($F_{(1,36)}=1.59$, $p=.215$). At the longest RSI, the main effect of trial type was significant, indicating a significant residual switch cost ($F_{(1,36)}=48.54$, $p<.001$). The interaction between trial type and group was significant at this RSI ($F_{(1,36)}=5.17$, $p<.05$) suggesting that the residual switch cost was larger for the schizophrenia group. However, once again, the effect was not significant when analysing proportional switch cost ($F_{(1,36)}=2.1$, $p=.154$). Analysis of RT switch cost using a 4 RSI by 2 Task ANCOVA with one SAPS/SANS global symptom rating at a time as covariate, indicated that symptom ratings did not systematically affect RT switch cost variance.

---

[21] Proportional switch cost was calculated by dividing switch cost by mean RT for repeat trials. An ANCOVA on switch cost using mean RT as a co-variate also showed that mean repeat RT could fully account for RT switch cost group differences.
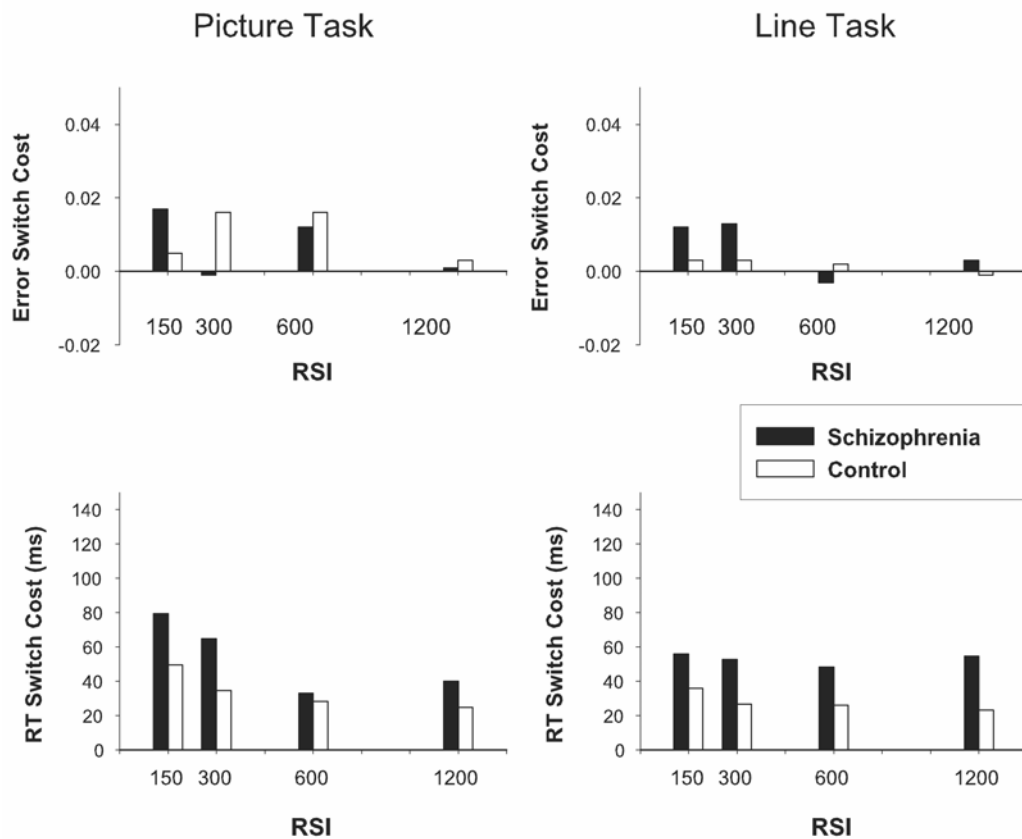
Figure 8-3. Error (top) and RT (bottom) switch cost for Picture and Line tasks.

Response-locked ERPs

Response-locked waveforms for control and schizophrenia groups are shown in Figure 8-4. All conditions showed a large positive dip associated with response onset, followed by a post-response negative shift that was larger centroparietally, peaking around 200 ms post-response. After 200 ms, the morphology of the response-locked ERPs varied depending on RSI length. At the two shorter RSI conditions, the negativity was replaced by ERPs associated with stimulus processing, including occipital P1, N1 and frontal P2, N2 components. At RSI-600, a sustained negativity remained until stimulus onset, whereas at RSI-1200, the waveforms returned to baseline by 400 ms post-response. The morphology of response-locked ERPs was broadly similar in schizophrenia and control groups at the long RSI conditions.

Response-locked: Control

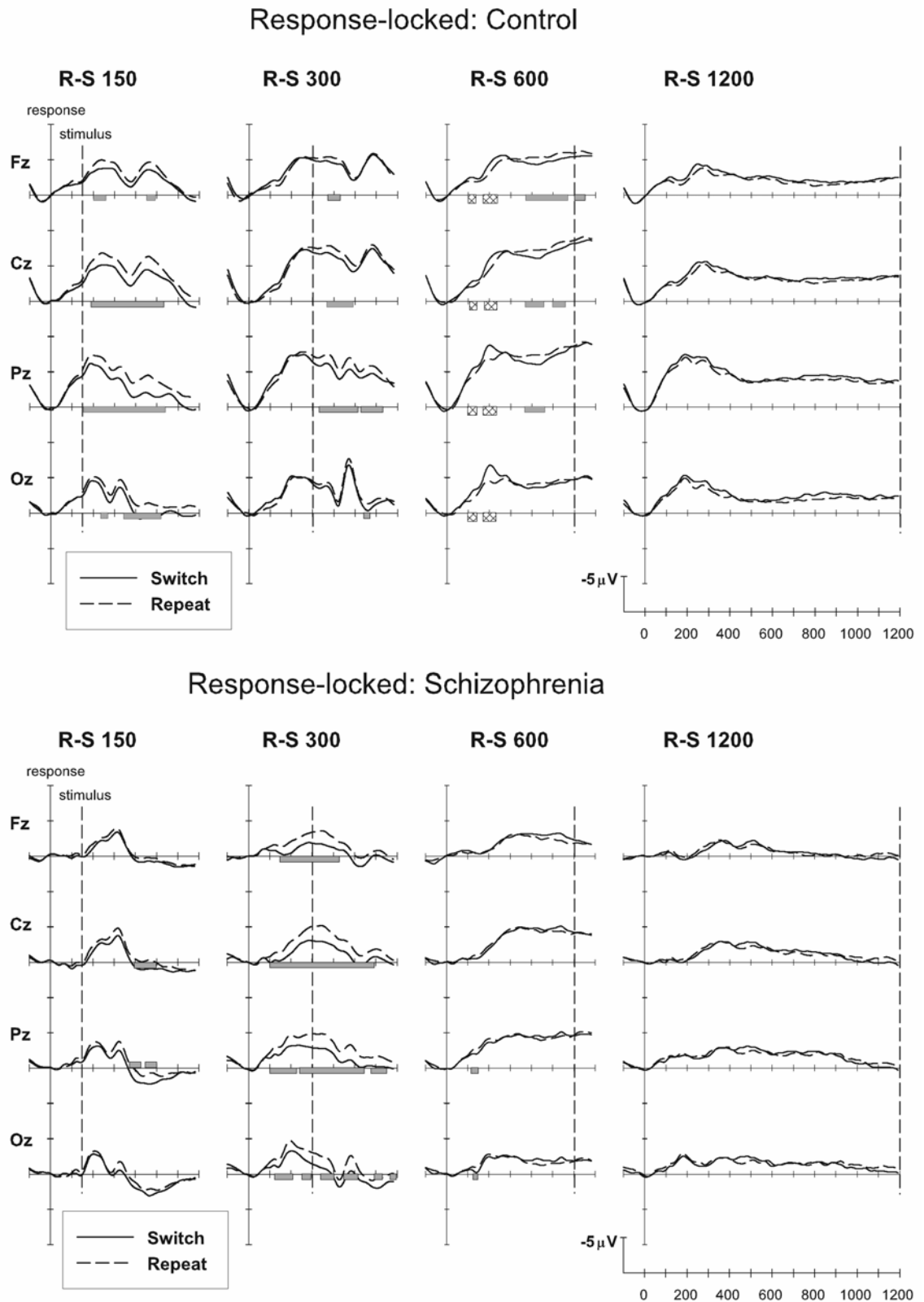## Response-locked: Schizophrenia

Figure 8-4. Response-locked ERP waveforms at midline electrodes for each RSI in control (top) and schizophrenia (bottom) groups. Broken line represents stimulus onset. The averaging epoch is prolonged for RSI-1200 to depict the entire RSI.

A number of differences were evident between response-locked waveforms in anticipation of a switch or a repeat trial (Figure 8-4) and these are highlighted in the difference waveforms in Figure 8-5. Figure 8-4 also shows areas of significant deviation from baseline (for detailed results of point by point analyses see Table 8-2) and Figure 8-5 shows areas of significant deviation between the difference waveforms for control and schizophrenia groups (see Table 8-3, top). The control group (Figure 8-4, top) showed a significant positive shift in the switch waveform emerging as early as 150 ms parietally at the shortest RSI condition but after 300 ms for RSI-300 and RSI-600 conditions. No switch-related differential positivity was evident for the longest RSI condition. The differential positivity was more pronounced centroparietally, except for the RSI-600 conditions, where it showed a more frontal distribution. Interestingly, in the latter condition, the differential positivity was preceded by a negative shift for the switch relative to the repeat waveform, extending from approximately 100 ms to 230 ms.
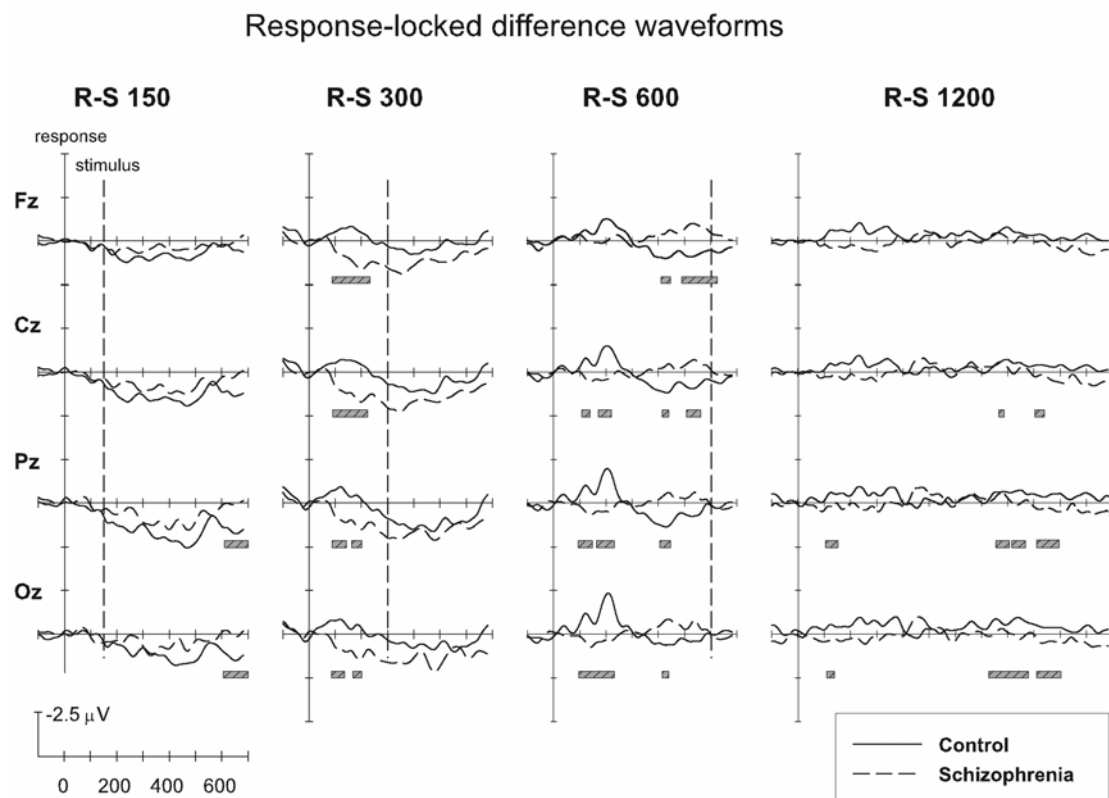

Figure 8-5. Response-locked difference ERP waveforms at midline electrodes for each RSI superimposed for control and schizophrenia groups. Broken line represents stimulus onset. The averaging epoch is prolonged for RSI-1200 to depict the entire RSI. Bars represent areas of significant deviation between difference waveforms for control and schizophrenia groups.

In the schizophrenia group (Figure 8-4, bottom), the positive shift in the switch relative the repeat waveform is not significant for RSI-150 until after 350 ms, whereas for RSI-300 it emerges as early as 100 ms. Again this positive shift is more prominent parietally. However, the schizophrenia group showed no significant difference between switch and repeat waveforms for RSI-600 or RSI-1200 (with the exception of a marginal posterior effect over 116-148 ms in RSI-600). As shown in Figure 8-5, the response-locked difference waveforms did not differ significantly between the two groups at RSI-150, with the exception of a prolonged differential positivity for the control group over 600-700 ms, which extends 450 ms into the stimulus processing window. For RSI-300 and RSI-600, significant differences over 90-120 ms reflect the early onset of the differential positivity in the former interval for the schizophrenia group and the relative differential negativity that is more pronounced in the latter interval for controls.

Table 8-2

Areas of significant deviation of response-locked difference waveforms from baseline for control and schizophrenia groups (standard font: positive shift; italics: negative shift).

|	**RSI-150**	**RSI-300**	**RSI-600**	**RSI-1200**
	Control Group			
Fz	204-262 454-492	372-424	*102-138* *174-238* 372-574 600-650	-
Cz	188-530	364-496	*106-142* *174-234* 368-456 496-558	-
Pz	154-540	328-514 524-630	*98-140* *170-234* 368-460	-
Oz	236-268 342-520	540-570	*98-148* *168-238*	-
	Schizophrenia Group			
Fz	-	144-426	-	-
Cz	386-494	100-582	-	-
Pz	374-424 442-500	100-224 240-544 578-654	116-148	-
Oz	-	122-206 250-292 338-400 446-514 584-628 664-696	122-146	-

A negativity build up before stimulus onset emerged for both trials types (Figure 8-4) and was measured using two 50 ms mean amplitude windows before stimulus onset (-100 ms to -50 ms and -50 ms to stimulus onset). Analyses were run using a 2 Group by (3 RSI by 2 Trial Type by 4 Site). The RSI-150 condition was excluded from these analyses because of the close temporal proximity between response and stimulus onset. The main effect of group was significant for both intervals ($F(1,35)=11.22$, $p<.005$ & $F(1,35)=12.77$, $p<.001$, respectively) indicating that this pre-stimulus negativity was larger for the control group across all RSI conditions (approximately $-5.1\mu V$ versus $-2.1\mu V$). Significant main effects of RSI, site and interactions between RSI and site (RSI: $F(2,70)=15.26$, $p<.001$; $F(2,70)=16.7$, $p<.001$; Site: $F(3,105)=15.91$, $p<.001$; $F(3,105)=19.39$, $p<.001$; RSI by Site: $F(6,210)=8.65$, $p<.001$; $F(6,210)=8.97$, $p<.001$) indicated that the negativity was smaller for RSI-1200 compared to the other two timing conditions (approximately $-1.6\mu V$ versus $-4.6\mu V$), with the condition effect being more pronounced centroparietally.

In summary, both groups showed a significant switch-related differential positivity for RSI-150 and RSI-300 conditions that emerged around 100-150 ms and peaked around 400 ms. In the control group, this positivity was also evident at RSI-600, where it was preceded by a switch-related negativity, but not at RSI-1200. The schizophrenia group showed no differentiation between switch and repeat trials at either RSI-600 or RSI-1200. A large pre-stimulus negativity developed for all groups and was larger for RSI-300 and RSI-600 than RSI-1200, but was significantly smaller for the schizophrenia group at all three timing conditions.

Stimulus-locked ERPs

Stimulus-locked ERPs for control and schizophrenia groups are shown for all four RSI conditions in Figure 8-6. Note that only the three longer RSI conditions were included in statistical analyses (see method).

Stimulus-locked: Control
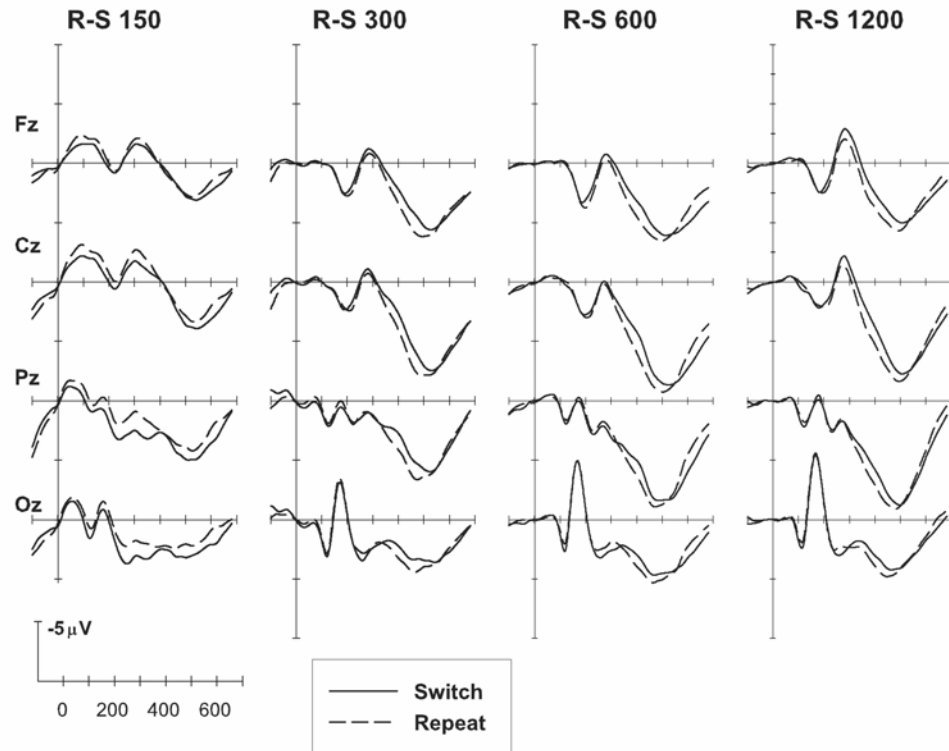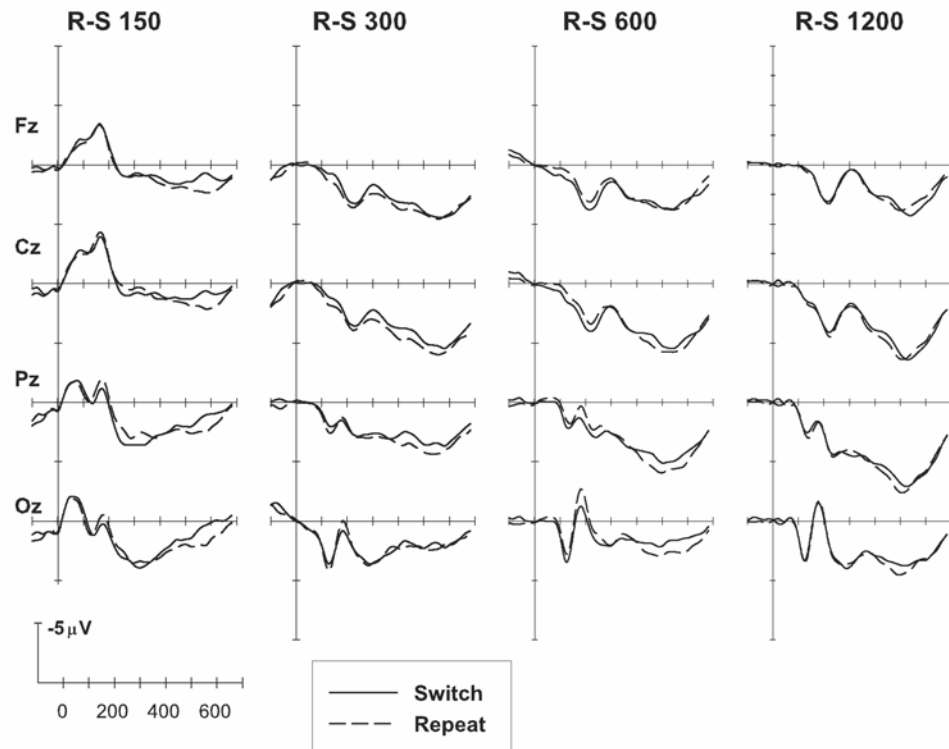

Stimulus-locked: Schizophrenia

Figure 8-6. Stimulus-locked ERP waveforms at midline electrodes for each RSI in control (top) and schizophrenia (bottom) groups. Note: similarity between response-locked (Figure 8-4) and stimulus-locked waveforms for RSI-150 results from considerable temporal overlap due to short RSI.

Control group: The three longer RSI conditions show a clear pattern of early posterior P1 and N1 components that were largest at Oz (site: 50-100 ms $F_{(3,54)}=9.1$, p<.001 and 150-200 ms, $F_{(3,54)}=66.6$, p<.001; Figure 8-6, top). Occipitally, P1 amplitude reduced and N1 amplitude increased as RSI increased from 300 to 1200 ms (RSI by site: 100-200 ms, $F_{(6,108)}=3.9-4.5$, p<.05). These early components were followed by an anterior N2 over 250-300 ms that was largest frontocentrally (site: $F_{(3,54)}=11.8$, p<.001) and for the longest RSI condition (RSI by site: $F_{(6,108)}=6.0$, p<.005). Finally, a large centroparietally maximal LPC emerged in all three long RSI conditions between 300 and 700 ms (site: 300-700 ms, $F_{(3,54)}=3.7-41.0$, p<.05) and was differentially affected by RSI across midline sites (RSI by site: 300-600 ms, $F_{(6,108)}=4.6-7.9$, p<.01). Parietally, LPC amplitude increased as RSI increased from 300 to 600 ms and remained stable thereafter (300-700 ms, $F_{(2,36)}=4.8-13.2$, p<.05; Figure 8-6, top). Trial type differences emerged at 200 ms (type by site: 200-400 ms, $F_{(3,54)}=3.9-13.1$, p<.05; type: 350-500 ms, $F_{(1,18)}=11.78-17.18$, p<.005). Differences between switch and repeat trials emerged earliest at Fz (200-500 ms, $F_{(1,18)}=11.8-17.2$, p<.05) followed by Cz (300-500 ms, $F_{(1,18)}=5.2-16.3$, p<.05) and then Pz and Oz (350-500 ms, Pz: $F_{(1,18)}=10.0-14.4$, p<.005; Oz: $F_{(1,18)}=7.0-11.7$, p<.05) and reflected a negative shift in the switch compared to the repeat waveform. Frontally, this switch-related negativity first emerged over the P2-N2 transition and continued across the ascending arm of the LPC across all midline sites. This was followed by a reversal of switch and repeat waveforms over 600-700 ms as the LPC resolved later for switch trials (type: $F_{(1,18)}=4.78-8.30$, p<.05). There was no interaction between trial type and RSI across the three longer RSI conditions. LPC peak amplitude and latency was analysed across Fz, Cz and Pz[22]. Switch trials were associated with a small reduction in LPC peak amplitude (8.8 to 8.3μV, $F_{(1,16)}=4.03$, p=.062) and a significant increase in LPC peak latency (490 to 513 ms; $F_{(1,16)}=27.06$, p<.001). The switch-repeat difference waveforms (Figure 8-7) for controls (solid lines) show the broad differential negativity emerging first frontally around 200 ms and extending to approximately 500 ms for the longer RSI conditions.

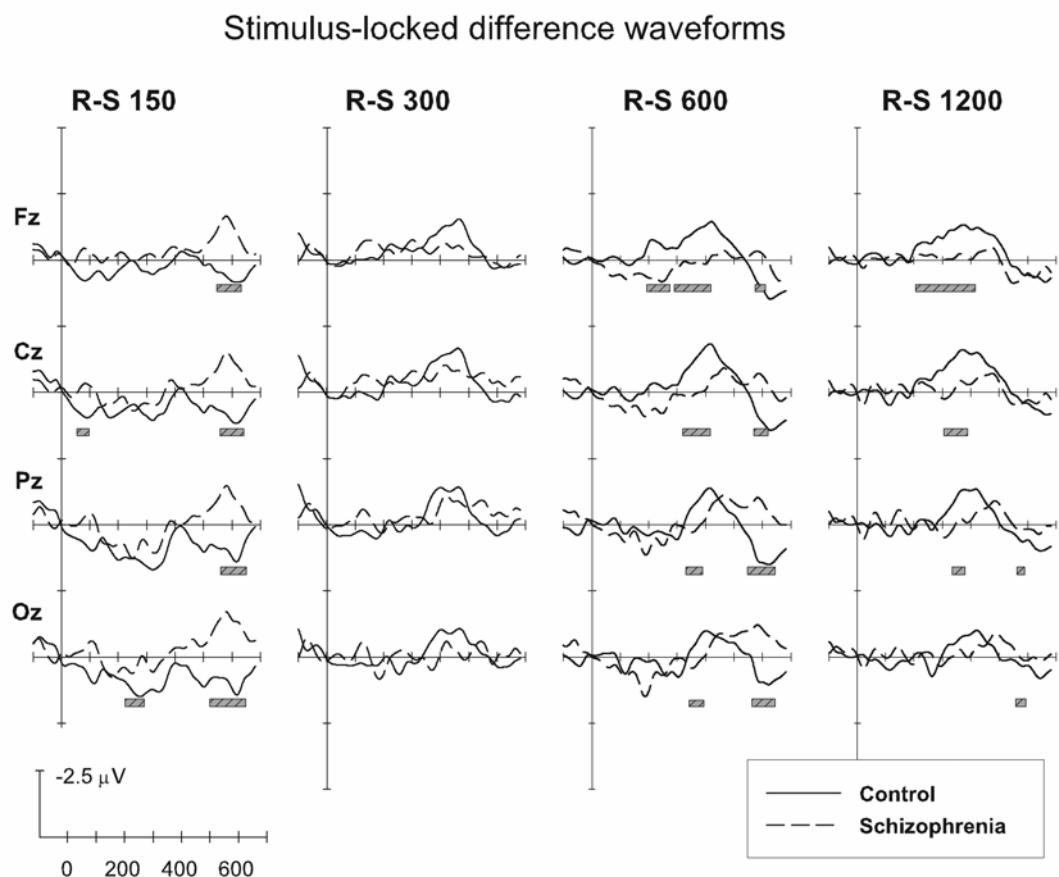[22] P3 peak could not be reliably measured at Oz in seven participants.

Figure 8-7. Stimulus-locked difference ERP waveforms at midline electrodes for each RSI superimposed for control and schizophrenia groups. Bars represent areas of significant deviation between difference waveforms for control and schizophrenia groups.

Schizophrenia group: As noted earlier, ERP components associated with stimulus processing were first compared across schizophrenia and control groups in repeat trials alone to identify group difference in stimulus processing (Figure 8-8). Occipital N1 amplitude was reduced in the schizophrenia group, but the effect was only marginally significant (100-200 ms: group, $F_{(1,35)}=3.5-3.7$, p=.06; 150-200, group by site, $F_{(3,105)}=3.5$, p=.06). This was followed by a significant reduction in frontal N2 amplitude over 250-350 ms (250-350 ms: group by RSI, $F_{(2,70)}=3.3-3.4$, p<.05, 250-300, group, $F_{(1,35)}=4.1$, p<.05), with the effect being larger for RSI-300. In the schizophrenia group, LPC had reduced overall amplitude (450-500 ms: group, $F_{(1,35)}=7.3$, p<.01) and was prolonged centro-parietally for the long RSI (550-700: group by RSI by site, $F_{(6,210)}=2.8-3.5$, p<.05).
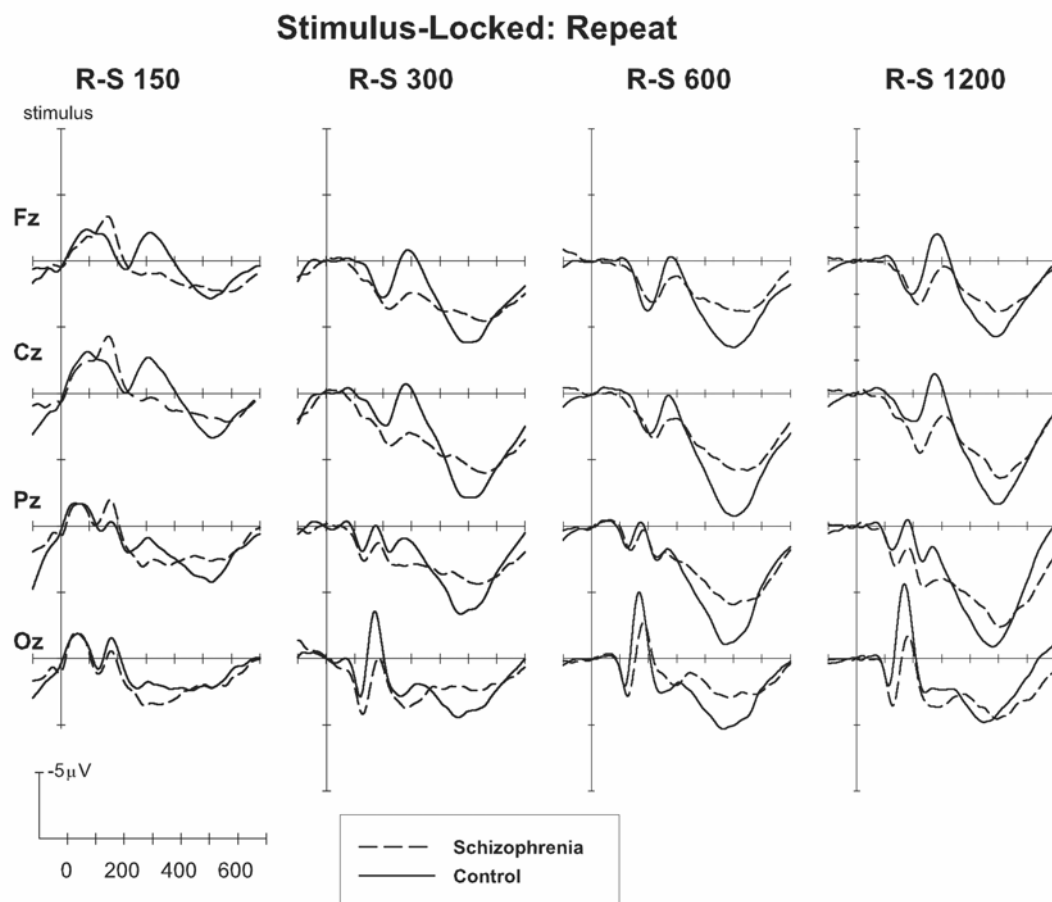
Figure 8-8. Stimulus-locked ERP waveforms at midline electrodes for repeat stimuli only are superimposed for control and schizophrenia groups.

Overall, the schizophrenia group showed similar effects of trial type on ERP waveforms as controls, but the effects were less pronounced (Figure 8-6, bottom). The differential negativity for switch trials that emerged frontally around 200 ms in the control group, did not emerge until after 400 ms and was largely restricted centroparietally in the schizophrenia group (group by type by electrode: 200-250, $F(3,105)=2.4$, $p=.105$, 250-300, $F(3,105)=3.6$, $p<.05$, group by type, 350-400, $F(1,35)=4.4$, $p<.05$). The significant group main effects over 450-550 ms ($F(1,35)=5.2$-7.8, $p<.05$) and group by type by site interaction over 500-550 ms ($F(3,105)=5.5$, $p<.01$) indicate that, despite overall reduced LPC, the switch/repeat difference extended later in the schizophrenia group than the control group. Comparison of difference waveforms for schizophrenia and control groups (Figure 8-7) highlights the absence of a frontal negativity, especially at the two longer RSI conditions, and the delayed onset of the

centroparietal negativity in the schizophrenia group (see Table 8-3, bottom for results of point

by point comparison of control and schizophrenia difference waveforms).

Table 8-3
Areas of significant deviation of response-locked difference waveforms (top) and stimulus-locked difference waveforms (bottom) between control and schizophrenia groups.

	Schizophrenia versus Control Groups Response-locked difference waveforms			
	RSI-150	**RSI-300**	**RSI-600**	**RSI-1200**
Fz	-	96-236	418-452 488-626	-
Cz	-	96-226	108-146 170-224 420-444 510-566	768-792 910-944
Pz	612-700	88-144 166-204	98-156 166-228 406-448	108-152 760-804 820-870 914-998
Oz	604-700	84-140 166-200	100-234 422-446	112-146 728-866 914-1002
	Stimulus-locked difference waveforms			
Fz	552-642	-	190-284 294-426 574-614	206-418
Cz	54-96 562-646	-	324-416 570-624	304-394
Pz	554-636	-	338-396 550-642	332-380 560-596
Oz	266-296 528-648	-	344-396 566-646	562-594

LRPs

Stimulus- and response-locked LRP waveforms are shown in Figure 8-9. Across both groups, stimulus-locked LRPs emerged and peaked earlier with increasing RSI (F(3,59)=5.5, p<.005, F(2,71)=3.58, p<.05, respectively), with the largest effect from RSI-150 to RSI-300 (Figure 8-10, left). Stimulus-locked LRP onset was later for schizophrenia than controls (371 versus 327 ms, respectively), but this difference was only marginally significant (F(1,23)=3.7, p=.068). LRP peak amplitude increased with RSI (F(3,89)=7.5, p<.001) and was larger in controls than schizophrenia patients (F(1,33)=4.8, p<.05). Stimulus-locked LRP did not differ for switch and repeat trials (Figures 8-9 and 8-10, left).
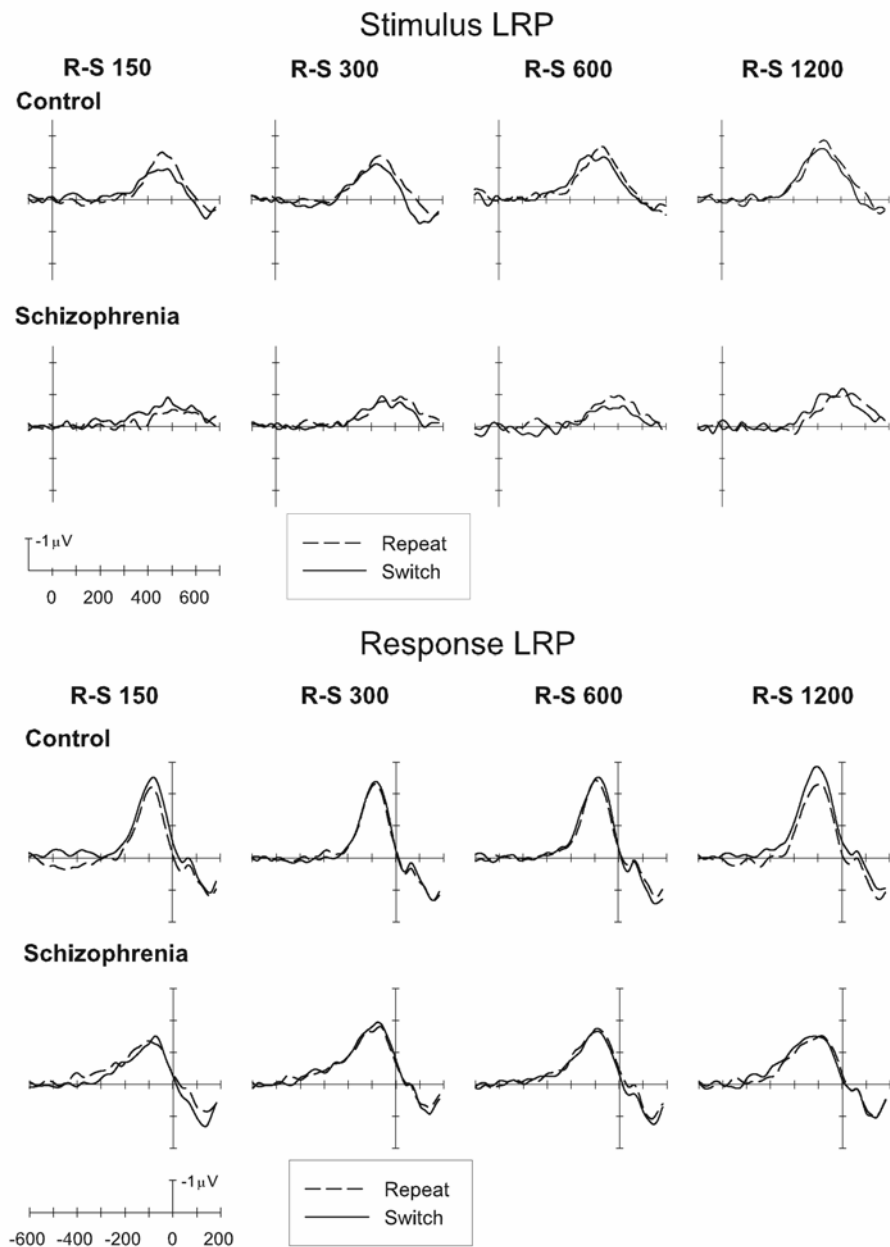
Figure 8-9. Stimulus- (left) and response-locked (right) LRPs at each RSI for both groups.

Response-locked LRP peak amplitude (Figures 8-9 and 8-10, right) increased with increasing RSI ($F(3,57)=4.9$, $p<.05$) and was larger for switch than repeat trials ($F(3,57)=4.1$, $p<.05$). Although response-locked LRP amplitude appears to be smaller in patients, this difference was only marginally significant ($F(1,29)=3.5$, $p=.07$). Response-locked LRP peaked earlier with increasing RSI ($F(2,75)=13.5$, $p<.001$) with the effect being greater for the schizophrenia group (RSI by group: $F(2,75)=4.4$, $p=<.01$). These effects were also reflected in response-locked LRP onset, but were not significant ($F(3,57)=2.9$, $p=.10$). Response-locked LRP began around 50 ms earlier in patients than in controls ($F(1,32)=6.4$, $p<.05$).
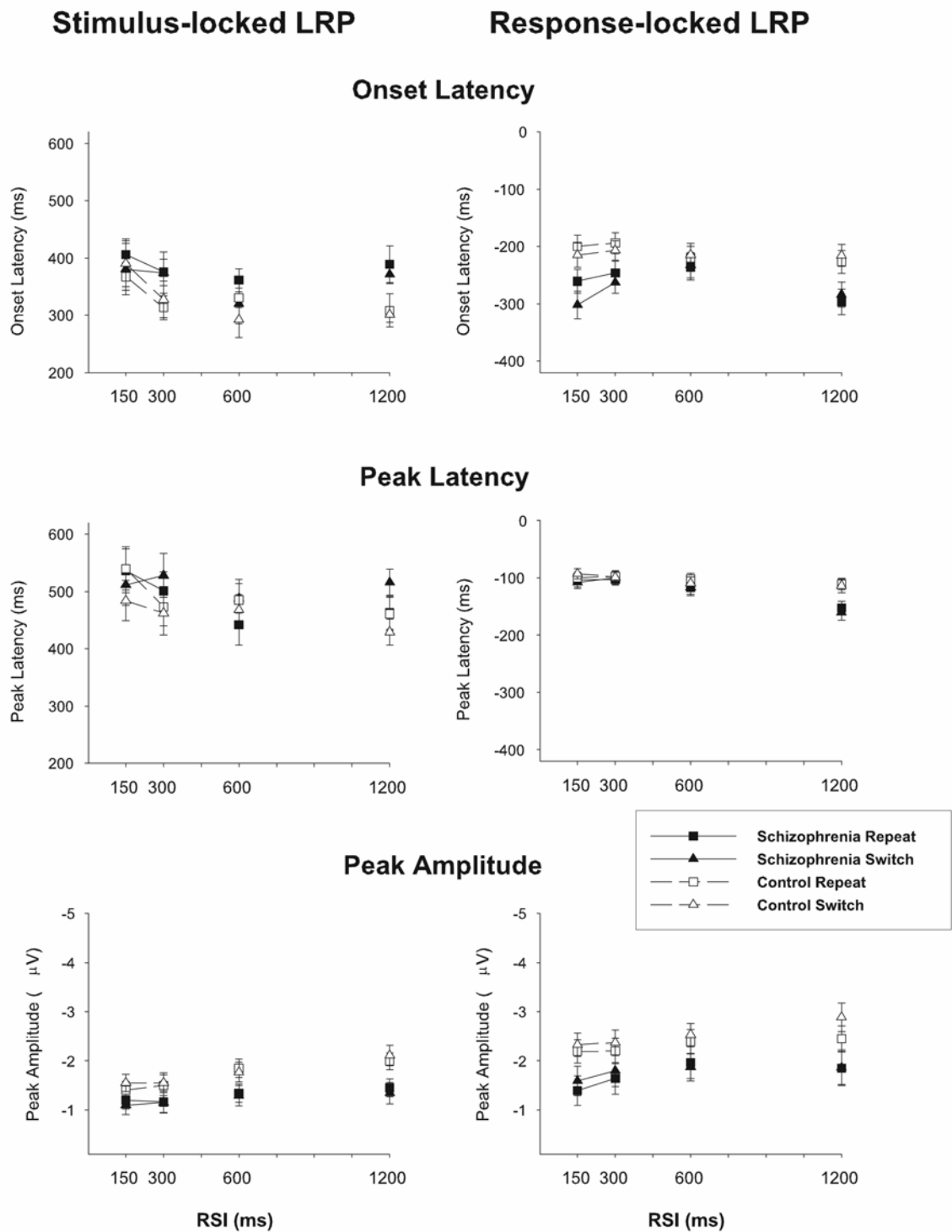
Figure 8-10. Onset latency, peak latency and peak amplitude measures for stimulus- and response-locked LRPs. Bars represent standard error.

8.3 Discussion

Firstly, the implications of the control data for models of task-switching is examined so to provide a framework within which to discuss the implications of the present data for cognitive processing in schizophrenia.

Switching between non-overlapping task-sets

In this univalent stimulus-sets version of the alternating task paradigm, differences between switch and repeat trials emerged at various stages of processing in the control group. A differential positivity was evident in response-locked waveforms over approximately 200-500 ms at all except the longest RSI condition and, in some instances, was preceded by a brief differential negativity. Stimulus-locked waveforms showed a differential negativity emerging frontally around 200 ms and spreading posteriorly, peaking at around 400 ms. There was no effect of task switching on stimulus-locked LRP latency or amplitude measures. Response-locked LRP peak amplitude was larger for switch than repeat trials, but there was no significant effect of trial type on response-locked LRP onset or peak latency. Behaviourally, the control group showed a significant RT switch cost in the order of 20-50 ms, a reduction in RT switch cost with increasing RSI, albeit only significant for the picture task, and a small (20 ms) but significant residual RT switch cost at the longest RSI. Error rate was very low (1-3%), but significantly larger for switch trials, at least for the picture task.

Response-locked and stimulus-locked ERP findings are highly compatible with the differential positivity and differential negativity previously reported by Karayanidis et al (2003) and the current thesis experiments, as well as with data on these same tasks from a group of young University students (Karayanidis et al., 2001). RT and error switch cost were quite low, but in accordance with levels previously found with no-cross-talk paradigms or univalent stimuli. For example, Karayanidis et al. (2001, 2003) also showed that, with univalent tasks, the response-locked differential positivity was evident with an RSI of 150 ms, but not 1200 ms. The current data extend this finding showing that a differential positivity is also evident with univalent stimuli at RSIs of 300 and 600 ms. A reduction in D-Pos amplitude with increasing RSI (Karayanidis et al. 2003) has also been reported with bivalent stimuli or cross-talk tasks, with a very small positivity at a RSI of 1200 ms, even with bivalent stimuli (Karayanidis et al. 2001; 2003). It has been suggested that the small or absent positivity at RSI 1200 ms may be

due to smearing of the waveforms occurring as a result of greater between- and within-subject variability in the onset of anticipatory task-set reconfiguration (e.g., Karayanidis et al. 2003).

The stimulus-locked negativity is compatible with the differential negativity reported previously (Karayanidis et al. 2003; see also Barceló et al., 2002; Rushworth et al., 2002; 2005; Experiments 1-5). In the present data, this negativity first emerged frontally before spreading posteriorly and extending over a wide temporal window. The fact that this negativity overlaps many ERP components suggests that it may reflect a switch-related component superimposed on the stimulus-processing ERPs (Karayanidis et al.). Alternatively, it is possible that there are two effects here: a frontal early switch-related negativity followed by a later modulation of LPC (e.g., Barceló et al.). A two component effect is partly supported by the increase in LPC peak latency for switch trials and the fact that the early frontal component was not evident in previous work with the similar paradigms (Karayanidis et al., 2001) or in the schizophrenia group in the present experiment (see below). Nevertheless, the finding that the centroparietal LPC did not peak until approximately 500 ms after stimulus onset whereas stimulus-locked LRP emerged around 250 ms and peaked around 450 ms and that RT averaged around 600 ms, suggests that any switch-related effect on LPC peak latency is unlikely to reflect stimulus evaluation processes or to have directly contributed to the decision-making process, but more likely reflects post-decision processes. In contrast, the early frontal component of the differential post-stimulus negativity that emerged at 200 ms, as well as its later centroparietal component at 300 ms, may have contributed to differential evaluation of stimuli on switch versus repeat trials.

The finding that switch and repeat trials did not differentially affect the onset or peak latency of either stimulus-locked LRPs or response-locked LRPs indicates the behavioural costs of task-switching reflect differential activation of task-set reconfiguration in the anticipatory period and post-stimulus identification or evaluation processes, but at least in this context, are not due to differences in response selection or activation processes. The absence of any switch-related modulation of stimulus-locked LRP onset contrasts with recent findings by Hsieh and Yu (2002) and Hsieh and Liu (2005). In Rushworth's terms (Rushworth et al., 2002), Hsieh's

paradigm involves switching intentional set, whereas the current task involves switching both attentional and intentional set. This could account for the absence of switch-related differences in the stimulus-locked ERPs in Hsieh's data, as the switch component of the task involved reversal of stimulus-response mapping and therefore largely involved interference at the level of response selection. The absence of a switch-related effect on stimulus-locked LRP in the current data suggests that, with univalent stimuli, after completion of task-set reconfiguration and stimulus processing, there is little switch-related interference at response selection and activation levels, even with very short preparation intervals[23].

The behavioural, ERP and LRP findings in controls are compatible with the multi-component model of task-switching previously discussed. The differential positivity triggered immediately after a response and in anticipation of a switch trial is compatible with activation of task-set reconfiguration processes. With increasing RSI, there is greater opportunity for activation of task-set reconfiguration prior to stimulus onset, resulting in reduction of RT switch cost. Differential processing of switch and repeat stimuli was also evident after stimulus onset emerging as early as 200 ms and peaking around 400 ms. This switch-related negativity was not affected by RSI values between 300 and 1200 ms. Differential post-stimulus processing of switch and repeat trials was evident even at the interval that provides optimal opportunity for preparation (RSI-600 ms; Rogers and Monsell, 1995; Karayanidis et al., 2003; Experiment 1) and for univalent stimuli that would be expected to have minimal interference from previously activated task-sets (Allport & Wylie, 2000). These findings support Rogers and Monsell's original proposition that the process of task-set reconfiguration can not be completed prior to stimulus onset. Within this framework, the differential negativity appears to, at least partially, reflect the stimulus-triggered component of task-set reconfiguration. Alternatively, it is possible that, despite using distinct stimulus sets and non-overlapping response labels, participants still experienced some degree of interference between task-sets.

---

[23] With bivalent stimuli in a cued task-switching paradigm, stimulus-locked LRP onset is delayed on switch trials at short but not long CSI (experiment 1b).

Task-switching performance in schizophrenia

The schizophrenia group showed increased overall RT and increased RT switch cost across all RSIs compared to the control group. However, the increase in RT switch cost was not significant when using proportional scores to control for group differences in overall RT (Meiran, Levine, Meiran & Henik, 2000). This finding is compatible with some recent studies examining task-switching in schizophrenia. Manoach et al. (2002) reported no deficit in cued switching between prosaccade and antisaccade tasks. Using an alternating runs paradigm with bivalent task-sets, Cools et al. (2002) found no increase in RT switch cost, but surprisingly also no increase in overall RT in schizophrenia. With a cued trials task-switching paradigm, Meiran et al. found that, when corrected for RT slowing, patients showed larger RT switch cost across a range of values of RSI with a constant and short CSI (132 ms). However, increasing CSI (432 to 3032 ms) resulted in comparable reduction in proportional RT switch cost in schizophrenia and control groups. Meiran et al. argue that that there is no switch-specific deficit in schizophrenia, but that the increased RT switch cost at all RSI conditions when using a very short CSI and the 30% patient drop-out rate reflect a difficulty with maintaining the stimulus-response assignment in working memory, thereby reflecting poor memory for the currently relevant task context.

The use of univalent stimuli in the current experiment may have further reduced the need to maintain task context in working memory, thereby resulting in no group difference in corrected switch cost, even at the shortest RSI. Poor memory for task context, rather than a specific task-switching deficit, may also underlie the deficit in switching attention across different stimulus attributes or different targets (Smith et al., 1998) as well as the increased error rate on the perseveration component of the attentional set-shifting task (Elliot et al., 1998). However, a memory for context deficit can not easily account for the specificity of the group differences in both the above studies. In Smith et al. (1998), memory for task context was also important for completion of selective attention for pattern and divided attention tasks, but there was no performance decline in schizophrenia. In Elliot et al. (1998), the increase in error rate was specific to intradimensional shifts of the perseveration task and was not evident for

extradimensional shifts or for the learned irrelevance task. Furthermore, schizophrenia patients were found to effectively use context to reduce interference but not facilitation in Stroop task performance (Henik et al., 2002).

These studies suggest that the pattern of cognitive performance deficits found in schizophrenia show both specificity and selectivity and can not be fully accounted for by either a general cognitive decline or a global memory for context deficit (see also Schatz, 1998). Nevertheless, the absence of a group difference in proportional RT switch cost in the current experiment suggests that, with univalent stimuli, patients with schizophrenia are not slower or less accurate when switching between tasks even when using an alternating runs paradigm that involves internal task cueing. By implication, a set-shifting or switching deficit with internal cueing (e.g., Elliott et al., 1998; Smith et al., 1998) may emerge with bivalent task-sets (i.e., task-sets where stimulus attributes overlap).

Global and switch-specific ERP differences between schizophrenia and controls

Overall, ERPs showed the typical pattern of differences between schizophrenia and control groups. Patients showed reduced build-up of negativity in anticipation of the stimulus. Given that response completion provides a valid cue as to onset timing of the next stimulus, this negativity is compatible with development of a CNV in preparation to respond to the upcoming stimulus. CNV amplitude reduction has been consistently reported in schizophrenia (e.g., Heimberg et al., 1999; Verleger et al., 1999; for review of early studies see Pritchard, 1986) and may reflect reduced overall arousal or attention (McCallum & Walter, 1968; Tecce et al., 1976), reduced preparation to respond to the impending stimulus (Rohrbaugh et al., 1976) and/or reduced anticipation for stimulus onset (Damen & Brunia, 1994).

In post-stimulus ERPs, the occipital N1, frontal N2 and centroparietal LPC all showed significant amplitude attenuation in the schizophrenia group. This pattern of overall amplitude attenuation is very commonly reported in schizophrenia (see Pritchard, 1986) and is compatible with reduced overall attentional allocation to the task. Both stimulus- and response-locked LRP amplitude were attenuated in the schizophrenia group indicating greater response preparation

conflict due either to relatively reduced preparation of the correct hand or relatively increased preparation of the incorrect hand (Coles et al., 1995; Falkenstein et al., 1995; Luu et al., 2000). The overall pattern for the patients suggests their LRPs were less synchronised than controls, such as they had more jitter in the build-up perhaps reflecting difficulty in the pyramidal discharge that triggers the motor act.

Interestingly, despite no group difference in proportional RT switch cost, ERP waveforms showed important differences in the processing of switch and repeat stimuli between schizophrenia and control groups. Firstly, although patients showed intact activation of the differential switch-related positivity at short RSIs (150 and 300 ms), there was no evidence of any differential positivity at RSI-600, a condition that provides optimal opportunity for preparation (Karayanidis et al., 2003; Rogers & Monsell, 1995) and that elicited a differential positivity in the control group. Secondly, again in response-locked waveforms, patients did not show the early anterior differential negativity that was especially clear in controls for RSIs of 300 and 600 ms. Thirdly, patients showed no evidence of the early frontal component of the switch-related negativity in stimulus-locked ERPs, especially at longer RSIs (600 & 1200 ms). Finally, although the centroparietal LPC emerged around 300 ms in both groups, differentiation between switch and repeat trials was delayed in schizophrenia compared to controls.

The present data indicate that, even in the absence of behavioural differences in task switching performance, anticipatory and stimulus-triggered ERP indices of task-switching suggest group differences in processing of switch and repeat trials, especially at longer RSI conditions that for control participants provide opportunity for anticipatory activation of task-set reconfiguration processes. Given stimulus-locked LRP onset latency around 350 ms and mean RT of 700-800 ms, delayed onset of the centroparietal differentiation between switch and repeat trials in the stimulus ERP waveforms (around 300 ms in controls and 400 ms in patients) is unlikely to reflect processes directly involved in differential processing of switch and repeat stimuli or response selection and more likely to represent post-decision processes. In contrast, the absence of the anticipatory switch-related positivity at RSI-600 and negativity at both RSI-

300 and RSI-600, as well as that of the post-stimulus frontal switch-related negativity at RSI-600 and RSI-1200 are likely to reflect group differences in anticipatory preparation for a switch trial and differential processing of switch and repeat stimuli, respectively.

Specifically, the finding that patients show reduced differentiation between switch and repeat ERPs both in the anticipatory interval and after stimulus onset at long RSI, as well as a global increase in RT despite no specific increase in RT switch cost may indicate that patients treat switch and repeat trials similarly at longer RSI conditions. If this is the case, one possibility is that patients treat each trial as a potential switch trial and prepare for both switch and repeat trials. This would be expected to be reflected in increased overall arousal in the pre-stimulus interval and to result in a relative reduction in overall RT for both trial types, neither of which were the case in the current data.

Alternatively, with a longer RSI, patients may not actively prepare for either switch or repeat trials. Since stimulus location and stimulus identity provided redundant but valid cues as to which task was active on any given trial, successful performance on the alternating runs paradigm was not dependent on anticipatory activation of task-set reconfiguration, especially given the use of univalent stimuli. It is possible that at RSI-600 patients processed each stimulus as a separate trial regardless of whether it required a switch from the previous task-set or a repeat of the same task-set, resulting in an overall increase in RT but not in proportional RT switch cost relative to controls. This interpretation is compatible with previous studies suggesting that patients with schizophrenia show impaired use of internally-driven task cues and greater reliance on external cues for task performance (e.g., Williams et al. 2000) and specific impairments at long response intervals (e.g., Conklin et al., 2005) and slow stimulus presentation rates (Baribeau et al., 1983). This interpretation is also compatible with the finding that group differences in both response-locked and stimulus-locked ERPs were less pronounced at the shortest RSI which do not depend on maintenance of active task-set across the RSI but rely more on post-stimulus processing. A specific deficit in sustaining an attentional strategy

over longer intervals is compatible with findings that schizophrenia patients show in sustaining a selective attention strategy (Mathalon et al., 2004).

Thus, despite no increase in proportional RT switch cost, schizophrenia patients still showed evidence of a disruption on anticipatory task-set reconfiguration, especially at RSI-600 that produced optimal switching performance in controls. It is suggested that patients compensate for this deficit by processing both switch and repeat stimuli identically after stimulus onset. An obvious prediction arising from this conclusion would be that patients' performance would deteriorate markedly if stimulus position or identity provided no information about which task-set was active on any particular trial. For example, the cued task-switching paradigm from Experiment 5 could be replicated with schizophrenia patients and controls so that the spatial position cues are removed, bivalent stimuli are presented and the cue is removed prior to stimulus onset to encourage anticipatory task-set reconfiguration. This is clearly an area for future research.

The fact that ERP evidence of switch-related processing deficits occurred in the absence of proportional switch cost differences suggests either that patients compensate for these deficits prior to response onset or that the proportional switch cost measure masks differences in underlying cognitive processes. The use of proportional correction implies that the increase in RT is not simply an overall motor delay that would equally affect switch and repeat trials and could therefore be eliminated by the subtraction of repeat from switch trials. Rather it implies a more general slowing in cognitive processing that compounds with increasing number of processes (e.g., switching involves additional processes than repeat) or difficulty of processing (switch trials take longer to complete each/some processes than repeat). Yet many ERP studies in schizophrenia show larger and more consistent differences in the amplitude rather than the latency of stimulus-related ERP components (e.g., Jeon & Polich, 2003). Furthermore, calculating RT switch cost as a proportion of repeat trial RT assumes that task-set reconfiguration is a process that is specifically and exclusively activated on switch trials. Yet, it is possible that, under certain conditions, task-set reconfiguration is also activated on some

proportion of repeat trials. If this occurs disproportionately for patients compared with controls, then the use of mean repeat trial RT to estimate proportional RT switch cost will result in overcorrection in the former group.

Summary

These findings suggest that even high functioning people with schizophrenia show evidence of generalised response slowing and reduced attentional capacity on an alternating runs task-switching paradigm with univalent tasks. ERPs suggest that people with schizophrenia do not use anticipatory preparation strategies to reduce the cost of task-switching, but rely on post-stimulus processing strategies. The specificity of this differential deficit to the optimal preparation interval of 600 ms suggests that it is unlikely to reflect a working memory dysfunction and is more likely to result from a difficulty in updating and switching internally represented information (Braver et al., 1999).

9   General Discussion

The investigation of what controls of our cognitive processes enabling us to successfully achieve purposeful behaviour has fascinated researchers throughout history. Traditional theories have tended to emphasise a single unitary executive function thought to be localised within the prefrontal cortex (i.e., the homunculus) that is responsible for controlling and coordinating subordinate functions (e.g., Baddeley's, 1986, central executive; Norman & Shallice's, 1986, supervisory attentional system). More recent reviews however, suggest the possibility that control may be exercised by multiple independently functioning systems (e.g., Hommel et al., 2002; Logan, 2003; Monsell, 1996; 2003; Monsell & Driver, 2000). Over the last decade, task-switching paradigms have become a popular tool in this exploration of what it is that controls our cognitive processes and how this control is executed. The overall aim of the experiments conducted as part of this thesis was to investigate the behavioural and ERP correlates of the processes involved in task-switching. Specifically, the experiments were designed to investigate the component processes involved in task-switching, and in particular, to investigate the cognitive control processes involved in anticipatory task-set reconfiguration.

To summarise the individual experimental outcomes; Experiment 1 dissociated the effects of passive dissipation of task-set interference from anticipatory task-set reconfiguration by using a cueing paradigm and independently manipulating the RSI and CSI. The results demonstrated that the switch-related differential positivity previously observed (e.g., Karayanidis et al., 2003; Rushworth et al. 2002; 2005) reflects anticipatory task-set reconfiguration processes initiated following cue presentation. Experiment 2 further verified that the switch-related differential positivity reflects processes associated with anticipatory task-set reconfiguration, particularly the retrieval and application of the new task-set from long term into working memory.

A simplified paradigm was developed in Experiment 3 that strongly encouraged participants to engage in anticipatory task-set reconfiguration. This resulted in a greater reduction in RT switch cost with increasing CSI relative to the paradigm used in Experiment 1. Experiment 4 demonstrated that the RT switch cost and switch-related positivity observed in

cueing paradigms *do* reflect processes involved in task-set reconfiguration and are not simply a by product of reduced cue repetition benefit as suggested by Logan and Bundesen (2003). Experiment 5 revealed that the switch-related differential positivity can be localised to greater activation in the prefrontal cortex followed by increased parietal activation, reflecting the initiation of anticipatory task-set reconfiguration followed by the organisation and maintenance of response-stimulus mappings. Finally, Experiment 6 demonstrated how these findings can be applied to clinical populations to assist in delineating the cognitive control processes that underlie deficits in disorders such as schizophrenia. The implications of these findings will be discussed below, especially as regards the number and type of components involved in task-switching, the electrophysiological correlates of these components and current models of cognitive control.

9.1   Components of Task-switching

Consistent with previous research (e.g., Rogers & Monsell, 1995; Meiran et al., 2000), trials requiring a switch, as compared to a repeat in task, were associated with increased RT and poorer accuracy in all experiments. Combined with previous task-switching literature, the manipulations conducted across the current experiments demonstrate that this RT switch cost is attributable to multiple factors involved in task switching, which can be grouped into three separate components; the passive dissipation of task-set interference, anticipatory task-set reconfiguration and post-stimulus processes. Each of these will be discussed in turn.

Passive Dissipation of Task-set Interference

The RT switch cost is partially attributable to interference between the multiple tasks being performed. Numerous studies, particularly those by Allport and colleagues (Allport et al. 1994; Allport & Wylie, 2000; Wylie & Allport, 2000; Waszak, et al, 2003; but see also Gilbert & Shallice, 2002, Yeung & Monsell, 2003a; Yeung & Monsell, 2003b) have demonstrated that when switching tasks, the previously relevant, but now irrelevant task-set remains active and positively primed leading to a type of proactive interference. Negative priming interference associated with inhibition of the previously irrelevant, but now relevant task-set also affects

performance on the current task (e.g., Arbuthnott & Frank, 2000; Mayr & Keele, 2000; Schuch & Koch, 2003).

This task-set interference (or 'task-set inertia', Allport et al., 1994) passively dissipates as the interval between the previous response and the onset of the next cue or stimulus (i.e., the RCI or overall RSI, respectively) increases, leading to reduced RT switch cost. For example, Mayr and Keele (2000) and Koch, Gade and Philipp (2004) found that the amount of backward inhibition (i.e., the increase in RT when switching back to the most recently abandoned task-set as compared to switching to a third task) was reduced when there was a longer RCI that facilitated greater passive dissipation of the task-set interference. Gade and Koch (2005) showed that it is opportunity for passive dissipation of interference across the interval between trial n and trial n-2 that has a greater effect as compared to the interval between n and n-1 (e.g., in task sequence ABA the amount of backward inhibition was affected more so by the interval between tasks A and then A again rather than B and then A). Meiran et al. (2000) also found that the standard RT switch cost measure (i.e., switch – repeat) reduced as the overall RSI increased, even with the preparation interval (i.e., the CSI) held constant. This was replicated in Experiment 1, as the RSI increased from 750 to 1200 ms (for a fixed CSI of either 150 or 600 ms) a significant reduction was observed in RT switch cost. In comparison, Experiment 2 showed no reduction in switch cost as the RSI increased from 1200 to 1600 ms (for fixed CSI of 1000 ms), possibly reflecting that the effects of passive dissipation had already reached an asymptote by the 1200 ms RSI. This is consistent with Meiran et al. who found no reduction in RT switch cost as the RSI increased from 1000 to 3000 ms, suggesting that the effects of passive dissipation of task-set interference may begin to plateau at around 1000 ms.

Anticipatory Task-set Reconfiguration

Notably, the passive dissipation of task-set interference is not a form of cognitive control as it occurs *passively* over a period of time without any conscious effort. However, in *addition* to this effect, the increase in RT on switch trials (i.e., the RT switch cost) has also been shown to be associated with the processes of task-set reconfiguration. This involves a shift from a

readiness to perform one task to a readiness to perform another task and can be separated into two sub-components (Rogers & Monsell, 1995). The first, which has been the primary focus of the present experiments conducted, is anticipatory task-set reconfiguration. Anticipatory task-set reconfiguration refers to a *cognitive control process* that is endogenously triggered in preparation for an impending switch in task (Rogers & Monsell).

The results from the current experiments suggest that anticipatory task-set reconfiguration involves multiple processes. When the sequence of tasks is random and the task is validly cued on a trial-by-trial basis, as in Experiments 1-5, the cue and the information it conveys must be processed. For example, in Experiments 3-5, processing of the cue involved identifying the colour of the cue followed by retrieval of the relevant cue-task association (e.g., the cue is blue in colour and therefore the next trial will be the parity task). Under certain conditions, processing of the cue can become a substantial task within itself, potentially contributing to further RT cost (Logan & Bundesen, 2003; 2004; Mayr & Kliegl, 2003), such as when the cues are overly complicated and difficult to interpret or cue-task associations have not been properly established (Monsell & Mizon, 2006). However, as Experiment 4 clearly demonstrated, when there is an adequate preparation interval (i.e., CSI of $\geq$ 600 ms) and participants are well practiced and highly motivated, there is no significant RT cost associated with cue processing and ERP effects of cue processing are restricted to within the first 300 ms after cue onset.

Once the cue has been processed, it can then be determined whether, relative to the trial just completed, the next trial will require a repeat or switch in task. If the same task is to be repeated, then no further task preparation is required because the relevant task-set (e.g., for the parity task) is still loaded in working memory and primed for execution. All that is required is the maintenance of this task-set. Alternatively, if a switch in task is required (e.g., to the magnitude task), or the repeat in task has not been correctly identified (e.g., the task performed on the previous trial has been forgotten due to a lapse in concentration), participants may initiate anticipatory task-set reconfiguration in preparation for the upcoming trial. This may include an

increase in general arousal and alertness (Meiran & Chorev, 2005) and the inhibition of information irrelevant to the current task.

Previous behavioural studies suggest that inhibitory processes are only triggered after stimulus onset and are closely linked with the actual execution of the response (e.g., Dreisbach et al., 2002; Hubner et al., 2003; Schuch & Koch, 2003; see stimulus-triggered component of task-set reconfiguration below). However, RT distribution analysis of the Experiment 1 data by Poboka et al. (2005) showed that increased passive dissipation of task-set interference is most beneficial when participants are unprepared for the switch in task (i.e., when they haven't engaged in anticipatory task-set reconfiguration). This suggests that anticipatory task-set reconfiguration may involve the active inhibition of information irrelevant to the upcoming trial, such as inhibition of the previously relevant, but now irrelevant task-set (i.e., inhibition of the task-set implemented on the previous trial), negating the benefit presented by the greater passive dissipation of task-set interference.

This is consistent the results from Experiment 3, which showed that the increased passive dissipation of task-set interference over a longer RSI did not affect mean RT switch cost when participants were encouraged to engage in anticipatory task-set reconfiguration on a greater proportion of trials (Figure 5-2). That is, the effect of increased opportunity for passive dissipation of task-set interference on mean RT (i.e., the reduction in switch cost with increasing RSI) became redundant as participants engaged in anticipatory task-set reconfiguration on the majority of trials, suggesting that interference effects can be actively overcome during the preparation interval. Further, the ERP results from Experiment 2 showed that participants were initiating preparation processes for a switch in task, even when they did not know which specific task they would be switching to. The differential positivity observed for switch-away relative to repeat trials across a 1000 ms CSI was thus interpreted as most likely reflecting inhibition of the just abandoned task-set.

The crucial process of anticipatory task-set reconfiguration that facilities the reduction in RT switch cost when it can be completed prior to the onset of the stimulus, is the retrieval and

application of the new task-set from long term memory into working memory (Mayr & Kliegl, 2000). Experiment 2 showed that there was no difference in RT switch cost for short (200 ms) versus long (1000 ms) CSI when participants were cued that there would be a switch in task, but were not informed about which specific task they would be required to perform. That is, on *switch-away* trials participants were unable to retrieve the new task-set into working memory until after stimulus onset, resulting in a RT switch cost comparable for short and long CSI. This is consistent with previous studies by Dreisbach et al. (2002) and Hubner et al. (2003) showing that pre-cueing a switch in task with semi-specific cues provided no behavioural benefit. It is only when the cue signals both that the upcoming trial requires a switch in task *and* the specific task being switched to is identified (as in all valid cuing conditions in Experiments 1-5) that longer CSIs facilitate a significant reduction in switch cost, as participants are able to retrieve and apply the task-set relevant for the upcoming trial prior to stimulus onset.

It is important to emphasise that anticipatory task-set reconfiguration is a voluntary active process that is endogenously (i.e., internally) triggered. It can thus be affected by parameters that either promote or impede engagement in this process. For example, in a predicable sequence task-switching paradigm, Goschke (2000) interrupted anticipatory task-set reconfiguration by requiring participants to recite irrelevant verbal material during a long RSI (1200 ms). This resulted in a RT switch cost that was similar to that obtained when there was a short RSI (150 ms). In comparison, 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, which was equivalent to that obtained with a long RSI when there was no verbalisation required. This shows that anticipatory task-set reconfiguration can be interrupted and / or impaired due to competition from other cognitive processes leading to a behavioural deficit (i.e., increased RT switch cost). Conversely, Experiment 3 demonstrated that task parameters can be manipulated to encourage participants to engage in anticipatory task-set reconfiguration on an increased proportion of trials (Figure 5-2), such as by removing information identifying the currently relevant task prior to stimulus onset and by having short

runs of trials with behavioural feedback. Experiment 5 also suggested that restricting the time available for a correct response encouraged participants to make faster and more accurate responses resulting in a minimal RT switch cost with a 600 ms CSI.

Overall, the current experiments clearly support the proposition that anticipatory task-set reconfiguration can be initiated, and potentially completed, prior to stimulus onset provided certain conditions are met (e.g., Rogers & Monsell, 1995; Meiran et al., 2000). The first condition required to achieve this is valid foreknowledge that the next trial will require a switch in task (either through a predictable sequence of trials or as validly signalled by a cue). The length of the preparation interval (i.e., the RSI or CSI, respectively) must then be of an adequate length. Rogers and Monsell suggest that an optimal preparation interval for engagement in anticipatory task-set reconfiguration is around 500-600 ms. This was supported by the findings from Experiment 1, which showed no further reduction in RT switch cost as the CSI increased from 600 to 1050 ms (for a constant RSI of 1200 ms). Interestingly, Experiment 1 also suggested that a preparation interval of only 150 ms provides some opportunity for participants to engage in anticipatory task-set reconfiguration, resulting in a significant reduction in RT switch cost as compared to a completely unprepared (i.e., uncued) condition for the same overall RSI. Likewise, Experiment 2 showed that a CSI of only 200 ms lead to a significant reduction in the RT switch cost for the *switch-to* condition where participants know the upcoming task, relative to the *switch-away* trial where they did not know the specific identify of the upcoming task (Figure 4-2). This suggests that even very minimal preparation intervals (i.e., 150-200 ms) provide some opportunity to initiate anticipatory task-set reconfiguration leading to a behavioural benefit compared to when there is absolutely no preparation interval.

Mean RT switch cost can also be affected by the degree to which participants are encouraged and motivated to utilise any preparation interval for anticipatory task-set reconfiguration processes. Failures to engage in anticipatory task-set reconfiguration on some proportion of trials partially accounts for the residual RT switch cost that remains with long preparation intervals (see post-stimulus component of task-set reconfiguration below; De Jong,

2000; Monsell & Mizon, 2006). This was demonstrated in Experiment 3 with modifications to task parameters resulting in significantly greater reductions in RT switch cost relative to the tasks used in Experiment 1, even though identical short versus long CSIs were used.

If these conditions are met, participants can initiate and potentially complete, anticipatory task-set reconfiguration prior to stimulus onset. That is, on switch trials, they can inhibit irrelevant information and retrieve the now relevant task-set into working memory. The successful execution of these processes means participants are prepared for the switch in task at the point of stimulus onset. This reduces the RT cost of switching tasks (i.e., RT is almost comparable for repeat and switch trials) and may increase accuracy on switch trials (i.e., in Experiment 3 there was a significant reduction in error switch cost as the CSI increased from 150 to 600 ms). In contrast, when the above conditions are not met due to a short or non-existent preparation interval (e.g., CSI of ≤ 200 ms) or a failure to engage in anticipatory task-set reconfiguration, successful task completion de[ends on the activation of task-set reconfiguration after the stimulus is presented. This then results in an increase in switch trial RT and decreased accuracy (i.e., greater RT and error switch cost).

Post-stimulus Component of Task-set Reconfiguration

The second component of task-set reconfiguration, as originally proposed by Rogers and Monsell (1995), is exogenously triggered by the onset of the stimulus. These post-stimulus processes can not be prepared in advance of the stimulus, irrespective whether anticipatory task-set reconfiguration has been completed or not. The stimulus-triggered component of task-set reconfiguration thus partly underlies the residual switch cost that remains even when there has been a long preparation interval, which was robust effect evident in all the current experiments. For example, in Experiment 4 with a 600 ms CSI, the RT distribution analysis showed that even at the first decile representing the most prepared responses, a significant RT switch cost of 29 ms was still evident (Figure 6-2).

Post-stimulus task-set reconfiguration processes occur because stimuli tend to acquire associations with the tasks and response-mappings that are being performed. This is due to the

large number of trials and the limited stimulus sets typically used in task-switching experiments (Allport & Wylie, 2000; Wylie & Allport, 2000). Stimulus-response mappings can be univalent, such as where there are four response options (e.g., odd or even, vowel or consonant), and each are mapped to a separate key on a keyboard. Alternatively, stimulus-response mappings can be bivalent, such as where two responses are each mapped to a single button press on either the left or right hand (e.g., odd or vowel = left, even or consonant = right hand response). Stimuli can also be univalent or neutral in that they are only mapped to a single task (e.g., 'A%' can only be a vowel in the letter task from Experiment 1). In contrast, stimuli can be bivalent in that they afford a response on both tasks (e.g., '1' is both less than 5 *and* odd in Experiments 3-5). Bivalent stimuli can then be either congruently mapped (e.g., '1' if both less than 5 and odd are mapped to a left hand response) or incongruently mapped (e.g., '7' where greater than 5 requires a right hand response and odd requires a left hand response).

The presentation of a bivalent stimulus or the use of bivalent response-mappings can thus trigger interference between task-sets. For example, Waszak et al. (2003) found that the RT switch cost was affected by the presentation of a specific bivalent stimulus, even when there had been over 100 intervening trials between the first and repeated presentation of the specific stimuli. Meiran (2000a) found that the residual switch cost was reduced for univalent compared to bivalent response mappings and for univalent compared to bivalent stimuli. Relative to univalent stimuli, bivalent stimuli have also been shown to produce slower RT overall (Rogers & Monsell, 1995; Woodward, Meier, Tipper & Graf, 2003). Moreover, incongruent bivalent stimuli usually result in larger switch cost as compared to congruent bivalent stimuli (e.g. Rogers & Monsell, 1995; Goschke, 2000). Intriguingly, Hunt and Klein (2002) observed a residual switch cost when participants were required to make manual keyboard responses. However, this cost was eliminated when participants switched between performing prosaccades and antisaccades to a target.

These studies suggest that the use of manual bivalent responses and / or bivalent stimuli, as were used in Experiments 1-5, activate additional processes for switch trials after stimulus

presentation. That is, the presentation of the stimulus elicits interference between the multiple task-sets. For example, in Experiment 3, presentation of a blue cue indicating the parity task followed by the stimulus '7', which is odd and hence requires a left hand response. However, '7' is also greater than 5, which is mapped to a right hand response for the alternative magnitude task. The stimulus-triggered component of task-set reconfiguration that underlies the persisting residual switch cost thus reflects an initial slowing in RT on switch relative to repeat trials due to this interference followed by the triggering of inhibitory processes recruited to overcome the task-set interference (e.g., Mayr & Keele, 2000). It may thus be possible to minimise the residual switch cost by providing a long CSI and encouraging participants to engage in anticipatory task-set reconfiguration on the majority of trials *combined with* the use of univalent stimuli as well as univalent or non-manual stimulus-response mappings (e.g., eye saccades or verbal responses).

Summary of Task-switching Components

It is now clear that there are multiple components and factors that contribute to the RT switch cost. However, the complex relationships between these factors and their relative levels of contribution to task-switching outcomes remain unresolved. For example, Experiment 1 showed that the RT switch cost reduced with both increasing RSI and CSI, reflecting the involvement of both anticipatory task-set reconfiguration and passive dissipation processes. The finding that there was no interaction between the RSI and CSI factors suggests that the effects may be additive (Sternberg, 1969). Conversely, Experiment 3 showed that the passive dissipation of task-set inertia is most beneficial when participants haven't engaged in anticipatory task-set reconfiguration, suggesting an interaction between the two processes. The large volume and complexity of factors shown to affect the RT switch cost suggest that the issue of the interrelationship between task-switching components will be best addressed through analysis across multiple methodologies (e.g., behavioural and ERP as in the current experiments) *combined* with the use of computational simulation (see Kieras, Meyer, Ballas & Lauber, 2000 and Gilbert & Shallice, 2002 for example previous attempts at simulations) and

mathematical modelling of these factors (e.g., Sohn and Anderson, 2001; Yeung & Monsell, 2003b; Logan & Gordon, 2001; Meiran, 2000b). Clearly this is an area for future research.

9.2   Electrophysiological Correlates of Task-set Reconfiguration Components

In order to define the functional and neural substrates of cognitive control processes, it is important to analyse converging evidence from different methodologies (Logan, 2003; Monsell, 2003). The parallel analysis of behavioural effects *and* ERPs in task-switching experiments can thus help elucidate the cognitive processes that lead up to the behavioural differences between switch and repeat trials in general and more specifically, the processes involved in task-set reconfiguration. In all experiments reported here, both ERP and behavioural data were analysed in order to provide further insight into the components involved in task-set reconfiguration and to identify the brain correlates associated with these components, particularly those associated with anticipatory task-set reconfiguration.

Response-locked Effects for Both Trial Types

ERPs time-locked to the onset of the response were calculated in Experiment 1. For all timing conditions and both trial types, the response-locked ERP waveforms tended to show a slow negative drift emerging after the response and extending across the entire epoch leading up to the onset of the cue. This post-response negativity can be seen preceding the onset of the cue in the cue-locked waveforms for conditions that have a very short interval between the response to the preceding stimulus and the onset of the next cue (i.e., RCI of only 150 ms). Considering that Karayanidis et al. (2003) observed the differential positivity in the response-locked waveforms in a predicable task-switching paradigm, response-locked waveforms in Experiment 1 were thus compared for switch versus repeat trials. As Figure 2-5 showed, there was no systematic difference between switch and repeat trials in the response-locked waveforms until *after* cue onset. Consequently, response-locked waveforms were not analysed in any of the later experiments (with the exception of Experiment 6 that used the alternating runs paradigm).

Cue-locked Effects for Both Trial Types

ERP analysis for all five cued experiments focused on waveforms time-locked to the onset of the cue that validly informed participants what task they would be required to perform on the upcoming trial. Presentation of the cue elicited standard early visual ERPs for both switch and repeat trials. Cue-locked waveforms tended to show a P1, N1, P2 pattern of ERP components. The P1 refers to a small positivity that usually peaks prior to 100 ms. This is followed by the N1, a negativity that peaks slightly after 100 ms that is then followed by the P2, which indicates a positivity that peaks at around 180-300 ms. These are standard ERP components exogenously triggered by the presentation of a stimulus, in this case, the cue, that requires visual processing, as was the case for both switch and repeat cues (e.g., Mangun & Hillyard, 1990). Importantly, Experiment 4 demonstrated that it is only these early visual components occurring less than 300 ms after cue onset that were affected by whether there was a switch or repeat in the type of cue category (colour or shape).

From around 300 ms after cue onset, both switch and repeat waveforms tended to show a large positive component that was maximal over central and parietal sites. This was evident in all experiments and may partially reflect a P3b type effect related to evaluating the cue (e.g., McCarthy & Donchin, 1981; Donchin & Coles, 1988), such as identifying what task it represents, which was necessary on every trial irrespective of whether the cue signalled a switch or repeat in task. For example, in Experiments 3-5, cue colour would be identified during the early visual processing stage and must then be identified as being associated with a particular task. In conditions with a short CSI (i.e., $\leq$ 200 ms), stimulus onset occurs shortly after cue onset (e.g., at 150 ms) and consequently cue and stimulus related processes (see below) overlap temporally and are difficult to separate. In contrast, for both switch and repeat trials when there is a long CSI (i.e., $\geq$ 600 ms), the LPC tends to clearly peak around 400-500 ms after cue onset

and to be followed by a sustained CNV type shift[24] in the lead up to stimulus onset. The CNV was usually most evident fronto-centrally and tended to extend until slightly after stimulus onset. This most likely reflects processes involved in preparation for the response to the upcoming stimulus, such as expectancy in readiness to respond to the stimulus (e.g., Walter et al., 1964; Loveless & Sanford, 1974).

In summary, cue-locked waveforms elicited a number of ERP components that were highly comparable for both switch and repeat trials. Indeed, ICA conducted on the cue-locked ERPs in Experiment 5 suggested that switch and repeat trials have a very similar underlying structure of ERP components. Three almost identical components were identified for both trial types over the 700 ms following cue onset. Two of these ERP components appeared to map to early ERP components associated with cue processing and orienting of attention (i.e., the P1, N1, P2 pattern). The third component, which accounted for the largest amount of variance, was consistent with the LPC followed by the broad CNV drift.

Switch-related Differential Positivity

In addition to ERP components that occurred for both trial types, a broadly distributed positive shift was evident for switch relative to repeat trials in all experiments emerging as early as 100 ms after cue onset. This effect was measured in the switch minus repeat ERP difference waveform. The switch-related differential positivity was maximal over central and parietal sites and tended to be greater over the left hemisphere (e.g., Figure 7-2). In Experiments 1 and 2 (for *switch-to* trials), the differential positivity emerged around 150 ms after presentation of the cue and peaked at around 350-400 ms. In Experiment 1, the differential positivity tended to resolve (i.e., retuned to baseline against the repeat waveform) by 500-600 ms, while it extended slightly longer in Experiment 2 to around 800 ms, most likely due to the longer CSI of 1000 ms.

---

[24] While this effect is referred to as a CNV throughout the current experiments, it is acknowledged that the CNV is traditionally associated with longer stimulus-stimulus intervals that extend beyond 1 second and potentially up to around 6 seconds (e.g., Walter et al., 1964). It is thus possible that the CNV type effect observed over quite fast CSIs (e.g., 600 ms) may reflect more of a stimulus preceding negativity type effect, such as that described by Damen and Brunia (1994).

In contrast, in Experiments 3-5, the differential positivity tended to emerge later (at around 300 ms), peaking at approximately 500 ms and then resolving by around 700 ms post-cue. These differences between experiments most likely reflect variations in experimental paradigms. Experiments 1 and 2 used spatial location to cue the task. For Experiments 3-5, this was changed to a single location box and the cue was either the colour of the outside defining the box or a shape presented within the box. In addition, the cue was removed prior to stimulus onset in order to encourage participants to engage in anticipatory task-set reconfiguration on a greater proportion of trials. Thus, the later onset and peak of the differential positivity in Experiments 3-5 may reflect decreased trial-by-trial and between subject variations in the timing of the onset anticipatory task-set reconfiguration processes. That is, relative to Experiments 1 and 2, in Experiments 3-5 participants initiated anticipatory task-set reconfiguration within a more consistent and tighter timeframe due to removal of the cue prior to stimulus presentation, resulting in a shift in the grand average ERP waveforms.

The switch-related differential positivity observed following presentation of the cue in Experiments 1-5 is highly consistent with the differential positivity observed by Karayanidis et al. (2003) in a predicable task-switching paradigm (see also response-locked waveforms in Experiment 6). In Karayanidis et al., response-locked waveforms showed a large parietally-maximal differential positivity for switch compared to repeat trials, that began as early as 100 ms after the onset of a response to the previous (repeat) trial and peaked around 400 ms post response. With a short RSI (150, 300 ms), the differential positivity began prior to stimulus onset, but continued after stimulus onset, overlapping early ERP components associated with stimulus processing. With a longer RSI (600, 1200 ms), the differential positivity was superimposed on a CNV-like negativity and fully completed before stimulus onset. Gladwin et al. (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 et al. (2003) 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. Despite using a very different paradigm, Rushworth et al (2002; 2005) and Miniussi et al. (2005) also showed a switch-related positivity over 350-500 ms after cue onset.

The current findings support the contention by Karayanidis et al. (2003) that the switch-related differential positivity reflects processes involved in anticipatory task-set reconfiguration. Experiment 4 demonstrated that differential positivity is not affected by cue characteristics and can not be attributed to a cue repetition benefit for repeat trials (Logan & Bundesen, 2003). Experiment 1 showed that with a long 600 ms CSI, the differential positivity was fully contained within the CSI and there was maximal reduction in RT switch cost (i.e., anticipatory reconfiguration could be initiated and completed prior to stimulus onset). At short CSIs (150 ms), the differential positivity still peaked at around the same 350-400 ms after cue onset but RT switch cost was larger than for longer CSI conditions suggesting that anticipatory reconfiguration could not be completed until after stimulus onset. This is consistent with the pattern observed by Karayanidis et al. and was replicated again in Experiment 3 (i.e., D-Pos peaks around same duration from cue onset irrespective of CSI, but RT switch cost is greater on short versus long CSI)..

Experiment 2 further supported the proposal that the differential positivity reflects processes involved in anticipatory task-set reconfiguration. Relative to repeat trials, both *switch-to* and *switch-away* trials showed a cue-locked differential positivity emerging after cue onset. This shows that forewarning of an impending switch in task initiates differential processing between switch and repeat trials, even in the absence of information that specifies which particular task will be active on the upcoming trial. The differential positivity observed for both types of switch trials may reflect the active inhibition of the previously relevant but now irrelevant task-set. For *switch-to* trials, the differential positivity remained significant centroparietally across the entire CSI, while for *switch-away* trials it reduced in amplitude early in the CSI and returned to baseline by 600 ms. Comparisons between *switch-to* and *switch-away* cue-locked difference waveforms showed that the later portion of the positivity was significantly smaller centroparietally over the later portion of the CSI for *switch-away* trials.

This suggests that on *switch-to* trials, the early processes common to both types of switch trials were followed by the activation of the relevant task-set and possibly maintenance of this preparation in working memory until stimulus onset, resulting in the sustained differential positivity. In contrast, for *switch-away* cues, it was not possible to activate the relevant task-set before stimulus onset and consequently the later portion of the differential positivity is absent on *switch-away* trials. For *switch-away* trials this process could only be activated after stimulus onset. The post-stimulus differential positivity in the switch-away condition is consistent with the active engagement of the relevant task-set after task specific information becomes available.

The results from Experiment 2 thus support the behavioural data suggesting that if anticipatory task-set reconfiguration is not initiated and / or completed before stimulus onset (e.g., the new task-set hasn't been retrieved), it must be competed after stimulus onset. This is also consistent with the no cue condition in Experiment 1 where participants could not initiate any form of task preparation prior to stimulus onset (i.e., they didn't know whether the task would switch or repeat until after the stimulus was presented). The no cue condition showed an increase in RT switch cost relative to the short 150 ms CSI condition (for the same RSI of 750 ms). Moreover, a differential positivity was evident for switch relative to repeat trials *after* stimulus onset in the no cue condition that was highly comparable to the differential positivity observed in the cued conditions.

A growing number of other recent studies have also used ERPs to examine the processes that underlie task-switching, however few have attempted to isolate processes associated with anticipatory task-set reconfiguration. Most have instead focused on differences between ERPs to switch and repeat stimuli occurring after stimulus onset (e.g., Barceló et al., 2000; Barceló et al. 2002; Gehring et al., 2003; Hsieh & Yu, 2002; Hsieh & Liu, 2005; Swainson et al., 2003). This is problematic in that ERP differences between switch and repeat trials occurring after stimulus onset may reflect processing differences occurring for a number of reasons. These include that there are differential levels of proactive interference for switch compared to repeat stimuli, differential levels 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. When attempting investigate ERP effects associated with anticipatory task-set reconfiguration, it is hence important to isolate them by examining either the interval preceding stimulus onset in an alternating runs predictable switching paradigm (e.g., Karayanidis et al., 2003) or the interval following cue onset in a cued task-switching paradigm, as in the current experiments.

If, as suggested, the differential positivity reflects anticipatory task-set reconfiguration processes, which have been shown to affect the RT switch cost, there should be a relationship between the differential positivity and RT. For example, the latency of the P300 is thought to reflect the time taken for stimulus evaluation, with shorter peak latencies associated with quicker RT (e.g., Donchin & Coles, 1988). To examine whether such a relationship can be established between D-Pos and the RT, data from Experiment 5 were reanalysed. This dataset was selected because it had the highest number of trials per condition (i.e., switch or repeat) and thus the cleanest ERP signal-to-noise ratio. Cue- and stimulus-locked ERPs and stimulus-locked LRPs were averaged separately for the fastest and slowest quartiles of RT. A quartile split was selected because the RTs were exceptionally fast (mean RT < 500 ms), so that even the relatively slow responses were still very fast. A half or thirds RT split would have provided less distinct groups. For each participant, separately for switch and repeat trials, RT cut-off values were estimated for the fastest and slowest 25% of responses. Across all participants, the fastest quartile RT cut-off ranged from 223-371 ms for repeat trials and 213-392 ms for switch trials and the slowest quartile ranged from 508-1322 ms for repeat trials and from 543-1424 ms for switch trials.
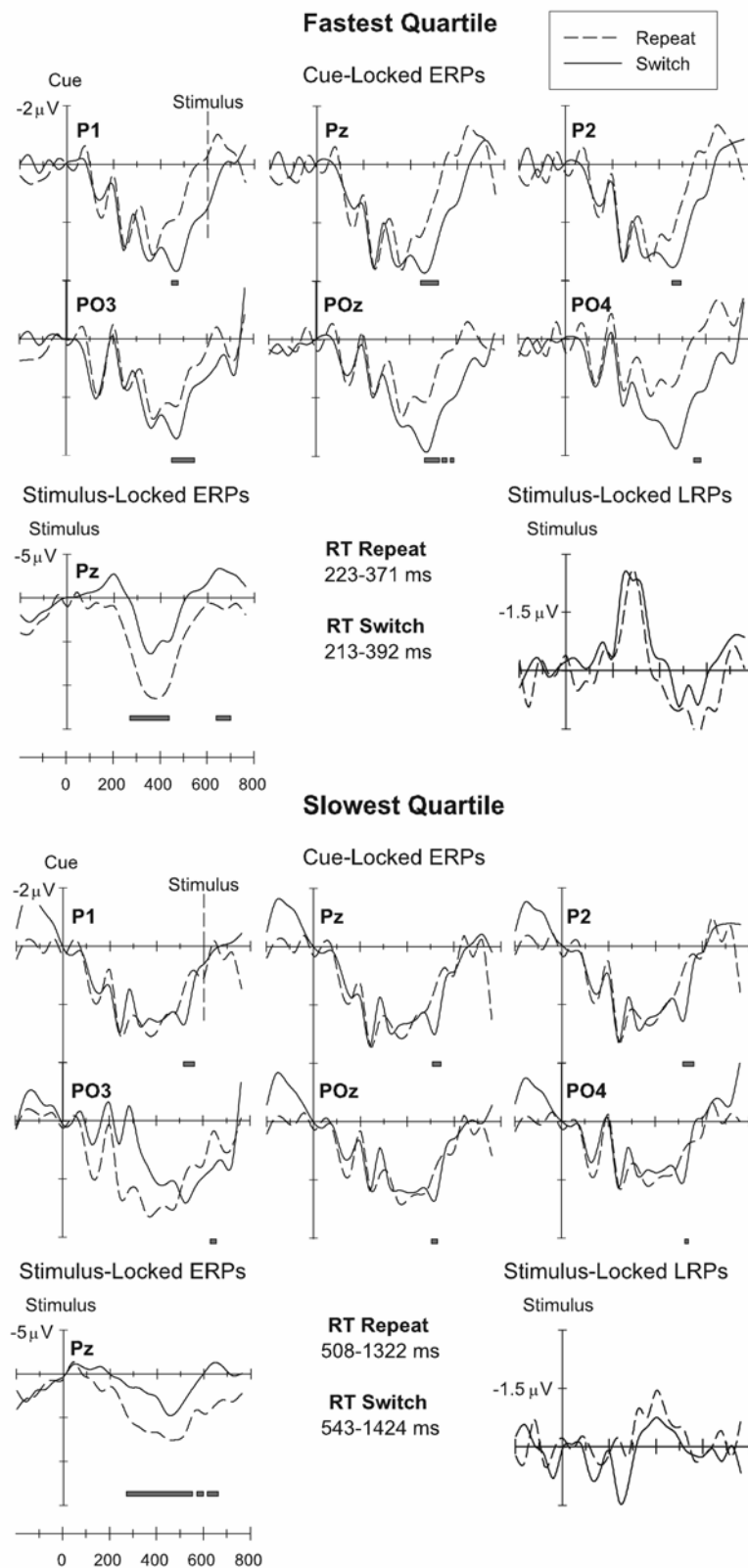
Figure 9-1. Cue- and stimulus-locked ERPs and stimulus-locked LRPs from Experiment 5 separated into the fastest versus the slowest quartiles of RT. Grey bars indicate regions of significant deviation between switch and repeat trials.

As Figure 9-1 shows, for the fastest quartile of responses a clear switch-related differential positivity was evident across the CSI at the parietal sites depicted. Stimulus-locked ERPs also show a differential negativity for switch trials and stimulus-locked LRPs show a sharp peak similar for both switch and repeat trials. These findings are consistent with the pattern observed across the entire RT range for long CSI conditions in Experiments 1-5. For the slowest quartile of responses (Figure 9-1, bottom), the differential positivity was almost non-existent with only a small window of significance emerging just prior to stimulus onset. The stimulus-locked waveforms showed an overall reduction in amplitude of the LPC, but a large negative shift for switch versus repeat waveforms was still evident. The peak of the LRPs is also reduced for both trial types and switch trials showed a tendency towards activation of the incorrect response (the positive peaks over 100-300 ms, Coles, 1988). These findings suggest a relationship between RT and the differential positivity, with a larger and clearer differential positivity associated with faster RT. Unfortunately, statistical analyses did not produce significant differences between ERP component measures for slow versus fast RT quartiles. This is most likely due to variability in the measurements (e.g., repeat and switch trials over slightly different timeframes and the longer range of RTs for the slowest quartile) and increased noise in the ERPs from the reduced number of trials contributing to the average waveforms (approximately 65 trials), combined with the relatively small number of participants (only 16).

However, these results point to the need for further work to examine the relationship between behavioural and ERP task-switching components. An interesting future study would thus be to analyse a RT split in a very simple paradigm with many subjects and attempt different methods to better equate switch and repeat trials (e.g., by using the same RT ranges for both trials types). A study with a large sample size may also allow investigation of individual differences in the relationship between RT switch cost and the differential positivity. For example, it would be important to determine whether participants with a greater and /or earlier onset of the differential positivity may have reduced RT switch cost. The development of new techniques enabling ERP analysis of a small number of trials based on the cumulative RT

distribution functions (i.e., small n ERP analyses) is an intriguing possibility and would have clear applications to this type of data analysis (i.e., application of the orthogonal polynomial trend analysis technique, Woestenburg, Verbaten, van Hees & Slangen, 1983).

The consistent finding of the switch-related differential positivity shows there is differential brain activity on switch relative to repeat trials. Experiment 5 attempted to localise and identify the brain regions differentially activated in anticipation of a switch trial by using EEG tomography analysis (LORETA). This analysis was conducted over two timeframes within the CSI where there maximal differentiation between switch and repeat trials (i.e., where there was the greatest differential positivity): 350-450 ms and 450-550 ms after cue onset. The LORETA results showed there were multiple areas of differential activation on switch as compared to repeat trials, with the pattern of differential activation varying across the two time intervals. Over 350-450 ms after cue onset, differential activation on switch as compared to repeat trials was evident in the prefrontal cortex, including the inferior, middle and superior frontal gyrus and more so in the left hemisphere. The activation in the superior frontal gyrus was also sustained over 450-550 ms, although it was slightly more anterior over the later time interval. This increased activation for switch trials in prefrontal cortical areas is consistent with the view that anticipatory task-set reconfiguration involves a cognitive control processes (Monsell, 2003; Rogers & Monsell, 1995) which has been traditionally associated with prefrontal cortex functioning (e.g., Miller & Cohen, 2001). It is also highly consistent with recent fMRI studies, which show larger prefrontal cortex activation in preparation for a switch in task (e.g., Brass & von Cramon, 2002; 2004; Brass et al., 2003; Braver et al., 2003; Dreher et al., 2002; Sohn et al., 2000).

The LORETA analysis also showed that a parietal network of activation involved in anticipatory task-set reconfiguration. There was significantly greater activation on switch trials in the precuneus over 350-450 ms after cue onset, with the strength of this parietal activation increasing over 450-550 ms as well as extending into the superior parietal lobule. This is consistent with a large number of fMRI studies that have found increased parietal activation

associated with a switch in task (Barber & Carter, 2005; Brass & von Cramon, 2004; Braver et al., 2003; Dove et al., 2000; Dreher & Grafman, 2003; Dreher et al., 2002; Erickson et al., 2006; Kimberg et al., 2000; Ruge et al., 2005; Rushworth, Paus & Sipila., 2001; Sohn et al., 2000). This parietal activation has been proposed to reflect multiple processes, including the shifting and orienting of attention and the interpretation of stimulus features that enable the application of stimulus-response mappings (Brass & von Cramon, 2004; Barber & Carter, 2005).

These findings suggest that the switch-related differential positivity reflects a network of brain activation that involves both prefrontal and parietal regions. Anticipatory task-set reconfiguration recruits cognitive control processes within the prefrontal cortex, which can identify the broadly relevant task goals (i.e., switch to the parity task) and accordingly signal more posterior processes to implement specific task goals, such as organisation of the stimulus–response mapping required for the upcoming trial, and then maintain this task preparation (e.g., odd = left hand response; even = right hand response; Brass & von Cramon, 2002; Brass, et al., 2005; Dreher & Grafman, 2003).

Stimulus-locked Effects for Both Trial Types

ERP waveforms were also analysed time-locked to stimulus onset in all experiments. Stimulus-locked ERPs tended to show a consistent pattern of P1, N1, P2 components emerging after stimulus onset for both trial types reflecting early visual processing. On both switch and repeat trials, these early ERPs then tended to be followed by a broad fronto-central negativity over 150-400 ms and a parietal LPC over approximately 300-600 ms.

Switch-related Differential Negativity

In addition to these effects, a negative deviation was consistently evident for switch relative to repeat trials, beginning as early as 150 ms after stimulus onset and extending until approximately 700 ms. This post-stimulus switch-related differential negativity tended to be maximal centro-parietally and peaked at around 400 ms after stimulus onset. These findings are consistent with stimulus-locked ERPs reported by Karayanidis et al. (2003). The differential

negativity was evident at all RSIs and emerged in some instances as early as 180 ms after stimulus onset, peaking around 550 ms for short RSIs, but earlier (400 ms) for longer RSIs (Karayanidis et al.). Other studies have also reported greater posterior negativity and later frontal positivity for switch compared to repeat trials following stimulus onset (Rushworth et al., 2002; 2005). Even though the differential negativity was larger centroparietally and peaked around 300-600 ms, it is unlikely to simply reflect a reduction in P3b for switch relative to repeat trials, as is suggested by Barceló et al. (2002; see discussions in Experiment 1 and 2).

In conditions where anticipatory task-set reconfiguration could not be completed prior to stimulus onset (i.e., the no cue condition in Experiment 1, *switch-away* trials in Experiment 2 and CSI was ≤ 200 ms in Experiments 1-3), the differential positivity emerged and resolved for switch trials *prior* to the onset of the differential negativity. This delay in onset of the differential negativity suggests that the processes represented by the negativity can not be initiated until completion of the processes reflected in the preceding differential positivity (i.e., anticipatory task-set reconfiguration). As Karayanidis et al. (2003) proposed, the consistent finding of the differential negativity, in combination with the residual RT switch cost, suggests that anticipatory task-set reconfiguration does not completely account for the RT switch cost. Rather, as suggested in the stimulus-triggered component of task-switching above, presentation of the stimulus on a switch trial is likely to trigger differential stimulus-response priming and / or response interference as compared to repeat trials (e.g., Allport and Wylie, 2000; Waszak et al., 2003), thereby contributing to the residual switch cost. The differential negativity may therefore partially reflect these processes.

LORETA analysis in Experiment 5 focused on brain regions differentially activated for switch compared to repeat trials during the CSI and the brain regions activated after stimulus onset were not analysed. Future task-switching research should thus aim to utilise paradigms like that in the current experiments that encourage participants to engage in anticipatory task-set reconfiguration while minimising possible confounds from other task-switching components. Combined behavioural, ERP, EEG topography *and* fMRI analysis would then enable further

investigation of the brain regions involved in task-set reconfiguration, both in anticipation of a switch in task and after stimulus onset. Compared with the prefrontal and parietal activations over the CSI, different brain regions would be expected to be recruited after stimulus onset that may be more active on switch compared to repeat trials, as switch trials are associated with increased difficulty and higher error rates (e.g., Rogers & Monsell, 1995). For example, the anterior cingulate cortex may triggered by the detection of response conflict (Badre & Wagner, 2004; Dreher & Berman, 2002; MacDonald, Cohen, Stenger & Carter, 2000) and the monitoring of performance outcomes may result in increased posterior medial frontal cortex activation (Ridderinkhof, Ullsperger, Crone & Nieuwenhuis, 2004; Ridderinkhof, van den Wildenberg, Segalowitz & Carter, 2004).

Effects on LRPs

LRPs, which represent differential activation over the contralateral motor cortex leading up to an overt lateralised hand response (Coles, 1989), were analysed for Experiment 1. There was no differences between switch and repeat trials for the response-locked LRPs, which are associated with motor processes involved in response execution (Miller & Hackley, 1992). In comparison, stimulus-locked LRPs, which are associated with pre-motor processes including response selection and activation, had a later onset for switch relative to repeat trials. Moreover, switch trials with a long CSI resulted in earlier stimulus-locked LRP onset as compared to switch trials with a short CSI. This suggests that switch trials are associated with more difficult stimulus processing and later response activation. This increased difficulty can however be reduced by engagement in anticipatory task-set reconfiguration when there is a long CSI, leading to earlier onset of response evaluation processes reflected by the stimulus-locked LRP.

Summary of Electrophysiological Correlates

The current findings provide strong evidence for differential ERP processing in preparation for an anticipated switch as compared to a repeat in task. Specifically, a parietally maximal switch-related positivity can be observed that peaks at around 350-500 ms after cue presentation. This differential positivity appears to reflect processes involved in anticipatory

task-set reconfiguration, such as recognising that the upcoming trial will require a switch in task followed by the retrieval and application of the now relevant task-set. This can be localised to greater activation in the prefrontal cortex, which is associated with the use of cognitive control processes, as well as increased activity in the parietal lobe as stimulus-response mappings are organised in preparation for the upcoming response and this preparation is maintained until stimulus onset. A consistent pattern of electrophysiological effects also emerged for switch versus repeat trials after stimulus onset. Where anticipatory task-set reconfiguration processes could not be initiated and completed prior to stimulus onset, these processes were executed immediately after stimulus presentation, prior to the initiation of other post-stimulus processes. The reliable finding of a residual RT switch cost and a switch-related differential negativity emerging after stimulus onset supports the involvement of a stimulus-triggered component in task-set reconfiguration, which is related to the detection and inhibition of task-set interference elicited by the presentation of the stimulus.

9.3 Implications for Models of Cognitive Control

The current experiments support the existence of an anticipatory component of task-set reconfiguration functioning as a cognitive control process, as originally proposed by Rogers and Monsell (1995). Participants were forewarned whether the upcoming trial would be a repeat of the task they had just performed or whether they would be required to switch tasks. Identification that a switch in task was required then necessitated the involvement of cognitive control processes to organise, implement and maintain other cognitive processes used in executing this switch in task. This includes processes involved in initiating the inhibition of task irrelevant information, such as general distractions and the no longer relevant task-set, triggering the retrieval of the now relevant task-set and preparation of the stimulus-response mappings, as well as the constant monitoring and, when necessary, resolution of any problems that may arise (e.g., task-set interference).

Traditional theories of cognitive control have tended to revolve around a unitary executive operating as a discrete control centre from within the prefrontal cortex (i.e., the

homunculus). This control centre is then responsible for overseeing sub-ordinate processes that have specific and dedicated functions, much like a manager supervising employees working on a production line. However, the current experiments suggest that the cognitive control processes involved in anticipatory task-set reconfiguration are consistent with a more distributed network of control. This network involves the frontal and parietal lobes and forms an intricate and adaptive circuit that organises, monitors, troubleshoots and adjusts the delicate balance between activation and inhibitory processes to facilitate task preparation and execution (e.g., Brass & von Cramon, 2002; Brass et al., 2005; Dreher & Grafman, 2003; Gruber & Goschke, 2004). Within this framework, the conscious experience of having an intention to act (i.e., a participant's mental awareness of their initiation of anticipatory task-set reconfiguration) is thought to occur as a by-product of the activation of these brain regions and associated processes. That is, current research does not support a dualist mind-body causation approach to conscious intention, such as where the mental desire to prepare for the upcoming task triggers the physical activation of the brain regions involved in anticipatory task-set reconfiguration. Rather, the experience of having a conscious intention to act occurs as the consequence of, as opposed to the cause of, brain activation (Haggard, 2005).

The question thus remains as to how the brain ascertains that control processes are required and then how such processes are implemented. One possibility is that cognitive control processes are triggered based on the constant monitoring for conflict (Botvinick, Braver, Barch, Carter & Cohen, 2001). For example, having just performed Task A, the cognitive system is primed for the repeat execution of this task. A cue signalling that the upcoming trial will require performance of Task B creates conflict between the goal representations for task performance (need to do Task B) compared with the current state of readiness (currently ready for Task A). Cognitive control processes, which in this case refers to anticipatory task-set reconfiguration, may thus be initiated to resolve this conflict. Control processes thus play a vital role in enabling and setting the desired outcomes for autonomously-running processes, which can then be monitored and adjusted over time, such as initiating the application of the new task-set.

While the prefrontal cortex undoubtedly plays an important role in the functioning of cognitive control processes (e.g., Miller & Cohen, 2001; Ridderinkhof, Ullsperger, Crone & Nieuwenhuis, 2004; Ridderinkhof, van der Wildenberg, Segalowitz & Carter, 2004; Stuss & Alexander, 2000), it is now clear that it does not function as the single universal and ubiquitous control centre as was previously thought. Current findings are only just beginning to better understand that cognitive control stems from the activation of complex and reciprocal neural pathways linking the prefrontal cortex to other areas of the brain enabling the performance of any given task. Clearly, this will be an area of burgeoning research interest over the coming decades and slowly the mystery of cognitive control processes will begin to unravel.

9.4   General Issues and Future Directions

The current experiments demonstrate that task-switching paradigms are a useful tool in the ongoing investigation of cognitive control processes and there are many avenues for future research to explore bearing in mind a few caveats. In most task-switching studies, including the current experiments, repeat trials are used as a baseline condition against which to compare performance on switch trials. This is based on the assumption that common processes occur on both trial types with additional processes recruited for switch trials (Rogers & Monsell, 1995). However, the tendency to merely look at the switch minus repeat differential can be potentially misleading. For example, a reduction in RT switch cost can occur due to either a *decrease* in RT on switch trials and / or an *increase* in RT on repeat trials. It is hence important to verify that a reduction in switch cost, or an apparent absence of switch cost, is due to a reduction in RT on switch trials, for a reasonably consistent RT on repeat trials. By extension, the switch-related differential positivity may be reduced in amplitude and /or duration either due to a decrease in the component on switch trials or due to an increase on repeat trials. Notably, such effects may occur on some proportion of repeat trials as participants accidentally engage in task-set reconfiguration. This can occur due to a variety of factors including a temporary loss of concentration, a misinterpretation of the task cue or a specific task strategy, such as if the task is overwhelmingly complicated or demanding, participants may engage in task-set reconfiguration

on repeat *and* switch trials as a coping strategy to minimise the task complexity and amount of effort required. Task parameters should thus be designed to minimise this effect, such as by using simple visual cues that can be easily interpreted and by providing participants with substantial task practice to ensure strong associations between cue-task and stimulus-response mappings (Monsell & Mizon, 2006).

As Experiment 3 highlighted, because anticipatory task-set reconfiguration is an endogenously activated process, experimental parameters affect whether or not this process is activated for switch trials prior to stimulus onset. The current experiments utilised a number of methods for maximising engagement in anticipatory task-set reconfiguration, most simplistically the novel method of removing the cue prior to stimulus onset (Experiments 3-5) and limiting the time available for a correct response (Experiment 5; see also Lien et al., 2005). Other parameters may also potentially be manipulated to further increase the proportion of trials on which participants engage in anticipatory task-set reconfiguration. Nieuwenhuis and Monsell (2002) modified Rogers and Monsell's (1995) paradigm to provide behavioural feedback about mean RT for switch and repeat trials after each run of trials. They developed a pay-off reward system for increasingly faster responses in an attempt to motivate participants. Overall RT for both switch and repeat trials, as well as the RT switch cost, reduced and the estimated number of prepared trials increased relative to Rogers and Monsell (1995), although a significant residual switch cost remained. Notably, feedback was provided for both switch and repeat trial RT, not switch cost. An interesting manipulation would thus be to provide participants with their current mean RT switch cost at the end of each run of trials and motivate them to try and reduce this as much as possible, such as through a competitive ranking and reward type system.

Monsell and Mizon (2006) also suggest that the proportion of switch relative to repeat trials can affect engagement in anticipatory task-set reconfiguration. Monsell and Mizon found that RT switch cost reduced most significantly with increasing CSI when switch trials occurred on only one quarter of all trials. This effect was less pronounced when a task switch occurred on one third of trials, although significant reductions with increasing CSI were still observed with

an equal proportion of switch and repeat trials, as in Experiments 1 and 3-6. It would thus be expected that if Experiment 5 were replicated with only one quarter of switch trials and / or a motivational feedback reward system, the RT switch cost would be reduced as participants engage in anticipatory task-set reconfiguration on an even more trials.

Notably, in the last two experiments, the CSI was always fixed at 600 ms, with an exceptionally low RT switch cost of only 32 ms observed in Experiment 5 with overall mean RT of less than 500 ms. As previously discussed, this suggests participants were using the long CSI to engage in anticipatory task-set reconfiguration. However, this is in conflict with recent studies, such as Altmann (2004), which suggest participants must experience a range of CSIs in order to capitalise on the benefit presented by the longer CSI. That is, participants need to experience a short preparation condition in order to recognise the opportunity presented by the longer preparation interval. This may have been unnecessary Experiments 4 and 5, as parameters such as the removal of the cue forced participants to use the CSI to prepare for the switch in task. However, a further interesting manipulation would thus be to replicate Experiment 5 with three between-subject groups; one with a short and long CSI, one with a short CSI only and one with a long CSI only. If Altmann is correct, the lowest RT switch cost should be in the long CSI condition in participants who experience both the long and short CSI.

Blocking versus randomising the preparation interval may also affect engagement in anticipatory task-set reconfiguration. Rogers and Monsell (1995) initially varied the RSI randomly on a trial-by-trial basis in their second experiment. The results did not show any significant pattern of reduction in switch cost with increasing RSI. In comparison, in Rogers and Monsell's Experiment 3, when they varied the RSI across a block of trials, the RT switch cost significantly declined as the RSI increased (Figure 1-2). Rogers and Monsell proposed that participants failed to engage in anticipatory task-set reconfiguration with a random variation in RSI due to the confusing and unpredictable nature of the task and the resulting task strategies adopted by participants to cope with this. That is, because participants were unaware of when the stimulus would appear, potentially interrupting any reconfiguration processes they were

currently undertaking, it was easier for task-set reconfiguration to be delayed until after stimulus onset. Based on these findings, in Experiments 1-3 and 6 that manipulated CSI and RSI, the intervals were always varied across a block of trials, with the order of the RSI / CSI conditions counterbalanced across participants using a Latin square design. However, in terms of counterbalancing and randomising effects it would be preferable to vary the CSI randomly within a block a trials. Monsell and Mizon (2006) show that similar behavioural results can be obtained in a cueing paradigm for blocked versus random CSI manipulations. However, it remains unclear what effect the randomisation of the CSI would have on ERP effects, such as it may be expected to introduce greater variability and hence noise into the waveforms and should thus probably be avoided without prior systematic investigation of such potential effects.

As in most task-switching paradigms, in the current experiments the timing and sequence of tasks was always fixed. That is, participants had no control over what they were required to do or when to do it, such as when or whether they were required to switch or repeat tasks. However, it seems intuitively obvious that cognitive control processes are likely to be more consistently and effectively activated for tasks that are unstructured and require greater self-initiation and organisation of performance (Lezak, 1983). Fixed-pace experimental protocols, as typically used in task switching paradigms, also tend to increase the sequential structure in RT distributions, as opposed self-paced responding that results in more realistic random performance (Kelly, Heathcote, Heath & Longstaff, 2001). An interesting adaptation to current task-switching paradigms that would make findings more comparable with real world performance is thus analysing the effects of a voluntary switch in task.

Arrington and Logan (2004a) required participants to select which of two possible tasks to perform on any given trial at stimulus onset. RT switch cost reduced as the RSI increased from 100 to 1000 ms suggesting that similar anticipatory task-set reconfiguration processes are activated in voluntary and experimenter-controlled task-switching. Using a similar manipulation, Arrington and Logan (2005) reported smaller RT switch cost for a voluntary switch in task relative to an externally cued switch in task. Clearly this is another area for future

research as it would be expected that with an optimal preparation interval, participants should be fully prepared for the current trial when they initiate a voluntary switch in task. It would also be expected that under these conditions there would be only minimal interference from task-set inertia as participants would be unlikely to initiate a switch in task until task-set interference effects had almost completely passively decayed over the time since the previous response.

9.5   Significance and Innovations

In conclusion, recent research has focused on understanding the mystery of cognitive control processes and banishing, or at least attempting to dissect, the homunculus. Over the last decade or so task-switching paradigms have emerged as one of a number of useful tools in this quest. It is now clear that many complex factors and components contribute to the classic task-switching effect of a RT switch cost. The current experiments utilised both behavioural and electrophysiological measures to clearly demonstrate that one pivotal component involved in task-switching is anticipatory task-set reconfiguration. This refers to an endogenously triggered act of cognitive control that recognises an upcoming switch in task is required and organises cognitive processes accordingly, such as abandoning the no longer relevant task-set and retrieving and applying the new task-set. This process is reflected in the increased positivity of ERP waveforms, most clearly evident over parietal electrodes, which can be localised to greater activation in the prefrontal and parietal regions of the brain.

The massive variability in paradigms and experimental parameters in task-switching research conducted over the last decade has created a large and somewhat uncohesive field of literature. As manipulations and tasks become more standardised with easily replicable effects, clear patterns are beginning to emerge in normative populations. Eventually, research such as that presented in the current experiments may assist in the development of formal models of cognitive control that can then test and verify different theoretical formulations. This fractionation of cognitive control components will enable further understanding of how to better manage or even overcome the deficits in cognitive control processes evident in clinical conditions such as autism, attention deficit hyperactivity disorder and schizophrenia.

10   References

Allport, A., Styles, E. A., & Hsieh, S. (1994). Shifting intentional set: Exploring the dynamic control of tasks. In C. Umilta & M. Moscovitvh (Eds.), *Attention and Performance XV* (pp. 421-452). Cambridge, MA: MIT Press.

Allport, D. A., & Wylie, G. (2000). Task-switching, stimulus response bindings, and negative priming. In S. Monsell & J. Driver (Eds.), *Attention and Performance XVIII* (pp. 35 - 70). Cambridge, MA: MIT Press.

Altmann, E. M. (2003). Task switching and the pied homunculus: Where are we being led? *Trends in Cognitive Sciences, 7*(8), 340-341.

Altmann, E. M. (2004). The preparation effect in task switching: Carryover of SOA. *Memory & Cognition, 32*(1), 153-163.

Anderson, S.W., Damasio, H., Jones, R. D., & Tranel, D. (1991). Wisconsin Card Sorting Test performance as a measure of frontal lobe damage. *Journal of Clinical and Experimental Neuropsychology, 13,* 909-922.

Andreasen, N. C. (1984a). *Scale for the assessment of negative symptoms (SANS).* Iowa: UNI of Iowa.

Andreasen, N.C. (1984b). *Scale for the assessment of positive symptoms (SAPS).* Iowa: UNI of Iowa.

Andreasen, N.C., Rezai, K., Alliger, R., Swayze, V. W., Flaum, M., Kirchner, P., Cohen, G., & O'Leary, D.S. (1992). Hypofrontality in neuroleptic-naïve patients with chronic schizophrenia: Assessment with xenon 133 single photon emission computed tomography and the Tower of London. *Archives of General Psychiatry, 49,* 943-958

Andreasen, N.C., Paradiso, S., & O'Leary, D. (1998) "Cognitive Dysmetria" as an integrative theory of schizophrenia: A dysfunction in cortical-subcortical-cerebellar circuitry? *Schizophrenia Bulletin, 24,* 203-218.

Arbuthnott, K., & Frank, J. (2000). Executive control in set switching: Residual switch cost and task-set inhibition. *Canadian Journal of Experimental Psychology, 54*(1), 33-41.

Aron, A. R., Monsell, S., Sahakian, B. J., & Robbins, T. W. (2004). A componential analysis of task-switching deficits associated with lesions of left and right frontal cortex. *Brain, 127 (7),* 1561-1573.

Aron, A. R., Robbins, T. W., & Poldrack, R. A. (2004). Inhibition and the right inferior frontal cortex. *Trends in Cognitive Sciences, 8 (4),* 170-177.

Arrington, C. M., & Logan, G. D. (2004a). The cost of a voluntary task switch. *Psychological Science, 15*(9), 610-615.

Arrington, C. A., & Logan, G. D. (2004b). Episodic and semantic components of the compound stimulus strategy in the explicit task cuing procedure. *Memory & Cognition, 32*(6), 965-976.

Arrington, C. M., & Logan, G. D. (2005). Voluntary task switching: Chasing the elusive homunculus. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31*(4), 683-702.

Baddeley, A. D. (1986). *Working memory*. Oxford: Oxford University Press.

Badre, D., & Wagner, A. (2004). Selection, integration, and conflict monitoring: Assessing the nature and generality of prefrontal cognitive control mechanisms. *Neuron, 41,* 473-487.

Barber, A. D., & Carter, C. S. (2005). Cognitive control involved in overcoming prepotent response tendencies and switching between tasks. *Cerebral Cortex, 157,* 899-912.

Barceló, F., Munoz-Cespedes, J. M., Pozo, M. A., & Rubia, F. J. (2000). Attentional set shifting modulates the target P3b response in the Wisconsin card sorting test. *Neuropsychologia, 38*(10), 1342-1355.

Barceló, F. C. A., Perianez, J. A., & Knight, R. T. (2002). Think differently: A brain orienting response to task novelty. *Neuroreport, 13*(15), 1887-1892.

Barkley, R. A. (1997) Behavioural inhibition, sustained attention and executive functions: Constructing a unifying theory of ADHD. *Psychological Bulletin, 121,* 65-94.

Barrett, G. (1996). Event-related potentials (ERPs) as a measure of complex cognitive function. In C. Barber (Ed.), *Functional Neuroscience: Electroencephalography and clinical neurophysiology supplement number 46.* The Netherlands: Elsevier.

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108*, 624–652.

Brass, M., Derrfuss, J., Forstmann, B., von Cramon, D. Y. (2005) The role of the inferior frontal junction area in cognitive control. *Trends in Cognitive Sciences, 9,* 314-316.

Brass, M., & Yves von Cramon, D. (2002). The role of the frontal cortex in task preparation. *Cerebral Cortex, 129*, 908-914.

Brass, M., von Cramon, D. Y. (2004). Decomposing components of task preparation with functional magnetic resonance imaging. *Journal of Cognitive Neuroscience, 16(4),* 609-6(20.

Brass, M., Ruge, H., Meiran, N., Rubin, O., Koch, I., Zysset, S., Prinz, W., & von Cramon, D. Y. (2003). When the same response has different meanings: Recoding the response meaning in the lateral prefrontal cortex. *NeuroImage, 202*, 1026-1031.

Brass, M., Ullsperger. M., Knoesche, T. R., von Cramon, D. Y., & Phillips, N. A. (2005). Who comes first? The role of the prefrontal and parietal cortex in cognitive control. *Journal of Cognitive Neuroscience, 17*, 1367-1375.

Braver, T. S., Barch, D. M. & Cohen, J.D. (1999). Cognition and control in schizophrenia: A computational model of dopamine and prefrontal function. *Biological Psychiatry, 46,* 312-328.

Braver, T. S., Reynolds, J. R., & Donaldson, D. I. (2003). Neural mechanisms of transient and sustained cognitive control during task switching. *Neuron, 394,* 713-726.

Brown, S., Lehmann, C. & Poboka, D. (2006). A critical test of the failure-to-engage theory of task switching. *Psychonomic Bulletin and Review,* 13 (1), 152-159.

Brown, R. G., & Marsden, C.D. (1988). Internal versus external cues and the control of attention in Parkinson's disease. *Brain, 111,* 323-345.

Burgess, P. W. (2000). Strategy application disorder: the role of the frontal lobes in human multitasking. *Psychological Research, 63,* 279-288.

Callaway, E. (1975). *Brain electrical potentials and individual psychological differences.* New York: Grune & Stratton.

Cohen, J.D., Barch, D. M., Carter, C., & Servan-Schreiber, D. (1999). Context-processing deficits in schizophrenia: Converging evidence from three theoretically motivated cognitive tasks. *Journal of Abnormal Psychology, 108,* 120-133.

Coles, M. G. H. (1989). Modern mind-brain reading: psychophysiology, physiology, and cognition. *Psychophysiology, 26, 251-269.*

Coles, M. G. H., Bernstein, P. S. & Fournier, L. (1995). Where did you go wrong? Errors, partial errors, and the nature of information processing. *Acta Psychologica, 90,* 129-144.

Conklin, H. M., Curtis, C. E., Calkins, M. E., & Iacono, W. G. (2005) Working memory functioning in schizophrenia patients and their first-degree relatives: cognitive functioning shedding light on etiology. *Neuropsychologia. 43,* 930-942.

Cools, R., Brouwer, W. H., de Jong, R., & Slooff, C. (2000). Flexibility, inhibition, and planning: Frontal dysfunctioning in schizophrenia. *Brain and Cognition, 43,* 108-112.

Damen, E. J. P. & Brunia, C. H. M. (1994). Is a stimulus conveying task-relevant information a sufficient condition to elicit a stimulus-preceding negativity? *Psychophysiology, 31,* 129-139.

De Jong, R. (2000). An intention - activation account of residual switch costs. In S. Monsell & J. Driver (Eds.), *Attention and Performance XVIII* (pp. 357-376). Cambridge, MA: MIT Press.

Donchin, E. & Coles, M. G. H. (1988). Is the P300 component a manifestation of context updating? *Behavioural and Brain Sciences, 11,* 357–374.

Dove, A., Pollmann, S., Schubert, T., Wiggins, C. J., & von Cramon, D. Y. (2000). Prefrontal cortex activation in task-switching: An event related fMRI study. *Cognitive Brain Research, 9,* 103-109.

Dreher, J.-C., & Berman, K. F. (2002). Fractionating the neural substrates of cognitive control processes. *Proceedings of the National Academy of Sciences, 99 (22),* 14595-14600.

Dreher, J.-C., Koechlin, E., Ali, S. O., & Grafman, J. (2002). The roles of timing and task order during task switching. *NeuroImage, 17(1),* 95-109.

Dreher, J.-C., & Grafman, J. (2003). Dissociating the roles of the rostral anterior cingulate and the lateral prefrontal cortices in performing two tasks simultaneously or successively. *Cerebral Cortex, 134*, 329-339.

Dreisbach, G., Haider, H., & Kluwe, R. H. (2002). Preparatory processes in the task-switching paradigm: Evidence from the use of probability cues. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 28*(3), 468-483.

Duncan, J. (1986). Disorganisation of behaviour after frontal-lobe damage. *Cognitive Neuropsychology, 3,* 271-290.

Elliott, R., McKenna, P., Robbins, T., & Sahakian, B. J. (1998). Specific neuropsychological deficits in schizophrenic patients with preserved intellectual function. *Cognitive Neuropsychiatry, 3,* 45-70.

Falkenstein, M., Hohnsbein, J. & Hoorman, J. (1995). Event-related potential correlates of errors in reaction tasks. In: G. Karmos, M. Molmar, V. Csepe, I. Czigler, & J. E. Desmedt (Eds). *Perspectives of event-related potential research. (EEG Supplement, 44, pp. 287-296).* Amsterdam, Elsevier Science BV.

Erickson, K. I., Colcombe, S. J., Wadhwa, R., Bherer, L., Peterson, M. S., Scalf, P. E., & Kramer. A. F. (2006). Neural correlates of dual-task performance after minimizing task-preparation. *NeuroImage, 28 (4),* 967-979.

Fagot, C. (1994). *Chronometric investigations of task switching.*, Ph.D. dissertation., University of California, San Diego, USA.

Fallgatter, A. J., Bartsch, A. J., & Herrmann, M. J. (2002). Electrophysiological measurements of anterior cingulate function. *Journal of Neural Transmission, 109*, 977– 988.

Forstmann, B. U., Brass, M. & Koch, I. (in press). Methodological and empirical issues when dissociating cue-related from task-related processes in the explicit task-cuing procedure. *Psychological Research.*

Fuchs., M., Wagner, M., Kohler, T., & Wischmann, H. A. (1999). Linear and non-linear current density reconstructions. *Journal of Clinical Neurophysiology, 16*, 267–95.

Gade, M.& Koch., I. (2005). Linking inhibition to activation in the control of task sequences. *Psychonomic Bulletin & Review, 12*(3), 530-534.

Gehring, W. J., Bryck, R. L., Jonides, J., Albin, R. L., & Badre, D. (2003). The mind's eye, looking inward? In search of executive control in internal attention shifting. *Psychophysiology, 40*(4), 572-585.

Gilbert, S., & Shallice, T. (2002). Task switching: A PDP model. *Cognitive Psychology, 44*, 297-337.

Gladwin, T. E., Lindsen, J. P., & de Jong, R. (2006). Pre-stimulus EEG effects related to response speed, task switching and upcoming response hand. *Biological Psychology*, *72*, 15-34.

Goffaux, P., Phillips, N., Sinai, M., & Pushkar, D. (2006). Behavioural and electrophysiological measures of task switching during single and mixed-task conditions. *Biological Psychology*, 72, 278-290.

Gold, J. M., Carpenter, C., Randolph, C., Goldberg, T. E. & Weinberger, D. R. (1997). Auditory working memory and Wisconsin Cars Sorting performance in schizophrenia. *Archives of General Psychiatry, 54,* 159-165.

Goldberg, T. E., & Weinberger, D. R. (1994). The effects of clozapine on Neuro cognition: An overview. *Journal of Clinical Psychiatry*, *55 (B),* 88-90.

Goldman-Rakic, P. (1987) Circuitry of primate prefrontal cortex and regulation of behaviour by representational memory. In F. Plum (Ed.) *Handbook of Physiology: The Nervous System.* American Physiological Society.

Goldman-Rakic, P. (1994) Cerebral cortical mechanisms in schizophrenia. *Neuropsychopharmacology, 10,* 22-27.

Goldstein, L. H., Bernard, S., Fenwick, P. B. C., Burgess, P. W. & McNeil, J. (1993) Unilateral frontal lobectomy can produce strategy application disorder. *Journal of Neurology, Neurosurgery and Psychiatry, 56,* 274-276.

Goschke, T. (2000). Intentional reconfiguration and involuntary persistence in task set switching. In S. Monsell, & J. Driver (Ed.), *Attention and Performance XVIII* (pp. 331-355). Cambridge MA: MIT Press.

Grave de Peralta, M. R., & Gonzalez, S. L. (2000). Discussing the capabilities of Laplacian minimization. *Brain Topography, 13,* 97–104.

Gruber, O., & Goschke, T. (2004). Executive control emerging from dynamic interactions between brain systems mediating language, working memory and attentional processes. *Acta Psychologica, 115*(2), 105-121.

Guthrie, D., & Buchwald, J. S. (1991). Significance testing of difference potentials. *Psychophysiology, 28,* 240-244.

Haggard, P. (2005). Conscious intention and motor cognition. *Trends in Cognitive Sciences, 9 (6),* 290-295.

Hahn, S., Andersen, G. J., & Kramer, A. F. (2003). Multidimensional set switching. *Psychonomic Bulletin & Review, 10* (2), 503-509.

Hämäläinen, M.S., & Illmoniemi, R.J. (1994). Interpreting magnetic fields of the brain – minimum norm estimates. *Medical and Biological Engineering and Computing, 32,* 35-42.

Hart Jr., J., & Gordon, B. (1990). Delineation of single-word semantic comprehension deficits in aphasia, with anatomical correlation. *Annals of Neurology, 27 (3),* 226–231.

Hahn, S., Andersen, G. J., & Kramer, A. F. (2003). Multidimensional set switching. *Psychonomic Bulletin & Review, 10*(2), 503-509.

Heaton, R. K., Chelune, G. J., Talley, J. L., Kay, G. G., & Curtiss, G. (1993). *Wisconsin Card Sorting Test: Computer Version-2.* Odessa, FL: PAR.

Heimberg, D. R., Naber, G., Hemmeter, U., Zechner, S., Witzke, W., Gerhard, U., Dittman, V., Holsboer-Trachsler, E. & Hobi, V. (1999). Contingent negative variation and attention in schizophrenia and depressed patients. *Neuropsychobiology, 39,* 131-140.

Henik, A., Carter, C. S., Salo, R., Chaderjian, M., Kraft, L., Nordahl, T. E., & Robertson, L.C. (2002). Attentional control and word inhibition in schizophrenia. *Psychiatry Research, 110,* 137-149.

Herrmann, M. J., & Fallgatter, A. J. (2004). Visual oddball paradigm: stability of topographical descriptors and source localization of the P300 component. *Journal of Psychophysiology, 18,* 1– 12.

Hodges, J. R., Patterson, K., Oxbury, S., & Funnell, E. (1992). Semantic dementia. Progressive fluent aphasia with temporal lobe atrophy. *Brain, 115*, 1783–1806.

Hommel, B., Daum, I., & Kluwe, R. H. (2004). Exorcizing the homunculus, phase two: Editors' introduction. *Acta Psychologica, 115*(2-3), 99-104.

Hommel, B., Ridderinkhof, R. K., Theeuwes, J. (2002). Cognitive control of attention and action: Issues and trends. *Psychological Research, 66,* 215-219.

Hsieh, S., & Yu, Y. T. (2003). Switching between simple response-sets: Inferences from the lateralized readiness potential. *Cognitive Brain Research, 17, 228-237.*

Hsieh, S., & Liu, L.C. (2005). The nature of switch cost: Task set configuration or carry-over effect? *Cognitive Brain Research, 22,165-175.*

Hsieh, S. (2006). The lateralised readiness potential and P300 of stimulus-set switching. *International Journal of Psychophysiology, 60(3),* 284-291.

Hubner, M., Dreisbach, G., Haider, H., & Kluwe, R. H. (2003). Backward inhibition as a means of sequential task-set control: Evidence for reduction of task competition. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 29*(2), 289-297.

Hunt, A. R., & Klein, R. M. (2002). Eliminating the cost of task set reconfiguration. *Memory & Cognition, 30*(4), 529-539.

Hyvärinen, A. (1999). Fast and Robust Fixed-Point Algorithms for Independent Component Analysis. *IEEE Transactions on Neural Networks, 10,* 626-634.

Hyvärinen, A., Oja, E. (1997). A Fast Fixed-Point Algorithm for Independent Component Analysis. *Neural Computation, 9,* 1483-1492.

Hyvärinen, A., Oja, E. (2000). Independent Component Analysis: Algorithms and Applications. *Neural Networks, 13,* 411-430.

Hyvärinen, A. & Karhunen, J., Oja., E. (2001). *Independent Component Analysis*. Wiley InterScience; John Wiley & Sons.

Isreal, J., Wickens, C., & Donchin, E. (1979). P300 amplitude changes during a tracking task as a function of continuous variations of tracking difficulty. *Psychophysiology, 16*, 175.

Jablensky A, McGrath J, Herrman H. (1999). *People living with psychotic illness: an Australian study 1997-98*. Canberra: Commonwealth of Australia.

James (1890) *The principles of Psychology*. Oxford: Holt.

Jutten, C., & Herault, J. (1991). Blind separation of sources, Part I: An adaptive algorithm based on neuromimetic architecture. *Signal Processing, 24*, 1-10.

Karayanidis, F., Coltheart, M., Michie, P. T., Murphy, K. (2003). Electrophysiological correlates of anticipatory and post-stimulus components of task -switching. *Psychophysiology, 40(3),* 329-348.

Karayanidis, F., Jenkins, L., Fox, L. (2001). Attentional control in children: Behavioural and ERP measures of task switching. 13th Conference on Event-Related Potentials of the Brain (EPIC), Paris, France, 9-14 July, *International Journal of Psychophysiology, 41,* 213.

Keele, S. W., & Rafal, R. (2000). Deficits in task set in patients with left prefrontal cortex lesions. In S. Monsell & J. Driver (Eds.), *Attention and Performance XVIII* (pp. 627-651). Cambridge: MIT Press.

Kelly, A., Heathcote, A., Heath, R. A. & Longstaff, M. (2001). Response time dynamics: Evidence for linear and low-dimensional non-linear structure in human choice sequences. *Quarterly Journal of Experimental Psychology, 54*, 805-840.

Kieras, D. E., Meyer, D. E., Ballas, J. A., & Lauber, E. J. (2000). Modern computational perspectives on executive mental control: Where to from here? In S. Monsell & J. Driver (Eds.), *Attention and Performance XVIII* (pp. 681-712). Cambridge, MA: MIT Press.

Koch, I., Gade, M., & Philipp, A. M. (2004). Inhibition of response mode in task switching. *Experimental Psychology 2004, 51*(1), 52-58.

Kimberg, D. Y., Aguirre, G. K., & D'Esposito, D. (2000). Modulation of task-related neural activity in task-switching: An fMRI study. *Cognitive Brain Research, 10,* 189-(196.

Knight, R. T. (1991). Evoked potential studies of attention capacity in human frontal lobe lesions. In H. S. Levin, H. M. Eisenberg, & A. L. Benton (Eds). *Frontal lobe function and dysfunction* (pp. 139-53). Oxford University Press, New York.

Koch, I. (2001). Automatic and intentional activation of task sets. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 27*(6), 1474-1486.

Kounios, J., Smith, R. W., Yang, W., Bachman, P., & D'Esposito, M. (2001). Cognitive association formation in human memory revealed by spatiotemporal brain imaging. *Neuron, 29,* 297– 306.

Liddle, P. F. Friston, K. J. Frith, C.D. Frackowiak R. S. (1992). Cerebral blood flow and mental processes in schizophrenia. *Journal of the Royal Society of Medicine, 85,* 224-227.

Lien, M. C., Ruthruff, E., Remington, R. W., & Johnston, J. C. (2005). On the limits of advance preparation for a task switch: Do people prepare all the task some of the time or some of the task all the time? *Journal of Experimental Psychology: Human Perception and Performance, 31*(2), 299-315.

Levine, B., Stuss, D. T., Milberg, W. P., Alexander, M. P., Schwartz, M. P., & Macdonald, R. (1998). The effects of focal and diffuse brain damage on strategy application: Evidence from focal lesions, traumatic brain injury and normal aging. *Journal of the Int. Neuropsychological Society, 4,* 247-264.

Lezak, M. D. (1983). *Neuropsychological assessment* (2nd ed.) Oxford: Oxford U Press.

Loftus, G. R. & Masson, M. E. (1994). Using confidence intervals in within-subject designs. *Psychonomic Bulletin and Review, 1,* 476-490.

Logan, G. D. (1985). On the ability to inhibit simple thoughts and actions: II. Stop-signal studies of repetition priming. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *11*, 675-691.

Logan, G. D. (2003). Executive control of thought and action: In search of the wild homunculus. *Current Directions in Psychological Science, 12(2),* 45-48.

Logan, G. D., & Bundesen, C. (2003). Clever Homunculus: Is There an Endogenous Act of Control in the Explicit Task-Cuing Procedure? *Journal of Experimental Psychology: Human Perception and Performance, 29(3),* 575-599.

Logan, G. D., & Bundesen, C. (2004). Very clever homunculus: Compound stimulus strategies for the explicit task-cuing procedure. *Psychonomic Bulletin & Review, 11*(5), 832-840.

Logan, G. D., & Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychological Review*, *108*, 393-434.

Logan, G. D., & Schneider, D. W. (in press). Priming or executive control? Associate priming of cue encoding increases 'switch costs' in the explicit task-cuing paradigm. *Memory and Cognition.*

Lorist, M. M., Klein, M., Nieuwenhuis, S., De Jong, R., Mulder, G., & Meijman, T. F. (2000). Mental fatigue and task control: Planning and preparation. *Psychophysiology, 37,* 614-625.

Loveless, N. E. & Sanford, A. J. (1974) Effects of age on the contingent negative variation and preparatory set in a reaction-time task. *Journal of Gerontology, 29,* 5 2-63.

Luks, T. L., Simpson, G. V., Feiwell, R. J., & Miller, W. L. (2002). Evidence for anterior cingulate cortex involvement in monitoring preparatory attentional set. *NeuroImage, 172,* 792-802.

Luu, P., Flaisch, T. & Tucker, D. M. (2000). Medial frontal cortex in action monitoring. *Journal of Neuroscience, 20,* 464-469.

MacDonald, A. W. & Carter, C. S. (2002). Cognitive experimental approaches to investigating impaired cognition in schizophrenia: A paradigm shift. *Journal of Cognitive and Experimental Neuropsychology, 24,* 873-882.

MacDonald, A., W., III, Cohen, J. D., & Stenger, V. A. (2000). Dissociating the role of Dorsolateral Prefrontal and Anterior Cingulate Cortex in cognitive control. *Science, 288,* 1835-1838.

Mangun, G. R, & Hillyard, S. A. (1990). Allocation of visual attention to spatial locations: trade-off functions for event-related brain potentials and detection performance. *Perceptual Psychophysiology, 47,* 532–50.

Makeig, S., Debener, S., Onton, J., & Delorme, A. (2004). Mining event-related brain dynamics. *Trends in Cognitive Sciences, 8,* 204-210.

Manoach, D.S., Lindgren, K. A., Cherkasova, M. V., Goff, D.C., Halpern, E. F., Intriligator, J., & Barton, J. J. S. (2002). Schizophrenic subjects show deficient inhibition but intact task switching on saccadic tasks. *Biological Psychiatry, 51,* 816-826.

Mayr, U., & Keele, S. W. (2000). Changing Internal Constraints on Action: The Role of Backward Inhibition. *Journal of Experimental Psychology: General, 129(1),* 4-26.

Mayr, U., & Kliegl, R. (2000). Task-Set Switching and Long-Term Memory Retrieval. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 26(5),* 1124-1140.

Mayr, U., & Kliegl, R. (2003). Differential Effects of Cue Changes and Task Changes on Task-Set Selection Costs,. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29,* 362-372.

McCallum, W. C., Walter, W. G. (1968). The effects of attention and distraction on the contingent negative variation in normal and neurotic subjects. *Electroencephalography and Clinical Neurophysiology, 25,* 319-329.

McCarthy, G. & Donchin, E. (1981). A metric for thought: a comparison of P300 latency and reaction time. *Science, 211*, 77–80.

McCarthy, G., & Wood, C. C. (1985). Scalp distributions of event-related potentials: An ambiguity associated with analysis of variance models. *Electroencephalography and Clinical Neurophysiology, 62(3),* 203-208.

McGuffin P, Farmer A, Harvey I (1991): A polydiagnostic application of operational criteria in studies of psychotic illness. Development and reliability of the OPCRIT system. *Archives of General Psychiatry, 48,* 764-70.

Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22*, 1423-1442.

Meiran, N. (2000a). Reconfiguration of stimulus task sets and response task sets during task switching. In S. Monsell & J. Driver (Eds.), *Attention and Performance XVIII* (pp. 377-399). Cambridge: MIT Press.

Meiran, N. (2000b). Modelling control in task-switching. *Psychological Research, 63*, 234-249.

Meiran, N., & Chorev, Z. (2005). Phasic alertness and the residual task-switching cost. *Experimental Psychology, 52*(2), 109-124.

Meiran, N., Chorev, Z., & Sapir, A. (2000). Component processes in task switching. *Cognitive Psychology, 41,* 211-253.

Meiran, N., Levine, J., Meiran, N., & Henik, A. (2000). Task set switching in schizophrenia. Neuropsychology, 14, 471-482.

Miller, E. K., & Cohen, J. D. (2001. An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience, 24,* 167-202.

Miller, J., & Hackley, S.A. (1992). Electrophysiological evidence for temporal overlap among contingent mental processes. *Journal of Experimental Psychology: General, 121, 195–209.*

Miniussi, C., Marzi, C. A., & Nobre, A. C. (2005). Modulation of brain activity by selective task sets observed using event-related potentials. *Neuropsychologia, 43 (10),* 1514-1528

Monsell, S. (1996). Control of mental process. In V. Bruce (Ed.), *Unsolved mysteries of the mind: Tutorial essays in cognition* (pp. 93-148). Hove, England: Erlbaum, Taylor, & Francis.

Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences, 7*(3), 134-140.

Monsell, S., & Mizon, G.A. (2006). Can the task-cueing paradigm measure an "endogenous" task-set reconfiguration process? *Journal of Experimental Psychology: Human Perception and Performance, 32*, 493-516

Monsell, S., Sumner, P., & Waters, H. (2003). Task-set reconfiguration with predictable and unpredictable task switches. *Memory & Cognition, 31(3),* 327-342.

Mordkoff, J.T. & Gianaros, P.J. (2000). Detecting the onset of the lateralized readiness potential: A comparison of available methods and procedures. *Psychophysiology, 37, 347-360.*

Näätänen, R. (1990). The role of attention in auditory information processing as revealed by event-related potentials and other brain measures of cognitive function. *Behavioural and Brain Sciences, 13*, 201–288.

Nelson, H. E. (1982). *National Adult Reading Test: Test Manual.* Windsor, UK: NFER Nelson.

Nichols, T. E. & Holmes, A. P. (2002). Nonparametric permutation tests for functional neuroimaging: a primer with examples. *Human Brain Mapping, 15*,1–25.

Nieuwenhuis, S., & Monsell, S. (2002). Residual costs in task -switching: Testing the failure to engage hypothesis. *Psychonomic Bulletin and Review, 9*(1), 86-92.

Norman, D. A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behaviour. In G. Davidson & D. Shapiro (Eds.), *Consciousness and self -regulation* (pp. 1-18). New York: Plenum.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh Inventory. *Neuropsychologia, 9,* 97-113.

Pantelis, C., Barnes, T. R., Nelson, H. E., Tanner, S., Weatherley, L., Owen, A. M., & Robbins, T. W. (1997). Frontal-striatal cognitive deficits in patients with chronic schizophrenia. *Brain, 120,* 1823-1843.

Pascual-Marqui, R.D. (1999). Review of Methods for Solving the EEG Inverse Problem. *International Journal of Bioelectromagnetism, 1,* 75-86.

Pascual-Marqui, R.D., Esslen, M., Kochi, K. & Lehmann, D. (2002). Functional imaging with low resolution brain electromagnetic tomography (LORETA): review, new comparisons, and new validation. *Japanese Journal of Clinical Neurophysiology, 30,* 81-94.

Pascual-Marqui, R.D., Michel, C. M. & Lehmann, D. (1994). Low resolution electromagnetic tomography: a new method for localizing electrical activity in the brain. *International Journal of Psychophysiology, 18*, 49-65.

Perlstein, W. M., Carter, C. S., Noll, D.C. & Cohen, J.D. (2001). Relation of prefrontal cortex dysfunction to working memory and symptoms in schizophrenia. *American Journal of Psychiatry, 158,* 1105–1113.

Picton, T. W., Bentin, B., Berg, P., Donchin, E., Hillyard, S. A., Johnson, J. R., Miller, G. A., Ritter, W., Ruchkin, D., Rugg, M., & Taylor, M. J. (2000). Guidelines for using human event-related potentials to study cognition: Recording standards and publication criteria. *Psychophysiology, 37*, 127-152.

Poboka, D., Heathcote, A., Karayanidis, F. & Nicholson, R. (2005). An Investigation of Task Switch Costs: Preparation Activation, Timing and Readiness Decay. *International Conference on Attentional Control,* Jan 4-7, National Chung Cheng University, Taiwan.

Poulsen, C., Luu, P., Davey, C., & Tucker, D. M. (2005). Dynamics of task sets: Evidence from dense-array event-related potentials. *Cognitive Brain Research, 24*, 133-154.

Pritchard, W. S. (1986). Cognitive event-related potential correlates of schizophrenia. *Psychological Bulletin, 100,* 203-208.

Rasser, P., Johnston, P., Lagopoulos, J., Ward, P., Schall, U., Thienel, R., Bender, S., Toga, A. W., Thompson, P.M. (2005) Functional MRI BOLD response of Tower of London performance of first-episode schizophrenia patients using cortical pattern matching. *NeuroImage, 26,* 941-951

Ridderinkhof, K. R., Ullsperger, M., Crone, E. A., & Nieuwenhuis, S. (2004). The role of the medial frontal cortex in cognitive control. *Science, 306(15),* 443-447.

Ridderinkhof, K. R., van den Wildenberg, W., Segalowitz, S. J., & Carter, C. S. (2004). Neurocognitive mechanisms of cognitive control: The role of prefrontal cortex in action selection, response inhibition, performance monitoring, and reward learning. *Brain and Cognition, 56*, 129-140.

Rogers, R. D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology, 124 (2),* 207 - 231.

Rohrbaugh, J. W., Syndulko, K. & Lindsley, D. B. (1976). Brain wave components of the contingent negative variation in humans. *Science, 191,* 1055-1057.

Rubia, K., Russell, T., Taylor, E., Bullmore, E. T., Brammer, M. J., Williams, S. C. R., Andrew, C., & Sharma, T. (2001). An fMRI study of reduced left prefrontal activation in schizophrenia during normal inhibitory function. *Schizophrenia Research, 52*, 47-55.

Rubinstein, J. S., Meyer, D. E., & Evans, E. (2001). Executive control of cognitive processes in task switching. *Journal of Experimental Psychology: Human Perception and Performance, 27*(4), 763-797.

Ruge, H., Brass, M., Koch, I., Rubin, O., Meiran, N., & von Cramon, D. Y. (2005). Advance preparation and stimulus-induced interference in cued task switching: Further insights from bold fMRI. *Neuropsychologia, 43(3),* 340-355.

Rugg, M. D. & Coles, M. G. H. (1995). *Electrophysiology of mind: Event-related brain potentials and cognition.* New York: Oxford University Press.

Rushworth, M. F. S., Passingham, R. E., & Nobre, A. C. (2002). Components of switching intentional set. *Journal of Cognitive Neuroscience, 14(8),* 1139-1150.

Rushworth, M. F. S., Passingham, R. E., & Nobre, A. C. (2005). Components of attentional set-switching. *Experimental Psychology, 52*(2), 83-98.

Rushworth, M., Paus, T., & Sipila, P. K. (2001). Attention systems and the organization of the human parietal cortex. *The Journal of Neuroscience, 2114*, 5262-5271.

Ruthruff, E., Remington, R. W., & Johnston, J. C. (2001). Switching between simple cognitive tasks: The interaction of top-down and bottom-up factors. *Journal of Experimental Psychology: Human Perception & Performance, 27*(6), 1404-1419.

Semlitsch, H. V., Anderer, P., Schuster, P., & Presslich, O. (1986). A solution for reliable and valid reduction of ocular artefacts. *Psychophysiology, 23,* 695-703.

Shallice, T., & Burgess, P. W. (1991). Deficits in strategy application following frontal lobe damage in man. *Brain, 114,* 727-741.

Schall, U., Catts, S. V., Chaturvedi, S., Liebert, B., Redenbach, J., Karayanidis, F., & Ward, P. B. (1998). The effect of clozapine therapy on frontal lobe dysfunction in schizophrenia: neuropsychology and event-related potential measures. *International Journal of Neuropsychopharmacology,. 1,* 19-29.

Schatz, J. (1998). Cognitive processing efficiency in schizophrenia: generalized versus domain specific deficits. *Schizophrenia Research, 30,* 41-49.

Schuch, S., & Koch, I. (2003). The role of response selection for inhibition of task sets in task shifting. *Journal of Experimental Psychology: Human Perception and Performance, 29*(1), 92-105.

Sohn, M.-H., & Anderson, J. R. (2001). Task preparation and task repetition: Two-component model of task switching. *Journal of Experimental Psychology: General, 130*(4), 764-778.

Sohn, M. H., & Carlson, R. A. (2000). Effects of repetition and foreknowledge in task-set reconfiguration. *Journal of Experimental Psychology: Learning, Memory & Cognition, 26,1445-1460.*

Sohn, M., Ursu, S., Anderson, J. R., Stenger, V. A., & Carter, C. S. (2000). The role of prefrontal cortex and posterior parietal cortex in task-switching. *Proceedings of the National Academy of Sciences, 97,* 13448-13453.

Schuch, S., & Koch, I. (2003). The role of response selection for inhibition of task sets in task shifting. *Journal of Experimental Psychology: Human Perception and Performance, 29*(1), 92-105.

Smith, G. L., Large, M. M., Kavanagh, D. J., Karayanidis, F., Barrett, N. A., Michie, P. T., & O'Sullivan, P. T. (1998). Further evidence for a deficit in switching attention in schizophrenia. *Journal of Abnormal Psychology, 107,* 390-398.

Spector, A., & Biederman, I. (1976). Mental set and mental shift revisited. *American Journal of Psychology, 89 (4),* 669-679.

Sternberg, S. (1969). The discovery of processing stages: extensions of Donders' method. *Acta Psychologia, 30,* 276-315.

Stuss, D. T. & Benson, D. F. (1986) *The Frontal Lobes.* Raven Press: New York.

Stuss, D. T., & Alexander, M. P. (2000). Executive functions and the frontal lobes. *Psychological Research, 63,* 289-98.

Sudevan, P., & Taylor, D. A. (1987). The cueing and priming of cognitive operations. *Journal of Experimental Psychology: Human Perception and Performance, 13,* 89-103.

Swainson, R., Cunnington, R., Jackson, G., Rorden, C., Peters, A., Morris, P., & Jackson, S. R. (2003). Cognitive control mechanisms revealed by ERP and fMRI: Evidence from repeated task-switching. *Journal of Cognitive Neuroscience, 15*(6), 785-799.

Talairach, J., & Tournoux, P. (1988). *Co-Planar Stereotaxic Atlas of the Human Brain.* Thieme, Stuttgart.

Tecce, J. J., Savignano-Bowman, J. & Meinbresse, D. (1976). Contingent negative variation and the distraction-arousal hypothesis. *Electroencephalography and Clinical Neurophysiology, 41,* 277-286.

Tornay, F. J., & Milan, E. G. (2001). A more complete task-set reconfiguration in random than in predictable task switch. *Quarterly Journal of Experimental Psychology A, 54*(3), 785-803.

Trujillo-Barreto, N.J., Aubert-Vazquez, E. Valdes-Sosa, P.A. (2004). Bayesian model averaging in EEG/MEG imaging. *NeuroImage, 21*, 270.

Ulrich, R., & Miller, J. (2001). Using the jack-knife-based scoring method for measuring LRP onset effects in factorial designs. *Psychophysiology, 38,* 816–827.

Van den Wildenberg, W. P. M., van der Molen, M. W., & Logan, G. D. (2002). Reduced response readiness delays stop signal inhibition. *Acta Psychologica*, *111*, 155-169.

Vasey, M. W., & Thayer, J. F. (1987). The continuing problem of false positives in repeated measures ANOVA in psychophysiology: A multivariate solution. *Psychophysiology, 24(4),* 479-486.

Verleger, R., Wascher, E., Arolt, V., Daase, C., Strohm, A. & Kömpf, D. (1999). Slow EEG potentials (contingent negative variation and post-imperative negative variation) in schizophrenia: their association to the present state and to Parkinsonian medication effects. *Clinical Neurophysiology, 110,* 1175-1192.

Vigario, R., Sarela, J., Jousmaki, V., Hamalainen, M., & Oja, E. (2000). Independent component approach to the analysis of EEG and MEG recordings. *IEEE Transactions on Biomedical Engineering, 47*, 589–593.

Walter, W. G., Cooper, R., Aldridge, V. J., McCallum, W. C., & Winter, A. L. (1964). Contingent negative variation: an electrical sign of sensorimotor association a expectancy in the human brain. *Nature, 230*, 380-4.

Waszak, F., Hommel, B., & Allport, A. (2003). Task-switching and long term priming: Role of episodic stimulus-task bindings in task-shift costs. *Cognitive Psychology, 46(4),* 361-413.

Williams, S. B. K., Phillips, J. G., Bellgrove, M., Bradshaw, J. L., Bradshaw, J. A. & Pantelis, C. (2000). Use of advance information in patients with schizophrenia. *Journal of Experimental and Clinical Neuropsychology, 22,* 472-482.

Williams, B. R, Ponesse, J. S., Schachar, R. J., Logan, G. D., & Tannock, R. (1999). Development of inhibitory control across the life span. *Developmental Psychology, 35,* 205-213.

Woestenburg, J. C., Verbaten, M. N., van Hees, H. H., & Slangen, J. L. (1983). Single trial ERP estimation in the frequency domain using orthogonal polynomial trend analysis (OPTA): estimation of individual habituation. *Biological Psychology, 17*, 173-191.

Woodward, T. S., Meier, B., Tipper, C., & Graf, P. (2003). Bivalency is costly: Bivalent stimuli elicit cautious responding. *Experimental Psychology, 50(4),* 233-238.

Wylie, G., & Allport, A. (2000). Task switching and the measurement of 'switch costs'. *Psychological Research, 63*, 212-233.

Wylie, G. R., Javitt, D. C., & Foxe, J. J. (2003). Task switching: A high-density electrical mapping study. *NeuroImage, 20*, 2322-2342.

Yeung, N., & Monsell, S. (2003a). The effects of recent practice on task switching. *Journal of Experimental Psychology: Human Perception and Performance, 29*, 919-936.

Yeung, N., & Monsell, S. (2003b). Switching between tasks of unequal familiarity: The role of stimulus-attribute and response-set selection. *Journal of Experimental Psychology: Human Perception & Performance, 29*, 455-469.

11 Appendix

Publications incorporated within thesis

Paper Number: 1

Corresponds to experiment number: 1 (chapter 2)

Authors: Rebecca Nicholson, Frini Karayanidis, Dane Poboka, Andrew Heathcote & Pat Michie

Title: Electrophysiological correlates of anticipatory task-switching processes

Journal: Psychophysiology

Status: Published 2005, issue 42(5), pages 540-554

Notes and acknowledgements regarding the roles and contributions of co-authors: Portions of this experiment, including some of the preliminary ERP analysis, were presented as part of my Bachelor of Arts Honours thesis at the University of Newcastle, Australia, in 2002 (under maiden name of Rebecca Hannan). Preliminary analysis of the cumulative distribution functions based on the RT data (not included as part of the experiment in this thesis) were also presented as part of the Honours thesis submitted by Dane Poboka in 2002 (titled 'the effects of anticipatory preparation and passive dissipation processes relative to switch costs', unpublished honours thesis, the University of Newcastle, Australia; see also Poboka et al., 2005). Andrew Heathcote provided advice regarding paradigm design and behavioural analysis. As per all publications arising from this thesis, Frini Karayanidis and Pat Michie were my PhD supervisors and thus played a crucial role in all experiments.

Paper Number: 2

Corresponds to experiment number: 2 (chapter 4)

Authors: Rebecca Nicholson, Frini Karayanidis, Anna Davies & Pat Michie

Title: Components of Task-set Reconfiguration: Differential Effects of '*Switch-to*' and '*Switch-away*' Cues

Journal: Brain Research

Status: in revision

Notes and acknowledgements regarding the roles and contributions of co-authors: Preliminary ERP analysis with a smaller sample size (N=24) was presented as part of the Honours thesis submitted by Anna Davies in 2003 (titled 'active preparation in task-switching: effects of 'switching to' versus 'switching away' from a task-set', unpublished honours thesis, the University of Newcastle, Australia) and she was responsible for assistance with data collection for these 24 subjects.

Paper Number: 3

Corresponds to experiment number: 4 (chapter 6)

Authors: Rebecca Nicholson, Frini Karayanidis, Elizabeth Bumak, Dane Poboka & Pat Michie

Title: ERPs dissociate the effects of switching task-sets and task-cues

Journal: Brain Research

Status: Published 2006, issue 1095, pages 107-123.

Notes and acknowledgements regarding the roles and contributions of co-authors: A small section of the analysis was presented as part of the Honours thesis submitted by Elizabeth Bumak in 2004 (titled 'capturing the homunculus: evidence from task-switching paradigms', unpublished honours thesis, the University of Newcastle, Australia) and she was responsible for assistance with data collection. The RT cumulative distribution function analysis was conducted with the assistance of Dane Poboka.

Paper Number: 4

Corresponds to experiment number: 5 (chapter 7)

Authors: Rebecca Nicholson, Frini Karayanidis, Ross Fulham & Pat Michie

Title: Organization of anticipatory task-switching processes using low-resolution electromagnetic tomography (LORETA)

Journal: International Journal of Psychophysiology

Status: in revision

Notes and acknowledgements regarding the roles and contributions of co-authors: Ross Fulham provided advice regarding the parameters and interpretations of the LORETA analysis.

Paper Number: 5

Corresponds to experiment number: 6 (chapter 8)

Authors: Frini Karayanidis, Rebecca Nicholson, Ulrich Schall, Lydia Meem, Ross Fulham & Pat Michie

Title: Switching between univalent task-sets in schizophrenia: ERP evidence of an anticipatory task-set reconfiguration deficit

Journal: Clinical Neurophysiology

Status: in press

Notes and acknowledgements regarding the roles and contributions of co-authors: Sections of the behavioural data only from this publication was presented as part of the Psychology Clinical Masters thesis by Lydia Meem (co-supervised by Frini Karayanidis and Ulrich Schall) in 2004 (titled 'task switching in schizophrenia: anticipatory and stimulus-driven components of task set reconfiguration processes associated with a predictable task switch', unpublished Masters thesis, the University of Newcastle, Australia). Mean amplitude ERP analysis was conduced using the EEG Display program, developed by Ross Fulham.