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Behavioural and electrophysiological measures of task switching during single and mixed-task conditions

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Abstract

In order to understand how the brain prepares for and executes a switch in task demand, we measured reaction time (RT), accuracy, and event-related brain potentials associated with performance in single and mixed-task blocks using a cued design. Our results show that trials which repeat in a mixed-task block (repeat trials) were more demanding than trials which repeated in a single-task block, as reflected by the presence of a RT mixing cost and by the presence of a smaller target-locked positivity (P3b) on repeat trials. Within a mixed-task block, repeat and switch trials also differed, where repeat trials showed evidence of greater preparation (larger cue-locked negativity), more efficient target processing (larger target-locked P3b), and shorter RTs. In addition, the cue-locked negativity difference remained despite equating repeat and switch trials on RT, suggesting that this negativity difference is specific to the switching process. Our results are discussed in light of existing models of task switching.

Keywords: Task switching; Switch costs; Working memory; Preparation; Event-related brain potentials; P300; Negative slow wave

Multitasking has recently become a hot topic for empirical research, perhaps partly because we are increasingly required to work in such a way. As our workdays increasingly require that we execute multiple tasks (for example, when we must answer the phone while writing an e-mail), our attention must be diverted from one task to another and it is logical that our performance comes to suffer. In fact, recent research shows that switching frequently between different tasks takes a toll on efficiency as measured by reaction time (RT) tasks (e.g., see Rogers and Monsell, 1995; Meiran et al., 2000; Rubinstein et al., 2001). The decrement in efficiency observed when one is multitasking is believed to come, in large part, from the need to shift attention and implement changes in cognitive routines, both of which require conscious, effortful control.

The goal of this study was to explore behavioural and electrophysiological measures of multitasking using a task switching paradigm. In the following paragraphs, we provide a brief overview of task switching and of the different associated costs. Following this, we review some of the most pertinent neurophysiological studies of task switching that have been published.

In one of the first of the recent generation of studies, Rogers and Monsell (1995) argued that effective switching requires the reconfiguration of task set. This, in turn, entails shifting attention and retrieving and implementing relevant stimulus–response action rules (Rubinstein et al., 2001). Rogers and Monsell (1995) had participants alternate tasks predictably on every second trial in a given block of trials, such that a participant had to either repeat the same task or switch to a different task. This design, known as the alternate runs paradigm, allowed Rogers and Monsell (1995) to isolate transient cognitive control processes and show that it takes longer to switch between competing task-demands than it does to repeat the same task, a phenomenon labelled the local switch cost. They also showed that the local switch cost decreases when the time prior to a predictable switch trial increases, indicating that one can engage in advanced preparation to facilitate the reconfiguration of the task set. However, no matter how much preparatory time was given, it remained more costly to switch between tasks than it did to repeat a task, which suggests that advanced preparation alone is not sufficient to complete task set reconfiguration. The local switch cost that

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remains despite a long preparatory interval is known as a residual switch cost. Rogers and Monsell concluded that although the active or endogenous control processes engaged during a long preparatory interval allow a participant to complete part of the task set reconfiguration process in advance, the presentation of the target stimulus is necessary to complete this process. This latter phenomenon reflects externally driven, target-triggered processes. In short, Rogers and Monsell proposed a two-step model where both preparatory, pre-target, endogenously controlled processes and target-driven, exogenous processes contribute to the reconfiguration of task sets under goal-directed conditions.

Rogers and Monsell's alternate runs paradigm stood in contrast to the way multitasking had been investigated up to that point. Previous work on task switching (Jersild, 1927; Spector and Biederman, 1976) had compared RT performance between blocks of trials which continually repeated (i.e., homogeneous or single-task blocks) and blocks which contained only switch trials (i.e., heterogeneous or mixed-task blocks). This comparison revealed larger RTs for heterogeneous task blocks than for homogeneous task blocks, but could not be exclusively tied to the cognitive control processes underlying the switch cost. Important state differences including fatigue, motivation, and arousal could conceivably explain RT differences between homogeneous and heterogeneous blocks. In order to control for this, Rogers and Monsell, as well as others (Allport et al., 1994; Meiran, 1996; Meiran et al., 2000), compared repeat and switch trials when these occurred within the same block of mixed trials, thus minimising block-related differences. However, a comparison between performance on homogeneous and heterogeneous blocks remains interesting. Indeed, unlike homogeneous blocks, heterogeneous blocks require that multiple, competing task sets be maintained and co-ordinated in working memory (Kray and Lindenberger, 2000). Competing task sets are believed to interfere with performance, even on heterogeneous repeat trials that require no switch in task set (Los, 1999). The cognitive control processes exerted to deal with this interference is captured by comparing homogeneous RTs to heterogeneous repeat RTs and is defined as the mixing cost (Meiran et al., 2000, 2001). Notwithstanding potential block differences in arousal and motivation, the homogeneous versus heterogeneous repeat RT difference is believed to capture an important task switching difference in sustained cognitive control processes and continues to be a useful index of task switching.

Although RT and accuracy are sensitive measures of changes in task set, they do not provide information on how the brain prepares for and responds to these changes. To adequately observe the cortical activity related to switching between tasks and repeating tasks, the neuroimaging technique of choice should be sensitive to processing changes evoked over very short periods of time. Given their high temporal resolution, electroencephalographic recordings are ideally suited to capture these changes. When time-locked to the presentation of a stimulus event and averaged across trials, electroencephalographic recordings reflect voltage variation in cortical activity associated with specific events. Known as event-related brain potentials (ERPs), these time-locked voltage changes are defined according to their polarity (positive or negative), latency (ms), amplitude (μV), and topographic scalp distribution. To date, only a handful of studies have used ERPs to examine control processes involved in task switching and all have used different task switching designs. For example, some studies used an alternate runs paradigm (Karayanidis et al., 2003; Lorist et al., 2000; Wylie et al., 2003) while others used an externally cued paradigm (Brass et al., 2005; Poulsen et al., 2005, 2001; Rushworth et al., 2002; Sinai and Phillips, 2002). Task set difficulty also varied, ranging from either simple classification tasks (e.g., categorising a number as either even or odd) to more complex tasks (e.g., categorising a word as either living or non-living). Finally, some task switching designs varied stimulus–response mappings rather than the tasks themselves (Rushworth et al., 2002). Although the studies cited above involve task switching, their designs were quite different, making it difficult to observe a consistent picture from their findings.

Nevertheless, two findings do appear to emerge from many of these studies. The first is the presence of a larger negative slow wave obtained over posterior scalp regions during the period preceding a repeat target, as opposed to a switch target. This is possibly a stimulus preceding negativity (SPN), which is believed to reflect the anticipatory activity sustained by a network involving thalamo-cortical pathways. According to Brunia and van Boxtel (2001), these pathways activate both frontal and parietal regions when preparing for a forewarned or predictable task. Brunia and van Boxtel (2001) argue that negativity observed at frontal scalp regions indexes the ongoing control exerted over attentive processes, while negativity observed over parietal regions indexes anticipation of task relevant stimuli. The posterior negativities observed prior to predictable task repetitions in the task switching studies reported above (Brass et al., 2005; Karayanidis et al., 2003; Lorist et al., 2000; Poulsen et al., 2005, 2001; Rushworth et al., 2002; Sinai and Phillips, 2002) suggest facilitated processing during repeat as opposed to switch trials. As for switch- and repeat-related frontal negativities, task switching studies have not provided consistent results. Some authors report larger frontal negativities on switch trials (Lorist et al., 2000; Poulsen et al., 2005, 2001) while others report large frontal negativities on repeat trials (Rushworth et al., 2002). Still others report no differences between the frontal negativities of repeat and switch trials despite posterior negativity differences (Karayanidis et al., 2003; Sinai and Phillips, 2002). It is not yet clear what can account for these discrepant findings but methodological differences among these studies are at least one probable cause. In spite of these differences, what is needed is a functional understanding of the negativities elicited during task preparation. We attempt to provide this in the present study by conducting within-subject analyses of the relationship between negative slow waves and the local switch cost when RT for repeat and switch trials are equated. That is, one of our goals was to determine whether the negative slow wave discriminates between repeat and switch trials. To do so, we compared repeat and switch trials equated

for RT to be able to evaluate task-specific differences independent of RT differences.

The second consistent electrophysiological finding observed among ERP task switching studies is a larger P3b-like waveform following the presentation of a repeat as opposed to a switch target (Karayanidis et al., 2003; Lorist et al., 2000; Poulsen et al., 2001; Rushworth et al., 2002; Sinai and Phillips, 2002). The P3b component is a late (300 to ∼800 ms), posteriorily distributed positive deflection linked to target evaluation. Its amplitude is believed to increase proportionally as target processing is facilitated, a process affected by working memory resources (Johnson, 1984; Kok, 2001; Kramer and Spinks, 1991). Thus, a larger target-locked positivity on repeat as opposed to switch trials may indicate a greater amount of available working memory resources with which to process repeat targets.

To date, no study has examined the electrophysiological correlates of mixing and local switch costs in the same study. The present study used ERP recordings to investigate both preparatory and target-driven processes engaged during a cued task switching paradigm. The presence and functional significance of mixing and switch costs was investigated by analysing RT, accuracy, and ERP data. Given the results obtained by previous studies, it was expected that trials that offered the opportunity for facilitated pre-target preparation should show faster RT, higher accuracy scores, and larger pre-target posterior negativities. Thus, we expected to find greater preparatory effects on homogeneous trials, less on repeat trials, and lesser still on switch trials. Furthermore, we examined within-subject differences in repeat and switch waveforms when these were equated for overall RT. Observing a larger negativity for repeat as opposed to switch trials despite similar RTs would indicate that the negativity is associated with specific local switch cost differences over and above general response speed.

Also expected was a larger post-target positive deflection (P3b) distributed over posterior scalp regions on trials where target evaluation is facilitated. Thus, we expected to see greater post-target target processing effects (larger P3bs) on homogeneous trials, followed by repeat trials, and then by switch trials, respectively. We also wanted to know if target-locked P3b differences between repeat and switch trials persist when their RTs are equated. By exploring both the cue- and target-locked activity of repeat and switch trials when these have the same RTs, we will be able test whether or not repeat–switch differences persist throughout target-triggered processes when time to prepare is afforded.

1. Method

1.1. Participants

Twenty young adults (6 men and 14 women; mean age = 24.5 years, S.D. = 3.4) participated in this study. Eighteen reported being right handed and two reported being left handed. All participants were recruited from either the Concordia University student population or through word of mouth and all reported being in good health. Informed consent was obtained from all participants and each was remunerated $20 for his/her participation.

1.2. Materials and apparatus

The target stimuli consisted of 16 concrete nouns (*beetle*, *nail*, *worm*, *stone*, *apple*, *marble*, *banana*, *ladder*, *tank*, *boulder*, *hippo*, *train*, *snake*, *bear*, *pencil*, and *tree*) for which the participant performed one of three semantic classification tasks: (A) an existence judgement (is it living or non-living?), (B) a size judgement (is it large or small?), or (C) a breadth judgement (is it wide or narrow?) on any given trial. For each classification task, 50% of the stimuli were associated with each dichotomous response (e.g., for the existence classification task, eight nouns required a living response and the other eight required a non-living response). Using the psycholinguistic database available at the University of Western Australia's website (http://www.psy.uwa.edu.au/MRCDataBase/uwa_mrc.htm), each set of eight nouns assigned to the two possible categories (e.g., the eight living and eight non-living sets) were matched for concreteness, imageability, and frequency (all Fs < 3.37 and ps $> .05$).

Each experimental trial consisted of a cue–target sequence (see Fig. 1). The same target words were used for each semantic classification task (e.g., "pencil" was categorised as small, narrow, or non-living) and responses were mapped to the same two buttons for all tasks (e.g., the left button was pressed for living, large, and narrow judgements while the right button was pressed for non-living, small, and wide judgements). These task–response mappings were counterbalanced across participants. Each of the 16 nouns (and the 3 cue words "existence", "size", or "breadth") were presented in a white, 24-point font and appeared on a black background computer screen.

1.3. Procedure

Each participant provided informed consent and then completed a demographic and health questionnaire. Given that this experiment was part of a larger study, participants completed both the task switching experiment and a series of neuropsychological tests in the same session, although the details of the latter are not relevant to the present study. Participants were tested individually in a single session which took approximately 2 h for the task switching experiment, followed by 1.5 h for the neuropsychological tests. Short breaks were given when necessary.

Participants were seated 1 m away from a computer monitor and instructed to read silently each of the stimuli presented. Instructions informed the participants that cue–target pairs were to be presented and that the cue would inform them as to which semantic classification task to perform on the subsequent target word. Each cue word was presented on-screen for 1 s and was followed by a target (1 of the 16 concrete nouns) 1180 ms afterwards. This period of time represented the cue–target interval (CTI). The period of time between the response and the presentation of the cue for the next trial (i.e., the response–cue interval, RCI) was either 200 ms following a correct response or 800 ms following an incorrect response. A short 200 Hz tone (100 ms duration) was presented following incorrect responses and, combined with the increased

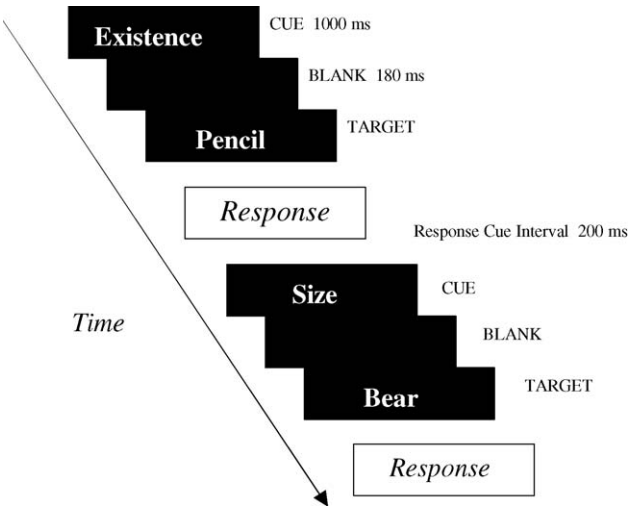

Fig. 1. Example of the cue–target sequencing and timing used in our design.

RCI, allowed participants to monitor and optimise their performance on following trials. Participants were instructed to respond as accurately and as quickly as possible. Target words were kept on-screen for a maximum of 5 s or until a response was given. So as to minimise electrophysiological artefacts, participants were also instructed not to move, talk, or blink during the presentation of the stimuli.

Participants first learned the target–response pairings for each of the three semantic tasks (existence, size, and breadth) in separate homogeneous blocks. Each of the 3 homogeneous blocks consisted of 160 trials of cue–target pairs for a single semantic task. By definition, then, each homogeneous trial was a repeat trial. The first 80 trials of each block were to learn and practice the response-key assignments. The remaining 80 trials were experimental trials on which behavioural and ERP data were collected. Ordering of the three task blocks was randomised across participants. Following the three homogeneous blocks, participants completed two heterogeneous blocks consisting of trials randomly sampled with equal frequency from each of the three different semantic tasks. These two blocks contained 260 trials each plus 10 warm-up trials at the beginning of each block. Each trial within a heterogeneous block was either a repetition of the previous semantic task or a switch to another semantic task. Heterogeneous block trials were defined as a function of the task performed on one ($n-1$) or two ($n-2$) trials previously. Repeat trials consisted of a trial where the same semantic task was performed only twice in a row (e.g., A in an BAA trial sequence). Switch trials consisted of a trial where the participant switched from performing one semantic task to another, without having performed that task on trial $n-2$ (e.g., A in a CBA trial sequence). None of the 16 target words were repeated within any three-trial sequence in homogeneous or heterogeneous blocks. This minimised stimulus–response associations (i.e., negative priming) from interfering with the task–response associations. Finally, repeat trials (as defined above) accounted for 20% of all trials within a heterogeneous block, whereas switch trials (as defined above) accounted for 26%. The remaining 54% were trials that did not follow the specific triplet pattern defined above and included runs of repeat trials (e.g., AAA) or switch trials where the task had been performed recently (e.g., A in an ABA trial sequence); however, these were outside the focus of the current report.

1.4. Electroencephalogram (EEG) recordings

EEG recordings were obtained from a nylon cap fitted with tin electrodes (Electro-Cap International). The EEG signal was obtained from 6 midline sites (FPz, Fz, FCz, Cz, CPz, and Pz) and 22 lateral sites over the left and right hemisphere, respectively (prefrontal: FP1 and FP2; frontal: F3, F7, F4, and F8; frontocentral: FC3 and FC4; frontotemporal: FT7 and FT8; central: C3 and C4; centroparietal: CP3 and CP4; temporal T5 and T6; temporoparietal: TP7 and TP8; parietal: P3 and P4; occipital: O1 and O2). A forehead location was used as ground. All EEG electrodes were referenced to the left ear during acquisition and re-referenced offline to a linked ear reference. The electro-oculogram (EOG) was recorded bipolarly from electrodes placed at the outer canthi of both eyes (horizontal EOG) and above and below the left eye (vertical EOG). EOG artefacts were corrected off-line for all participants using a regression algorithm (Gratton et al., 1983). EEG activity was sampled continuously at 100 Hz and amplified using Neuroscan Synamps in a DC-30 Hz bandwidth.

1.5. Rational for hypothesis testing

In order to assess the different executive abilities involved in task switching, two different cost analyses were carried out. The mixing cost is presumed to reflect demands of keeping more than one task active in working memory and was investigated by comparing the average behavioural and ERP measures of trials within a homogeneous block to repeat trials within a heterogeneous block. ERP mixing cost contrasts were analysed during both the pre-target (i.e., cue-locked) and post-target (target-locked) periods. The local switch cost is presumed to measure task set reconfiguration. It was investigated by comparing the average behavioural and ERP measures of repeat trials within a heterogeneous block to switch trials within a heterogeneous block. Here, too, the local switch cost contrast was analysed during both the pre- and post-target periods.

2. Results

2.1. Behavioural data reduction

Prior to any cost analyses, RTs were trimmed for each of the five blocks such that RTs greater than or smaller than 2.5 standard deviations of the block mean or less than 200 ms were eliminated. This represented no more than a 7.4% loss of trials in any given block. RT data were analysed only for correct trials that followed at least two correct responses. In order to pool data, two analyses of variance (ANOVAs) were conducted to determine whether RT and accuracy scores for repeat and switch trials could be collapsed across the three semantic tasks (existence, size, and breadth) and across both heterogeneous blocks. These, and all other analyses reported below, were conducted using SPSS v.11.0 statistical software. Greenhouse–Geisser corrections for non-sphericity are applied where appropriate. A task (existence, size, and breadth) by block (heterogeneous blocks 1 and 2) by cost type (local switch cost and mixing cost) ANOVA was first conducted on RT and accuracy scores to test whether cost types differed as a function of block and/or semantic task. To ascertain this, only interactions involving cost type are described. The RT and accuracy analyses failed to show any significant interaction with cost type (all Fs < 1.05 and all ps $> .05$), indicating that the switch and mixing costs did not differ as a function of block or semantic task. We consequently collapsed RT, accuracy, and ERP measures across all three semantic tasks and across both heterogeneous blocks for the analyses reported below.

2.2. Behavioural results

Average RT data (see Table 1) revealed a significant mixing cost, such that participants were faster to respond to repeat trials within a homogeneous block than to repeat trials within the heterogeneous blocks, $t(19) = -10.72$, $p < .001$. A significant local switch cost was obtained, revealing that in heterogeneous blocks participants responded more quickly to repeat trials than to switch trials, $t(19) = -4.89$, $p < .001$.

When performance accuracy was analysed (Table 1), there were no significant effects for the mixing cost, $t(19) = .82$, $p = .42$, or the local switch cost, $t(19) = 1.42$, $p = .17$.

Table 1
Mean (standard deviation) for reaction time (ms) and accuracy (%) scores

	Trial type		Cost
	Homogeneous	Repeat	Mixing cost
Reaction time	550.0 (59.7)	748.2 (113.5)	198.2* (82.7)
Accuracy	96.2 (3.2)	95.6 (3.3)	−.06 (3.2)
	Repeat	Switch	Local switch cost
Reaction time	748.2 (113.5)	836.6 (180.1)	88.4* (80.8)
Accuracy	95.6 (3.3)	94.2 (3.9)	−1.4 (4.5)

* $p < .001$.

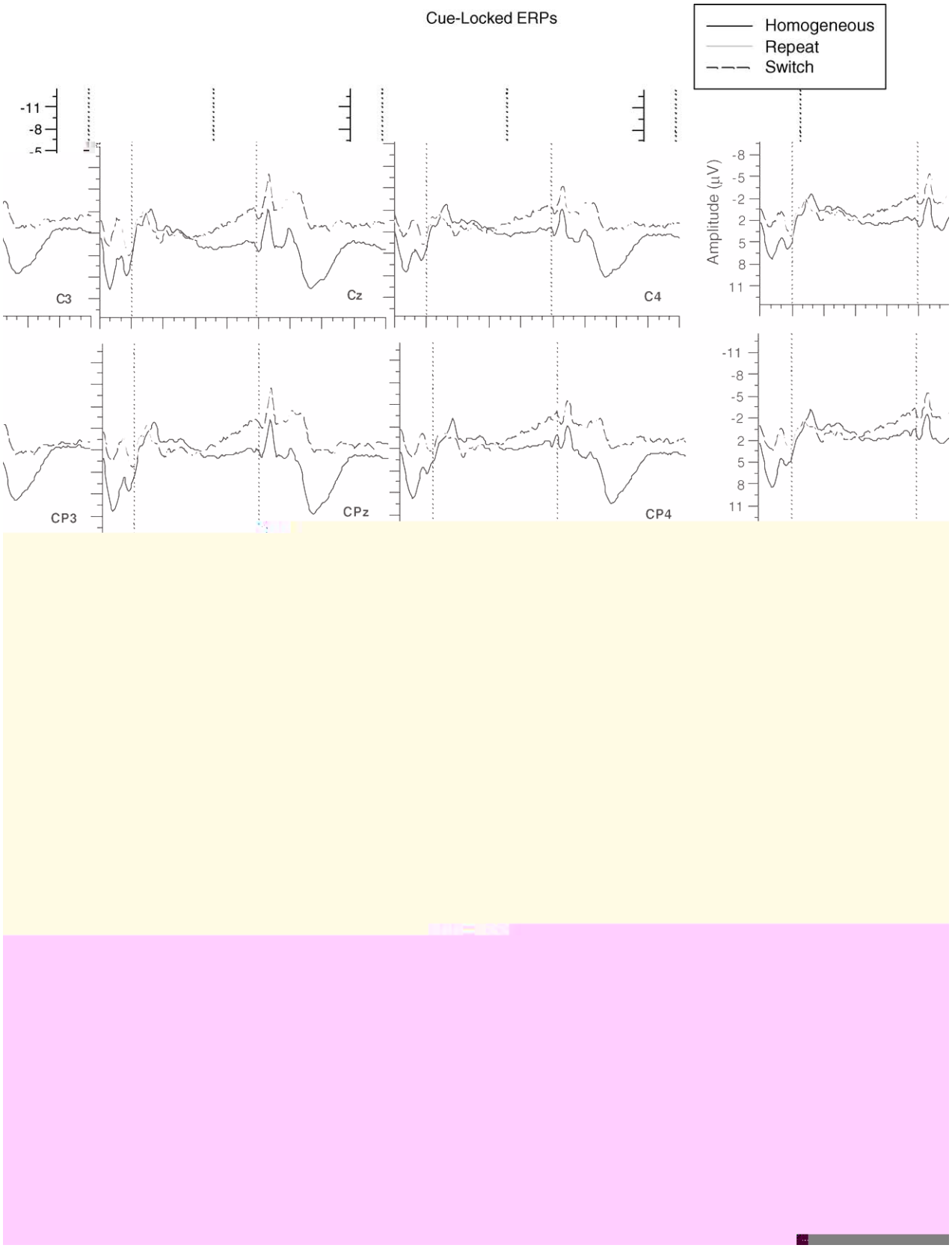

Fig. 2. Cue-locked grand average waveforms for homogeneous, repeat, and switch trials. ERP activity is shown over the entire cue–target interval, however, the waveform was baseline corrected from 0 to 100 ms into the cue interval. The first and second vertical dotted lines indicate cue and target onset, respectively. The upper *X*-axis time scale indicates latency referenced to the onset of the cue, while the lower *X*-axis time scale indicates latency referenced to the onset of the target. Waveforms recorded at anterior (F3, Fz, F4, FC3, FCz, and FC4), central (C3, Cz, and C4), and posterior (CP3, CPz, CP4, P3, Pz, and P4) electrode locations are shown.

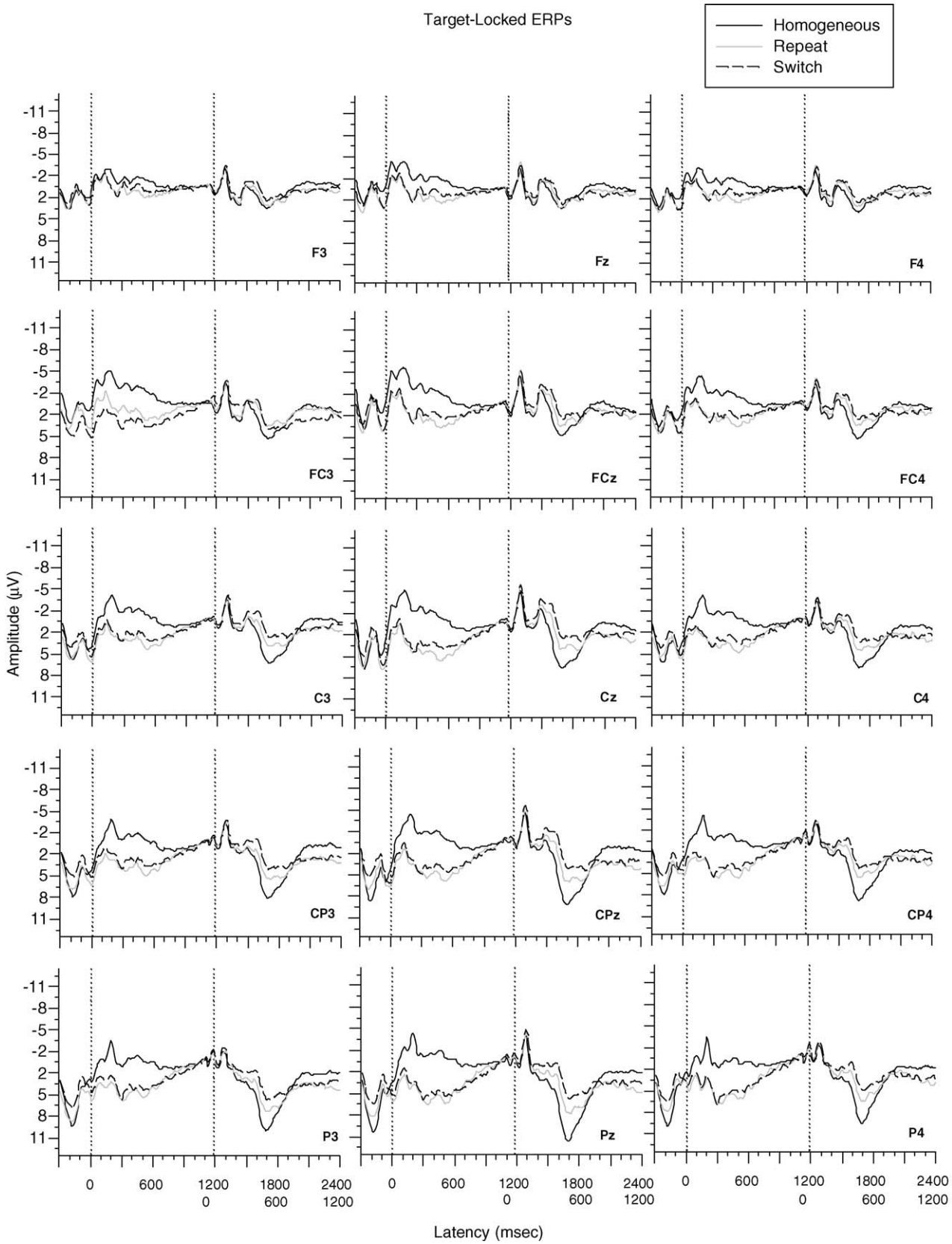

Fig. 3. Target-locked grand average waveforms for homogeneous, repeat, and switch trials. ERP activity is shown over the entire cue–target interval, however, the waveform was baseline corrected 0–100 ms into the cue interval. The first and second vertical dotted lines indicate cue and target onset, respectively. The upper *X*-axis time scale indicates latency referenced to the onset of the cue, while the lower *X*-axis time scale indicates latency referenced to the onset of the target. Waveforms recorded at anterior (F3, Fz, F4, FC3, FCz, and FC4), central (C3, Cz, and C4), and posterior (CP3, CPz, CP4, P3, Pz, and P4) electrode locations are shown.

2.3. ERP data reduction

Correct trials analysed for RT effects were also analysed for ERP effects. Epochs for both cue- and target-locked waveforms were time-locked to the presentation of the cue and spanned over 2400 ms. Epochs for cue-locked waveforms were baseline corrected between 0 and 100 ms after the cue's onset (see Fig. 2).[1] Epochs for target-locked waveforms were baseline corrected between 980 and 1180 ms after the cue's onset (i.e., 200 ms prior to target onset; see Fig. 3). Setting the cue-locked epoch to span a timeframe long enough to include the waveforms associated with both the cue and the target (i.e., 2400 ms) allowed us to appreciate the cortical activity across the whole cue–target period.

Both cue- and target-locked waveforms were analysed as a function of scalp region. Mean waveform amplitudes were computed as a function of anteriority (anterior: F3, Fz, F4, FC3, FCz, and FC4; central: C3, Cz, and C4; posterior: CP3, CPz, CP4, P3, Pz, and P4) and laterality (left: F3, FC3, C3, CP3, and P3; midline: Fz, FCz, Cz, CPz, and Pz; right: F4, FC4, C4, CP4, and P4). Cue-locked waveforms were also analysed as a function of time interval. Cue-locked mean amplitudes were examined in the 400–800 and 800–1180 ms post-cue intervals whereas target-locked P3b activity was examined through peak scoring (i.e., the amplitude and latency of the most positive point obtained in the 300–800 ms post-target interval). Figs. 2 and 3 show the grand average waveforms collapsed across subjects for each of the three different trial types (homogeneous, repeat, and switch trials) as a function of laterality and anteriority for both cue- and target-locked waveforms, respectively. Cue-locked waveforms show a negative-going deflection for both heterogeneous conditions observable at posterior scalp regions and evident at the later intervals (starting at approximately 600 ms), whereas the homogeneous condition exhibits a flattening of the waveform in the later portion of the cue–target interval. Target-locked waveforms show that all conditions were characterised by a P300 deflection observable over the posterior half of the scalp, which varied in amplitude as a function of condition.

2.4. ERP results

In order to verify the presence of mixing cost and local switch cost effects in the cue-locked waveforms, trial type differences were analysed as a function of scalp region and time interval using a series of four-way repeated measures ANOVAs (trial type × laterality × anteriority × time). Cost effects in the target-locked waveforms were analysed as a function of scalp region using a series of three-way repeated measures ANOVAs (trial type × laterality × anteriority) for both peak P3b amplitude and latency scores. Main effects of trial type are reported, followed by significant higher order interactions with time and/or scalp regions. If present, the higher order interaction is described and followed-up with either a three- and/or two-way repeated measures ANOVA and/or paired-sample *t*-tests. Significant contrasts not germane to our hypotheses are not reported (e.g., a time × scalp region interaction). Bonferroni corrections were applied to both ANOVAs and *t*-tests where appropriate. The reported post hoc findings include only the significant paired-sample *t*-tests' results.

2.5. Cue-locked data

2.5.1. Mixing cost

As shown in Fig. 2, during the second half of the cue interval, repeat trials show a negative slow wave potential which becomes progressively larger by the time the target appears and which is absent from the homogeneous condition. A trial type (homogeneous versus repeat) by anteriority (anterior, central, posterior) by laterality (left, midline, right) by time (400–800 and 800–1180 ms) ANOVA revealed a significant main effect of trial type, $F(1, 19) = 23.99$, $p < .001$, as well as a significant trial type by anteriority by time interaction, $F(2, 738) = 26.88$, $p < .001$, $\varepsilon = .638$. Post hoc comparisons indicated that repeat trials had larger negative amplitudes than homogeneous trials across anterior, $t(19) = 6.07$, $p < .001$; central, $t(19) = 9.40$, $p < .001$; posterior, scalp regions $t(19) = 7.51$, $p < .001$. This was observed only during the 800–1180 ms interval. These results confirm that repeat trials have a larger negative amplitude than homogeneous trials in the late cue-locked period.

2.5.2. Local switch cost

Cue-locked ERP waveforms presented in Fig. 2 also show a late negative slow wave for switch trials, although less pronounced than that of repeat trials. A trial type (repeat versus switch) by anteriority (anterior, central, posterior) by laterality (left, midline, right) by time ANOVA revealed a significant trial type by anteriority interaction, $F(2, 38) = 14.45$, $p < .001$, $\varepsilon = .576$. Post hoc comparisons indicated that repeat trials showed larger negative amplitudes than switch trials over the posterior region, $t(19) = -2.17$, $p < .02$. These results indicate that the repeat–switch negative slow wave difference observed throughout the 400–1180 ms interval is more pronounced over the posterior scalp region.

To examine whether this negative slow wave reflects a specific repeat versus switch processing difference or a non-specific reaction time difference favouring repeat trials, additional cue-locked waveforms were computed for repeat and switch trials when these trials were equated for reaction times. In other words, a subset of the fastest switch trials ($M = 636.88$ ms, S.D. = 102.86) were selected such that their average RT was equal to a subset of repeat trials ($M = 636.55$ ms, S.D. = 102.43; $t(19) = .96$, $p = .348$). This allowed us to determine if changes in the negative slow wave could be confidently related to differences in processing repeat versus switch trials while controlling for non-specific speed effects.

Fig. 4 shows a larger late negative slow wave for repeat as opposed to switch trials in the posterior part of the scalp. A trial

[1] We had originally chosen a −200 to 0 ms pre-cue baseline period. However, this baseline appeared to include the negative-going resolution of the P300 activity associated with the preceding trial. By baseline correcting from 0 to 100 ms into the cue period, we were able to reduce the influence of the negative-going resolution of the preceding P300 component.

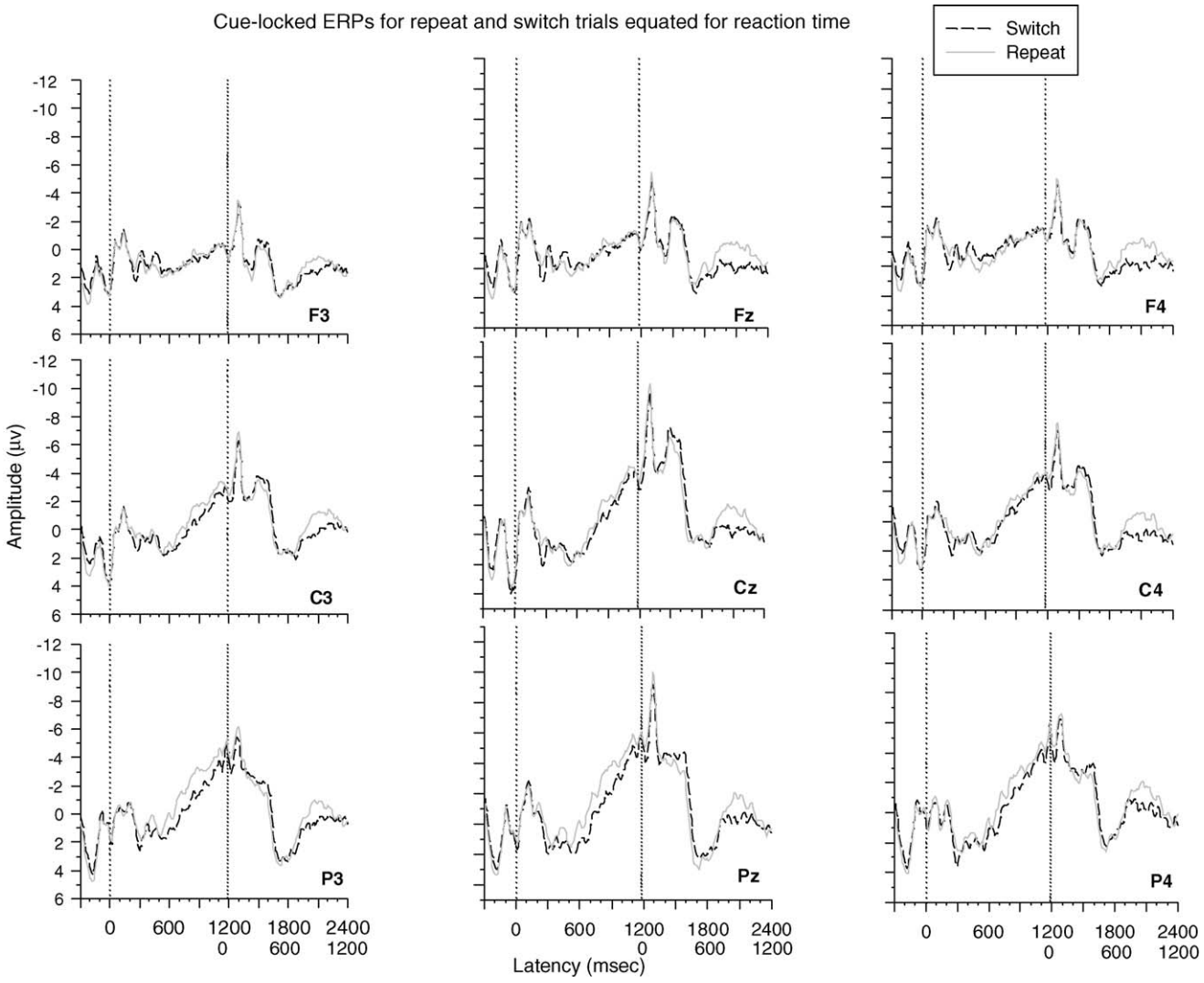

Fig. 4. Cue-locked grand waveforms averaged for repeat trials and switch trials equated for RT. ERP activity is shown over the entire cue–target interval with the waveform baseline corrected from −200 to 0 ms prior to cue-onset. The first and second vertical dotted lines indicate cue and target onset, respectively. The upper *X*-axis time scale indicates latency referenced to the onset of the cue stimulus, while the lower *X*-axis time scale indicates latency referenced to the onset of the target stimulus. Selected waveforms recorded at anterior (F3, Fz, F4), central (C3, Cz, C4) and posterior (P3, Pz, P4) electrode locations are shown.

type (repeat versus switch) by anteriority (anterior, central, posterior) by laterality (left, midline, right) by time ANOVA revealed a significant trial type by anteriority interaction, $F(2, 38) = 12.20, p < .001, \varepsilon = .609$. Post hoc comparisons indicated that, compared to switch trials, repeat trials showed larger negative amplitudes over the posterior part of the scalp, $t(19) = 2.39, p < .03$. These results suggest that even when trial types are equated for RT, cue-locked negative slow wave activity is still larger prior to a repeat trial than a switch trial and that the effect is not reducible to a mere difference in speed of responding.

2.6. Target-locked data

2.6.1. Mixing cost

Target-locked ERP waveforms presented in Fig. 3 show a large homogeneous versus repeat difference noticeable throughout the 300–600 ms post-target interval and across the entire posterior half of the scalp. A trial type (homogeneous versus repeat) by anteriority (anterior, central, posterior) by laterality (left, midline, right) ANOVA conducted on peak P3b amplitude scores revealed a significant main effect of trial type, $F(1, 19) = 19.58, p < .001$, as well as a significant trial type by anteriority interaction, $F(2, 38) = 9.68, p < .002, \varepsilon = .684$. Post hoc comparisons indicated that, compared to repeat trials, homogeneous trials showed larger positive amplitudes across central, $t(19) = -4.06$, $p < .001$, and posterior regions, $t(19) = -5.74$, $p < .001$. A trial type (homogeneous versus repeat) by anteriority (anterior, central, posterior) by laterality (left, midline, right) ANOVA conducted on peak P3b latency scores did not reveal a significant main effect of trial type ($F < 4.03, p > .05$) nor any interaction with trial type (all Fs < 1.62, all ps $> .05$). Together, the results indicate a larger P300 deflection for homogeneous trials than repeat trials at all electrode sites distributed in the posterior half of the scalp.

2.6.2. Local switch cost

Target-locked ERP waveforms presented in Fig. 3 also show a large repeat versus switch difference observed at the posterior half of the scalp and throughout the 300–600 ms interval. A trial type (repeat versus switch) by anteriority (anterior, central, posterior) by laterality (left, midline, right) ANOVA conducted on peak P3b amplitude scores revealed a significant main effect of trial type, $F(1, 19) = 13.37$, $p < .005$, as well as a significant trial type by anteriority interaction, $F(2, 38) = 4.39$, $p < .05$, $\varepsilon = .645$. Post hoc comparisons indicated that as compared to switch trials, repeat trials showed larger positive amplitudes across central, $t(19) = -3.487$, $p < .001$ and posterior regions, $t(19) = -4.24$, $p < .001$. A trial type (repeat versus switch) by anteriority (anterior, central, posterior) by laterality (left, midline, right) ANOVA conducted on peak P3b latency scores did not reveal a significant main effect of trial type ($F < 3.68$, $p > .05$) nor any interaction with trial type (all Fs < 2.06, all ps $> .05$).

Peak P3b comparisons between RT-equated repeat and switch trials were also conducted. These analyses were restricted to midline sites only. A trial type (repeat versus switch) by anteriority (Fz versus FCz versus Cz versus CPz versus Pz) ANOVA conducted on peak P3b amplitude scores and again on peak P3b latency scores revealed no difference between repeat and switch trials (all Fs < 4.15, all ps $> .05$) nor any interaction with trial type (all Fs < 1.13, all ps $> .05$).[2] This indicates that the repeat–switch processing difference that was observed in preparation of a target stimulus when repeat and switch trials were RT equated does not persist during target processing itself, at least not when 1180 ms of preparation was afforded.

2.6.3. Inter-block differences in P3b jitter

As can be appreciated in Table 1, the RTs were more variable in the heterogeneous block than in the homogeneous block. Since the peak latency of the P3b component is, in part, sensitive to variation in response time (Christensen et al., 1996; Verleger, 1997), greater response variability in the heterogeneous condition might yield greater variability in the P3b peak latency from trial to trial. Such intra-subject variability in P3b latency could result in a smeared and reduced peak amplitude when trials are averaged together for each subject and could explain our repeat versus homogeneous P3b amplitude difference. In order to eliminate this possibility, we computed peak-aligned averages for each condition by identifying the latency of the maximum positive peak in single EEG trials in a 350–750 ms window. New EEG epochs were computed from 200 ms before and 200 after the peak latency for each trial and were then averaged together as a function of condition (homogeneous, repeat, and switch trials). This was performed for each participant using data from the Pz electrode because it corresponds to the scalp location where the P3b waveform is most pronounced. Importantly, a sizeable and significant amplitude difference remained between the peak-aligned conditions having controlled for RT variability. Paired-samples t-tests confirmed that homogeneous trials were more positive (25.1 μV) than repeat trials (21.8 μV), $t(19) = 6.91$, $p < .0001$ and that repeat trials were more positive than switch trials (19.4 μV), $t(19) = 5.90$, $p < .0001$.

3. Discussion

3.1. Behavioural data

As expected, RT data revealed significant mixing and local switch costs, indicating that homogeneous trials were responded to more quickly than repeat trials, which in turn were responded to more quickly than switch trials. Accuracy was uniformly high and did not differ between trial types. Our behavioural results are largely consistent with past findings. That is, performance is poorer when having to switch between different tasks (Karayanidis et al., 2003; Meiran et al., 2000; Rogers and Monsell, 1995) or when having to repeat the same task in alternation with switch trials (Los, 1999; Meiran et al., 2001).

3.2. Electrophysiological waveforms

An interesting difference in morphology was evident between the cue-locked activity in homogeneous trials and heterogeneous repeat and switch trials. The heterogeneous repeat and switch trials were characterised by a negative slow wave late in the cue interval which was absent from the homogeneous trials.[3] Moreover, the late negative slow wave was larger on repeat trials than switch trials. In the discussion that follows, we will argue that the late negative slow wave reflects trial-by-trial task set preparation which is necessary during heterogeneous blocks only (and is therefore absent from homogenous block trials) and is enhanced on repeat trials compared to switch trials. We will then discuss the target-locked activity.

3.2.1. Mixing cost

Cue-locked averages showed that repeat trials were characterised by a late negative slow wave which became progressively larger over the last portion (800–1180 ms) of the cue–target interval. Homogeneous trials, on the other hand, failed to show the presence of negative slow wave activity. By the time the target appeared, then, repeat trials displayed a larger negativity than homogeneous trials.

What cognitive functions might underlie our cue-locked homogeneous versus repeat differences? One possibility

[2] The similar peak P3b amplitudes of RT-matched repeat and switch trials can be appreciated by looking at Fig. 4. Although this figure depicts cue-locked waveforms it is clearly apparent that repeat and switch trials did not differ immediately prior to target onset nor in their peak P300 activity. Target-locked waveforms did not differ from these cue-locked waveforms and so were not included.

[3] The negative slow wave we obtained in our waveforms may be similar to the negativity reported by Brunia and van Boxtel (2001), which they term "SPN". However, since our experimental paradigm differs markedly from the ones reported in Brunia and van Boxtel, we will continue to employ the neutral term negative slow wave.

involves sustained non-specific arousal or motivational differences across homogeneous and heterogenous task blocks. Although non-cognitive factors such as arousal and motivation might have contributed to the mixing cost, recent neuroimaging data suggest that the mixing cost reflects differences in effortful cognitive control. Braver et al. (2003) found that specific brain regions (prefrontal and cingulate cortex) to be more active during mixed-task blocks than single-task blocks and that this difference related to the magnitude of RT mixing costs on a trial-by-trial basis.

In our data, a cognitive account of the mixing cost also seems appropriate, especially given the nature of the waveform components driving our electrophysiological difference. As mentioned above, one of the most striking differences between our repeat and homogeneous trials can be found in the morphology of their respective cue-locked waveforms. Whereas repeat trials showed the presence of a late negative slow wave, homogeneous trials showed a flattening of the waveform throughout the late cue–target interval. Since late negative slow waves are evoked in preparation of an imperative stimulus (Brunia and van Boxtel, 2001) and since a substantial negativity was obtained on repeat trials, it is logical to conclude that repeat cues were important in helping participants prepare for a repeat target stimulus. Homogeneous cues, on the other hand, failed to elicit a negative slow wave. This is not altogether surprising since cues in the homogeneous block were not necessary to predict the upcoming task. Homogeneous blocks involved only one relevant task set which, in all likelihood, facilitated attention monitoring and the maintenance of the task set in working memory. A homogeneous cue, therefore, probably served a different purpose than did a heterogeneous cue, perhaps helping only to maintain an already prepared task set rather than to provide information that guides advanced preparation.

As mentioned above, cognitive control accounts of the mixing cost argue that a large part of this cost is associated with the added difficulty of having to maintain multiple task sets. Since multiple task sets are thought to compete during the selection of appropriate stimulus–response rules, target-locked differences should also be observed during the mixing cost contrast. Examination of our target-locked positivity (P3b) supports this prediction. We found significantly larger P3b amplitudes for homogeneous targets than for repeat targets. The P3b waveform is believed to be a sensitive index of target-triggered evaluation within working memory (Kok, 2001). In and of itself, this electrophysiological index says nothing about the specific nature of the processes active within working memory, such as rule activation, resolution of response competition, intentional task set implementation, or template matching and updating. However, it is generally well accepted that the amplitude of the P3b waveform reflects processing capacity and mental workload (see Kok, 2001 for a review). Our P3b results suggest, therefore, that greater target-triggered working memory demands are central to the mixing cost contrast, probably resulting from the need to co-ordinate multiple stimulus–response associations during heterogeneous trials. The functional significance we attribute to our target-locked P3b wave (be it for homogeneous or repeat trials) is in line with the interpretation of Rubinstein et al. (2001). From their behavioural experiments, Rubinstein et al. (2001) conclude that the processes engaged during target identification relate to rule activation and involve the selective engagement of response rules in working memory. It is logical, therefore, to interpret our mixing cost results as reflecting, at least in part, differences between mixed and single-task blocks in the selection and maintenance of task rules within working memory.

We were able to rule out another alternative explanation of our P3b findings, namely that smaller P3b amplitudes on repeat trials were a by-product of greater intra-subject latency jitter due to more variable response times on heterogeneous blocks compared to homogeneous blocks. Significant amplitude differences remained between the conditions even after we computed waveforms time-locked to the peak positivity in individual trials. Inter-block variance in latency jitter could not have explained this difference. This finding is consistent with the idea that the P3b amplitude is a sensitive index of stimulus evaluation and intensity of processing (Kok, 1990; Polich and Kok, 1995; Johnson, 1984).

3.2.2. *Local switch cost*

Cue-locked averages also showed evidence of negative slow wave activity for switch trials. However, as can be appreciated in Fig. 2, the amplitude of the late negativity in the posterior part of the scalp was greater for repeat trials than for switch trials. This suggests that by the end of the cue–target interval, repeat cues helped participants anticipate repeat targets to a greater extent than switch cues helped participants anticipate switch targets (Brunia and van Boxtel, 2001).

The idea that the repeat versus switch negativity difference might reflect preparation/anticipation differences is supported by Karayanidis et al. (2003). In their study, repeat versus switch differences in negativity varied as a function of preparatory time (longer response–target intervals) and, importantly, related to RT variations in the local switch cost. In other words, when preparation time was increased, the repeat versus switch negativity difference decreased and was followed by a reduction in the size of the RT local switch. In our study, the fact that repeat and switch slow waves were still different by the end of the CTI suggests that our local switch cost RT difference reflected preparation differences between our repeat and switch trials. Although we believe our cue-locked negativity difference reflected a difference in advanced preparation between repeat and switch trials, it could have also reflected a non-specific speed effect. To better understand the functional significance of our pre-target negativity, we looked at the negativity difference between our repeat and switch trials when these trials were equated for RT. Our results showed that despite similar RTs, repeat trials still had a greater negativity in the posterior part of the scalp than switch trials, suggesting that differences in preparation were still present. Our negative slow waves, therefore, were sensitive to specific advanced processing differences between repeat and switch trials which were not merely a by-product of RT. This means

that we can be confident in interpreting our posterior negativity difference as reflecting a true difference in the neural mechanism responsible for preparation during a switch in task demand. Although others have reported larger negativities and faster responses on repeat as opposed to switch trials (Brass et al., 2005; Karayanidis et al., 2003; Lorist et al., 2000; Poulsen et al., 2005, 2001; Rushworth et al., 2002; Sinai and Phillips, 2002), our demonstration that the posterior negativity distinguished repeat from switch trials even when differences in RT were controlled and strengthens the functional interpretation of the negative slow wave. Posterior negative slow waves, therefore, appear to reflect the cognitive control processes triggered when preparing to switch to a new task. Finally, the dissociation we observed between posterior negative amplitudes and reaction time is also consistent with findings from Travis and Tecce (1998), who showed that negative slow wave amplitude varied as a function of attention-related processes, not response time.

An alternative interpretation, not tied to task set preparation, may be raised to explain part of our switch cost. Logan and Bundesen (2003) proposed that much of the local switch cost in cued paradigms comes from cue priming, not cued preparation. This means that it is the repetition of the cue, not the task set itself, which facilitates response time on repeat trials. Indeed, our local switch cost contrast involved repeat trials which confounded cue repetition with task repetition. Brass et al. (2005) recently obtained a significant local switch cost in a cued task switching study which did not confound cue-encoding with task-encoding, indicating that local switch costs are not entirely accounted for by a cue priming confound. Nevertheless, this present study and many in the literature did not control for cue repetition; therefore, it is possible that a cue priming contribution remains. However, we argue that one would not expect to see cue priming effects appearing as late in the cue interval as where we observed our repeat–switch differences.

In our study, cue-locked differences between repeat and switch negativities were also followed by target-locked P3b waveform differences. Larger posterior positivities were obtained following repeat targets, indicating that target evaluation was facilitated on repeat trials (Kramer and Spinks, 1991; Barceló, 2003). However, given the presence of a significant repeat–switch difference in cue-locked negativity prior to the presentation of the target, it is possible that our target-locked period continued to reflect differences in preparation and not target-triggered differences. To answer this question, it is important to know whether changes affecting pre-target processing affected both the pre- and post-target waveforms. Karayanidis et al. (2003) varied the length of the pre-target interval and found that shorter pre-target intervals increased the repeat–switch difference in pre-target negativity and also increased the amplitude and latency of the post-target positivity difference. Since the pattern of our pre- and post-target results are similar to those described by Karayanidis et al. (2003) in their short interval, part of our repeat versus switch difference in P3b amplitude may be due to insufficient preparation. However, even when long pre-target intervals were given, Karayanidis et al. still obtained a repeat–switch difference in target-locked positivity, suggesting that the target-locked P3b difference also reflected target-triggered processes. Our reduced target-locked P3b on switch trials, therefore, likely reflects a combination of sub-optimal pre-target preparation and the extra processing required to retrieve the new set of stimulus–response rules.

Although this two-step cue- and target-driven reconfiguration process nicely accounts for the way switching might occur, De Jong (2000) recently proposed an intention activation model where task set reconfiguration follows an all-or-none process. De Jong argued that allowing more time for advanced preparation does not necessarily mean that every switch trial will become better prepared. Instead, he argued that advanced preparation allows for a larger proportion of switch trials (but not all) to be completely prepared or reconfigured prior to the presentation of the target. The crucial point here is that for those switch trials that are completely reconfigured in advance, the RT difference between repeat and switch trials should disappear. Since we compared repeat and switch trials equated for RT, we created a comparison in which repeat and switch trials should have been equally prepared, according to De Jong's argument. Thus, the cue-locked neural activity should differ between repeat and switch trials given their differing need for reconfiguration, but should not differ during target processing if the switching process was completed in advance of the target.[4] Interestingly, our results support this claim since we continued to find a significant difference between RT-matched repeat and switch trials during the cue-locked interval with respect to the negative slow wave activity but not during the target-locked interval (i.e., the P3b activity). These findings are consistent, therefore, with the idea that, at least on some trials, task set reconfiguration follows a discrete all-or-none process. However, a recent study by Nieuwenhuis and Monsell (2002) showed that even under conditions that encourage complete advanced preparation (i.e., use of a payoff system), a robust residual switch cost remained. These authors suggest that for a certain number of switch trials, some form of exogenous, target-driven process may remain necessary when reconfiguring for a new task set. A progressive, endogenous task set reconfiguration model may still be pertinent when explaining what takes place when preparing for a switch target. Future work is needed to explore the testing conditions under which task set reconfiguration proceeds in a probabilistic rather than in a progressive absolute fashion.

Finally, it is possible that the greater P3b on repeat trials versus switch trials reflects differences in the frequency of occurrence of these events and not in the cognitive resources related to switching. Given the difficulty associated with having to perform in a mixed-task context, it is possible that our participants kept themselves ready for a switch in task demand at all times. This means that repeat trials, when they occurred,

[4] This should be the case only when sufficient time for preparation is afforded; otherwise, the all-or-none reconfiguration process would be completed during the target period and electrophysiological differences would be expected only for target-locked contrasts.

may have been unexpected. Past findings have shown that the size of the P3 component increases when expectation violations occur (Johnson, 1986, 1993; Verleger et al., 1994). Thus, our repeat versus switch P3b difference might reflect nothing more than a mismatch between expectation and experience. However, it is important to remember that it was the task set which repeated, never the target word itself; thus, we think it is unlikely that the P3b activity measured at the target reflected the frequency of the repetition of tasks in general (which had been cued nearly 1200 ms previously).

3.3. Summary and future directions

This study has documented electrophysiological differences on trials which vary in the degree to which they call on sustained and transient shifts in cognitive control processes. Moreover, the ability to examine neural activity during pre- and post-target intervals separately has allowed us to further fractionate previous behavioural results. We were able to show that repeat trials were more easily prepared for than switch trials and obtained larger cue-locked negativities, which preceded significant differences in RT. Interestingly, repeat versus switch trial differences in negativity remained even after equating for RT, ruling out a general speed effect. We also showed that homogeneous trials were not characterised by negative slow wave activity which, when compared to repeat trial activity, likely reflects single-task versus mixed-task block differences in task set maintenance and cue processing. RT differences between homogeneous and repeat trials confirmed that participants performed more efficiently during single-task blocks than during mixed-task blocks.

Target-locked differences between our trial types were also obtained. We found the largest target-locked positivities (P3b) for homogeneous trials, followed by repeat trials, and switch trials, respectively. We interpret this finding as reflecting a difference in the target evaluation process, a process likely reflecting inter-trial differences in available working memory resources. Interestingly, we did not obtain a target-locked positivity difference between our RT-matched repeat and switch trials which suggests that, on some occasions at least, the reconfiguration process can be completed in advance of the switch trial target.

Finally, these findings reflect the way young, healthy adults prepare for and respond to task changes. We are currently examining how ERPs associated with anticipatory and post-target processing during task switching are influenced by advanced age. By examining performance and age-related changes in signal strength and topography, future studies will be able to explore how the aging brain multitasks.

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