Psychophysiology, 42 (2005), 540–554. Blackwell Publishing Inc. Printed in the USA.

DOI: 10.1111/j.1469-8986.2005.00350.x

Electrophysiological correlates of anticipatory task-switching processes

REBECCA NICHOLSON,[a,b] FRINI KARAYANIDIS,[a,b,c] DANE POBOKA,[a] ANDREW HEATHCOTE,[a] AND PATRICIA T. MICHIE[a,b,c]

[a]Discipline of Psychology, School of Behavioural Sciences, University of Newcastle, Callaghan, Australia
[b]Neuroscience Institute for Schizophrenia and Allied Disorders (NISAD), Darlinghurst, Australia
[c]Hunter Medical Research Institute, Newcastle, Australia

Abstract

Recent studies show a differential switch-related positivity emerging before a switch trial and reflecting anticipatory task-set reconfiguration processes. In this study, the switch-related positivity was examined in a cued task-switching paradigm. Cue-stimulus and response-stimulus intervals were independently manipulated to dissociate between the effects of anticipatory preparation and passive dissipation of task-set interference. Reaction time switch cost declined with increasing cue-stimulus and response-stimulus intervals, suggesting a contribution from both active preparation and passive interference processes. In cue-related difference waveforms, a switch positivity peaked around 350–400 ms and is interpreted as reflecting differential activation of task-set reconfiguration. In stimulus-related difference waveforms, a switch-related negativity is believed to indicate the role of S-R priming and response interference in task-switching.

Descriptors: Task-switching, Attentional control, Control processes, ERP

Task-switching paradigms require rapid alternation between simple tasks throughout a block of trials. Switch trials are associated with increased reaction time (RT) and error rate as compared to repeat trials (e.g., Meiran, 1996; Meiran, Chorev, & Sapir, 2000; Rogers & Monsell, 1995). This switch cost is presumed to reflect, at least partially, processes associated with or contributing to "task-set reconfiguration" (Rogers & Monsell, 1995), a set of processes involved in shifting from a readiness to perform task A to a readiness to perform task B. In Rogers and Monsell's alternating runs task-switching paradigm, increasing the interval between a response to the current stimulus and the onset of the next stimulus (i.e., response–stimulus interval) from 150 to 1200 ms resulted in a significant decline in RT switch cost. Rogers and Monsell proposed that this decline in RT switch cost reflects an active "anticipatory" component of task-set reconfiguration that is endogenously triggered and that, given a predictable switch in task and adequate time, can be initiated prior to stimulus presentation. This anticipatory component is assumed to involve processes such as suppression of the previously active but now irrelevant task set and activation of the previously inactive and currently relevant task set. A second component of task-set reconfiguration was inferred from the persistence of a "residual" switch cost even at the longest response-stimulus interval. Rogers and Monsell (1995) argued that this "stimulus-triggered" component reflects task-set reconfiguration processes that are initiated by the stimulus and, therefore, cannot be prepared in advance.

Other theoretical formulations have associated switch cost with passive interference processes elicited by the stimulus itself. Allport, Styles, and Hseih (1994) attributed RT switch cost to "task-set inertia" resulting from continued activation of the currently irrelevant task set (i.e., positive priming) and continued inhibition of the previously irrelevant, but now relevant task set (i.e., negative priming). Although Allport and Wylie (2000; see also Waszak, Hommel, & Allport, 2003; Wylie & Allport, 2000) acknowledged the existence of a "goal-setting" or "goal-activation" component (see also Fagot, 1994) that is involved in identifying task relevant goals and can be set prior to stimulus onset, they argued that RT switch cost is determined by the level of task "readiness," which, in turn, is affected by the amount of interference between the competing tasks (i.e., positive and negative task priming). With a long response-stimulus interval, this interference has more opportunity to passively dissipate, resulting in increased task readiness and hence reduced RT switch cost.

In the alternating runs paradigm, the task sequence is fully predictable, and therefore preparation for a switch trial can begin anytime after processing the preceding stimulus. Longer response-stimulus intervals provide more time for passive dissipation of the currently irrelevant task set as well as greater opportunity to initiate anticipatory task-set reconfiguration for

This work was supported by a postgraduate scholarship from the Neuroscience Institute for Schizophrenia and Allied Disorders (NISAD) and the University of Newcastle to Rebecca Nicholson.

Address reprint requests to: Dr. Frini Karayanidis, Discipline of Psychology, School of Behavioural Sciences, Newcastle University, Callaghan, NSW 2308, Australia. E-mail: Frini.Karayanidis@newcastle.edu.au.

the relevant task set. Meiran and colleagues (Meiran, 1996; Meiran et al., 2000) used trial-by-trial task cueing to examine the relative contribution of passive dissipation and anticipatory preparation to RT switch cost. Increasing response-stimulus interval (Meiran et al., 2000) and increasing cue to stimulus interval (Meiran, 1996) both produced a significant reduction in RT switch cost as well as a substantial residual switch cost, supporting multiple component models of task switching (e.g., Meiran, 2000).

Alternatively, De Jong (2000) argued that RT switch cost can be fully accounted for by task-set reconfiguration, an all-or-none process that may be activated before or after stimulus onset depending on task and subject parameters. On some trials, this task-set reconfiguration process is activated and completed prior to stimulus onset and there is no RT switch cost. On other trials, task-set reconfiguration occurs after stimulus onset, resulting in a switch cost. With increasing response-stimulus interval, task-set reconfiguration is engaged prior to stimulus onset in a greater proportion of trials, resulting in a reduction of average RT switch cost. However, as some trials remain unprepared even at the longest response-stimulus interval, a residual switch cost remains. Thus, De Jong argued that residual switch cost does not reflect a separate component of task switching, but rather occurs because, despite adequate preparation time, participants "fail to engage" in advance preparation on some percentage of switch trials.

Task Switching and Event-Related Brain Potentials (ERPs)

Event-related brain potentials (ERPs) can inform the debate over the number and type of processes underlying RT switch cost because they provide information regarding the timeline of processes leading up to the behavioral response. Karayanidis, Coltheart, Michie, and Murphy (2003) used the alternating runs paradigm (Rogers & Monsell, 1995) to identify ERP components associated with the anticipatory component of task-set reconfiguration in waveforms time-locked to the response to the preceding trial and in anticipation of the impending switch trial (i.e., in response-related waveforms covering the response-stimulus interval) and ERP components associated with the stimulus-triggered processes affecting switch cost in waveforms time-locked to the onset of a switch stimulus (i.e., in stimulus-related waveforms). Response-related waveforms showed a large parietally maximal differential positivity (termed D-Pos)[1] 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 (Karayanidis et al., 2003, Figure 6). At short response-stimulus intervals (150, 300 ms), D-Pos began prior to stimulus onset, but continued after stimulus onset, overlapping early ERP components associated with stimulus processing. At longer response-stimulus intervals (600, 1200 ms), D-Pos was superimposed on a CNV-like negativity and fully completed before stimulus onset. Stimulus-related waveforms showed a large posterior late positivity for both repeat and switch stimuli. This late positivity was much smaller for the switch trials, and Karayanidis et al. interpreted this as reflecting a superimposed negativity for switch as compared to repeat trials (D-Neg). D-Neg was evident at all response-stimulus intervals and emerged in some instances as early as 180 ms after stimulus onset, peaking around 550 ms for short response-stimulus intervals, but earlier (400 ms) for longer response-stimulus intervals. These findings supported a two-component model of task switching, with the differential positivity in the response-stimulus interval reflecting anticipatory task-set reconfiguration processes and the differential negativity after stimulus onset linked to stimulus-triggered processes (Karayanidis et al., 2003).

Although a growing number of studies have used ERPs to examine the processes that underlie task-switching, few studies have attempted to isolate processes associated with anticipatory preparation for an impending switch in task. Wylie, Javitt, and Foxe (2003) used a modified alternating runs paradigm with three run sequences (AAABBB). Stimulus-related ERPs derived across the whole S1–S2 epoch showed that, compared to repeat trials, pre-switch trials were associated with a large sustained posterior positivity emerging around 400 ms and a small anterior negativity. Wylie et al concluded that the absence of a frontal anticipatory component argues against a reconfiguration process and interpreted the posterior sustained effect as reflecting a "top-down" mechanism that adjusts the activation weights of the two task rules, leading to increased competition between rules that, in turn, increases poststimulus interference, thus leading to RT switch costs. Note, however, that anticipatory processes were not examined in ERP waveforms time-locked to the likely onset of preparatory processes (e.g., EMG onset, readiness potential, response completion). Given trial-by-trial variability in RT, stimulus-related waveforms are likely to smear any ERP components time-locked to decision or response onset.

The alternating runs paradigm used in the above two studies cannot precisely locate the onset of an anticipatory task-set reconfiguration process. The predictable nature of the task means that participants are aware of whether the next few trials will require a task switch or repeat and can commence preparation at any time. In addition, the paradigm confounds processes associated with the execution of a response to trial n with the likely onset of anticipatory preparation for trial $n + 1$. A number of studies have now examined task preparation using cued switching paradigms. Rushworth, Passingham, and Nobre (2002) used a simple S-R mapping switching paradigm (switching intentional set) in which participants were cued every 7–18 trials to either maintain or reverse S-R mapping between two simple shapes and response hand. Their findings support multicomponent models of task switching. With a 1200-ms cue-stimulus interval, cue-related waveforms showed an early frontal switch-related positivity (360–520 ms) succeeded by a later posterior positivity (520–1040 ms), whereas stimulus-related waveforms indicated greater early posterior negativity and later frontal positivity for switch compared to repeat trials. Rushworth, Passingham, and Nobre (2005) showed that switching attentional set (e.g., shifting between different stimulus dimensions) also produced large early modulation for switch compared to repeat waveforms. Cue-related waveforms (cue-stimulus interval 2000 ms) showed a

[1] As in Karayanidis et al. (2003), the terms D-Pos and D-Neg are used here as convenience labels to refer to the differential switch-repeat positivity in cue-related waveforms and the differential switch-repeat negativity in stimulus-related waveforms, respectively, without necessarily implying that each label represents a single ERP component, defines a new ERP component that is not evident in the original waveforms, or reflects a single underlying cognitive process (see also the Discussion). Given that the identity, number, and cortical source of ERP components differentially involved in task switching and the underlying cognitive processes are still being defined, we believe that there is no advantage to using existing ERP component labels to identify these effects until such correspondence has been empirically established. Therefore the terms D-Pos and D-Neg merely describe the data and provide bookmarks for phenomena that need to be defined.

right lateral frontal negativity and a left posterior positivity over 360–440 ms, followed by a later posterior central positivity spreading from 500 ms onward. These effects were followed by a stimulus-related negativity for switch compared to stay trials that persisted beyond the first few trials and occurred even on trials that did not require set implementation (no response).

Barcelo, Perianez, and Knight (2002; see also Barcelo, Munoz-Cespedes, Pozo, & Rubia, 2000) used a modified version of the Wisconsin Card Sorting Test and recorded ERPs to feedback tones presented after every trial (cue-stimulus interval 1400 ms). These feedback tones indicated whether the response to the previous trial was correct and therefore whether to continue using the same classification rule (stay cue) or to change to one of the other two classification rules (switch cue; every 4–8 stay trials). ERPs to switch cues resulted in a large frontal positivity (350–400 ms) and a large later parietal positivity (550–600 ms) that reduced in amplitude for the first stay cue and was not evident in subsequent stay trials. Test cards also elicited a late parietal positivity that was smaller for switch feedback cues and increased over successive stay trials. These effects were interpreted as modulation of frontal P3a and parietal P3b components as a result of switching task set and updating and/or implementing the new task set, respectively. Note, however, that the feedback tones provided information not only as to whether to switch or stay on the next trial, but also about whether the preceding response was correct.

Miniussi, Marzi, and Nobre (2005) used trial-by-trial cued switching (variable cue-stimulus interval of 500–900 ms) between verbal and spatial tasks that used distinct stimulus sets. Cue-related switch waveforms showed an early anterior negativity followed by a posterior positivity spanning 440–600 ms after cue onset. These switch-related effects were larger on the more difficult verbal task. Overall, these studies provide strong evidence for differential processing of switch and repeat cues in the cue-stimulus interval. Most studies identify one or more differential positivities within the 300–600-ms range. However there is large variability between studies and between conditions in the number, distribution, and range of differential switch versus repeat effects. None of these studies have systematically manipulated the duration of response-stimulus and cue-stimulus intervals. As a result, the long cue-stimulus interval confounds effects of passive processes associated with task-set interference and active processes associated with task-set reconfiguration on RT and ERP measures.

The present study used a cued version of the alternating runs paradigm to confirm the relationship between the differential switch-related positivity and task-set reconfiguration. Like Rogers and Monsell (1995), stimuli were presented on a 2×2 grid, and each quadrant on the grid was mapped to one of the two tasks (Figure 1). However, each trial commenced with a cue that validly indicated the position of the next stimulus and hence the task to be completed. To eliminate any potential confound between cue position change and task switch (e.g., Logan & Bundesen, 2003), on repeat trials, the cue never highlighted the same quadrant on successive trials. Passive dissipation of the competing task set was examined by varying the duration of the response-stimulus interval (short: 750 ms vs. long: 1200 ms) for fixed cue-stimulus interval in different blocks of trials. The opportunity for anticipatory preparation was manipulated by varying the duration of the cue-stimulus interval (short: 150 ms vs. long: 600 ms) for fixed response-stimulus interval. Based on earlier findings (Meiran, 1996; Meiran et al., 2000), it is expected that RT switch cost will be smaller for long as compared to short response-stimulus interval conditions and for long as compared to short cue-stimulus interval conditions. If the differential switch-related positivity identified by Karayanidis et al. (2003) reflects anticipatory task-set reconfiguration processes, it is expected to be closely time-locked to cue onset, regardless of cue-stimulus interval. With a very short cue-stimulus interval (e.g., 150 ms), it has been argued that cue processing may disrupt subsequent stimulus processing, resulting in artificial inflation of the RT switch cost (e.g., Logan & Bundesen, 2003). The current study included a no-cue condition in which stimulus location signaled the task to be completed on a given trial. If, at a short cue-stimulus interval, cue processing disrupts subsequent stimulus processing, then, when controlling response-stimulus interval, RT switch cost will be larger for the short cue-stimulus interval condition compared to the no-cue condition. Alternatively, even a short cue-stimulus interval of 150 ms may be sufficient to elicit task-set reconfiguration processes, in which case, RT switch cost will be *smaller* for the short cue-stimulus interval condition as compared to the no-cue condition. Earlier studies that manipulated response-stimulus interval alone have suggested that 600 ms represents an optimal preparation period, with minimal reduction in RT switch cost with further increases in response-stimulus interval (e.g., Rogers & Monsell, 1995). To examine whether 600 ms also represents an optimal value for cue-stimulus interval, RT switch cost was compared for two conditions that had an response-stimulus interval of 1200 ms and cue-stimulus interval of 600 ms and 1050 ms, respectively.

Method

Participants

Twenty-four undergraduate students (mean age 22.2 years, range 18 to 30; 15 women) from the University of Newcastle participated in the study for course credit in an introductory psychology course. Participants had no prior exposure to the paradigm and provided written informed consent.

Stimuli and Tasks

A rectangular box (15×13.5 cm) divided into four equal quadrants was continuously displayed on a monitor at approximately 90 cm viewing distance. In the cued conditions, the cue was a brightening of the line defining one of the quadrants (gray to white). A stimulus was displayed in the center of the highlighted quadrant. Two adjoining quadrants were assigned to a letter task and the other two to a digit task (Figure 1a). The letter task was assigned to the top two quadrants for half of the participants and to the right two quadrants for the other participants. Thus, the association between eye shifts (vertical vs. horizontal) and trial type (switch vs. repeat) was counterbalanced across participants.

For the letter task, stimuli were selected from a set of four vowels (A, E, I, U) or four consonants (G, K, M, R). For the digit task, stimuli were selected from a set of four odd (3, 5, 7, 9) or four even (2, 4, 6, 8) numbers. Participants used their left and right index fingers to respond vowel or consonant for the letter task and odd or even for the digit task (Figure 1b). The hand assigned to each response was counterbalanced across participants.

Stimuli consisted of a pair of characters in Times New Roman font. One character was selected from the currently active task set (e.g., letters for the letter task). The second character was selected from either a neutral set (nonalphanumeric characters: #, ?, *, %) or from the task-irrelevant set (e.g., digits for the letter task). The

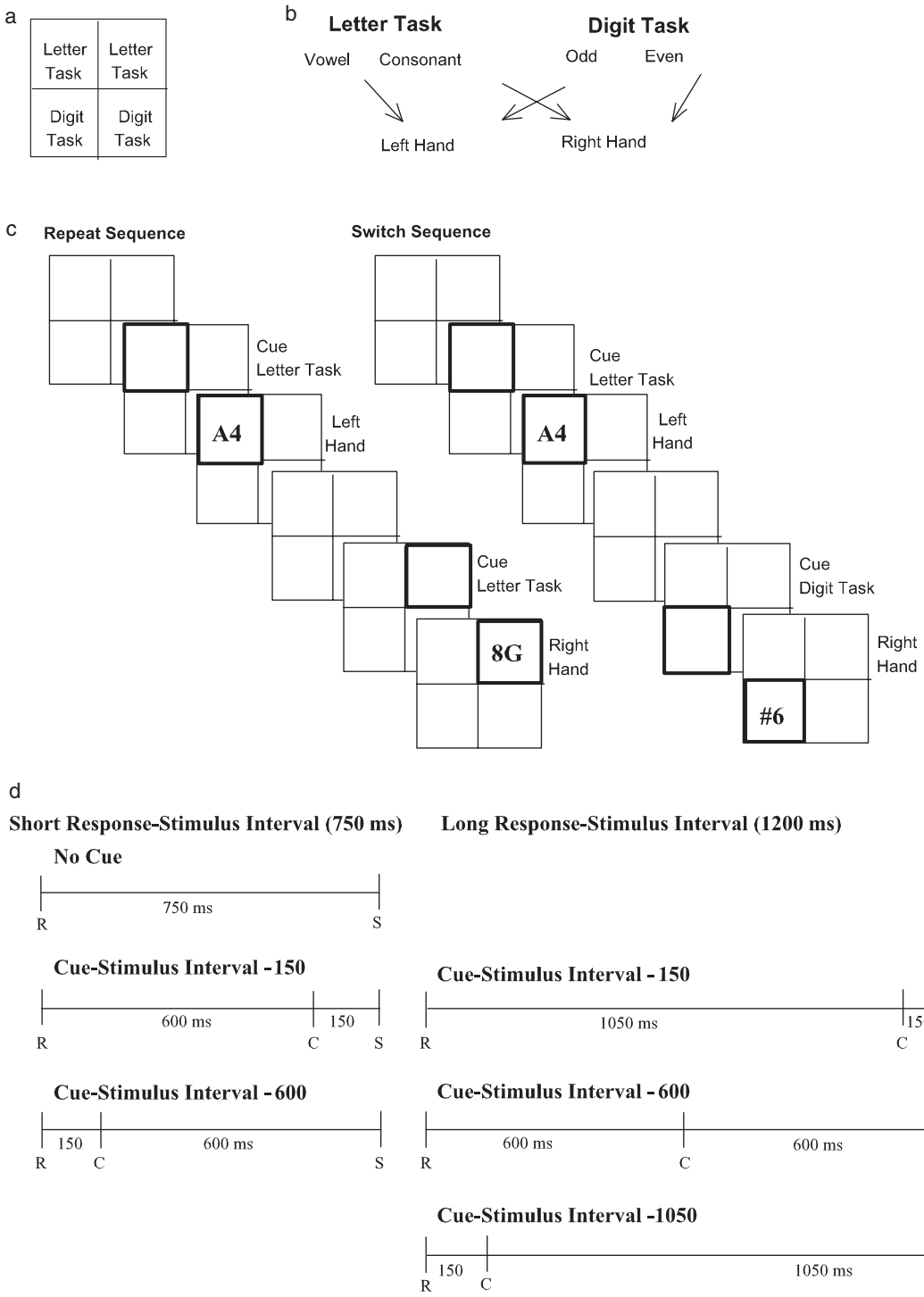

Figure 1. a: Stimulus display grid. Two adjoining positions were assigned to each task. b: Stimulus response mapping example. c: Examples of repeat and switch trial sequences. The cue was a highlight displayed around the specific box. d: Depiction of short (left) and long (right) response-stimulus interval conditions and nested cue-stimulus interval conditions.

task-relevant character was accompanied by a nonalphanumeric task-irrelevant character on one third of the trials (neutral stimulus, e.g., A%). On another third of the trials, the irrelevant character was mapped to a response on the opposite hand (incongruent stimulus; e.g., "A4" vowel-left hand, even-right hand), whereas for the remaining third, the irrelevant character was mapped to the same hand (congruent stimulus; e.g., "A3" vowel-left hand, odd-left hand). The order of the task-relevant and task-irrelevant character was varied randomly across trials (e.g., M%, %M). Stimuli were randomly selected from the respective character set with the restriction that the same stimulus from any set could not appear on two successive trials. Each stimulus remained on the screen until a response was recorded or 5000 ms had elapsed. In cued conditions, the cue remained visible

throughout the duration of the stimulus. After a response, the next cue could occur in either the horizontally or vertically adjacent quadrant, indicating the location of the next stimulus and hence the task to be performed (Figure 1c). Thus, on successive trials, the cue never repeated in the same location and never shifted to the diagonally opposite location.

Overall six conditions were included. Condition labels represent the duration of the response-stimulus interval (e.g., response-stimulus interval-750 = response-stimulus interval of 750 ms) and cue-stimulus interval (e.g., cue-stimulus interval-150 = cue-stimulus interval of 150 ms). Four conditions orthogonally manipulated response-stimulus interval and cue-stimulus interval (Figure 1d). Response-stimulus interval was manipulated across two levels: short (750 ms) and long (1200 ms). Cue-stimulus interval manipulated across two levels: short (150 ms) and long (600 ms). A fifth condition included a long response-stimulus interval (1200 ms) and a longer cue-stimulus interval of 1050 ms. This condition was compared to response-stimulus interval-1200; cue-stimulus interval-600 condition to determine whether switch cost reduces further as cue-stimulus interval increases beyond 600 ms. Note that in all these conditions, stimulus position provided a redundant cue for task type. The final condition was the no-cue condition with an response-stimulus interval of 750 ms. Here, a stimulus appeared 750 ms after a response to the preceding stimulus and its position validly indicated which task was to be performed. The no-cue condition was compared to the short cue-stimulus interval condition with the same response-stimulus interval to examine whether, at such a short cue-stimulus interval, cue processing facilitates or interferes with task-set reconfiguration. Each of the six conditions was presented in separate blocks of trials and the order of condition presentation was counterbalanced across participants using a Latin square design. Each block consisted of three runs of 100 trials, presented consecutively.

Procedure

All participants attended two sessions, scheduled 2–14 days apart. The first session included task training initially on each task alone and then in switching between tasks and practice with each of the six conditions. The second session included further practice followed by testing. Participants completed a total of 900 training and practice trials on the tasks before testing.

Behavioral and continuous EEG were recorded during the testing session that consisted of six conditions presented in blocks of three 100-trial runs. For all participants, stimulus-response mapping and task orientation were held constant across training and testing sessions. Participants were instructed to respond as quickly as possible while maintaining a high level of accuracy. At the start of each block, participants were informed of the specific response-stimulus interval and cue-stimulus interval to be used and were advised to use the cue-stimulus interval to prepare for the next trial. Following each run, behavioral feedback (overall mean RT and percentage of trials correct) was displayed and participants were encouraged to monitor and improve their performance. Prior to each run, task instructions were presented on the screen.

Data Analysis

The first four trials of every run, trials associated with an incorrect response, trials immediately following an incorrect response, and trials associated with a response occurring outside a 200–2000-ms window after stimulus onset were excluded from behavioral and ERP analyses.

Behavioral Data

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

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

EEG Recording and Data Analysis

EEG was recorded from 12 scalp electrodes according to the 10/20 system (Fz, Cz, Pz, F3, C3, P3, T5, F4, C4, P4, T6, Oz) using an electrode cap (Electro-cap International) and linked mastoids reference. Vertical electrooculogram (VEOG) was recorded bipolarly from electrodes attached to the supraorbital and infraorbital ridges of the left eye. Horizontal electrooculogram (HEOG) was recorded bipolarly from electrodes placed on the outer canthi of each eye. EEG and EOG were continuously sampled at 500 Hz/channel using NeuroScan Inc. software. EOG and EEG were amplified ($\times$ 5000 for EOG and frontal channels; $\times$ 20,000 for other EEG channels) using a Grass Neurodata system (Model 12) with a bandpass of 0.01–30 Hz ($-$ 6 dB down).

After correction for eyeblink artifact (Semlitsch, Anderer, Schuster, & Presslich, 1986), continuous EEG files were inspected and sections with movement artifact or channel saturation were excluded from further analysis. Response-related, cue-related, and stimulus-related averages were created by extracting 1400-ms epochs around the onset of the response, cue, or stimulus, respectively, including a 200-ms pre-onset interval. Baseline was set to $-$ 50 to 50 ms around the onset of the response, cue, or stimulus. This short baseline was used because of relatively large prebaseline shifts resulting from postresponse negativity in short response-cue interval conditions and buildup of contingent negative variation (CNV) in long cue-stimulus interval conditions (Karayanidis et al., 2003).

Within each condition, ERP waveforms were averaged across task (letter/digit) and congruency (neutral/incongruent/congruent) to increase the signal-to-noise ratio. Cue- and stimulus-related epochs within each condition were averaged separately based on whether the current trial required a task switch or repeat. Ten cue-related (5 cue conditions $\times$ 2 trial types) and 12 stimulus-related (6 conditions $\times$ 2 trial types) ERP average waveforms were created for each participant at each electrode site. Response-related epochs within each condition were averaged separately depending on whether the following cue (i.e., the cue on trial $n + 1$) signaled a switch or repeat trial. This enabled direct comparison between response-related, cue-related, and stimulus-related data.

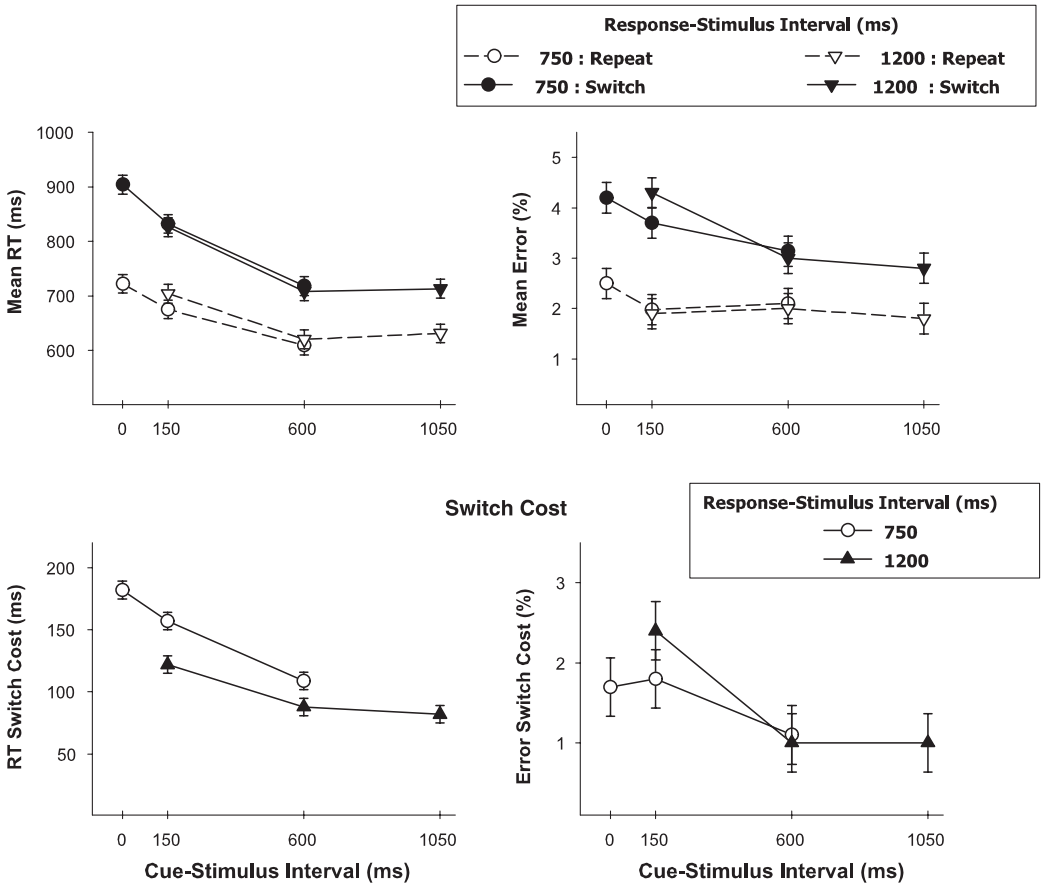

Figure 2. Top: Mean RT and percent error for each response-stimulus interval and cue-stimulus interval condition. Standard errors (17.26 ms and 0.301%, respectively) were calculated using Loftus and Masson (1994). Bottom: RT and error switch cost. Standard errors: 7.00 ms and 0.365%, respectively.

Difference waveforms were derived by subtracting the average ERP switch waveform from the average ERP repeat waveform for each participant. Thus, six response-related, five cue-related, and six stimulus-related difference waveforms were created for each participant at each of the 12 electrode sites. Response-, cue- and stimulus-related difference waveforms were analyzed using point-by-point t tests over 0–700 ms to establish points of significant deviation from baseline. This analysis was only conducted at the midline sites (Fz, Cz, Pz, and Oz) after visual inspection of grand averages indicated that the effects of switching were maximal at midline and did not show any discernible differences at lateral electrodes.[2] The Guthrie and Buchwald (1991) procedure was used to control for Type 1 error at $\alpha = .05$ using an autocorrelation coefficient of .9. Only effects significant by these criteria are reported.

Based on the results of the above analyses, mean amplitude measures were extracted for the differential switch positivity (D-Pos) over 350–400 ms after cue onset. Mean amplitude measures were taken and rescaled (McCarthy & Wood, 1985) at the four midline sites (Fz, Cz, Pz, and Oz). Interactions between electrode site and other factors are only reported when they remained significant after rescaling. Where significant interactions between electrode and one of the other factors emerged, separate analyses were conducted at each midline site using Bonferroni family-wise correction. The effects of cue-stimulus interval and response-stimulus interval manipulation on D-Pos amplitude were analyzed using an electrode (Fz, Cz, Pz, Oz) $\times$ cue-stimulus interval (150, 600 ms) $\times$ response-stimulus interval (750, 1200 ms) repeated-measures ANOVA. The effects of increasing cue-stimulus interval beyond 600 ms were examined using an electrode $\times$ cue-stimulus interval (600, 1050 ms) repeated-measures ANOVA. Short cue-stimulus interval and no-cue conditions were compared using an electrode $\times$ cue-stimulus interval (no cue, 150 ms) repeated-measures ANOVA.

For both behavioral and ERP analyses, degrees of freedom for factors with more than two levels were adjusted using Greenhouse–Geisser correction for the violation of the assumption of sphericity (Vasey & Thayer, 1987).

Results

Behavioral Data

RT switch cost ranged between 82 and 182 ms in different conditions (Figure 2). RT switch cost was significantly smaller for long (1200 ms) than short (750 ms) response-stimulus interval conditions, $F(1,23) = 19.5$, $p < .001$, and for long (600 ms) than short (150 ms) cue-stimulus interval conditions, $F(1,23) = 23.4$, $p < .001$. Thus, RT switch cost reduced with increasing values of both response-stimulus and cue-stimulus intervals. Although the effect of increasing cue-stimulus interval on RT switch cost tended to be greater for short than for long response-stimulus interval

[2]The use of a linked mastoid reference also precluded analysis of laterality effects.

(48 vs. 35 ms), the interaction between response-stimulus and cue-stimulus interval was not significant ($F<1$). For the 1200-ms response-stimulus interval, increasing the cue-stimulus interval from 600 ms to 1050 ms resulted in no further reduction in RT switch cost ($F<1$; Figure 2) and a significant residual RT switch cost of 82 ms remained at a cue-stimulus interval of 1050 ms, $t(23) = 7.53$, $p<.001$. At the 750-ms response-stimulus interval, the RT switch cost was 25 ms smaller at the short cue-stimulus interval (150 ms) compared to the no-cue condition, $t(23) = 2.9$, $p<.01$ (Figure 2). Overall, accuracy levels were very high, with error switch cost ranging from 1% to 2.4% (Figure 2). There was no effect of response-stimulus or cue-stimulus interval on error switch cost ($F<1$), no difference between no-cue and short-cue conditions or between the 600- and 1050-ms cue-stimulus interval. However, error switch cost significantly differed from zero in the latter cue-stimulus interval condition, $t(23) = 2.86$, $p<.01$.

ERP Data

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

For all conditions, both switch and repeat waveforms were characterized by the emergence of a large positive component that was maximal 350–400 ms after cue onset. At both short and long response-stimulus intervals, the 600-ms cue-stimulus interval condition showed a diffuse positivity for both switch and repeat trials emerging around 150 ms anteriorly and extending beyond 400 ms posteriorly. This positivity was followed by a slower, sustained negative CNV-type shift extending beyond stimulus onset. These effects all emerged before stimulus onset and were also evident at a cue-stimulus interval of 1050 ms. Short cue-stimulus interval conditions (150 ms) showed a sharper positivity that peaked after 350 ms and was preceded by a smaller centrally maximal positivity. These positivities peaked after stimulus onset and were followed by a frontocentrally maximal negative component (see stimulus-related averages in Figure 7).

Cue-related difference waveforms are depicted in Figure 4 with areas of significant positive deviation from baseline indicated by gray bars on the time axis. The results of point-by-point waveform analyses are summarized in Table 1. All cued conditions showed large switch-related differential positive deflections that emerged as early as 80 ms post cue and, in some cases, extended to 700 ms post cue (Table 1). Although a number of

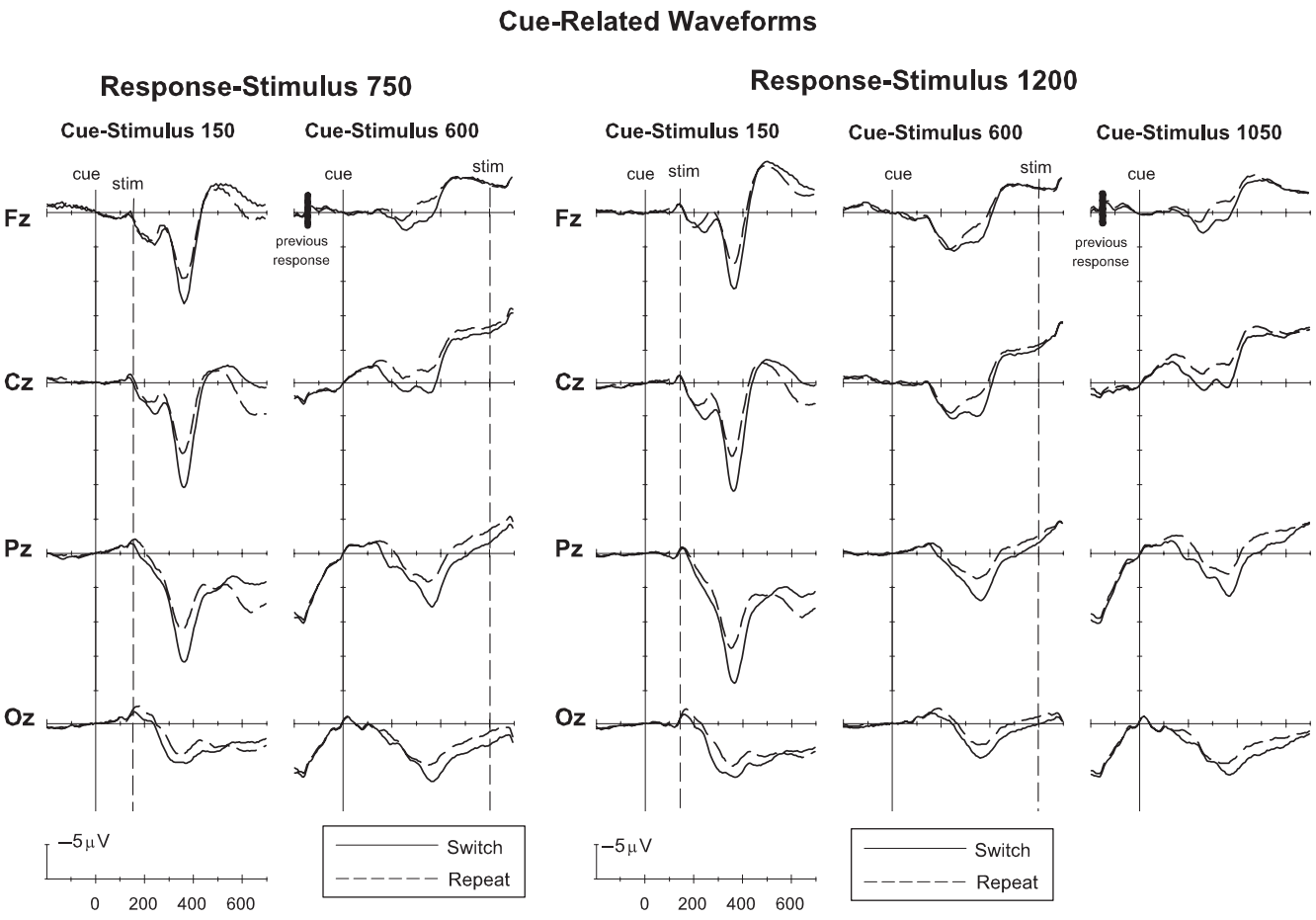

Figure 3. Cue-related waveforms for switch and repeat trials are depicted at four midline sites for each condition. Solid vertical line: cue onset; broken vertical line: stimulus onset. The preceding response is also displayed in conditions that had a short response-cue interval of 150 ms. Negative is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

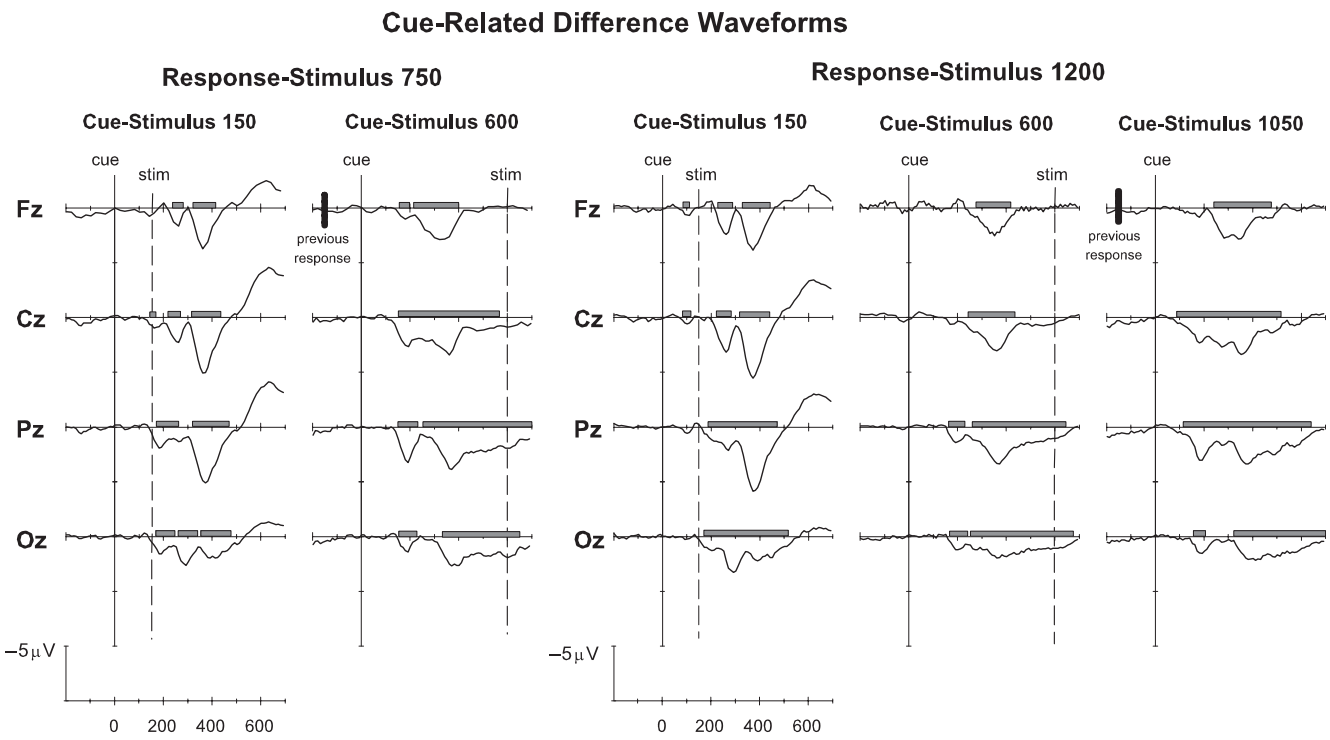

Figure 4. Cue-related difference waveforms are depicted at four midline sites for each condition. Gray bars denote regions of significant deviation from baseline (see Table 1).

different areas of significant deviation were evident, the most consistent deviation from baseline extended over 300 to 400 ms after cue onset, was largest at parietal and central sites, and appears to correspond to the differential switch-related positivity (D-Pos) identified by Karayanidis et al. (2003). This component was most clearly defined in the long response-stimulus interval condition with a 600-ms cue-stimulus interval, as this condition has no temporal overlap with either postresponse or stimulus-related components. In this condition, the D-Pos significantly deviated from baseline (i.e., was greater for switch compared to repeat waveforms) over 250–450 ms. At Pz and Oz, it was preceded by an earlier significant positive deviation over 160–240 ms. A similar pattern of findings was obtained in the other long cue-stimulus interval conditions (Response-Stimulus-750:Cue-Stimulus-600 and Response-Stimulus-1200:Cue-Stimulus-1050). However, note that in these latter conditions, the positive deflection extended centrally over approximately 100–550 ms and the earlier positive deviation was much larger at posterior electrodes. Comparison of Figures 3 and 4 suggests that a large broad positive shift developed centrally for both switch and repeat waveforms, but was largest for switch ERPs and that D-Pos overlapped the more posterior negativity and P3-like positivity. Note that these effects are fully contained within the cue-stimulus interval and could not have been affected by stimulus-related processing.

In short cue-stimulus interval conditions (150 ms), a large differential positivity was most clearly defined centro-parietally, deviating from baseline over approximately 300–400 ms post cue (Table 1). Here, D-Pos was preceded by a smaller centrally maximal positivity that was significant over approximately 220–290 ms post cue. Although Figure 3 shows that D-Pos overlapped a centroparietal P3 component elicited poststimulus, again the switch-related effect extended topographically across all midline sites and temporally across a much wider time window.

Mean amplitude analysis. Although the difference waveforms in Figure 4 suggest two or possibly three areas of differential positive deviation of switch compared to repeat waveforms, two of these positivities (frontocentrally maximal over 225–275 ms for short cue-stimulus interval conditions and parieto-occipitally maximal over 175–225 ms, especially for short response-cue interval conditions) were not predicted on the basis of our previous data and will not be examined here further. Mean amplitude was only analyzed for the differential positivity that closely corresponds to D-Pos and was measured over 350–400 ms in all conditions (Figure 5).

D-Pos amplitude was larger for short than long cue-stimulus interval (150 vs. 600 ms; $F[1,23] = 4.27$, $p < .05$; Figure 5), and was not affected by response-stimulus interval duration. A significant main effect of site, $F(3,69) = 14.43$, $\varepsilon = .566$, $p < .001$, reflected that D-Pos was larger at central and parietal sites (3.6 and 4.0 μV, respectively). The interaction between electrode and cue-stimulus interval, $F(2,50) = 9.368$, $p < .001$, indicated that the decline in D-Pos amplitude with increasing cue-stimulus interval was only statistically significant at Cz (2.0 μV decline, $F[1,23] = 8.11$, $p = .009$). D-Pos amplitude did not decline further as cue-stimulus interval increased from 600 ms to 1050 ms (Figure 5).[3]

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

[3]A correlation analysis between RT switch cost and D-Pos mean amplitude resulted in no significant effects. However, this is most likely due to the relatively low number of participants and the large number of within-subject conditions.

Table 1. *Results of Point-by-Point Analysis of Positivity in Cue-Related and Response-Related Difference Waveforms*

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

Notes: Numbers represent the area over which the difference waveforms significantly differed from baseline according to Guthrie and Buchwald's (1991) criteria. Numbers in italics represent the number of consecutive points that were significantly deviated from baseline.
[a]Although the no-cue condition is really not a cue-related waveform, it has been included here to show the areas of significant positive deviation after stimulus onset when there was no opportunity to prepare for a switch trial.

Stimulus-related waveforms. Stimulus-related ERPs and difference waveforms are shown in Figure 7 and Figure 6 (right). Note that, in the no-cue condition, stimulus location provided information about which task was active on that trial. Also note that, despite considerable temporal overlap between the cue-related and stimulus-related waveforms at short cue-stimulus intervals, minor differences between the two conditions may emerge because of different baselines. Occipital P1, N1, P2 components and frontal N1, P2 components can be seen most clearly at longer cue-stimulus intervals that had no overlap between cue- and stimulus-related waveforms. These early ERPs were followed by a broad negativity evident centrally over 200–400 ms and a parietal P3b-like positivity over 400–600 ms.

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

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

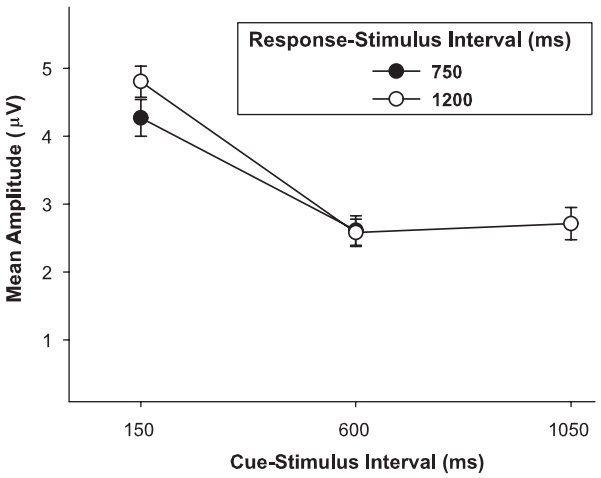

Figure 5. Mean amplitude of differential positivity (D-Pos) measured 350–400 ms after cue onset at electrode Cz.

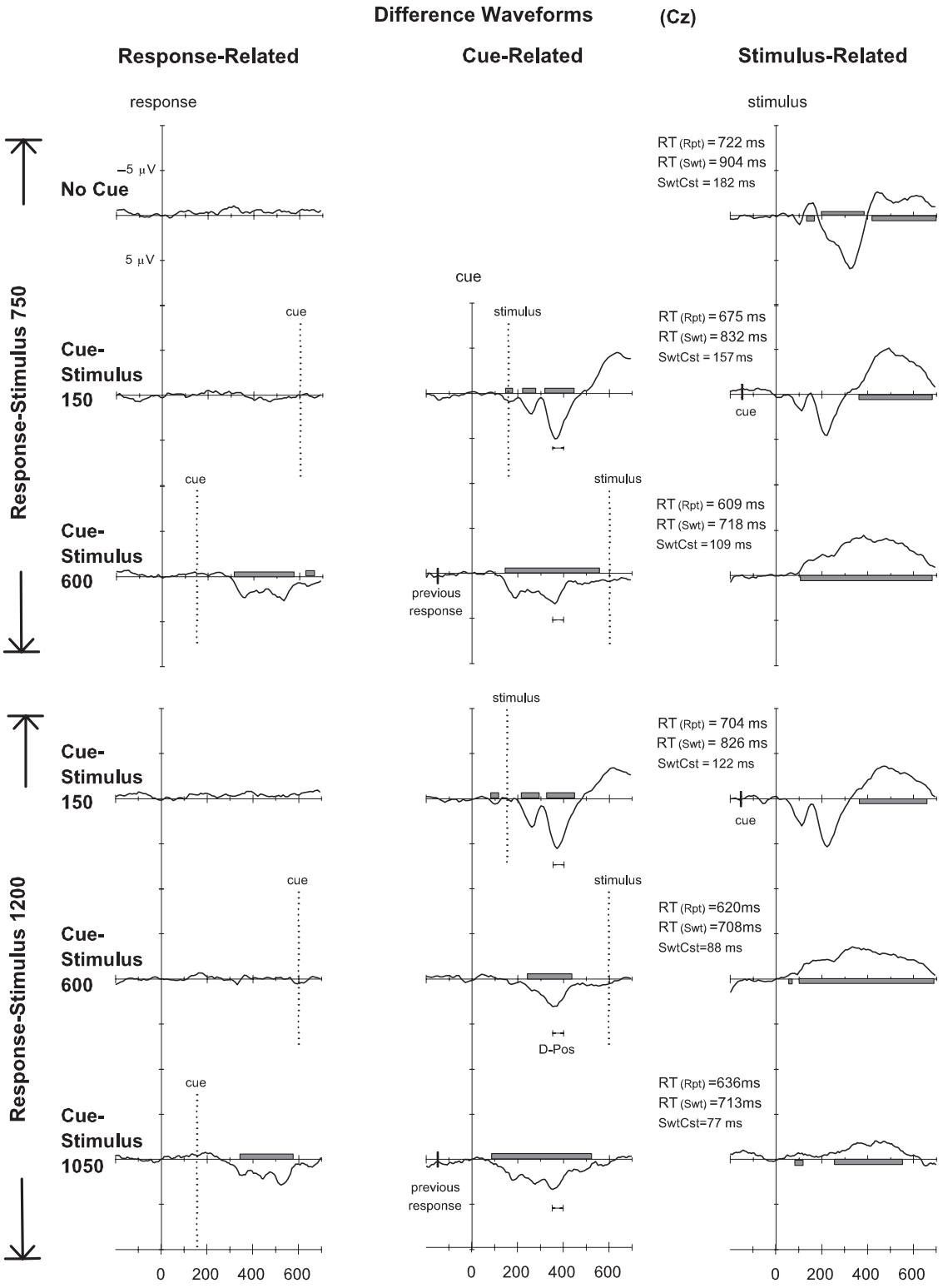

Figure 6. Response-related (left), cue-related (middle), and stimulus-related (right) difference waveforms at Cz. Gray bars denote regions of significant positive deviation from baseline in response- and cue-related waveforms (Table 1) and negative deviation from baseline in stimulus-related waveforms (Table 2). Note that stimulus-related no-cue condition also depicts significant positive deviation. Left: Solid and broken vertical lines indicate the onset of response and cue, respectively. Middle: Solid and broken vertical lines indicate the onset of cue and stimulus, respectively. Timing of the preceding response is also displayed in conditions that had a short R-C interval of 150 ms. Right: Solid vertical line indicates stimulus onset. Cue onset is also displayed in conditions with a short cue-stimulus interval (150 ms).

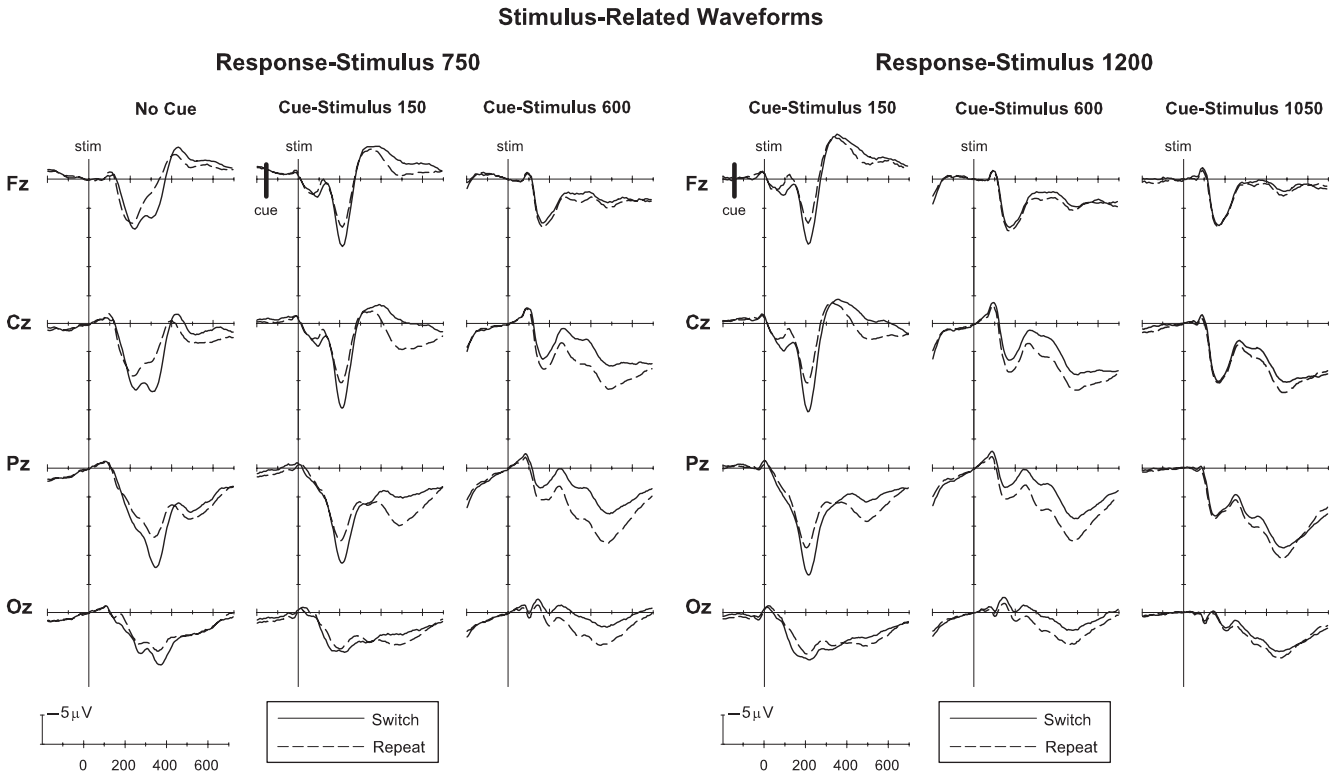

Figure 7. Stimulus-related waveforms for switch and repeat trials. Solid vertical line indicates stimulus onset. Cue onset is also displayed in conditions with a short cue-stimulus interval (150 ms).

was seen in cue-related and stimulus-related difference waveforms, whereas for long cue-stimulus interval conditions, it emerged only within the cue-stimulus interval. For short cue-stimulus interval conditions, D-Neg emerged much later (350 ms) than for the long cue-stimulus interval conditions.

No cue versus 150-ms cue-stimulus interval. The no-cue condition produced larger RT switch cost than the 150-ms cue-stimulus interval condition with the same response-stimulus interval (750 ms). Comparison of stimulus-related difference waveforms in these two conditions indicates that D-Pos was delayed in the no-cue condition, peaking around 300–400 ms after stimulus onset. This latency coincides with the latency of D-Pos when measured relative to the onset of the preceding cue for the cue-stimulus interval 150-ms condition (Figure 6).

Discussion

Across all conditions, switch trials were associated with larger RT and error rate compared to repeat trials (784 ms and 3.5% vs. 660 ms and 2%, respectively). When averaged across cue-stimulus intervals, RT switch cost significantly reduced as response-stimulus interval increased from 750 to 1200 ms (29 ms decline). Similarly, when averaged across response-stimulus intervals, RT switch cost significantly reduced as cue-stimulus interval increased from 150 to 600 ms (50 ms decline). Increasing the

Table 2. *Results of Point-by-Point Analysis of Negativity in Stimulus-Related Difference Waveforms*

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

Notes: Numbers represent the area over which the difference waveforms significantly differed from baseline according to Guthrie and Buchwald's (1991) criteria. Numbers in italics represent the number of consecutive points that were significantly deviate from baseline.

cue-stimulus interval from 600 ms to 1050 ms produced no further reduction in RT switch cost, and a significant RT and error switch cost remained at the longest cue-stimulus interval (82 ms and 1.0%, respectively).

These findings are compatible with multicomponent models of task switching. The reduction in RT switch cost with increasing response-stimulus interval is compatible with a decline in passive interference processes associated with switching between different task-sets (Allport & Wylie, 2000; Allport et al., 1994; Meiran, 2000), such as positive priming of the previously active task set and negative priming of the previously irrelevant task set (Allport & Wylie, 2000; Mayr & Keele, 2000). The reduction in RT switch cost with increasing cue-stimulus interval is compatible with active preparation processes (Goschke, 2000; Meiran, 2000; Rogers & Monsell, 1995), such as cue encoding (Logan & Bundesen, 2003; Mayr & Kliegl, 2003; Monsell, Sumner, & Waters, 2003), active inhibition of the irrelevant task set (Mayr & Keele, 2000), and/or retrieval of the relevant task set into working memory (Mayr & Kliegl, 2000). Although the reduction in RT switch cost with increasing cue-stimulus interval is also compatible with De Jong's (2000) intention-activation model, this model cannot readily account for the effect of response-stimulus interval on RT switch cost. The significant residual switch cost at the longest cue-stimulus interval (1050 ms) is consistent with differential response interference for switch trials (Woodward, Meier, Tipper & Graf, 2003), even after maximal anticipatory preparation, as well as with an "unprepared" state on some proportion of trials (De Jong, 2000). Interestingly, a cue-stimulus interval of only 150 ms resulted in smaller RT switch cost than the no-cue condition (25 ms reduction).[4] This finding suggests that anticipatory preparation processes may be initiated even with a short lead interval of 150 ms and questions the use of a 150-ms cue-stimulus interval as a "no preparation" baseline (e.g., De Jong, 2000; Nieuwenhuis & Monsell, 2002).

Cue-related ERP difference waveforms showed a differential positivity for switch compared to repeat trials. This differential switch-related positivity closely correspond to the D-Pos component reported by Karayanidis et al. (2003) in an alternating runs paradigm (see footnote 1). Despite large differences in paradigm, Rushworth et al. (2002, 2005) also showed a switch-related positivity over the 350–500-ms range, albeit differing in scalp distribution and accompanied by different additional effects (see also Barcelo et al., 2002). These findings are compatible with the existence of an active task-set reconfiguration process that can be initiated in anticipation of a predictable or cued switch in task. At a 600-ms cue-stimulus interval, D-Pos was fully contained within the cue-stimulus interval and there was maximal reduction in RT switch cost, indicating that anticipatory reconfiguration could be fully completed prior to stimulus onset. At a shorter cue-stimulus interval (150 ms), D-Pos emerged as early as 88 ms after cue onset (Table 1), but still peaked around 350–400 ms after cue onset and both D-Pos and RT switch cost were larger than for the longer cue-stimulus interval condition. The no-cue condition showed a further increase in RT switch cost and D-Pos was time-locked to stimulus onset, indicating firstly that cue-stimulus intervals as short as 150 ms can facilitate task switching and secondly that the process(es) reflected in D-Pos are necessary for task-set reconfiguration and may be initiated after stimulus onset if no cue is present. The fact that increasing cue-stimulus interval from 600 to 1050 ms produced no further reduction in RT switch cost or D-Pos amplitude, despite a significant residual RT switch cost, indicates that 600 ms provides optimal anticipatory preparation and that additional poststimulus processes contribute to RT switch cost. However the degree to which this reconfiguration process is specifically and exclusively activated in anticipation of switch trials is questioned by the fact that, although D-Pos represents a greater positivity for switch compared to repeat stimuli, cue-related ERP waveforms in Figure 3 indicate that both switch *and* repeat trials show a positive deflection within the time frame of the D-Pos.

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

The positivity for both switch and repeat cue-related waveforms may reflect cue processing. Recent studies by Logan and Bundesen (2003) and Mayr and Kliegl (2003) suggested that, in cued switching paradigms, RT switch cost can be accounted for by cue processing, because switch trials are preceded by a change in cue whereas repeat trials are preceded by the same cue. Although cue processing may account for the emergence of a positivity for repeat trials in the current cued switch paradigm that was not evident in the alternating runs paradigm, it is unlikely to account for the *differential* positivity in switch compared to repeat trials. In the current study, the cue was a highlight of one of the four quadrants of the grid. However, the same quadrant was never highlighted on successive trials, so both switch and repeat trials were preceded by a change in cue position. Therefore, the cue provided valid information about the location of the next stimulus, and this also determined which task set would be active on the next trial. Thus, on each trial, the cue position determined where to direct attention. This was equally relevant for switch and repeat trials, possibly accounting for the common positivity. In addition, the cue indicated whether to maintain the current task set or activate the alternative task set. This would be expected to result in differential processing for switch and repeat cues and could account for the differential positivity to switch cues. Recent behavioral (Monsell & Mizon, in press) and ERP (Nicholson, Karayanidis, Bumak, & Michie, 2005) data also indicate that, in many instances, task switch costs cannot be accounted for by differential cue processing for switch versus repeat trials.

Alternatively, the fact that both switch and repeat cue-related waveforms show a positivity, albeit larger for switch trials, may

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

indicate that the process of task-set reconfiguration can be activated on both switch and repeat trials, depending on task parameters, strategy formation, and trial-by-trial variations in performance. Comparison between cue-related ERPs on blocks with short versus long cue-stimulus intervals (Figure 3) supports the contention that participants may implement different processing strategies depending on specific timing parameters. First, the change in the morphology and amplitude of D-Pos with increasing cue-stimulus interval could reflect variations in the onset of task-set reconfiguration for switch trials resulting from differences in time pressure, particularly as the cue-stimulus interval was manipulated across blocks of trials. For example, when the cue-stimulus interval was short, onset of active preparation occurred, in the majority of trials, immediately following cue onset (as the stimulus appeared almost immediately after cue onset), resulting in little latency jitter and a sharp D-Pos. In comparison, when the cue-stimulus interval was long (i.e., 600 or 1050 ms), there was less time pressure to initiate preparation immediately following the cue. Hence, jitter in the onset of preparation may have resulted in jitter in D-Pos onset across individual trials, producing a broader and smaller average D-Pos. Second, *repeat* cues on short cue-stimulus interval conditions (150 ms) showed a sharp and large positivity around 300–400 ms, whereas repeat cues on long cue-stimulus interval conditions (600 ms) showed a much less prominent positivity. Like D-Pos, this positivity was clearly evident across all midline sites, but maximal centroparietally. RT to repeat trials was longer for short than for long cue-stimulus interval conditions (by 75 ms when averaged across response-stimulus intervals). Relative to repeat cues, switch cues showed a larger positivity at both short and long cue-stimulus interval conditions, measured here as the D-Pos over 350–400 ms, and a greater increase in RT for short as compared to long cue-stimulus interval conditions (by 116 ms when averaged across response-stimulus intervals).

These findings suggest that participants may have adopted different processing strategies in short and long cue-stimulus interval blocks. Given the time constraints of the short cue-stimulus interval blocks, participants may have adopted a strategy of initiating task-set reconfiguration processes in parallel with cue processing, rather than awaiting the outcome of cue processing to determine whether a change in task-set reconfiguration would or would not be required. The centroparietal positivity in the cue-related average waveforms for both repeat and switch trials suggests that cue processing, and possibly the onset of task-set reconfiguration, was initiated for both repeat and switch trials. That switch trials were associated with a further positivity (i.e., D-Pos), may indicate that these trials required additional processes or additional subcomponents relative to repeat trials (i.e., in the slow paced long cue-stimulus interval conditions, active task-set reconfiguration processes were more selectively initiated for switch trials and their onset was contingent upon having processed a switch cue). Alternatively, it may indicate that task-set reconfiguration can be completed more rapidly and/or efficiently for repeat trials because the stimulus-response associations were already primed on the previous trial. The fact that the data analyzed here were recorded after substantial task practice over 2 days and that cue-stimulus and response-stimulus interval conditions were varied across blocks supports the proposition that participants may have adopted different strategies depending on the duration of the cue-stimulus interval. In Monsell and Mizon (in press), switch probability was inversely related to active reconfiguration on switch trials, whereas Brass and von Cramon (2004) argued that using equal probability of switch and repeat trials might encourage preparation to both types of trials, thereby reducing switch/repeat trial differences. The use of a equal switch/repeat probability in this design may have increased the probability of task-set reconfiguration on repeat trials, especially at the short cue-stimulus interval. If the above interpretation is correct, it suggests that active task-set reconfiguration processes are largely under voluntary control and may be activated on both switch and repeat trials, depending on task parameters and participant strategy. It also suggests that D-Pos amplitude may represent the relative activation of these processes for switch versus repeat trials and may be affected by the relative strength of S-R priming carried over from the previous trial (or trials). Clearly further parametric task modifications are required to test these arguments. An obvious prediction would be that the differential strategies proposed here for short versus long cue-stimulus interval conditions would not be helpful if cue-stimulus interval were varied within, rather than between, blocks of trials.

Another possibility is that the parietal positivity in the repeat waveform represents a P3b component that is larger in amplitude for switch trials, reflecting updating and/or implementation of the new task set (Barcelo et al., 2002). However, this interpretation does not neatly fit our current and previous data (Karayanidis et al., 2003). In our earlier study, a centro-parietal differential positivity for switch trials was obtained in the interval leading up to a predictable switch trial, despite no evidence of a P3b to repeat trials. Although both repeat and switch trials here show a positivity in the long cue-stimulus interval, the difference waveforms show that the differentiation between switch and repeat ERP waveforms begins much earlier and extends beyond the latency range of the P3b. Even though the current analysis measured the differential positivity around 350–400 ms to capture the peak and be compatible with our previous study, the current data suggest that multiple ERP components extending across the measurement window are affected by whether the cue indicates an impending switch or repeat trial. Difference waveform analyses showed deviation between switch and repeat cue ERPs as early as 84 ms after cue onset and extending across the entire analysis epoch, in some instances. Figure 4 suggests that there is at least one earlier positivity for switch compared to repeat cues.[5] The present data cannot conclusively confirm or reject the possibility that a P3b is elicited by repeat cues and

[5]An early differential positivity (early D-Pos) peaked around 175–225 ms after cue onset and was maximal centrally and parietally. Although this early D-Pos was evident in all conditions, it was most distinct and largest for conditions with a very short response-cue interval of 150 ms when the cue indicated a switch. That this early D-Pos is a differential positivity for switch compared to repeat cues suggests that cue analysis has at least commenced if not been completed by 200 ms post cue. The fact that early D-Pos appears selectively enhanced in the short response-cue interval conditions may indicate increased overall arousal and perceived speed of stimulus presentation, resulting in earlier activation of cue processing and task-set reconfiguration processes. Early D-Pos may thus reflect early cue and cue-task association analysis occurring in all response-stimulus and cue-stimulus interval conditions, such as processing the location of the cue within the grid displayed on the screen (or the stimulus in the no-cue condition) to determine which task to perform (e.g., Logan & Bundesen, 2003; Mayr & Kliegl, 2003). These early processes are more cognitively demanding when the response to the previous task is very recent (i.e., short response-cue interval of 150 ms) due to interference with postresponse processes and/or task-set interference. Given that the present study made no specific hypotheses about these earlier effects and the rather restricted electrode montage used, no further analyses were conducted to differentiate the positivities seen in Figure 4.

increased for switch cues. However, even if the D-Pos over 350–400 ms represents partly a P3b modulation, this clearly cannot fully account for the differential ERP signature of switch trials that extends across most of the recording epoch. Future work needs to model the different positivities in switch and repeat cue trials using component analysis and source modeling procedures.

The stimulus-related difference waveforms showed a larger differential negativity for switch than repeat trials, similar to D-Neg reported by Karayanidis et al. (2003; see also Barcelo et al., 2002; Rushworth et al. 2005). D-Neg emerged less than 50 ms after stimulus onset in long cue-stimulus interval conditions but more than 300 ms later in short cue-stimulus interval conditions, wherein it was preceded by a D-Pos. The delay in onset indicates either that the process(es) represented by D-Neg cannot be initiated until completion of the processes reflected in the preceding D-Pos or, alternatively, that in short cue-stimulus interval conditions, D-Pos is superimposed on D-Neg, and D-Neg does not become visible until after D-Pos termination. Even though D-Neg was larger centroparietally and peaked around 300–600 ms after stimulus onset, it is unlikely to reflect a reduction in P3b for switch relative to repeat trials (but see Barcelo et al., 2002). Figure 6 shows a large single component spreading over more than 600 ms in some instances, suggesting a slow wave negativity superimposed on the switch trial ERPs (Karayanidis et al., 2003). This differential switch negativity, in combination with the residual RT and error switch cost, support the notion that anticipatory task-set reconfiguration processes do not completely account for behavioral switch costs. Rather, it is suggested that switch and repeat stimuli may trigger different processes, depending on the task and sequence parameters (e.g., Gehring, Bryck, Jonides, Albin, & Badre, 2003). These processes are likely to represent differential S-R priming and/or response interference for switch versus repeat trials (e.g., Allport & Wylie, 2000; Waszak et al., 2003; Yeung & Monsell, 2003a, 2003b) and to contribute to the residual switch cost.

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

Recent fMRI studies found no evidence for differential activation associated with anticipatory preparation for switch and repeat trials (Brass & von Cramon, 2004; Ruge et al., 2005) and concluded that anticipatory task-set initiation may occur at long cue-stimulus interval for both switch and repeat trials and does not require cognitive control. The current findings question these conclusions. The occurrence of a larger positivity for switch than repeat trials prior to stimulus onset in the long cue-stimulus interval conditions, together with the fact that increasing cue-stimulus interval had a greater effect on RT for switch than for repeat trials, strongly favor differential processing of switch stimuli and imply the involvement of cognitive control processes. Comparisons between inferences drawn from ERP and fMRI data need to be made with caution, given the large differences in temporal resolution, sensitivity, and paradigm. Clearly, further research is needed to combine the temporal accuracy of ERPs with the spatial capabilities of fMRI to characterize the spatiotemporal characteristics of processes that underlie task switching.

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.

Barcelo, 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*, 1342–1355.

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

Brass, M., & von Cramon, D. Y. (2004). Decomposing components of task preparation with functional magnetic resonance imaging. *Journal of Cognitive Neuroscience*, *16*, 609–620.

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.

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

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*, 572–585.

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

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

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

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

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*, 575–599.

Mayr, U., & Keele, S. W. (2000). Changing internal constraints on action: The role of backward inhibition. *Journal of Experimental Psychology: General*, *129*, 4–26.

Mayr, U., & Kliegl, R. (2000). Task-set switching and long-term memory retrieval. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *26*, 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.

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*, 203–208.

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

Meiran, N. (2000). 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, MA: MIT Press.

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

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

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

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

Nicholson, R., Karayanidis, F., Bumak, E., & Michie, P. (2005). ERPs dissociate the effects of switching task sets and task cues. Manuscript in preparation.

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

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

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*, 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*, 340.

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

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

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

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

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*, 361–413.

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

(Received September 2, 2004; Accepted June 20, 2005)