

Electrophysiological correlates of anticipatory and poststimulus components of task switching

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Abstract

Task-switching paradigms can shed light on cognitive and neural processes underlying attentional control mechanisms. An alternating runs task-switching paradigm (R. D. Rogers & S. Monsell, 1995) is used to identify ERP components associated with anticipatory and poststimulus components of task-switching processes. Subjects alternated between two tasks in a predictable series (AABB). Reaction time (RT) switch cost reduced with increasing response-stimulus (R-S) interval and a residual switch cost remained at the longest R-S interval. A switch-related positivity (D-Pos) developed in the R-S interval. D-Pos was time-locked to response onset, peaked around 400 ms post-response onset, and was unaffected by task-set interference. A switch-related negativity (D-Neg) emerged after stimulus onset. D-Neg peaked earlier with increasing R-S interval and its amplitude and latency were affected by task-set interference. D-Pos and D-Neg were interpreted within current models of task-switching.

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

Recent research has shown a renewed interest in the organization of mental control processes, that is, processes that supervise and orchestrate our intentions and actions leading to seemingly seamless and purposeful behavior. When functioning effectively, these processes are not readily evident. However, they become glaringly obvious as soon as they fail. For example, temporary disruption due to factors such as fatigue may lead people to absentmindedly drive home to their previous address rather than their new home. Involuntary lapses in organized and purposeful behavior are well documented in patients with prefrontal cortex lesions (e.g., perseverative errors: Milner, 1963; utilization behavior: Llermitte, 1983; capture errors: Reason, 1984).

Most theories of attention have postulated the existence of some type of “executive system” that resides in the prefrontal cortex and presides over behavior, especially under novel situations (e.g., Baddeley’s (1986) “central executive”; Norman & Shallice’s (1986) “supervisory attentional system”). According to these theories, it is the temporary or permanent dysfunction of

this system that brings about the slips in intentional behavior described above, by handing control over to lower level contextually driven systems. However, other theorists have dismissed the notion of a single control system (see Monsell, 1996; Monsell & Driver, 2000 for discussion). These theories argue for multiple, distributed levels of control rather than a single, all-powerful controller (Allport, 1993; Logan, 1985; Newell, 1980). A large wave of research has aimed at identifying and differentiating between different levels of control.

Within this framework, there has been resurgence of interest in task-switching paradigms as a tool for investigating control processes. Typically, task-switching paradigms require predictable or random alternation between two tasks that are defined on the basis of distinct or partially overlapping stimulus–response contingencies (or task-sets; Rogers & Monsell, 1995). Under most conditions, switching between tasks results in longer reaction times (RT) and, less frequently, increased error rates as compared to performance on each task separately (e.g., Allport, Styles, & Hsieh, 1994; Biederman, 1973; Meiran, 1996; Rogers & Monsell, 1995; Spector & Biederman, 1976; Sudevan & Taylor, 1987). These switch costs are believed to reflect processes involved in alternating between task-sets (or task-set reconfiguration; Rogers & Monsell, 1995).

The processes involved in task-set reconfiguration have been studied using a variety of task-switching paradigms. A number of factors have been shown to affect the size of the switch cost. These include: the degree to which task-sets overlap in stimulus and/or response attributes (Allport et al., 1994; Meiran, 2000;

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Spector & Biederman, 1976), prestimulus cueing that signals which task-set is active prior to each trial (e.g., Biederman, 1973; Meiran, 1996; Sudevan & Taylor, 1987), factors encouraging advance preparation of task-set reconfiguration (Nieuwenhuis & Monsell, 2002), relative task-set strength or familiarity (Allport et al., 1994; Rubinstein, Meyer, & Evans, 2001), and time to prepare for an imminent task switch (De Jong, 2000; Meiran, 1996; Rogers & Monsell, 1995).

The experiments of Rogers and Monsell (1995) will be described here in detail, as they form the basis for the current study. Rogers and Monsell pioneered the alternating runs paradigm of task switching, with subjects required to alternate between two tasks in a predictable sequence within the same block. Specifically, subjects were taught to switch between a letter classification task (Task A) and a digit classification task (Task B) in a predictable sequence (i.e., AABB). Stimuli were presented in one of four boxes continuously displayed on a computer screen, and stimulus position was rotated in a clockwise direction. Thus, on a given trial, the active task was cued by the position of the stimulus in display (e.g., Task A for upper two boxes, Task B for lower two boxes). In addition, as the display proceeded in a clockwise and predictable sequence, the position of the current stimulus also provided valid cueing as to which task-set would be active on the subsequent trial. Substantial task practice was provided so as to ensure that subjects clearly knew which task was active on each trial. The cost of switching tasks was estimated by subtracting performance measures on trials requiring no switch from trials requiring a switch (e.g., $RT_{\text{switch cost}} = RT_{\text{switch}} - RT_{\text{no-switch}}$). Response-stimulus interval (R-S interval) was varied in order to examine whether, given adequate time, task-set reconfiguration processes would be initiated in anticipation of a predictable switch in task-set.

With a very short R-S interval (150 ms), a large switch cost was obtained for both RT and error measures: performance was slower and less accurate on switch than no-switch trials (Experiment 1). This cost was larger when the stimulus consisted of exemplars from both task-sets (i.e., crosstalk), thereby reducing the effectiveness of the stimulus to cue the appropriate task-set, than when the stimulus unequivocally cued the active task-set (i.e., no-crosstalk). Although practice reduced switch costs from Day 1 to Day 2, significant switch costs were still evident on Day 2 after hundreds of trials. Varying R-S interval between 150 and 1,200 ms across different trials had no effect on switch cost (Experiment 2). However, a significant decline in switch cost was obtained when R-S interval was varied across different blocks. Specifically, under crosstalk conditions, switch cost declined sharply as R-S interval increased from 150 to 600 ms but remained relatively unchanged from 600 to 1,200 ms (Experiment 3). A similar but less sharp effect of R-S interval on switch cost was obtained under no-crosstalk conditions (Experiment 4). In both experiments, a significant switch cost was observed at the longest R-S interval of 1,200 ms.

Rogers and Monsell (1995) argue that task-set reconfiguration consists of two processes; one process, the “anticipatory” component, can be initiated endogenously prior to the onset of the switch trial, whereas the other, the “stimulus-triggered” component, is triggered exogenously by the onset of the stimulus. Thus, it is suggested that task-set reconfiguration is under the control of both internally driven and externally driven processes. Specifically, they argue that when subjects can predict an imminent switch in task-set and reliably estimate the timing of the next trial, they can initiate task-set reconfiguration prior to

the onset of the stimulus. The extent to which this component of task-set reconfiguration is completed prior to stimulus onset will depend on the length of the R-S interval, among other things. This “anticipatory” component presumably reflects an instance of an endogenous or “top-down” control process that facilitates advance preparation for a change in task-set. However, the fact that switch cost remains significant even with very long R-S intervals and predictable cueing of an imminent switch suggests that this control process cannot completely reconfigure the system for the change in task-set. Rather, completion of task-set reconfiguration depends on processes that are initiated after stimulus onset and are reflected in the residual switch cost. This “stimulus-triggered” component of task-set reconfiguration reflects externally driven processes, such as activation of S-R contingencies associated with task-relevant or task-irrelevant stimuli. A similar distinction between a prestimulus “goal-shifting” process and a poststimulus “rule activation” process is made by Rubinstein et al. (2001).

Many studies have replicated aspects of the above data. However, the interpretation of the processes underlying these components of task-set reconfiguration—indeed, the very existence of two components—has been questioned by other researchers. Allport et al. (1994) questioned the role of anticipatory or endogenously driven processes in contributing to the process of task-set reconfiguration. They argued that switch costs can be entirely attributed to proactive interference from the previously active (and now irrelevant) task-set on the currently active task-set, a process labelled “task-set inertia” that dissipates passively with time. However, as reviewed by Rubinstein et al. (2001), their data did not unambiguously support this contention. In a more recent formulation of this thesis, Allport and Wylie (2000) argue that, although endogenous processes may help determine which task is performed, and contribute to reducing switch costs with advanced cueing, the duration of this goal-setting or goal-activation process does not directly correspond to the amount of decline in switch cost at long versus short preparation intervals. Rather, they argue, switch costs largely reflect “performance readiness” (see also Fagot, 1994, for a similar distinction between task setting and task readiness). Performance readiness is affected by factors such as positive and negative priming from previous task practice, cued activation of relevant/irrelevant stimulus, response and/or task-set attributes and inhibition of incongruent attributes (Allport & Wylie, 2000).

Meiran, Chorev, and Sapir (2000) investigated the processes contributing to the reduction in switch cost with increasing R-S interval by independently manipulating response-cue interval (RCI) and cue-target interval (CTI) while maintaining R-S interval constant. In separate experiments, they found that increasing either RCI or CTI resulted in a significant decline in switch cost, with a significant residual cost remaining in both cases. Meiran et al. argue that at least three components of task switching can be differentiated. In addition to the stimulus-driven processes reflected in the residual component of task-switching, two more components can be defined. Specifically, the R-S interval effect consists of a preparatory reconfiguration component reflecting an active top-down process, as suggested by Rogers and Monsell (1995), and a task-set inertia component reflecting passive dissipation of activation of the previous task-set, as proposed by Allport et al. (1994).

In contrast, De Jong (2000) argues that a single process of task-set reconfiguration can account for the effects of task

switching. Preparation is conceptualized as an all-or-none process. Depending on task parameters and participant variables, participants will prepare task-set reconfiguration in advance on some trials but not on others. On trials they prepare, switch cost will be zero; on trials they do not, reconfiguration will be completed after the onset of the stimulus, resulting in some switch cost. De Jong argues that averaging across these two types of trials results in a mean value of switch cost that does not accurately reflect either of the above trial types. For long R-S intervals, subjects are more likely to have initiated (and completed) task-set reconfiguration before stimulus onset; therefore they will have low switch costs. With short R-S intervals, they will have completed preparation on a lower proportion of trials, leading to a greater switch cost (see also Nieuwenhuis & Monsell, 2002).

The Present Study

Although theorists differ in their conceptualization of the number and function of control processes involved in switch cost, they largely agree that more work is needed to characterize the phenomenon and identify the processes involved. The aim of the present study was to identify event-related potential (ERP) components associated with task-switching processes. Given that the claim for two components was made by Rogers and Monsell (1995) using the alternating runs paradigm, it was decided to employ this paradigm as a first step in investigating ERP correlates of task-switching processes. Specifically, the task parameters were modeled on Rogers and Monsell's Experiment 3, including four blocks of crosstalk trials presented at R-S intervals of 150, 300, 600, and 1,200 ms, respectively, as well as two no-crosstalk blocks of R-S intervals of 150 and 1,200 ms.

If there are two distinct components contributing to the process of task-set reconfiguration, one which is externally driven and can only be activated after stimulus onset and another which is internally driven and, given enough time, may be initiated and completed prior to the onset of the stimulus, it should be possible to identify different ERP components that are associated with each of these processes. The poststimulus component of processes involved in task switching would be reflected in ERP components occurring after stimulus onset, which should be identified in the stimulus-locked ERP waveform as a differential between waveforms for switch and no-switch trials. The preparatory processes activated in anticipation of task switching would be expected to have, at least, begun prior to the onset of the switch stimulus, especially for longer R-S intervals. The precise onset of preparation is hard to determine and may vary from trial to trial. However, it should presumably begin sometime between the decision or response to the previous no-switch trial and the onset of the impending switch trial. In the current study, the onset of the response to the previous stimulus was used as an indicator of the completion of processing related to the previous stimulus and a potential point of onset of processing in anticipation of the next stimulus. To target this interval, ERP waveforms were averaged around the response to the preceding no-switch trial and extended up to or beyond the onset of the subsequent switch trial (i.e., anticipating a switch trial), and around the response to the preceding switch trial through to or beyond the onset of the subsequent no-switch trial (i.e., anticipating a no-switch trial). Thus these response-locked waveforms covered the interval between the response to the current stimulus and the onset of the subsequent stimulus (i.e.,

the entire R-S interval). It was expected that ERP components associated with anticipatory processes would be identified as a differential between response-locked ERP waveforms for switch and no-switch trials. A third set of ERP averages were also constructed around the onset of the EMG response leading to the overt button press response. It was reasoned that these EMG onset-locked waveforms might provide a better indication of the timing of the decision regarding the response to the preceding trial, and thus provide better time-locking for the onset of anticipatory processing for the current trial.

Thus, it is claimed that ERP component(s) associated with anticipatory processes of task-switching will be evident in EMG onset-locked and/or response-locked ERP difference waveforms, developing in the interval between the completion of a decision/response to the previous trial and the onset of the following one (i.e., the R-S interval). If this anticipatory process is only triggered at long R-S intervals (i.e., when subjects have time to initiate task-set reconfiguration in advance of stimulus onset), then the ERP component associated with task-switching in the response- or EMG onset-locked waveforms will emerge for longer R-S intervals. It is also predicted that ERP component(s) associated with poststimulus processes involved in task switching will be evident in the stimulus-locked ERP waveform. If it is assumed that both anticipatory and stimulus-triggered processes contribute to the completion of the overall process of task-set reconfiguration, then the amount of reconfiguration necessary to be completed after stimulus onset will be reduced, as there is more time to complete reconfiguration prior to stimulus onset. This suggests that the ERP component associated with poststimulus processes will be less activated with increasing R-S intervals.

Finally, if, as suggested by De Jong (2000), there is only one process contributing to task-set reconfiguration and it is initiated sometimes prior to and sometimes after stimulus onset, then the same ERP component should be evident in both stimulus-locked and response-or EMG onset-locked data, differing in amplitude and/or latency across different R-S intervals.

To examine behavioral and ERP measures of task switching using well-learned tasks and relatively stable performance, participants were given extensive task practice in a separate training session. Practice effects are reported, but only data collected during the second testing session are analyzed in detail.

Method

Participants

Twenty-four undergraduate students (16 female; mean age = 22.5, range = 18–35) participated in this study for credit in an introductory psychology course. Participants gave written informed consent and had no prior exposure to this paradigm.

Stimuli

The stimulus setup and presentation parameters were selected to replicate as closely as possible the conditions used in Experiment 3 by Rogers and Monsell (1995). However, minor modifications of the paradigm were necessary to record electrophysiological data.

The stimulus display was under the control of a 486 PC. A square box (10 cm side) divided into four equal smaller squares was continuously displayed in the middle of a computer monitor (NEC MultiSync 4FGe, 90 cm viewing distance). On each trial, the stimulus was displayed in the center position of one of the

four boxes, rotating across the four boxes in a clockwise direction.

Two adjoining boxes were assigned to the letter task and the remaining two adjoining boxes were assigned to the digit task. For half the participants, the two boxes on the top were assigned to the letter task and the two bottom boxes were assigned to the digit task. For the remaining participants, the two boxes on the right were assigned to the letter task and the two boxes on the left were assigned to the digit task. This configuration was used so that, for half the participants, a task switch occurred on a vertical eye shift, and, for the other half, on a horizontal eye shift. For each participant, the task changed predictably every second trial (AABB). As the display proceeded in a predictable clockwise manner, the position of the current stimulus provided a valid cue with regards to the task active on that trial as well as the subsequent trial (Figure 1).

Stimuli consisted of a pair of characters displayed in upper case in the middle of the box (Arial 14 point font). Each stimulus consisted of two characters selected from two of three sets: letters, digits or nonalphanumeric characters. The letter set included four consonants (G, K, M, R) and four vowels (A, E, I, U). The digit set included four even (2, 4, 6, 8) and four odd (3, 5, 7, 9) numbers. The nonalphanumeric characters were #, ?, *, %.

The character pair was displayed on the screen until the participant responded to the stimulus or for a total of 5,000 ms. The following stimulus was presented in the next box in the sequence at a delay of 150, 300, 600, or 1,200 ms after the onset of the response or termination of the stimulus. This R-S interval remained constant within each block of trials and was manipulated across different blocks.

On the letter task, participants were required to classify the stimulus as a vowel or consonant using a button press response

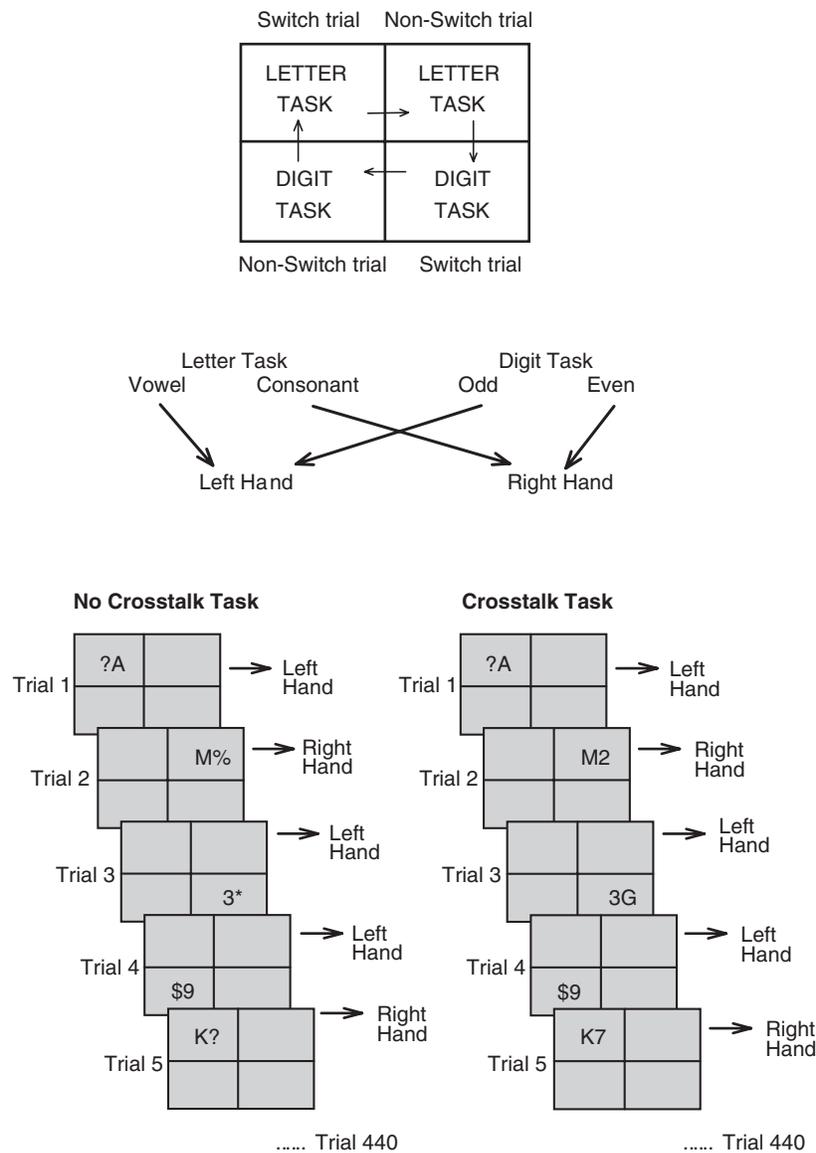


Figure 1. Top: A 2 × 2 grid showing the sequence of task alternation and the stimulus-response mapping for each of the two tasks. Bottom: A sequence of no-crosstalk and crosstalk trials and the correct response based on the stimulus-response mapping presented above.

with either their left or right index finger (e.g., vowel—left, consonant—right). On the digit task, participants used the same keys to classify the stimulus as odd or even. One key was mapped to vowel and odd decisions and the other to consonant and even decisions (Figure 1). The hand assigned to each key was counterbalanced across participants.

Each participant performed the task in six blocks. Two blocks used character pairs consisting of one digit (digit task) or one letter (letter task) and a nonalphanumeric character (e.g., A\$ or 3#). The position of the letter/digit in the character pair varied randomly across trials (e.g., A\$, #M). This condition corresponds to the no-crosstalk condition of Rogers and Monsell (1995). The R-S interval was 150 ms for one block (N-150) and 1,200 ms for the other block (N-1200).

The other four blocks correspond to the crosstalk condition of Rogers and Monsell (1995). In the crosstalk condition, one of the characters comprising the stimulus was selected from the task-relevant set (e.g., letter for letter task, digit for digit task), whereas the other was selected from either the neutral set (e.g., nonalphanumeric character), or from the task-irrelevant set (e.g., digit for letter task, letter for digit task). Thus, the task-relevant character was accompanied by a neutral character on one third of the trials and these trials were identical to the no-crosstalk condition. On half the remaining trials, the task-irrelevant character was mapped to a response with the same hand as the task-relevant character and on the other half, it was mapped to a response with the opposite hand (Figure 1). For example, if the task-relevant character was a vowel, then the task-irrelevant character could be nonalphanumeric (neutral), an odd digit (congruent trial), or an even digit (incongruent trial). The crosstalk condition was run under different R-S intervals in four separate blocks (C-150, C-300, C-600, and C-1200).

Procedure

All volunteers participated in two sessions scheduled 5 to 9 days apart. Each session included training and testing sections. For the purposes of training, simplified versions of the task were created. These were constructed by including only the letter task or only the digit task using a format identical to the display above. Thus the stimulus was rotated across the four boxes in a clockwise manner; however, all stimuli within a block were either letters (letter practice) or digits (digit practice). All participants received training on the letter practice task, the digit practice task, the no-crosstalk, and the crosstalk tasks, administered in the above order with an R-S interval of 450 ms. On Day 1, two consecutive practice runs (32 stimuli) of each task were administered, whereas on Day 2, only one practice run of each task was given. Throughout both training sessions, the assignment of response hand to stimulus type was displayed continuously under the computer monitor.

Training was followed by a testing session which was divided into six blocks: two no-crosstalk blocks (N-150, N-1200) and four crosstalk blocks (C-150, C-300, C-600, C-1200). These six blocks were counterbalanced using a Latin Square design both within subject (Day 1 to Day 2) and between subjects. Each block consisted of 2 to 4 runs of 104 stimuli. The first four stimuli in each run were excluded from behavioral and ERP analyses. Performance feedback was given, following each run, and participants were encouraged to use this feedback to improve their performance. On Day 1, each R-S interval block consisted of two consecutive runs and only behavioral data were recorded. On Day 2, both behavioral and ERP data were recorded, and

four consecutive runs of each R-S interval block were administered in order to increase signal-to-noise ratio in the ERP averages (i.e., 100 trials per Trial Type \times Task \times R-S Interval). Participants were instructed to respond as quickly as possible while maintaining a high level of accuracy. Prior to a change in block, participants were alerted to the change in R-S interval and that they could use this interval to prepare for the next trial.

ERP Recording and Data Acquisition

EEG and EOG were sampled continuously at 200 Hz/channel using NeuroScan Inc. software on a 486 personal computer. EEG was recorded from 28 scalp electrodes using an electrode cap (Electro-Cap International). Twenty-one sites were positioned according to the 10/20 system (FPz, Fz, Cz, Pz, Oz, FP1, F3, F7, C3, P3, T3, T5, O1, FP2, F4, F8, C4, P4, T4, T6, O2). Additional electrodes were included at positions midway between Fz and Cz (FCz), F3/F4 and FP1/FP2 (FF3 and FF4), T5/T6 and O1/O2 (TO5 and TO6), and T5/T6 and P3/P4 (TP5 and TP6). Vertical and horizontal EOG were recorded via electrodes situated above and below the left eye and on the outer canthi of each eye, respectively. EOG and EEG were amplified ($\times 5,000$ for EOG and frontal electrodes, $\times 20,000$ for other EEG channels) using a Grass Neurodata (Model 12) system with a bandpass of 0.01–30 Hz (-6 dB down). All EEG electrodes were referred to linked mastoids.

EMG Recording and Triggering

EMG was recorded with the same Grass Neurodata system (1.0–100 Hz, $\times 20,000$) as the EEG and EOG using gold electrodes placed on the left and right forearms using standard forearm flexor placements (Lippold, 1968). The EMG data were stored with the EEG data and were extracted off-line to determine the onset of the EMG response and insert the EMG trigger into the EEG file where the stimulus and response triggers were already stored.

Each channel of EMG data was scanned off-line and the maximum absolute value of EMG signal over all trials in each condition was determined. The threshold value of EMG signal was calculated as 25% of the maximum value. Periods of EMG activity were found using the premise that EMG activity begins when EMG signal is equal or greater than the threshold level and ends when its value drops below the threshold level for a period of 75 ms or longer. The absolute value of the local maximum of EMG signal was found for each EMG activity period. The EMG onset was defined as the point where the EMG signal first exceeded 25% of its local maximum value. The following restrictions were used in estimating the onset of the EMG response. EMG activity beginning less than 100 ms after stimulus onset was ignored. EMG activity in one hand was ignored if it occurred in the interval between the onset of EMG activity and the response trigger in the other hand. If more than one EMG trigger was found in a particular channel between a stimulus code and relevant response code, then the trigger associated with the largest local EMG value was accepted.

Data Analysis

Behavioral data. Responses occurring within a 100–4,000-ms time window after stimulus onset were classified as correct or incorrect depending on stimulus-response mapping. Correct and incorrect responses outside this time window were recorded as misses (no response). RT was measured for correct responses.

RT and arc-sine transformed proportion error data were analyzed using the following factors. The no-crosstalk condition included factors for Day (1, 2), Trial (switch, no-switch), Task (letter, digit), and R-S Interval (150, 1,200). The factors for the crosstalk condition were Day (1, 2), Task (letter, digit), Trial (switch, no-switch), R-S Interval (150, 300, 600, 1,200) and Irrelevant Character Type (neutral, congruent, incongruent). Practice effects were analyzed using a repeated measures Day \times Trial \times Task \times R-S Interval ANOVA. All other effects were analyzed using a repeated measures Trial \times Task \times R-S interval ANOVA for Day 2 data only. All significant main effects and interactions are reported. Where appropriate, critical values were adjusted using Greenhouse–Geisser correction for the violation of the assumption of sphericity (Vasey & Thayer, 1987).

ERP data. Vertical eye movement artifact was corrected in the continuous EEG data files using the algorithm developed by Semlitsch, Anderer, Schuster, and Presslich (1986) as implemented by NeuroScan software. These files were then inspected and sections of EEG contaminated with channel saturation or noise were excluded from further processing.

Three sets of epoched data were created. Stimulus-locked averages were constructed by extracting 1,700-ms epochs around the onset of the stimulus, including a 200-ms prestimulus epoch. EMG-locked and response-locked averages were constructed by averaging around the EMG onset and response markers, respectively (1,650-ms epoch, 400-ms premarker). In all three sets, the baseline was set from -50 to 50 ms around the stimulus, EMG, or response trigger, respectively. The need for such a short baseline arose because of large prebaseline shifts in some R-S interval conditions after the subject responded to one stimulus and prepared for the onset of the following stimulus. This was partly the result of the buildup of contingent negative variation (CNV) due to the use of a fixed interval between the occurrence of the response and the onset of the following stimulus.

For all conditions, ERP waveforms were averaged across task (letter, digit), as this was not a central issue in the study and behavioral analyses showed that task did not interact significantly with trial type and R-S interval. Stimulus-locked epochs within each block (N-150, N-1200, C-150, C-300, C-600, C-1200) were averaged separately according to whether the eliciting stimulus required performance of the same task as the immediately previous stimulus (N: no-switch) or a change in task (S: switch). Thus, 12 stimulus-locked ERP waveforms were constructed at each electrode site: N-150(S), N-150(N), N-1200(S), N-1200(N), C-150(S), C-150(N), C-300(S), C-300(N), C-600(S), C-600(N), C-1200(S), C-1200(N). The number of epochs contributing to each average were estimated using the stimulus-locked data and ranged over 93 to 194 ($M = 161.42$, $SD = 21.15$). For EMG- and response-locked averages, epochs within each block were averaged separately according to whether the stimulus *following* the current response required a change in task (S: switch) or performance of the same task (N: no-switch). For example, for EMG- and response-locked averages, the N-150(S) was constructed around the response to a no-switch trial and in anticipation of a switch trial.

To assist presentation of the results, the same labels will be used for stimulus-, EMG- and response-based averages. The reasoning is that N-150(S) for stimulus-based averages reflects the ERP effects associated with processing a stimulus associated with a change in task, whereas the same label for EMG- and

response-based averages will reflect ERP effects associated with the anticipation of and/or preparation for a change in task.

Due to the relatively low signal/noise ratio and the fact that differences between the different stimulus types in the crosstalk task were not central to the aims of this study, ERP data for this task were averaged across congruent, incongruent, and neutral stimulus types.

Stimulus-locked ERP averages. Given that the focus of this study is the cost of switching between tasks, analysis of the stimulus-locked data was based on the difference waveforms derived by subtracting the ERP waveform for no-switch trials from the ERP waveform for switch trials (i.e., switch – no-switch). A separate difference waveform was constructed for each of the six conditions (N-150(s-n), N-1200(s-n), C-150(s-n), C-300(s-n), C-600(s-n), C-1200(s-n)). These waveforms were analyzed at Fz, FCz, Pz, Oz, TO5, and TO6 sites, which, on the basis of visual inspection of the ERP waveforms, showed largest differentiation between switch and no-switch trials. Point by point t tests were conducted over 50 to 700 ms on each waveform to establish areas of significant deviation from baseline. Type 1 error rate was controlled at .05 using the Guthrie and Buchwald (1991) procedure, with autocorrelation estimated at .9. Only effects that reached significance by these criteria are reported. Sampling interval length was estimated independently for every section of each difference waveform to target the analysis to the specific components reflected in the subtraction.

Response-based and EMG-based ERP averages. Statistical analysis for response- and EMG-locked waveforms was essentially identical to that conducted for the stimulus-based averages. Briefly, ERP difference waveforms were constructed and deviation from baseline was determined as described above. Point-by-point t tests were conducted for EMG- and response-locked averages. Specifically, for EMG-based averages, deviation from baseline was measured over ranges of 55–250, 55–400, 55–700, and 55–1,200 ms for 150-, 300-, 600-, and 1,200-ms R-S intervals, respectively. For response-based averages, measures were taken over ranges of 55–200, 55–350, 55–650, and 55–1,200 ms for 150-, 300-, 600-, and 1,200-ms R-S intervals, respectively.

Results

Behavioral Data

Practice effects. RT showed a significant decline with practice for both no-crosstalk and crosstalk tasks, $F(1,23) = 48.86$, $p < .001$; $F(1,23) = 81.96$, $p < .001$, respectively. RT declined significantly from Day 1 to Day 2. This decline was significantly greater for switch than no-switch trials (no-crosstalk: 124 vs. 83 ms, $F(1,23) = 19.83$, $p < .001$; crosstalk: 237 vs. 153 ms, $F(1,23) = 65.83$, $p < .001$) and for the letter than the digit task (no-crosstalk: 109 vs. 83 ms, $F(1,23) = 7.05$, $p < .014$; crosstalk: 203 vs. 179 ms, $F(1,23) = 7.80$, $p < .010$). In the crosstalk condition, there was a greater improvement in RT at short compared to long R-S intervals (Day \times R-S Interval: $F(3,69) = 4.57$, $p < .006$). Error rate increased on Day 2, but the effect was significant only for the crosstalk condition (2.4% increase; $F(1,23) = 18.16$, $p < .001$).

Because the focus of the paper is on switching between two well-learned tasks, the remaining effects were examined using

only behavioral data from Day 2, which also correspond to the ERP data.

Effects of task-switching. The effects of trial type across the different conditions for RT and percent errors are shown in Figure 2. For both crosstalk and no-crosstalk conditions, RT increased from no-switch to switch trials, $F(1,23) = 56.01$, $p < .001$; $F(1,23) = 32.19$, $p < .001$, respectively, and declined with increasing R-S interval, $F(3,69) = 17.46$, $p < .001$, $\epsilon = .818$; $F(1,23) = 20.69$, $p < .001$, respectively.

RT switch cost, measured as the difference between no-switch and switch RT, is shown in Figure 3. Although RT switch cost shows a tendency to decline with increasing R-S interval in the no-crosstalk condition (N-150: 36 ms; N-1200: 32 ms), the effect did not reach significance. The crosstalk condition showed a large decline in RT switch cost with increasing R-S interval, dropping from 116 ms in C-150 to 63 ms in C-1200 (Trial \times R-S Interval: $F(3,69) = 9.52$, $p < .001$, $\epsilon = .668$). Despite the decline in RT switch cost with increasing R-S interval, there was a significant switch cost on RT in both conditions even at the longest R-S interval. This is reflected in the significant effect of trial type at an R-S interval of 1,200 ms for both no-crosstalk and crosstalk conditions, $F(1,23) = 25.37$, $p < .001$; $F(1,23) = 53.30$, $p < .001$, respectively.

In the crosstalk condition, there was a significant increase in percentage error from no-switch to switch trials (Figure 2),

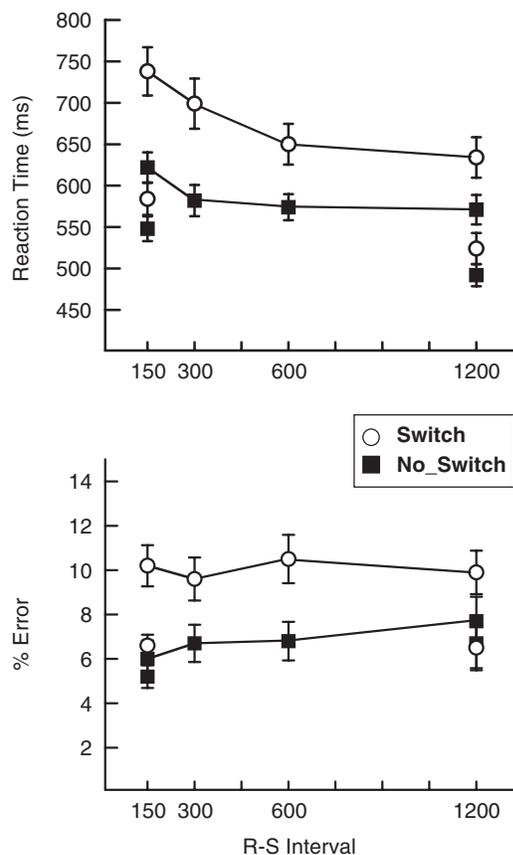


Figure 2. Mean reaction time (top) and percentage error scores (bottom) for switch and no-switch trials are shown for each level of R-S interval. Connected points denote crosstalk. Isolated points denote no crosstalk. Standard error bars are shown.

$F(1,23) = 43.05$, $p < .001$. Although error switch cost (switch – no-switch) showed a tendency to decline with increasing R-S interval (Figure 3), the interaction between trial type and R-S interval did not reach significance. Analysis at C-1200 alone showed that the residual error switch cost was significant, $F(1,23) = 8.08$, $p < .009$. In the no-crosstalk condition, the effect of trial type and the interaction between trial type and R-S interval failed to reach significance in the original analysis, $p < .070$, $p < .073$, respectively. However, as suggested in Figures 2 and 3, analyses at each R-S interval separately resulted in a significant effect of trial type at N-150 (error switch cost = 1.3; $F(1,23) = 7.91$, $p < .010$) but no effect at N-1200 (error switch cost = -0.2).

Effects of irrelevant character type. The effect of the presence of stimuli related to the alternative task-set was examined by comparing no-crosstalk and crosstalk conditions for common values of R-S interval [Condition \times Task \times Trial \times R-S Interval (150, 1,200)]. As shown in Figure 2, RT and error rates were significantly larger in crosstalk compared to no-crosstalk conditions, $F(1,23) = 149.93$, $p < .001$; $F(1,23) = 30.67$, $p < .001$. RT and error switch cost were significantly greater for the crosstalk condition (Figure 3), Condition \times Trial: $F(1,23) = 56.80$, $p < .001$; $F(1,23) = 13.89$, $p < .001$. The effect of crosstalk condition on RT switch cost was greater at short compared to long R-S interval (Figure 3), Condition \times R-S Interval \times Trial: $F(1,23) = 20.87$, $p < .001$. Thus, the presence of irrelevant

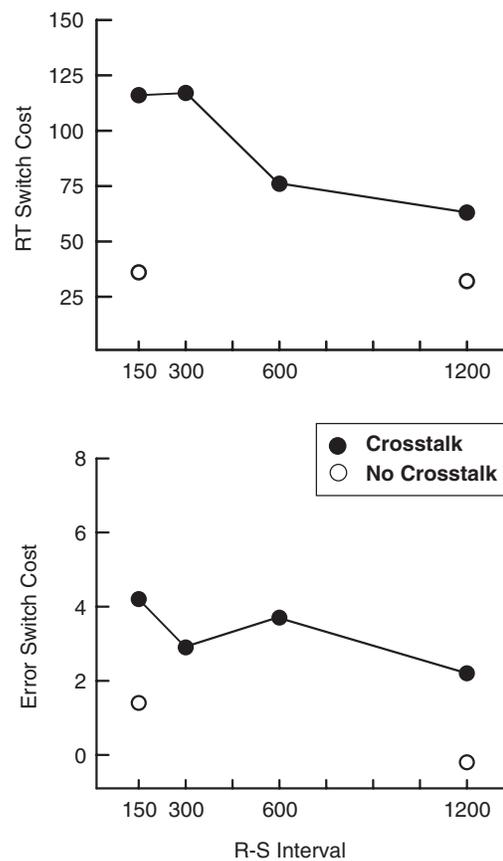


Figure 3. RT and error switch costs are shown based on (switch – no-switch) scores for each level of R-S interval. Connected points denote crosstalk. Isolated points denote no crosstalk.

characters related to the alternative task set on some trials increased task difficulty and task-switching difficulty. Whereas increasing R-S interval resulted in a decrease in the size of the crosstalk effect on RT switch cost, a significant effect of crosstalk on RT switch cost remained even for the long R-S interval of 1,200 ms, $F(1,23) = 28.30, p < .001$.

Within the crosstalk task, RT increased from neutral to congruent to incongruent irrelevant character trials (Table 1), $F(2,46) = 98.42, p < .001, \varepsilon = .829$. Table 1 shows that the RT switch cost was differentially affected by the type of irrelevant character (Trial \times Irrelevant Character: $F(2,46) = 42.62, p < .001, \varepsilon = .935$). Post hoc comparisons showed greater RT switch cost for incongruent and congruent than for neutral stimuli, $F(1,23) = 61.67, p < .001$, as well as for incongruent than for congruent stimuli, $F(1,23) = 11.42, p < .003$. Incongruent characters resulted in a greater number of errors overall (Table 1), $F(2,46) = 74.78, p < .001, \varepsilon = .575$. The interaction between character and trial type was also significant, $F(2,46) = 31.13,$

$p < .001, \varepsilon = .742$. Post hoc comparisons showed that error switch cost was greater for incongruent compared to congruent and neutral trials, $F(1,23) = 39.23, p < .001$, but no significant difference between congruent and neutral trials (Table 1).

Finally, switch cost in no crosstalk was compared to the neutral irrelevant character trials in crosstalk, to examine whether the possibility that the stimulus may contain irrelevant characters related to the alternative task-set affects stimulus processing on neutral trials [Condition (no crosstalk vs. neutral trials from crosstalk) \times Task \times Trial Type \times R-S Interval (150, 1,200)]. As shown in Table 1, RT and error rate were greater for neutral irrelevant characters trials in crosstalk compared to the no-crosstalk condition, $F(1,23) = 45.44, p < .001$; $F(1,23) = 19.62, p < .001$. The interaction between condition and trial, $F(1,23) = 16.02, p < .001$, and the three way interaction between condition, R-S interval and trial, $F(1,23) = 7.28, p < .013$, reflect that RT switch cost was greater for neutral irrelevant characters in crosstalk than for no-crosstalk conditions at the short R-S

Table 1. Mean (SE) for RT and Percent Error Scores on Day 2

Task	Character	Trial type	RT	% error
N-150	—	Switch	584 (19.4)	6.6 (0.5)
		No-switch	548 (14.9)	5.2 (0.5)
		Cost	36	1.4
N-1200	—	Switch	524 (18.9)	6.5 (1.0)
		No-switch	492 (13.4)	6.7 (1.1)
		Cost	32	-0.2
C-150	Neutral	Switch	651 (22.4)	5.2 (0.5)
		No-switch	568 (14.7)	4.0 (0.6)
		Cost	83	1.2
	Congruent	Switch	752 (34.5)	5.2 (0.8)
		No-switch	620 (19.4)	2.7 (0.5)
		Cost	132	2.5
	Incongruent	Switch	823 (33.5)	19.8 (2.2)
		No-switch	674 (22.6)	11.2 (1.8)
		Cost	149	8.6
C-300	Neutral	Switch	587 (25.1)	4.6 (0.8)
		No-switch	537 (14.0)	4.1 (0.8)
		Cost	50	0.5
	Congruent	Switch	689 (37.6)	5.7 (0.8)
		No-switch	589 (22.2)	4.7 (0.8)
		Cost	100	1.0
	Incongruent	Switch	738 (31.0)	17.9 (1.8)
		No-switch	620 (21.6)	10.8 (1.3)
		Cost	118	7.1
C-600	Neutral	Switch	572 (16.5)	5.7 (0.8)
		No-switch	526 (13.8)	4.5 (0.7)
		Cost	46	1.2
	Congruent	Switch	658 (26.9)	5.6 (0.9)
		No-switch	576 (17.3)	4.0 (0.8)
		Cost	82	1.6
	Incongruent	Switch	727 (31.6)	19.7 (2.1)
		No-switch	621 (18.5)	11.6 (1.3)
		Cost	106	8.1
C-1200	Neutral	Switch	564 (18.9)	2.9 (1.0)
		No-switch	523 (13.1)	2.4 (0.8)
		Cost	41	0.5
	Congruent	Switch	648 (30.4)	4.3 (1.2)
		No-switch	579 (21.0)	2.3 (0.8)
		Cost	69	2.0
	Incongruent	Switch	694 (25.7)	12.5 (1.7)
		No-switch	611 (20.6)	7.6 (1.9)
		Cost	83	4.9

Notes: Scores have been averaged across task and are presented separately for condition, trial type, and irrelevant character type.

Switch cost (Cost = switch - no-switch) in bold italics.

interval (150 ms: Condition \times Trial, $F(1,23) = 14.26$, $p < .001$) but not the long R-S interval (1,200 ms: Condition \times Trial, $p > .08$). Thus, at the slow rate, the presence of irrelevant characters from the currently suppressed task-set on two-thirds of trials did not significantly increase RT switch cost on neutral trials (Table 1). Percent errors showed no significant interactions between condition and trial type, $F > 1.0$ (Table 1), suggesting that despite an overall increase in error rate on neutral character trials in crosstalk compared to the no-crosstalk task, there was no differential effect on error switch cost.

ERP Data

Stimulus-locked averages. Stimulus-locked ERP averages at four midline and two lateral sites for switch and no-switch stimuli across different R-S intervals are depicted in Figure 4. Development of early stimulus-related ERPs is evident at all R-S intervals and for both switch and no-switch waveforms. These include a posterior P1/N2 complex and a frontal N1 that are more clearly observable at longer R-S intervals. These early effects are followed by a broad late positive component spreading posteriorly from 250 ms to the end or beyond the end of the analysis epoch.

ERP effects related to switching between task-sets appear to be characterized by slow broad changes in amplitude spanning a number of different stimulus-locked components, rather than by

a specific modulation of one ERP component. At the shortest R-S interval (N-150, C-150), there was early differentiation between ERPs for switch and no-switch trials in both no-crosstalk and crosstalk conditions. The effect was evident as a positive shift for switch trials superimposed on the posterior N1/P2 complex. This positivity is most clearly evident at parietal and occipital sites, extending from approximately 100 to 400 ms. This early posterior positive shift for switch trials was not evident with longer R-S interval intervals (with the only exception seen for C-300 over the left posterior hemisphere; see TO5 in Figure 4). Instead, these longer R-S interval conditions are characterized by a *negative* shift for switch as compared to no-switch trials. This negativity was most prominent for C-300 and C-600, emerging at Pz around 200 ms and extending beyond the end of the analysis epoch. Close inspection of N-150 and C-150 conditions show a similar but smaller negativity emerging most clearly at FCz after 300 ms. Likewise, a small negative shift is evident at FCz and Pz for N-1200 and C-1200 conditions. So, in summary, stimulus-locked ERP waveforms showed an early switch-related positivity for short R-S intervals only, whereas a later switch-related negativity was evident for all R-S intervals, being more prominent for the longest values (Figure 4).

To isolate the effects of task switching and decision making, difference waveforms were derived by subtracting no-switch

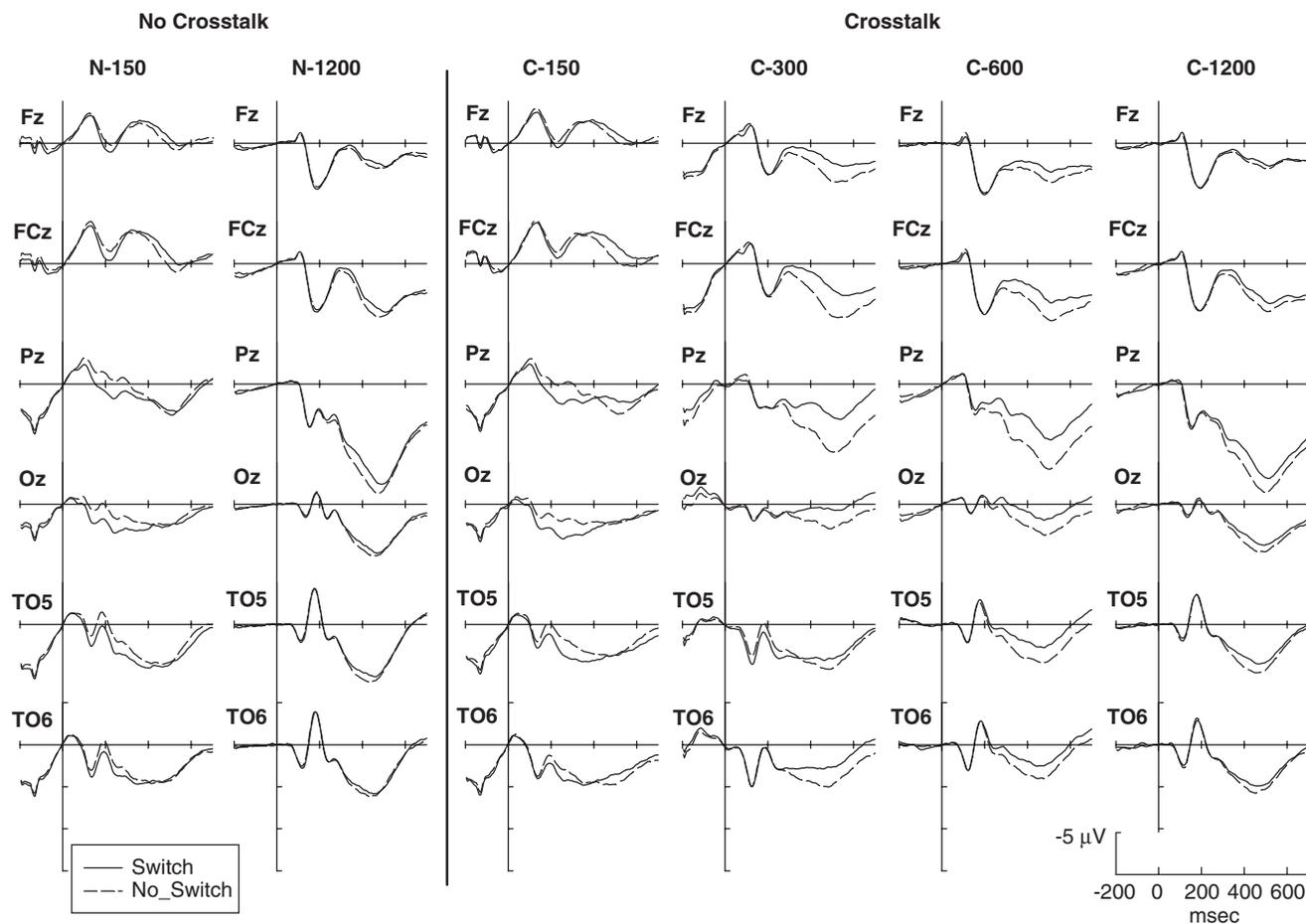


Figure 4. Stimulus-locked ERP waveforms for switch and no-switch trials are compared at four midline and two lateral sites for each level of R-S interval and separately for crosstalk (C-150, C-300, C-600, C-1200) and no-crosstalk (N-150, N-1200) conditions. Vertical line indicates stimulus onset. Negative is plotted up.

from switch ERP for each R-S interval and condition. Figure 5 shows stimulus-locked difference waveforms for the different R-S interval conditions across the midline and two lateral sites. The difference waveforms for the very short R-S interval of 150 ms shows a biphasic waveform including an immediate positivity followed by a negativity. With longer R-S interval values, only the negativity is evident. Given that these components differ quite considerably in their onset and duration across the different conditions and R-S intervals, point-by-point difference waveform analyses were conducted for each waveform to detect periods of significant deviation from baseline (for details see Methods). These results are summarized in Table 2.

N-150 and C-150 were associated with a large switch-related positivity that extended across 80–320 ms at Pz (Figure 5) emerging even earlier at Oz (see Table 2). This positivity will herein be referred to as D-Pos, the positive difference wave associated with task switching. A smaller but significant D-Pos was also obtained frontally for N-150, but not for C-150. Figure 5 also shows that D-Pos was not evident at Pz for longer R-S interval values. This was generally the case at other electrode sites as well with the exception of TO5, which showed a small but significant positivity over 65–275 ms for C-300 (see Table 2).

All stimulus-locked difference waveforms in Figure 5 show the development of the late switch-related negativity, which will be referred to as D-Neg. D-Neg was elicited at all R-S interval levels for both no-crosstalk and crosstalk conditions, but

appeared to be larger for C-300 and C-600. D-Neg onset appeared to be earlier for long R-S interval values. As shown in Table 2, when measured against baseline, D-Neg was significant across all midline sites for C-300 and C-600. It began earlier at Pz (295 ms and 180 ms for C-300 and C-600, respectively), extending to the end of the analysis epoch. At long R-S interval values (e.g., N-1200 and C-1200), D-Neg was restricted more posteriorly and dissipated before 500 ms for the N-1200 condition. D-Neg was also significant at short R-S interval values, however, for both N-150 and C-150, the effect was restricted to the frontocentral site, began a lot later (425 ms) and had a shorter duration, terminating around 550 ms (Table 2). However, note in Figure 5 that measurement of D-Neg amplitude relative to baseline was affected by the presence and relative amplitude of the preceding D-Pos.

Response-locked ERP averages. Response-locked ERP averages at four midline sites and two lateral sites for switch and no-switch stimuli across different R-S intervals are depicted in Figure 6. ERPs have been averaged using a 100-ms baseline centered around the onset of the response to the previous stimulus (vertical solid line) and depict activity in the interval between that response and the onset of the next stimulus, which is marked by the vertical broken line. Because the response-stimulus interval was held constant within each block of trials, the morphology of the response-locked waveforms corresponds

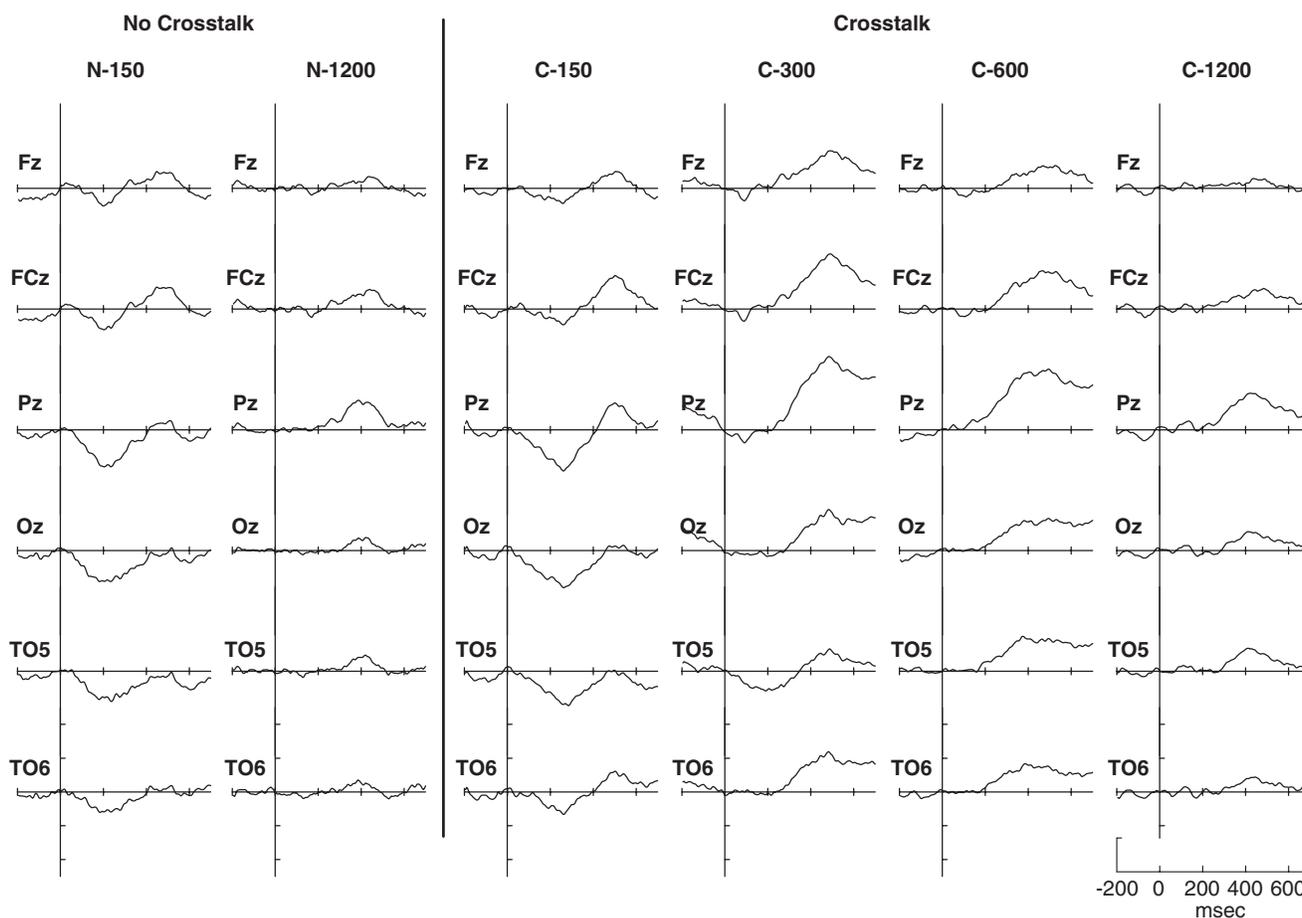


Figure 5. Stimulus-locked ERP difference waveforms derived using (switch – no-switch) subtraction are compared. See Figure 4 legend for more details.

Table 2. Results of Point-by-Point Analysis of Stimulus-Locked Difference Waveforms

	No crosstalk		Crosstalk			
	N-150	N-1200	C-150	C-300	C-600	C-1200
Positivity in stimulus-locked difference waveforms						
Fz	<i>100–300 (9)</i> 185–230 (10)	—	<i>100–350 (9)</i> n.s.	<i>50–150 (6)</i> 65–105 (9)	—	—
FCz	<i>100–300 (9)</i> 170–245 (16)	—	<i>100–350 (9)</i> n.s.	<i>50–150 (6)</i> 70–95 (6)	—	—
Pz	<i>50–400 (10)</i> 80–310 (47)	—	<i>50–400 (10)</i> 100–320 (45)	—	—	—
Oz	<i>50–400 (10)</i> 55–390 (67)	—	<i>50–450 (11)</i> 65–395 (67)	—	—	—
TO5	<i>50–500 (11)</i> 85–395 (63)	—	<i>50–500 (11)</i> 160–385 (46)	<i>50–350 (10)</i> 65–275 (43)	—	—
TO6	<i>100–400 (10)</i> 170–290 (25)	—	<i>100–400 (10)</i> 215–290 (16)	—	—	—
Negativity in stimulus-locked difference waveforms						
Fz	<i>350–600 (9)</i> n.s.	<i>300–600 (9)</i> n.s.	<i>400–600 (9)</i> n.s.	<i>200–600 (11)</i> 310–600 (58)	<i>200–600 (11)</i> 310–600 (59)	<i>200–600 (11)</i> n.s.
FCz	<i>350–600 (9)</i> 425–535 (23)	<i>200–600 (11)</i> 315–485 (35)	<i>350–600 (9)</i> 425–565 (29)	<i>200–600 (11)</i> 305–600 (59)	<i>200–600 (11)</i> 255–600 (70)	<i>200–600 (11)</i> 335–520 (38)
Pz	<i>400–500 (6)</i> n.s.	<i>200–500 (10)</i> 290–475 (38)	<i>400–600 (9)</i> n.s.	<i>200–600 (11)</i> 295–600 (62)	<i>100–600 (12)</i> 180–600 (85)	<i>200–600 (11)</i> 275–600 (66)
Oz	—	<i>300–500 (9)</i> 355–395 (9)	—	<i>300–600 (10)</i> 345–600 (52)	<i>200–600 (11)</i> 230–600 (75)	<i>300–600 (10)</i> 310–600 (59)
TO5	—	<i>300–500 (9)</i> 345–420 (16)	—	<i>350–600 (9)</i> 420–510 (19)	<i>200–600 (11)</i> 220–600 (77)	<i>250–600 (10)</i> 295–560 (54)
TO6	—	<i>300–450 (9)</i> n.s.	<i>400–600 (9)</i> 455–550 (20)	<i>250–600 (10)</i> 325–600 (56)	<i>200–600 (11)</i> 250–600 (71)	<i>300–600 (10)</i> 375–470 (20)

Notes: Numbers in italics represent the broad area over which deviation from baseline was assessed and are followed by the number of consecutive points that must significantly deviate from baseline for the effect to be statistically significant by Guthrie and Buchwald's criteria. Numbers underneath in bold represent the interval over which significant deviation from baseline was obtained with the number of consecutive data points showing significant deviation in parentheses.

very closely to that seen for the stimulus-locked waveforms in Figure 4. Any differences observed are due to the use of different baselines and depiction of different time windows. Due to PC memory limitations, it was not possible to depict ERPs after the onset of the stimulus in the very long R-S interval condition.

A quick inspection of Figure 6 shows that response-locked waveforms associated with switch and no-switch trials showed overall similar ERP patterns characterized by a build-up of a negativity in the interval between the emission of a response and the onset of the next stimulus. This negativity began immediately after the response and was maximal at parietal sites. However the development and shape of this negativity was influenced by the length of the R-S interval. At the two short R-S intervals (150, 300 ms), it peaked shortly after the onset of the subsequent stimulus, and then led on to the same pattern of effects seen in the stimulus-locked ERPs (see Figure 4). Longer R-S interval values showed a peak of this negativity between 200 and 400 ms after response onset, followed by a slower negative wave extending beyond the onset of the subsequent stimulus.

The effects of trial type can be seen in the differentiation between switch and no-switch waveforms. Relative to no-switch trials, switch trials were associated with a reduction in the amplitude of the negativity or a positivity superimposed in this negativity. This effect began between 200 and 300 ms after the onset of the response and was most clearly evident at the parietal site. For the shortest R-S interval, this positive shift clearly corresponds to the D-Pos seen in the stimulus-locked ERPs (Figure 4). What is apparent upon closer inspection of the

response-locked waveforms is that this positivity is also evident in the switch waveforms for longer R-S interval values. This was not evident in the stimulus-locked waveforms in Figure 4 because the positive deflection begins prior to the onset of the stimulus and is lost when baseline correction occurs around stimulus onset. Whether the positivity is evident before or after the onset of the stimulus appears to depend on the length of the response-stimulus interval for that condition. So, for example, for R-S interval of 150 ms, the switch-related positivity emerges after stimulus onset. However, for R-S intervals of 300 and 600 ms, this positivity emerges in the interval between the response and the next stimulus, and continues for a short interval after stimulus onset. In the longest R-S interval condition (1,200 ms), the positivity is considerably reduced in amplitude but still evident at least parietally.

To display the effects of trial type without the superimposed effects of response preparation and anticipation of the subsequent stimulus, difference waveforms were created for response-locked waveforms by subtracting ERPs for no-switch from switch trials (switch – no-switch). Deviation from baseline of response-locked difference waveforms was analyzed as for stimulus-locked difference waveforms and the results are shown in Table 3. Figure 7 depicts stimulus-locked (left) and response-locked (middle) difference waveforms for each R-S interval condition at Pz where the effects were maximal. The stimulus-locked difference waveforms are identical to those shown in Figure 5, but are included here to show the correspondence of ERP components across the three sets of difference waveforms.

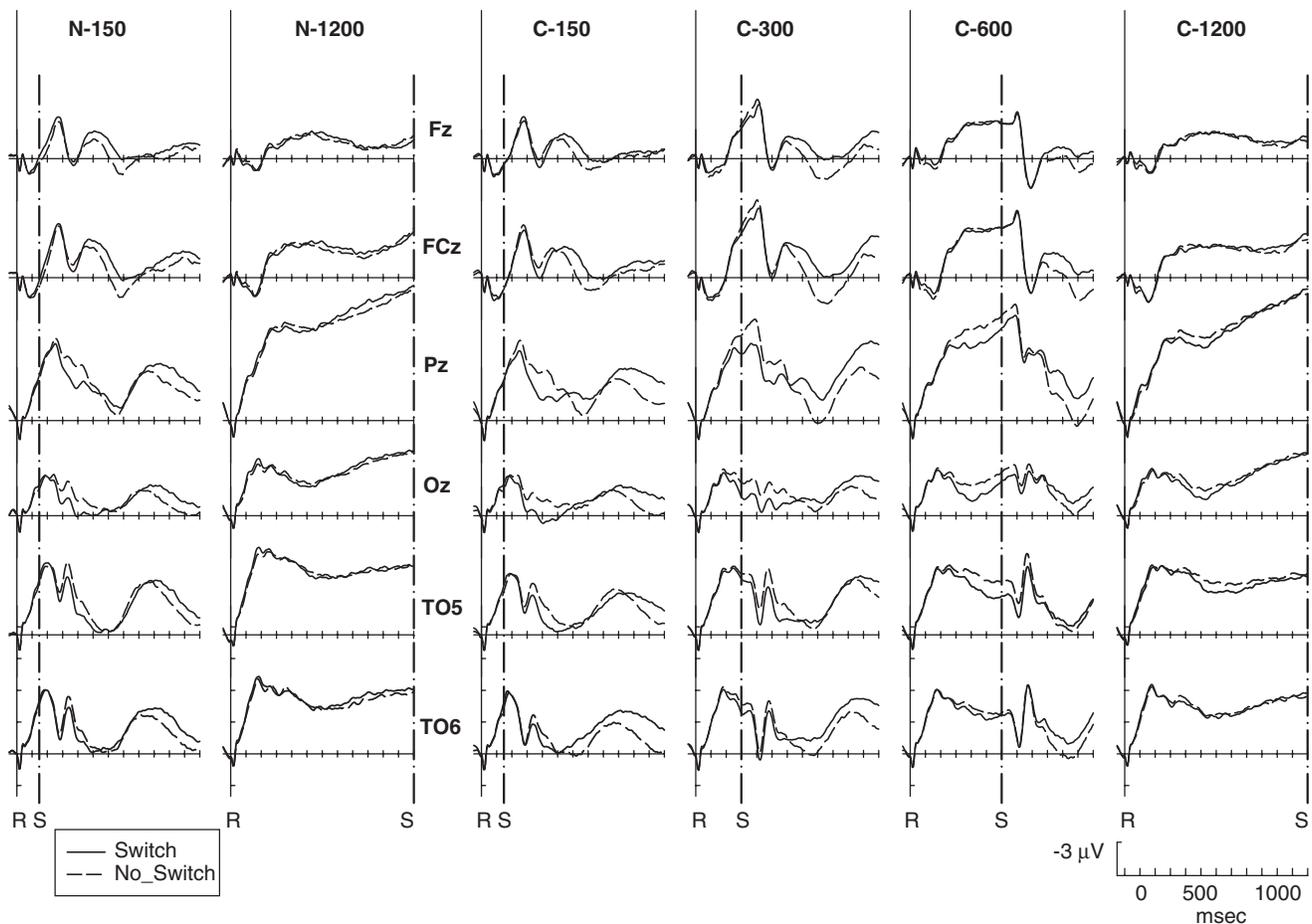


Figure 6. Response-locked ERP waveforms for switch and no-switch trials are compared. Vertical solid line denotes button press response (R). Vertical broken line indicates subsequent stimulus onset (S). Note change in time scale. Other details as in Figure 4 legend.

Response-locked difference waveforms show no significant switch-related activity in the response-stimulus interval at the shortest R-S interval of 150 ms. However, at R-S intervals of 300 and 600 ms, a large positivity is evident, emerging between 100 and 200 ms after response onset and, at least for C-600, peaking before the onset of the stimulus. This positivity is also evident for the longest R-S interval conditions (C-1200 and N-1200), but emerges later and is smaller in amplitude (Figure 7). Thus, it appears that, as R-S interval increases, D-Pos does not reduce in amplitude, as suggested by stimulus-locked difference waveforms in Figure 4, but instead emerges earlier, beginning prior to the onset of the switch-related stimulus. In fact, response-locked waveforms in Figure 7 suggest that this positivity may be triggered by processes initiated after the onset of a response to the preceding stimulus and in anticipation of the switch stimulus rather than being triggered by onset of the switch stimulus itself. In contrast, D-Neg, which develops after D-Pos, appears to be clearly time-locked to onset of the stimulus, peaking around 400–500 ms poststimulus.

Analysis of peak D-Pos and D-Neg. To investigate the effects of R-S interval and task condition on the amplitude and latency of these switch-related components, peak amplitude and latency measures of D-Pos and D-Neg were analyzed. Given that D-Pos appeared to emerge after the onset of the response to the previous

stimulus, D-Pos was measured in the response-locked difference waveforms. Positive peak amplitude (D-Pos) was calculated as the largest positive value over 200–600 ms. This interval was determined based on the difference waveform analyses (Table 3). If the peak value coincided with the limits of the above interval, then it was set to missing value for that subject for that waveform. D-Pos peak latency was estimated as the time point at which peak amplitude was reached. Although D-Pos showed a clear, sharp peak for most R-S intervals, it appeared as a much broader positivity at the longest R-S interval (Figure 7). Although peak measurements could still be obtained, both amplitude and latency measures would be expected to be more variable and less reliable than for shorter R-S intervals.

As D-Neg appeared to be temporally linked to stimulus onset, it was measured in stimulus-locked difference waveforms across 255–600 ms. Measurement of peak amplitude of this negativity relative to baseline was influenced by whether or not a D-Pos was evident in the post-stimulus interval in that particular condition. To overcome this problem, D-Neg peak amplitude was measured relative to D-Pos as a positive-to-negative peak measure. Specifically, D-Neg peak amplitude was derived by subtracting the value of the largest negativity over 255–600 ms from the value of largest positivity over 50–400 ms for the same condition (e.g., $D-Neg = \text{Peak Positivity (50-400)} - \text{Peak Negativity (255-600)}$). The latency of the peak negativity used to estimate

Table 3. Results of Point-by-Point Analysis of Response-Locked Difference Waveforms

	No crosstalk		Crosstalk			
	N-150	N-1200	C-150	C-300	C-600	C-1200
Positivity in response-locked difference waveforms						
Fz	<i>100–300 (9)</i> 140–195 (12)	<i>250–500 (9)</i> n.s.	<i>150–500 (10)</i> n.s.	<i>200–450 (9)</i> 360–395 (8)	—	—
FCz	<i>100–300 (9)</i> 145–185 (9)	<i>250–500 (9)</i> n.s.	<i>150–500 (10)</i> n.s.	<i>200–550 (10)</i> 335–400 (14)	—	<i>250–500 (9)</i> n.s.
Pz	<i>200–550 (10)</i> 260–450 (39)	<i>250–600 (10)</i> n.s.	<i>150–500 (10)</i> 245–465 (45)	<i>100–600 (12)</i> 255–560 (62)	<i>200–800 (12)</i> 295–700 (82)	<i>250–800 (12)</i> 365–545 (37)
Oz	<i>200–600 (11)</i> 255–485 (47)	<i>250–600 (10)</i> n.s.	<i>150–600 (11)</i> 225–535 (63)	<i>100–650 (12)</i> 220–590 (75)	<i>200–800 (12)</i> 260–710 (91)	<i>250–900 (12)</i> 440–555 (24)
TO5	<i>200–600 (11)</i> 270–500 (47)	<i>400–800 (11)</i> n.s.	<i>200–600 (11)</i> 320–495 (36)	<i>100–700 (12)</i> 370–595 (46)	<i>150–900 (12)</i> 350–830 (96)	<i>300–1,200 (12)</i> 450–760 (63)
TO6	<i>200–550 (10)</i> 345–420 (16)	—	<i>250–500 (9)</i> 370–430 (13)	<i>100–600 (12)</i> 260–525 (54)	<i>250–600 (11)</i> n.s.	<i>250–700 (10)</i> n.s.
Negativity in response-locked difference waveforms						
Fz	<i>400–1,200 (12)</i> 565–730 (34)	<i>500–900 (11)</i> 590–690 (21)	<i>500–800 (10)</i> 580–690 (23)	<i>500–1,200 (12)</i> 660–1,025 (74) 1,120–1,200 (17)	<i>800–1,200 (11)</i> 905–1,005 (21) 1,045–1,200 (32)	<i>500–900 (11)</i> n.s.
FCz	<i>400–1,200 (12)</i> 540–725 (38)	<i>500–1,050 (12)</i> 590–690 (21)	<i>500–1,200 (12)</i> 575–735 (33)	<i>550–1,200 (12)</i> 650–1,200 (111)	<i>800–1,200 (11)</i> 895–1,200 (62)	<i>850–1,100 (9)</i> n.s.
Pz	<i>800–1,200 (12)</i> 925–1,200 (156)	<i>600–1,200 (12)</i> n.s.	<i>550–1,200 (12)</i> 610–685 (16) 985–1,200 (44)	<i>600–1,200 (12)</i> 665–1,200 (108)	<i>800–1,200 (11)</i> 880–1,200 (65)	—
Oz	<i>800–1,200 (12)</i> 900–1,200 (61)	<i>700–1,200 (12)</i> n.s.	<i>800–1,200 (11)</i> 955–1,200 (50)	<i>650–1,200 (12)</i> 1,035–1,200 (34)	<i>850–1,200 (10)</i> 930–1,200 (55)	—
TO5	<i>900–1,200 (10)</i> 930–1,200 (55)	—	<i>900–1,200 (10)</i> 1,030–1,200 (35)	<i>100–1,200 (9)</i> 1,135–1,200 (14)	<i>900–1,200 (10)</i> n.s.	—
TO6	<i>750–1,200 (11)</i> 890–1,200 (65)	<i>500–1,200 (12)</i> n.s.	<i>500–1,200 (12)</i> 585–775 (39) 810–1,200 (79)	<i>600–1,200 (12)</i> 665–805 (29) 1,010–1,200 (39)	<i>800–1,200 (11)</i> 870–1,200 (67)	—

Notes: Numbers in italics represent the broad area over which deviation from baseline was assessed and are followed by the number of consecutive points that must significantly deviate from baseline for the effect to be statistically significant by Guthrie and Buchwald's criteria. Numbers underneath in bold represent the interval over which significant deviation from baseline was obtained with the number of consecutive data points showing significant deviation in parentheses.

D-Neg peak amplitude was used as a measure of D-Neg peak latency.

Two participants' data were not included in this analysis due to an overall lower signal-to-noise ratio affecting the precision of peak measurement. Another 3 participants were excluded from no-crosstalk analyses because of specific problems with measuring peaks in the long R-S interval condition. These peak measures were analyzed at Pz separately for no-crosstalk (N-150, N-1200) and crosstalk (C-150, C-300, C-600, C-1200) conditions using a R-S interval (two or four levels) ANOVA. The effect of condition on these components was examined using a Condition (no-crosstalk/crosstalk) \times R-S Interval (150/1,200) ANOVA. All significant main effects and interactions are reported.

Figure 8 (top) shows D-Pos peak amplitude (left) and latency (right) across different conditions at Pz. D-Pos amplitude significantly declined with increasing R-S interval for both no-crosstalk and crosstalk conditions, $F(1,18) = 9.71$, $p < .006$; $F(3,63) = 3.96$, $p < .022$, $\epsilon = .752$, respectively. As shown in Figure 8 (top, left), at R-S intervals of 150 and 1,200 ms, D-Pos amplitude did not differ significantly for crosstalk and no-crosstalk conditions.

D-Neg amplitude was significantly affected by R-S interval in both no-crosstalk and crosstalk conditions, $F(1,18) = 4.95$, $p < .039$; $F(3,63) = 5.05$, $p < .011$, $\epsilon = .654$. Figure 8 (bottom) shows that although at the two extreme R-S interval values, the

effect of R-S interval on D-Neg parallels that seen on D-Pos (e.g., large decline in amplitude), there is a difference in the development of the effect at intermediate R-S interval values. Specifically, D-Neg amplitude showed a small increase from R-S interval 150 ms to 300 ms, $F(1,21) = 10.21$, $p < .004$. This was followed by a decline in D-Neg amplitude that was statistically significant between 600 ms and 1,200 ms, $F(1,21) = 8.99$, $p < .007$. At the two extreme R-S interval values, D-Neg amplitude was larger in the crosstalk than in the no-crosstalk condition, $F(1,18) = 8.53$, $p < .009$.

D-Pos and D-Neg peak latency measures are shown in Figure 8 (right). Although D-Pos latency appears to increase for the longest R-S interval values in both no-crosstalk and crosstalk conditions, no significant effects were found. D-Neg latency significantly reduced with increasing R-S interval for both no-crosstalk and crosstalk conditions, $F(1,18) = 11.21$, $p < .004$; $F(3,63) = 5.38$, $p < .004$, $\epsilon = .885$ (Figure 8, bottom, right). Comparisons showed no difference between C-150 and C-300, but significant differences between C-150 and both C-600 and C-1200, $F(1,21) = 11.69$, $p < .003$; $F(1,21) = 10.96$, $p < .003$. D-Neg peak latency was significantly greater for crosstalk than no-crosstalk conditions, when compared at the two extreme R-S interval values, $F(1,18) = 19.89$, $p < .001$.

In summary, difference waveforms showed the emergence of a switch-related positivity (D-Pos) and a switch-related negativity (D-Neg). D-Pos was elicited after the response to the preceding

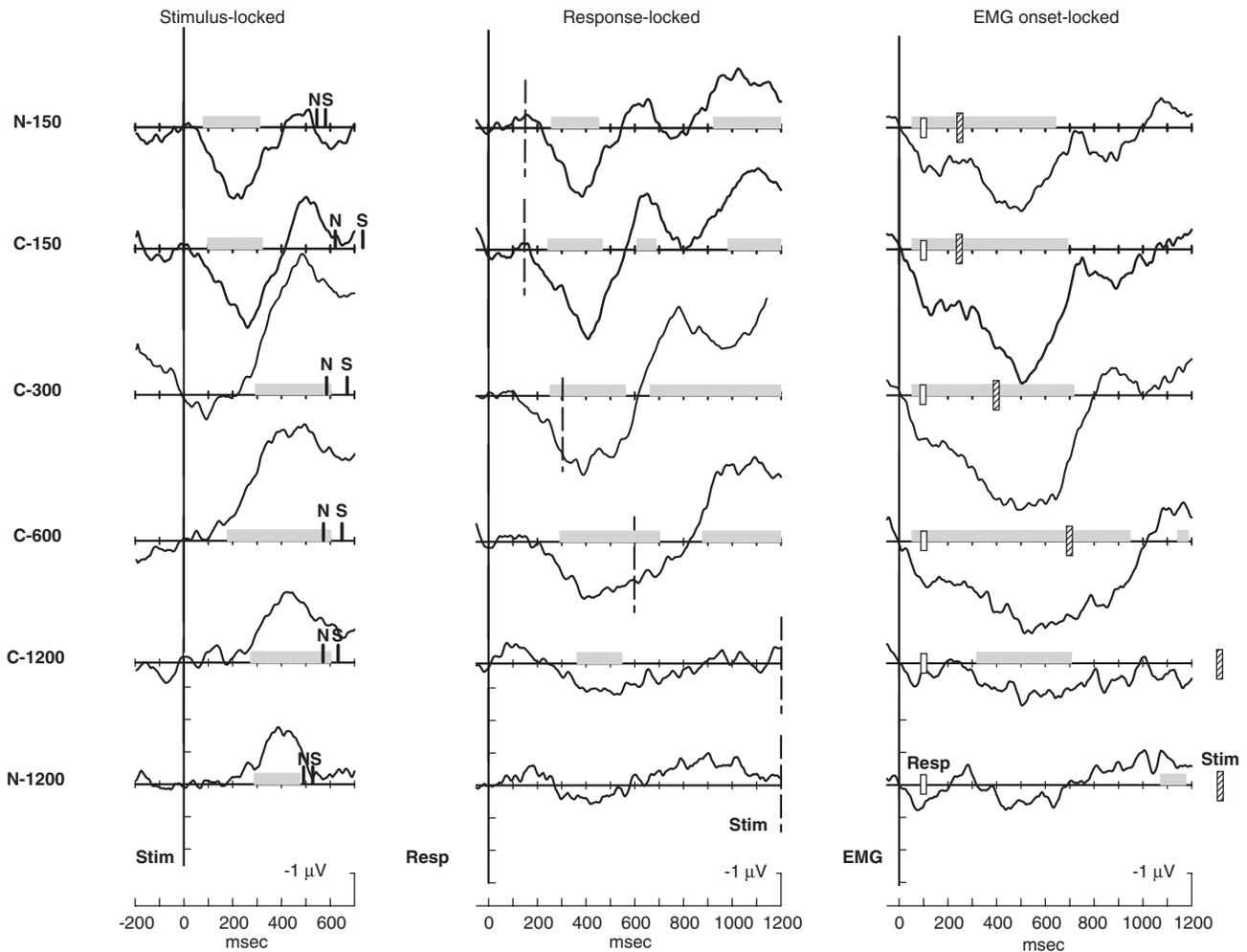


Figure 7. Comparison of stimulus-locked (left), response-locked (middle), and EMG onset-locked (right) ERP difference waveforms at Pz. Gray bars denote regions of significant deviation from baseline, thereby indicating a significant effect of task switching. Left: vertical lines shows stimulus onset (Stim). Average RT for no-switch (N) and switch (S) trials is indicated on time axis. Middle: vertical solid line shows button press response (Resp), short broken line shows subsequent stimulus onset (Stim). Right: vertical line shows EMG onset (EMG), open bar shows approximate timing of button press response (Resp), striped bar show approximate timing of subsequent stimulus onset (Stim).

stimulus, peaking around 400 ms after response onset. D-Pos amplitude reduced with increasing R-S interval in both no-crosstalk and crosstalk conditions. The presence of stimulus-response mapping interference (i.e., crosstalk) had no effect on D-Pos amplitude or latency. D-Neg emerged after D-Pos and was time-locked to the onset of the stimulus. D-Neg amplitude showed an initial increase from 150 to 300 ms R-S interval, but reduced thereafter. At the largest R-S interval value, D-Neg amplitude was larger and D-Neg latency was longer for crosstalk than for no-crosstalk blocks. D-Neg latency reduced significantly with R-S interval for both crosstalk and no-crosstalk blocks.

EMG-locked ERP averages. Figure 7 (right) depicts Pz ERP difference waveforms time-locked to the onset of the EMG response. The interval between the onset of the EMG and the actual depression of the push button was, of course, variable across trials. Based on the temporal correspondence between response-locked and EMG-locked waveforms, Figure 7 (right) shows a marker that gives a rough indication of response onset (R) at around 100 ms after EMG onset. The onset of the next

stimulus (S) is then depicted in relation to the response marker. Thus, broadly, the EMG-locked averages correspond to the response-locked averages with approximately 100 ms shift to the left. However, the latency jitter due to variability in the interval between EMG onset and response and the shift in baseline results in some differences in morphology. Point-by-point analysis of deviation of the EMG-locked difference waveform from baseline is presented in Table 4.

EMG-locked difference waveforms show that, for all but the longest R-S interval conditions, switch-related differentiation emerges almost immediately after EMG onset and is clearly evident at the time of actual button press. As seen in Figure 7 (right), this early positivity significantly deviated from baseline almost immediately after the onset of the EMG response and appeared to blend into the subsequent D-Pos, at least for the three shorter R-S interval conditions. The long R-S interval conditions suggest that this early positivity may be independent of the later D-Pos. For example, in C-1200, the early positivity does not reach significance and is followed by a return to baseline prior to the development of D-Pos.

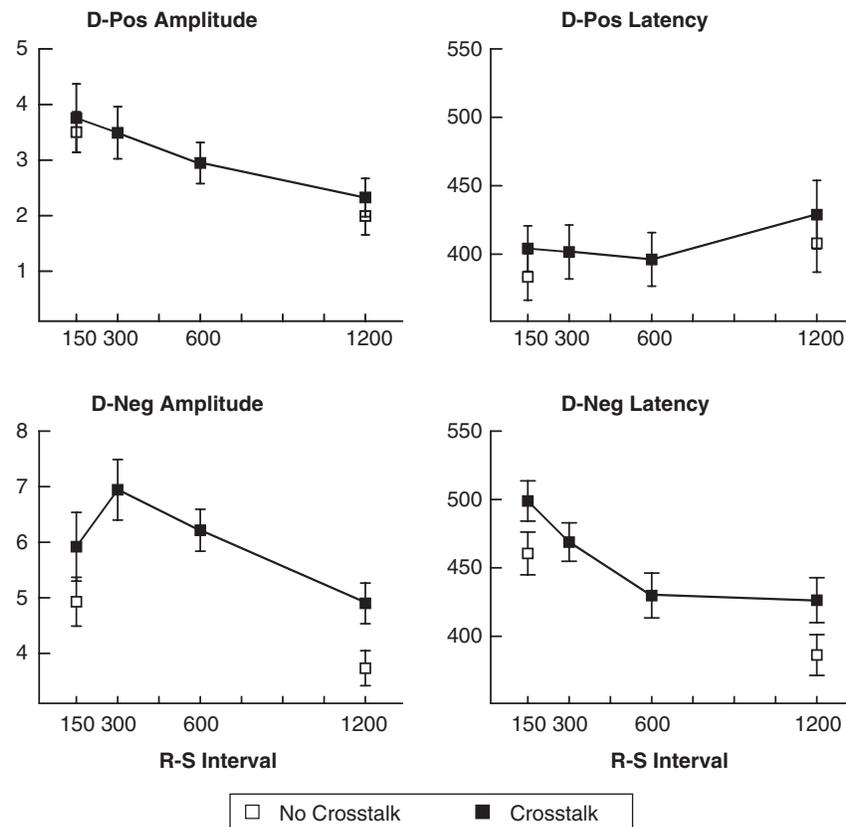


Figure 8. Top: D-Pos peak amplitude (left) and peak latency (right) recorded in response-locked difference waveform at Pz. Bottom: D-Neg peak amplitude (left) and peak latency (right) recorded in stimulus-locked difference waveform at Pz.

Discussion

Behavioral Effects of Task Switching

As in many previous studies, switching between different tasks resulted in a decline in performance evidenced by an increase in RT and error rate (e.g., Allport et al., 1994; Rogers & Monsell, 1995; Spector & Biederman, 1976; Sudevan & Taylor, 1987). That this deterioration in performance occurred when switch and no-switch trials were mixed within the same block suggests that the switch cost is related to mechanisms involved in task-set reconfiguration rather than nonspecific effects such as differential task difficulty or arousal (Rogers & Monsell, 1995).

The effect of task switching on performance reduced dramatically with practice. When averaged across all crosstalk blocks, RT switch cost halved from 170 ms on Day 1 to 86 ms on Day 2. However, the cost of switching remained significant for both RT and error rate on Day 2, indicating that the effect does not simply reflect strategy development processes, but is a robust feature of task switching (Rogers & Monsell, 1995).

Both overall performance and task-switch efficiency were affected by the presence of irrelevant characters associated with the currently inactive task-set. In crosstalk blocks, subjects responded more slowly and less accurately and showed a greater cost of task switching on both RT and error rates, compared to no-crosstalk blocks. Comparison of neutral trials from the crosstalk condition to identical trials in the no-crosstalk condition showed that, for short R-S intervals, the presence of stimuli cueing the alternative task-set on two-thirds of trials had a carryover effect on performance even on those trials that did not

contain any ambiguous information. However, this effect was not reliable for the long R-S interval. Within the crosstalk condition, RT switch cost was smaller on neutral trials than on trials containing stimuli from the currently inactive task-set, and smaller on congruent than on incongruent trials. The difference between neutral and nonneutral (congruent/incongruent) trials was more than double that observed between congruent and incongruent trials. These findings are compatible with Roger and Monsell's (1995, Experiment 1) argument that the presence of a stimulus from the alternative task-set activates the complete set of stimulus-response associations defined by the alternative task-set, as well as the specific association triggered by the stimulus presented on each trial.

Increasing the time between emission of a response to a stimulus and the onset of the next stimulus (R-S interval) resulted in a significant decline in RT switch cost, especially for the crosstalk task. Specifically, RT switch cost was around 116 ms for the shortest R-S interval (C-150) but reduced to almost half that value for longest R-S intervals (C-1200). A sizeable RT switch cost remained, however, even at the longest R-S interval. Although RT switch cost was considerably smaller for the no-crosstalk compared to the crosstalk task, it remained significant for the no-crosstalk task at both short and long R-S intervals. These findings parallel those reported earlier by Rogers and Monsell (1995: Experiments 3 and 4). Whereas in the present study, there was no evidence for a decline in RT switch cost with increasing R-S interval in the no-crosstalk condition (36 ms for N-150 vs. 32 ms for N-1200), error switch cost tended to decline with increasing R-S interval.

Table 4. Results of Point-by-Point Analysis of EMG-Locked Difference Waveforms

	Positivity in EMG-locked difference waveforms					
	No crosstalk		Crosstalk			
	N-150	N-1200	C-150	C-300	C-600	C-1200
Fz	<i>50–300 (9)</i> n.s.	—	<i>50–700 (12)</i> 85–145 (13) 255–550 (61)	<i>50–700 (12)</i> 55–200 (30) 320–645 (66)	<i>50–1,000 (12)</i> n.s.	—
FCz	<i>50–300 (9)</i> 85–200 (24)	—	<i>50–700 (12)</i> 75–570 (100)	<i>50–700 (12)</i> 55–660 (122) 830–975 (30)	<i>50–1,000 (12)</i> n.s.	—
Pz	<i>50–1,000 (12)</i> 55–640 (119)	<i>50–700 (12)</i> n.s.	<i>50–1,000 (12)</i> 55–690 (128)	<i>50–800 (12)</i> 55–715 (133)	<i>50–1,000 (12)</i> 55–945 (179)	<i>50–1,200 (12)</i> 320–705 (78)
Oz	<i>50–1,000 (12)</i> 75–170 (20) 295–690 (80)	<i>50–900 (12)</i> 445–545 (21) 590–655 (14)	<i>50–1,000 (12)</i> 70–705 (131)	<i>50–1,100 (12)</i> 55–775 (145)	<i>50–1,200 (12)</i> 55–975 (185)	<i>50–1,200 (12)</i> 320–770 (91)
TO5	<i>50–1,000 (12)</i> 70–165 (20) 305–695 (79)	<i>50–1,200 (12)</i> 585–755 (35)	<i>50–1,100 (12)</i> 70–155 (18) 320–700 (69)	<i>50–1,200 (12)</i> 55–780 (146) 950–1,075 (26)	<i>50–1,200 (12)</i> 55–1,060 (202)	<i>50–1,200 (12)</i> 355–460 (23) 490–945 (92)
TO6	<i>50–700 (12)</i> 55–175 (25) 340–580 (49)	<i>50–900 (12)</i> 400–535 (28)	<i>50–750 (12)</i> 70–680 (123)	<i>50–900 (12)</i> 55–710 (132)	<i>50–900 (12)</i> 55–145 (19) 275–420 (30)	<i>50–1,200 (12)</i> 315–580 (54)

Notes: Numbers in italics represent the broad area over which deviation from baseline was assessed and are followed by the number of consecutive points that must significantly deviate from baseline for the effect to be statistically significant by Guthrie and Buchwald's criteria. Numbers underneath in bold represent the interval over which significant deviation from baseline was obtained with the number of consecutive data points showing significant deviation in parentheses.

Overall, these results replicate the findings of Rogers and Monsell (1995) and can be interpreted within their two-component model of task switching. In this context, the decline in switch cost with increasing R-S interval is interpreted as reflecting anticipatory task-set reconfiguration processes, whereas the residual switch cost at very long R-S intervals reflects stimulus-triggered processes. However, alternative models of task-switching cannot be excluded. For instance, the decline in switch cost with increasing R-S interval is also compatible with Allport's task-set inertia model, and the residual switch cost can also be accounted for by De Jong's intention-activation model.

Search for ERP Indices of Task Switching

The main aim of the present study was to identify electrophysiological components associated with anticipatory and poststimulus components of task switching. Specifically, it was argued that ERP correlates of anticipatory task-switch processes should be evident in the R-S interval. This component would begin sometime after the decision/response to the previous trial and, depending on the length of the R-S interval, before the onset of the subsequent stimulus. Likewise, ERP correlates of stimulus-triggered processes would be evident in the poststimulus interval, even when the R-S interval allows maximal preparation. If stimulus-triggered processes are hierarchically dependent on the completion of the preceding "anticipatory" processes, then this ERP component may be delayed when the R-S interval is minimal and task-set reconfiguration does not practically begin until after the onset of the stimulus.

To identify these ERP components, ERP difference waveforms were derived by subtracting no-switch from switch ERP waveforms, as the process of task-set reconfiguration would be expected to be differentially activated for switch trials, and

therefore, to be reflected only in switch ERPs. ERP waveforms were averaged around stimulus onset to identify components related to stimulus-triggered processes and around the onset of the response to the preceding stimulus to identify anticipatory processes.

Switch-no-switch positivity (D-Pos) in response-stimulus interval. Response-locked difference waveforms exhibited an increased positivity (D-Pos) for switch compared to no-switch ERP waveforms. D-Pos began around 200–300 ms after the onset of a response to a switch trial and in anticipation of a switch trial (Figure 7, middle). D-Pos peak amplitude declined with increasing R-S interval, whereas peak latency remained around 400 ms after response onset for all R-S intervals (Figure 8, top). Neither peak amplitude nor peak latency of D-Pos were affected by task condition (i.e., crosstalk vs. no-crosstalk). Given that D-Pos peaked around 400 ms after response onset, it is evident that, for long R-S intervals, D-Pos peaked in the interval between the response and the onset of the subsequent stimulus, whereas for short R-S intervals, it peaked or even emerged (for R-S interval of 150 ms) after the onset of the switch stimulus.

The fact that D-Pos is differentially triggered in switch versus no-switch trials and occurs for all R-S intervals suggests that it reflects processes associated with task switching. The possibility that this component reflects differential arousal in anticipation of a switch than a no-switch trial is unlikely, as D-Pos emerges within an alternating runs paradigm, remains robust even after extensive practice, and is not affected by task-cueing parameters (i.e., as reflected in task condition) that would be expected to result in greater arousal. That D-Pos appears to emerge after the onset of a response to the preceding trial and, at long R-S intervals, peaks prior to the onset of a switch trial, suggests that, given adequate time, these processes can be activated in anticipation of a switch in task. However, that D-Pos is also

clearly evident at very short R-S intervals, emerging and peaking after stimulus onset, suggests that it reflects processes necessary for task switching to occur.

The decline in D-Pos amplitude with increasing R-S interval may reflect differential latency jitter in D-Pos peak amplitude across different R-S intervals. For instance, for short R-S intervals, the processes underlying D-Pos would be more closely time-locked to the onset of the response, and would be completed as quickly as possible given the imminent onset of the next stimulus. This would lead to small variability in D-Pos onset and peak latency, resulting in a sharp, short duration, large amplitude ERP component. Conversely, with longer R-S intervals, there is less time pressure to commence or complete these processes rapidly. This may lead to larger variability in the onset and peak latency of D-Pos both within and across subjects, resulting in a wider spanning, lower amplitude waveform. In fact, Figure 7 (middle) shows that for the shortest R-S interval, D-Pos amplitude is significant over a 200-ms interval beginning just 250 ms after response onset. It is also clear in this figure that, as R-S interval increases, not only does D-Pos amplitude reduce, but its duration is prolonged, spanning over 300 ms for RSI-300 and over 400 ms for RSI-600 and RSI-1200.

Switch–no-switch negativity (D-Neg) in stimulus-response interval. Stimulus-locked ERP waveforms revealed that D-Pos was followed by a large, late negativity (D-Neg) for switch compared to no-switch trials. While it appears in Figure 4 that switch trials are associated with a decline in the amplitude of the late positive component (LPC), the fact that the differentiation between switch and no-switch waveforms begins, in some instances, earlier than 200 ms and that this differentiation is clearly evident at frontal sites, where the LPC is substantially smaller, suggests that the switch–no-switch differential represents a negativity superimposed on the parietal LPC rather than a modulation of the LPC itself.

As shown in Figure 7 (left), D-Neg emerged immediately after D-Pos for short R-S interval but was clearly differentiated from D-Pos when R-S interval was over 1,000 ms. This suggests that the two ERP components reflect two distinct processes that can be at least temporally separated. While D-Pos is temporally linked to the onset of the response to the preceding stimulus, D-Neg appears to be linked to the onset of the switch stimulus. The fact that D-Neg is differentially triggered for switch vs. no-switch trials, does not occur within the R-S interval and is time-locked to stimulus onset suggests that D-Neg is related to post-stimulus processes associated with task-switching or the effect of task-switching on these processes.

D-Neg peak amplitude showed a small increase as R-S interval increased from 150 to 300 ms, but progressively declined as R-S interval increased further. D-Neg onset latency is difficult to quantify accurately, because the relationship between D-Neg and baseline was affected by whether D-Pos peaked before or after stimulus onset. However, D-Neg peak latency was clearly affected by R-S interval changes. Specifically, D-Neg peaked earlier as R-S interval increased, reducing by approximately 75 ms as the R-S interval increased from 150 ms to 1,200 ms. Thus, when there is more time to commence and/or complete processes reflected in D-Pos within the R-S interval, then D-Neg is smaller in amplitude and peaks earlier. This suggests that the poststimulus processes reflected by D-Neg may depend on the completion of earlier processes reflected in D-Pos.

D-Neg peak amplitude and peak latency were affected by task condition. Specifically, D-Neg was larger and peaked later for crosstalk than for no-crosstalk task blocks. However, the effect of task condition on D-Neg did not interact with R-S interval. So, D-Neg reduced with increasing R-S interval for both task conditions, and crosstalk had an additive effect on D-Neg amplitude and latency.

There are two potential problems associated with the definition and interpretation of D-Neg. One problem was discussed earlier (see Results) and relates to teasing apart D-Pos and D-Neg at short R-S intervals. This was dealt with in the present study by measuring D-Neg as a peak to peak differential. However, this does not completely resolve the problem, as differences in D-Pos amplitude and R-S interval are likely to affect the value of the positive peak used in the above estimation of D-Neg. In addition, the use of difference waveforms is based on the assumption that the no-switch or repeat trials are a suitable baseline, so that the difference between switch and no-switch trials largely reflects processes related to task switching. This was justified here given that Rogers and Monsell (1995, Experiment 5) showed that RT remained stable across repeated trials on the same task, suggesting that task-set reconfiguration processes were completed after the first switch trial. However, more recent studies have questioned this. Salthouse, Fristoe, McGuthry, and Hambrick (1998) reported that RT continues to decline across the first few repeat trials. De Jong (2000) showed RT differences between “pure” trials (i.e., same task across block) and no-switch trials (i.e., repeat trials within an alternating runs paradigm). Allport and Wylie (2000) provided evidence for continued interference from the alternative task-set even after many repeat trials. Clearly, the present study cannot differentiate between the above influences on D-Neg. Future work is needed to deal with the problem of baseline in differentiating between active task-set reconfiguration processes specific to switch trials and effects of interference from the alternative task-set affecting both switch and no-switch trials.

The other problem is that, given the fact that response latencies are longer for switch than for no-switch trials, it is likely that decision-making and response selection and preparation processes will also be delayed. Hence, the negative differential between switch and no-switch trials may reflect that the ERP components associated with the above processes are delayed or have a smaller amplitude for switch than for no-switch trials. Undoubtedly, the response delay must differentially affect switch and no-switch ERPs, and this must be reflected in D-Neg. However, it is unlikely that response delay can fully account for D-Neg.¹

First, if D-Neg simply reflects differences in the latency of decision- and response-related processes, it would be expected to affect late ERP components associated with these processes (i.e., LPC, slow late negativity). However, the difference between switch and no-switch trials emerges, in some cases, as early as 180 ms after stimulus onset, which is more than 400 ms before response onset (Table 2). Figure 4 shows the first evidence of this negative difference around the N2 latency range.

Second, if D-Neg emerges as an artefact of RT differences between switch and no-switch trials, one would expect that its onset or peak latency would vary with RT differences across task conditions and R-S interval and its amplitude to vary with the

¹We thank Martin Eimer, Stephen Monsell, and an anonymous reviewer for helpful comments and suggestions regarding this issue.

RT switch cost.² Inspection of stimulus-locked waveforms in Figure 7 (left) shows that there is no clear pattern of covariation between RT or RT switch cost and measures of D-Neg. For instance, although RT for no-switch and for switch stimuli as well as RT switch cost (switch – no-switch) are largest for C-150, D-Neg is largest for C-300. Similarly, RT and RT switch cost are smallest for N-1200, which shows the latest D-Neg onset.

Third, the differential effects of task condition on D-Neg and RT switch cost argue that these measures are affected by task-cueing interference at different levels of processing. Both D-Neg (amplitude and latency) and RT switch cost were affected by task condition, showing a significant increase in crosstalk compared to no-crosstalk blocks. Although RT cost declined significantly with R-S interval for crosstalk, it remained unaffected by R-S interval for no-crosstalk blocks. D-Neg, however, was significantly larger and peaked later for short than for long R-S intervals in both crosstalk and no-crosstalk blocks. So, task condition had no effect on D-Pos, had an effect on D-Neg additive with that of R-S interval, and interacted with R-S interval in its effect on RT switch cost. This pattern of findings suggest that task-cueing interference and R-S interval affect the same or different mechanisms at different stages of processing. Task-cueing interference left anticipatory processes reflected in D-Pos unaffected, whereas increasing R-S interval affected D-Pos amplitude and shifted these processes prior to stimulus onset. Both R-S interval and task-cueing interference affected D-Neg amplitude and latency in an additive manner; D-Neg amplitude and latency increased with greater interference and less time to prepare for an imminent switch trial. The early onset of D-Neg suggests that these manipulations, at least partially, reflect effects on stimulus selection and S-R mapping or decision making. RT switch cost reduced significantly with increasing R-S interval and increased with task condition; however, the effect of task condition was disproportionately larger for the short R-S interval. This suggests that task-cueing interference acts differently on D-Neg and RT cost, and that therefore D-Neg reflects at least partially distinct processes to those reflected in RT cost. The fact that increasing R-S interval reduced RT cost for crosstalk but not for no crosstalk, despite a clear D-Pos and a significant RT switch cost for both task conditions, suggests that R-S interval does not affect only anticipatory processes reflected in D-Pos, but also influences late response activation processes that are affected by task condition.

Finally, and perhaps most convincingly, if D-Neg were simply an artefact of delayed decision and response processes leading to longer RT for switch compared to no-switch trials, one would expect large latency shifts in LPC peak amplitude for switch trials. However, Figure 4 shows no evidence of this, with switch and no-switch ERPs showing similar LPC peak latency at approximately 500 ms.

In summary, although response timing differences between switch and no-switch trials may contribute to the amplitude and latency of D-Neg, the data suggest that this negativity also reflects processes associated with task switching that are initiated after the onset of the stimulus and that, although affected by the length of the R-S interval, are triggered even when the processes

reflected in the preceding D-Pos have been largely completed prior to stimulus onset. Given that D-Neg begins as much as 400 ms prior to response onset, peaks prior to response onset, and is affected by task condition, it is suggested that D-Neg may represent processes related to task switching that are activated after the onset of the stimulus.³

Functional Significance of D-Pos and D-Neg

This study revealed the emergence of two ERP waveforms, D-Pos and D-Neg, that differentially respond to switch compared to no-switch stimuli. D-Pos emerges in the R-S interval, and D-Neg is evident in the S-R interval.

One plausible interpretation of these findings is to interpret D-Pos and D-Neg as reflecting anticipatory and stimulus-triggered processes of task-set reconfiguration, respectively, as defined by Rogers and Monsell (1995). This interpretation fits well with many of the characteristics of these processes as defined by the present and previous behavioral data. The anticipatory component is evident in the reduction in RT switch cost with increasing R-S interval and has been interpreted as reflecting the activation of task-set reconfiguration processes in preparation of a predictable switch in task-set. The findings that D-Pos was temporally linked to the onset of the response to the previous stimulus, peaked around 400 ms after response onset, reduced in amplitude with increasing R-S interval, and was not affected by task-cueing condition,⁴ are compatible with the above interpretation. Additionally, the finding that D-Pos latency remained constant at around 400 ms regardless of R-S interval fits well with the behavioral data showing asymptotic preparation being achieved by 500–600 ms.⁵

The robust residual switch cost that remains significant after large preparation intervals has been interpreted as reflecting task-set reconfiguration processes that are triggered by the onset of the stimulus. D-Neg emerged around 200 ms after stimulus onset and peaked around 500 ms, thus preceding response onset. It was clearly defined for all values of R-S interval and was larger and slower for crosstalk than for no-crosstalk conditions. These findings are compatible with D-Neg representing the “stimulus-triggered” processes reflected in the residual RT costs. That D-Pos was unaffected by irrelevant task-cueing, whereas D-Neg was larger in amplitude and peaked later when crosstalk stimuli were used, supports the suggestion by Rogers and Monsell (1995) that task-cueing effects act upon exogenous or stimulus-driven processes rather than endogenous or internally driven processes.

³The negative difference could also reflect earlier resolution of CNV-like activity after response execution for no-switch than for switch trials. Inspection of Figure 6 shows a large positive dip immediately after the response, followed by CNV buildup in the R-S interval resolving shortly after stimulus onset (Figure 6). Given that the stimulus-locked waveforms depicted in Figure 4 were baseline corrected around stimulus onset, this differential has been removed. In fact, close inspection of Figure 6 shows that D-Neg is unrelated to the presence of a preceding differential between switch and no-switch trials, as it is clearly evident at sites where no response-locked difference is observed (i.e., see Fz, FCz for N-150, C-150, C-300, and C-600, which show activity after the onset of the switch stimulus). Note also that the subsequent CNV cycle can be seen for N-150, C-150, and C-300 emerging after the onset of the response to the stimulus (i.e., 500–600 ms after stimulus onset). Thus, it seems unlikely that D-Neg is simply an artefact of delayed CNV resolution after response execution.

⁴This is the case at least with respect to crosstalk versus no-crosstalk differences. It was not possible to analyze ERP differences between congruent, incongruent, and neutral stimuli within the crosstalk condition, due to a relatively low signal-to-noise ratio.

⁵We wish to thank Steve Monsell for this observation.

²As noted by an anonymous reviewer, although this could be examined by looking at the correlation between RT switch cost and D-Neg amplitude, it is not possible to measure D-Neg on a trial-by-trial basis. Attempts to examine these correlations across individuals using averaged data were not successful due to large variability and relatively low statistical power.

However, this interpretation of D-Pos and D-Neg fails to account for the finding that D-Neg amplitude and latency were modulated by R-S interval. According to Rogers and Monsell's hypothesis, R-S interval affects largely or exclusively the anticipatory component. Thus, it would have been expected to modulate D-Pos but not D-Neg.

Meiran et al.'s (2000) three-component model of task-switching may assist in explaining this finding. According to Meiran et al., task-set reconfiguration consists of at least three processes: anticipatory processes, stimulus-triggered processes, and task-set inertia. Variations in R-S interval can affect both the opportunity to initiate anticipatory task-set reconfiguration processes given prior warning of a task-switch, as described by Rogers and Monsell (1995), as well as the passive dissipation of activation of the previously active task-set or task-set inertia, as described by Allport et al. (1994). These two components are clearly differentiated when response-cue and cue-stimulus intervals are varied independently. However, with the present paradigm, this differentiation is not possible. So the decline in RT switch cost with increasing R-S interval could presumably reflect contributions from both active anticipatory processes and passive task-set inertia. The passive processes would become evident after stimulus onset as, for instance, differential priming of stimuli from active versus inactive task-sets, differential priming of stimulus-response mappings, and so forth. Within this framework, R-S interval could therefore affect ERP components measured in the R-S interval as well as ERPs elicited after stimulus onset. D-Pos remains associated with these anticipatory processes of task-set reconfiguration, whereas D-Neg would reflect processes operating after stimulus onset, including task-set inertia (as reflected by the component of D-Neg that is affected by R-S interval) and other processes related to task-cueing, activation of relevant response attributes, and inhibition of irrelevant response attributes, and so forth.

According to De Jong's (2000) intention-activation model, task-set reconfiguration is an all-or-none process, which is completed either before or after stimulus onset, depending on task parameters and subject factors. In this framework, we would expect only one ERP component to emerge in switch versus no-switch trials. This component would be more likely to be time-locked to response onset with long R-S intervals and to stimulus-onset with short R-S intervals. D-Pos partially fulfils this requirement, peaking after stimulus onset for short R-S intervals and before stimulus onset for long R-S intervals. Additionally, at long R-S intervals, it would be expected that on the trials where reconfiguration is completed prior to stimulus onset, the component would be triggered in the R-S interval, whereas on the trials where reconfiguration is completed after stimulus onset, this component would be triggered after stimulus onset. For long R-S intervals, when averaging across both these types of trials, one would expect to see the same ERP component evident both in the R-S interval and after stimulus onset. C-1200 and N-1200 conditions show no evidence for this. Thus, in its current form, De Jong's model does not readily account for the presence of two ERP components associated with task switching, unless one were to assume that these two components represent the same process that is reflected in ERPs of opposite polarity depending on the timing of the process relative to stimulus onset. However, the fact that D-Pos and D-Neg were differentially affected by task-cueing interference and R-S interval does not support this assumption.

Neural Substrates Underlying Task Switching Processes

Many theories view the prefrontal cortex as exerting an essentially supervisory role in setting goals, planning, monitoring, and implementing feedback and orchestrating behavior, particularly under novel situations (e.g., Goldman-Rakic, 1987; Shallice, 1988; Stuss & Benson, 1986). It would therefore be expected that the prefrontal cortex would be an essential component of a network involved in switching attention between different task-sets, especially when switching is internally cued. Patients with prefrontal lesions perform poorly on tasks requiring shifting between different stimulus classification attributes (e.g., Milner, 1964; Owen et al., 1993). Left frontal lesions result in increased switch cost, especially under crosstalk conditions (Rogers et al., 1998). A PET study showed greater activation in left prefrontal areas under task-switching versus single task conditions (Meyer et al., 1997). However, other studies question whether the increased switch costs following left frontal lesions reflect a specific deficit in task-set reconfiguration processes (Keele & Rafal, 2000) and whether task-switching deficits are specific to frontal lesions (Mecklinger, von Cramon, Springer, & Mathes-von Cramon, 1999).

Based on the above findings, it would appear logical to expect that ERP components associated with task switching would involve at least some generators in the prefrontal cortex. At first consideration, this expectation is at odds with the current finding that both D-Pos and D-Neg are larger at the midline parietal electrode Pz, potentially suggesting a bilateral parietal source of activation. It must be stressed, however, that scalp recorded ERPs provide little information as to the cortical generators of ERP components. Although activity recorded over the parietal scalp may be more likely to have a greater influence from activation in the parietal cortex, in fact, it reflects the summation of activity from many different cortical generators, the relative contribution of which depends on dipole orientation and location (Regan, 1989). In addition, given that the EEG recording was recorded using an average mastoids reference, it was not suitable for analysing laterality effects (Regan, 1989).

Recent functional MRI studies using modifications of the Rogers and Monsell (1995) paradigm suggest that task-switching processes involve activation in prefrontal and parietal areas. Dove, Pollman, Schubert, Wiggins, and von Cramon (2000) identified task-switching activation in prefrontal, premotor, SMA, parietal, thalamic, and other areas. Kimberg, Aguirre, and D'Esposito (2000) identified selective switch-related activation of the left superior parietal lobule. However, these studies do not allow direct reference to anticipatory and stimulus-triggered components of task switching. In addition, the very slow stimulus presentation rate (8 s and 15 s) is likely to have introduced other confounding parameters within the preparation period, including fatigue and loss of concentration. In fact, our data suggest that these confounds may start interfering with optimal task performance even with R-S intervals of 1,200 ms.

Using an event-related fMRI design, Sohn, Ursu, Anderson, Stenger, and Carter (2000) found that areas of prefrontal cortex and parietal cortex were activated in both the "preparation" period (i.e., after onset of the first stimulus and in anticipation of the second stimulus), when subjects had foreknowledge of an imminent task-switch, and in the "switch" period (i.e., the interval after the onset of the second stimulus), when subjects had no foreknowledge. Interestingly, these conditions activated different regions within prefrontal and parietal cortices. For example, foreknowledge resulted in activation in the left superior

posterior parietal cortex and right lateral prefrontal cortex *inter alia*, whereas task switching in the absence of foreknowledge resulted in activation of the left posterior parietal cortex and the superior prefrontal cortex *inter alia*. The posterior cingulate cortex and the occipital cortex were activated for switch compared to repeat trials regardless of whether the subject had prior knowledge of trial type, suggesting that these areas are

involved in mechanisms related to the actual change in task-set required to perform a switch in task.

Thus, task switching appears to involve a complex, and as yet poorly defined, neural network that includes frontal, parietal, and other cortical as well as subcortical components. Further work is needed to establish which components of this network are represented by D-Pos and D-Neg.

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