Neurophysiological signature of effective anticipatory task-set control: a task-switching investigation

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Abstract
Changing between cognitive tasks requires a reorganization of cognitive processes. Behavioural evidence suggests this can occur in advance of the stimulus. However, the existence or detectability of an anticipatory task-set reconfiguration process remains controversial, in part because several neuroimaging studies have not detected extra brain activity during preparation for a task switch relative to a task repeat. In contrast, electrophysiological studies have identified potential correlates of preparation for a task switch, but their interpretation is hindered by the scarcity of evidence on their relationship to performance. We aimed to: (i) identify the brain potential(s) reflecting effective preparation for a task-switch in a task-cuing paradigm that shows clear behavioural evidence for advance preparation, and (ii) characterize this activity by means of temporal segmentation and source analysis. Our results show that when advance preparation was effective (as indicated by fast responses), a protracted switch-related component, manifesting itself as widespread posterior positivity and concurrent right anterior negativity, preceded stimulus onset for ~300 ms, with sources primarily in the left lateral frontal, right inferior frontal and temporal cortices. When advance preparation was ineffective (as implied by slow responses), or made impossible by a short cue–stimulus interval (CSI), a similar component, with lateral prefrontal generators, peaked ~300 ms poststimulus. The protracted prestimulus component (which we show to be distinct from P3 or contingent negative variation, CNV) also correlated over subjects with a behavioural measure of preparation. Furthermore, its differential lateralization for word and picture cues was consistent with a role for verbal self-instruction in preparatory task-set reconfiguration.

Introduction
The cognitive processes and actions triggered by a stimulus depend on our current ‘task-set’. Although task-set is to some degree stimulus-driven (e.g. text evokes reading, even when this is unwanted and interferes with performance; Stroop, 1935), it is normally under voluntary control, and can seemingly be reconfigured at will to prepare to process an upcoming stimulus. To capture such executive preparation in the laboratory, researchers have used task-cuing (e.g. Meiran, 1996): each stimulus is preceded by a cue specifying one of two or more tasks. Changing the task typically prolongs reaction time (RT) relative to performing the same task on successive trials. This ‘switch cost’ can be substantially reduced by increasing the CSI available for preparation (for review see Monsell, 2003). A natural interpretation is that enabling a changed task-set (and suppressing the previous one) requires a control process: task-set reconfiguration. If time permits it can be accomplished before the stimulus onset, whereas later reconfiguration delays or prolongs response selection, increasing RT (Rogers & Monsell, 1995; Meiran, 1996).

Studies using functional magnetic resonance imaging (fMRI; see Discussion) have found it difficult to distinguish prestimulus activation reflecting preparation for a task change from poststimulus activation consequent upon a task change. In contrast, event-related potential (ERP) studies (see Discussion) have detected several prestimulus components that potentially reflect anticipatory reconfiguration on task-switch trials: a positive deflection ~400 ms or more into the preparation interval, maximal over the posterior scalp (e.g. Karayanidis et al., 2003), an anterior negativity in the same latency range (e.g. Astle et al., 2006), a longer latency anterior–central negativity (Tieges et al., 2006, 2007) and an early anterior positivity (Rushworth et al., 2002b). However, important questions remain unanswered. First, do all (or any of) these effects reflect anticipatory task-set reconfiguration? We need evidence that they relate to effective preparation, as indexed by behavioural measures (e.g. reduction in switch cost). To date, no switch-related ERP deflection has been unequivocally associated with effective preparation. Second, the cortical generators of these components should be further explored. Third, the relationship between the posterior positivity and other well-documented ERP components in its time-range (P3, CNV) remains unclear; some authors identify the former with one of the latter (Kieffaber & Hetrick, 2005; Hsieh & Chen, 2006). Fourth, behavioural evidence suggests a critical role for linguistic self-instruction in task-set reconfiguration (e.g. Goschke, 2000), but relevant manipulations, such as verbal vs. non-verbal cues, have not yet been studied with ERPs.

To establish which switch-induced ERP effects (if any) relate to effective anticipatory task-set reconfiguration, we assessed the relationship between ERPs and behavioural measures of performance using a task-cuing paradigm based on recent behavioural research (Monsell & Mizon, 2006). We examined the cortical correlates of the switch-related ERPs using distributed source
estimation, complementing previous dipole-fitting studies (Rushworth et al., 2002b, 2005; Brass et al., 2005b). We characterized switch-induced effects in relation to other known ERP components by means of statistical decomposition. Finally, we compared effects of verbal vs. pictorial task-cuing on reconfiguration-related ERP effects.

Materials and methods

Subjects

Sixteen right-handed students, aged between 18 and 34 years (mean, 22), of whom 10 were women, were paid £5 per hour to participate, supplemented by a performance bonus (average £4) for minimizing RT and error rate, having given informed consent following guidelines set by the University of Exeter School of Psychology ethics committee.

Behavioural paradigm

The stimulus (see Fig. 1) was one of four outline shapes (circle, triangle, square and pentagon), presented in one of four colours (red, orange, green and blue), subtending a maximum visual angle of between 4.4° and 6.6° and centred in the screen, on a white background; the thickness of the coloured outline was ~0.4°. The task was to identify with a key-press either the colour or the shape of the stimulus, depending on which task-cue had been presented. Each stimulus was preceded by one of four cues presented in the centre of the screen: the word ‘COLOUR’ or ‘SHAPE’, or a pictorial cue consisting of a collage of the four colours or of the four shapes (Fig. 4b). The stimulus shape then surrounded the cue until the response (Fig. 1). Subjects responded by pressing one of four keys on the computer keyboard (v, h, n or m) using the middle and index fingers of the two hands. The mappings of shapes and colours to keys were, left to right, as in the lists above.

The design was optimized on the basis of prior behavioural research (see Monsell & Mizon, 2006) to maximize the likelihood of capturing a task-set reconfiguration process via the interaction between the switch–repeat contrast and CSI. In most task-cueing studies, task switches have been as frequent as task repeats, but this may encourage preparation for a task change before the cue. Indeed, task-switch costs and their reduction with preparation have recently been shown to reduce with increasing switch probability (Monsell & Mizon, 2006). For this reason we kept the probability of a task change relatively low (one in three trials).

The cue preceded the stimulus by a 200-ms (‘short’) or 800-ms (‘long’) CSI, which varied between blocks. The stimuli, tasks and CSIs used had previously produced a substantial reduction in switch cost at the longer interval, indicating successful preparation for a task change (Monsell & Mizon, 2006). The design was also intended to avoid some problematic confounds. Each stimulus followed the previous response by a constant interval of 1650 ms in both CSI conditions (unless an error was made, in which case ‘ERROR’ was displayed for a further 2 s before the next trial). A constant response–stimulus interval ensures that that the time available for preparation following the cue is not confounded with the time available for any passive dissipation of ‘task-set inertia’ following the previous response (Meiran, 1996). Because a change in cue from the previous trial can have a substantial effect on performance (Logan & Bundesen, 2003), it is important to unconfound cue-change and task-change. We used two cues per task, and the cue always changed from one task to the next, so there were no cue-repeat trials. [Among published ERP studies using the task-cuing paradigm, only Nicholson et al. (2005, 2006a) have done this.] The need to use two cues per task also provided an opportunity to contrast the efficacy of verbal and non-verbal cues; both were transparent in meaning to minimize the difficulty of cue interpretation.

In a practice session a day before the EEG recording session, subjects were trained with 64 trials on each task without switching, followed by four blocks of 97 trials using the task-cuing procedure. On a subsequent day, subjects were tested in the EEG lab in a session of 12 blocks of 97 trials, alternating between short- and long-CSI blocks. Ignoring the lead-in trial starting each block, there were equal numbers of trials for each combination of task, stimulus, cue and CSI, and each combination had a 1 : 2 ratio of task-switch and -repeat trials; subject to these constraints, the order of trials was randomised anew for each subject.

The following incentive scheme was employed. A score (mean RT/10 + errors × 5) was computed for each block. A bonus payment was made for blocks on which the score was lower than a running average of previous blocks with the same CSI, adjusted for the marked improvement in performance from Day 1 to Day 2; the maximum bonus payment was £5.60.

Behavioural analysis

Mean correct RTs and error rates, for trials following correct responses only, were subjected to ANOVAs with the factors switch, CSI, task and cue type (word, picture). Successful task-set preparation is indexed by a reduction in switch cost with an increase in CSI, as may be seen in Fig. 2. To obtain an estimate of the effectiveness of preparation for each individual which can be correlated with the ERPs, we summed z-scores of (i) their reduction in RT switch cost scaled by their mean RT on task-repeat trials (as RT switch cost tends to increase with overall RT) and (ii) their difference on switch trials between the error rates for short and long CSI (as error rate on repeat trials was stable over CSIs and could be zero).

EEG recording

Subjects wore a 64-electrode Ag/AgCl cap (ElectroCap International Inc., Eaton, OH, USA) connected to Brain Amp amplifiers (Brain Products, Munich, Germany). There were 58 electrodes on the scalp in an extended 10–20 configuration, two on the outer canthi, two above and below the orbit of the right eye and two on the ear-lobes. Scalp locations were registered and adjusted with a CMS ultrasound digitizer (Zebris Medical, Isny, Germany). The EEG was sampled at 500 Hz with a bandpass of 0.016–100 Hz, the
reference at Cz and the ground at AFz. Following 40-Hz offline lowpass filtering the EEG was segmented into: (i) for the long CSI only, a cue-locked 800-ms epoch, from the cue onset to the stimulus onset, baseline-corrected relative to the average during the 100 ms prior to the cue; (ii) for both short and long CSI, a stimulus-locked 490-ms epoch beginning with the stimulus onset, baseline-corrected against the 100 ms prior to the stimulus. (The 490-ms duration of the stimulus-locked epoch was selected by subtracting 50 ms from the shortest median RT over individuals, to minimize contamination of these stimulus-locked ERPs by post-response processes.) Epochs containing artifacts due to eye or other movements were discarded on the basis of amplitude criteria determined for each subject from eye blink amplitudes. Epochs corresponding to trials with errors, or following errors, were excluded. ERP waveforms were re-referenced to the average reference for the statistical analyses (i) to (iii) below, and to linked ears for visualization, qualitative comparison to previous studies and conventional ANOVAS on ERP amplitudes; see (iv) below.

ERP analysis

Four types of analysis were performed for the long CSI epoch, and for the poststimulus epoch for both the short and the long CSI conditions. The first tested for statistically reliable effects across the entire ERP epoch, thus avoiding arbitrary choices of time-ranges for statistical analysis. The second analysis employed a statistical procedure for assessing whether temporally overlapping ERP effects (such as posterior positivity and anterior negativity, or posterior positivity and P3) were or were not manifestations of the same underlying activity. The third procedure was aimed at localising the intracerebral generators of ERP effects measured on the scalp. The fourth analysis, aimed at facilitating comparisons with other studies, employed conventional ANOVAS on mean ERP amplitudes in predefined time-windows. The details of these analyses were as follows:

(i) To identify temporal ‘windows’ in each epoch where there were significant differences between the ERPs for task-switch and -repeat trials, we performed a topographic analysis of variance (TANOVA; Pascual-Marqui et al., 1995). This computes for each subject the overall dissimilarity between the switch and repeat ERP topographies, treated as vectors defined by the 58 scalp electrodes, and tests its significance at each time point, using permutations to correct for inflation of type 1 error in multiple comparisons (Nichols & Holmes, 2002). Prior to TANOVA, ERPs were transformed to a global field power of 1, to unconfound the dissimilarity measure from any global (whole-scalp) differences in activity between conditions. In the 0–200 ms range of the epoch, consecutive series of significant differences < 10 ms in duration were ignored. Beyond 200 ms, consecutive series of < 20 ms were ignored, and significant series separated by gaps of < 20 ms were coalesced.

(ii) To identify components of processing underlying the ERP waveforms, we subjected the electrode × conditions × subjects × time-points matrix to a temporal principal components analysis (PCA; Donchin & Heffley, 1978), with time-points (of which there were 400 for the long CSI and 245 for the poststimulus interval) as the predictor variables. Varimax-rotated PCAs were performed on the covariance matrices, with eigenvalue ≥ 1 as the criterion for component identification. Only components accounting for at least 1% of the variance were considered further. To determine which components were sensitive to the switch–repeat manipulation, ANOVAS were then performed on the factor scores of PCA components that overlapped in time with significant TANOVA windows. The factor scores, obtained using the regression method, represent the ERP amplitude of an underlying PCA component at each combination of electrode, condition and subject. For the ANOVAS, the factor scores were averaged for five groups of electrodes in each hemisphere, ignoring the midline electrodes, to yield average scores for five regions on the left: anterior frontal (FP1, AF3, F1, F3, F5, F7), posterior frontal (FC1, FC3, FC5, C1, C3, C5), temporal (T7, TP7, CP5, P7), parietal (CP1, CP3, P1, P3, P5) and parieto-occipital (PO1, PO3, PO7, O1), and the corresponding regions on the right. This grouping of electrodes has several useful features: it increases the signal-to-noise ratio by spatial smoothing (the smoothing is uniform due to similar group sizes) and enables one to simultaneously apply straightforward tests of anterior vs. posterior and lateralization effects, while using > 86% of scalp electrodes. In TANOVA (above) and source localization (below) the information from all scalp electrodes was used, hence very little spatial information was discarded overall. Region and hemisphere were factors in the ANOVA along with switch–repeat and any other factors. Significance levels were adjusted using the Huynh-Feldt correction for violations of sphericity (but unadjusted degrees of freedom are reported). When significant interactions of switch–repeat with region or hemisphere were found, Bonferroni-corrected two-tailed t-tests were performed to identify regions with significant differences.

![Graph](image-url)  
**Fig. 2.** Behavioural data. Mean correct RT and error rate as a function of CSI and task-switch vs. -repeat, showing the reduction in switch cost with more time to prepare.
To relate the observed scalp distribution of switch-repeat differences in ERPs to the spatial distribution of differential activity in underlying brain regions, we used low-resolution electromagnetic topography (LORETA; Pascual-Marqui et al., 1994). This algorithm solves the inverse problem by assuming a relatively smooth distribution of current source densities and orientations; it does not constrain the number of sources. Recent studies have validated LORETA solutions against fMRI localizations (Mulert et al., 2004). The solution space consists of 2394 voxels of size 7 mm, restricted to cortical gray matter and hippocampi. The version used is registered to the MNI305 brain atlas. The digitized positions of electrodes measured for each subject were normalized onto the standard MNI scalp by the LORETA software. In the case of four subjects for whom the interelectrode distances and directions thus obtained were deemed unrealistic, given the constraints of the cap, the measured coordinates were replaced with standard coordinates of the extended 10–20 positions on the MNI scalp. LORETA solutions were obtained for each time point in windows of interest (where there were significant $t_{ANOVA}$ differences between switch and repeat conditions and significant effects on PCA components), averaged within the window of interest, log-transformed, and submitted to voxel-wise $t$-tests, corrected for multiple comparisons using permutations (Nichols & Holmes, 2002).

To facilitate comparisons between the present investigation and other ERP studies, we also ran conventional region × condition × hemisphere ANOVAs on raw ERP amplitudes averaged within the time ranges selected on the basis of switch-sensitive $t_{ANOVA}$ windows and PCA components, and over the same regions as in (ii) above.

Data from all subjects were used for the main analysis of prestimulus ERPs collapsing across cue type (Figs 3 and 4a). However, because of loss of data due to eye movement artifacts, errors, etc., one subject was omitted from the analysis of prestimulus ERPs as a function of cue type (Fig. 4b), two from the analysis of prestimulus ERPs from the fastest and slowest RT terciles (Fig. 4c), two from the analysis of poststimulus ERPs (Figs 5a and 6) and three from the analysis of poststimulus ERPs from the fastest and slowest RT terciles (Figs 5b and 6).

Results

**Behavioural data**

Mean correct RTs and error rates are shown in Fig. 2. The RT cost of switching tasks was significant ($F_{1,15} = 23.72; P < 0.001$), reducing reliably from 127 ms at the short CSI to 66 ms at the long CSI ($F_{1,15} = 15.11; P = 0.001$), a typical reduction of ~50% (cf. Monsell & Mizon, 2006). The error rate cost of a task switch was also reliable ($F_{1,15} = 22.04; P < 0.001$), reducing from 4.8% at the short CSI to 3.2% at the long, though this interaction was not reliable ($F_{1,15} = 2.2$). This robust reduction in mean switch cost indicates effective preparation for a task change during the long CSI, and justifies comparing ERPs during that interval for task-switch and task-repeat trials.

RTs were significantly longer after picture than after word cues ($F_{1,15} = 42.21; P < 0.001$), and more so at the short CSI ($F_{1,15} = 23.09; P < 0.001$). At the short CSI this must in part reflect

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Fig. 3. Task-switch and -repeat ERP waveforms at representative electrodes during the long CSI.
the difficulty of concurrent perceptual processing of a coloured shape and a cue consisting of colours or shapes. Nonetheless, even at the long CSI, word cues resulted in faster responses \((F_{1,15} = 8.53; P = 0.011)\) and fewer errors \((F_{1,15} = 15.08; P < 0.001)\) than picture cues, and the switch cost in RT (and errors) was 84 ms (3.3%) after a picture cue compared to only 47 ms (1.7%) after a word cue; this interaction was marginally reliable for errors \((F_{1,15} = 4.24; P = 0.057)\). Hence there is some evidence that the verbal cue led to more effective preparation. There were no significant effects or interactions involving task.

**Examining preparatory effects: cue-locked ERPs**

Inspection of the grand-average ERPs obtained during the 800-ms CSI reveals large switch–repeat differences emerging ~500 ms into the CSI, with greater positive-polarity amplitudes preceding a switch over the central–posterior scalp and greater negative-polarity amplitudes in anterior frontal electrodes (see Fig. 3). Whole-epoch analysis (TANOVA) identified a time window of significant difference between task switch and repeat ERPs corresponding to this time range (584–800 ms), plus a 500–542 ms window of marginally reliable \((P < 0.1)\) differences (Fig. 4a).

Can the ERP waveform be decomposed into underlying components, of which only some account for the switch–repeat contrast? Temporal PCA found an extended component, explaining 26.2% of the variance, developing steadily over the 584–800 ms TANOVA window (Fig. 4a). An ANOVA on its factor scores yielded a significant effect of switch \((F_{1,14} = 8.75; P = 0.01)\). This switch-sensitive PCA component is likely to reflect the ERP effect referred to by some groups (Karayanidis et al., 2003; Swainson et al., 2003) as switch-related ‘positivity’. However, this PCA component also showed a significant switch \(\times\) region ANOVA interaction \((F_{4,56} = 12.20, P < 0.001)\) reflecting the presence of a switch-induced anterior negativity (also seen in the ERP waveforms, see Fig. 3). Hence we will label this complex the ‘posterior positivity–anterior negativity’ (PP-AN) effect. The widespread posterior positivity was left-lateralised, reflected in the significant switch \(\times\) hemisphere interaction in this PCA component \((F_{1,14} = 6.54, P = 0.023)\). For each scalp region, correlations were run between the composite RT and error behavioural index of preparation (see above Behavioural analysis section) and the switch–repeat differences in the scores of the PP-AN-related PCA component. Prior to the correlations, the differences in PCA scores were scaled by the average unsigned scores in the repeat condition to control for global or non-specific differences between subjects in ERP amplitude. The correlations showed that subjects with a larger preparation index exhibited a significantly larger switch–repeat contrast in the anterior right frontal region \((r_{14} = 0.56; P = 0.04)\), permutation-corrected for multiple comparisons; the correlations in the other regions failed to reach significance.

Some authors (Kieffaber & Hetrick, 2005; Tiegges et al., 2006) have interpreted a late switch-related positivity as modulation of a P3b (late P3) component. However, the maximal amplitude of our PCA component associated with PP-AN was ~700–800 ms, well outside the range of the P3 peak in the ERP waveforms (300–550 ms; Fig. 3). Furthermore, we obtained a large PCA component whose amplitude maximum did correspond to the typical P3 (300–550 ms) peak in the waveform (Fig. 4a), and it showed no reliable switch–repeat differences.

To relate the PP-AN effect to underlying brain regions, we turned to intracerebral current density estimation (LORETA) analyses. These were performed in two time-windows: one corresponding to the marginally significant TANOVA window, 500–600 ms, and one to the 600–800 ms window of reliable TANOVA differences. (Examining two windows, rather than one, may provide some insight into the temporal evolution of the differential activity). The first time-window was dominated by widespread greater activity prior to a switch in the left inferior frontal cortex (PFC), left midtemporal and parietal cortices and the precuneus (Fig. 4a, right panel), while the second window’s extra activity on switch trials was primarily in the left sensorimotor and left superior and inferior temporal gyri.

In addition to the PP-AN difference, the ERP waveform also contained a much earlier brief amplification of positive peaks at anterior and central electrodes preceding a task switch, an ‘early positivity’ (see Fig. 3), whose presence was confirmed statistically by a TANOVA window of reliable differences (156–166 ms). A similar anterior positivity has been reported by Rushworth et al. (2002b, 2005), Tiegges et al. (2007) and Astle et al. (2008). PCA identified two brief components in this temporal range that were switch-sensitive (Fig. 4a). The first accounted for 4.8% of the variance, and ANOVA on its factor scores revealed a significant main effect of a task switch \((F_{1,14} = 17.3; P = 0.001)\). The second accounted for 4.4% of the variance, and this showed a significant switch \(\times\) region interaction, \((F_{4,56} = 12.13; P = 0.004)\), indicative of a positivity confined to the anterior scalp. LORETAs were run for two 40-ms windows corresponding to the two switch-sensitive components. A 140–180 ms window showed more activity before a switch principally in the left medial frontal and left premotor and sensorimotor cortices (Fig. 4a, left lower panel). A 180–220 ms window provided some evidence of switch-induced left premotor and sensorimotor activity, and left superior and mid-temporal activity.

**Relating prestimulus ERPs to performance: fast vs. slow responses**

A key aim of the present study was to identify anticipatory switch-induced ERP activity that shows some relationship to behavioural measures of effective task-set reconfiguration. One such piece of evidence has already been mentioned: a correlation of PP-AN amplitude with the behavioural reduction in switch costs. A second piece comes from partitioning the data into fast and slow responses.

There is evidence from RT distributions that the efficacy of anticipatory task-set reconfiguration varies substantially from trial to trial (De Jong, 2000; Nieuwenhuis & Monsell, 2002): the variance of the task-switch RT distribution is greater than that of the task-repeat RT distribution. However, the maximal amplitude of our PCA component associated with PP-AN was ~700–800 ms, well outside the range of the P3 peak in the ERP waveforms (300–550 ms; Fig. 3). Furthermore, we obtained a large PCA component whose amplitude maximum did correspond to the typical P3 (300–550 ms) peak in the waveform (Fig. 4a), and it showed no reliable switch–repeat differences.
distribution, and switch–repeat differences are small at the lower quantiles, consistent with the idea that particularly effective preparation for a task-change is achieved on a proportion of switch trials with short RTs. On the assumption that either the effort to prepare or the efficacy of preparation is variable from trial to trial, and that effective preparation leads to short RTs, we should see more evidence of the neural correlates of prestimulus reconfiguration on switch trials with relatively short RTs. We therefore partitioned the RT distributions from each subject’s switch and repeat trials into terciles, and repeated the above contrasts separately for the fastest and slowest terciles (henceforward Fast and Slow trials). The task switch cost for the Fast trials was 31.3 ms, and for the Slow trials 75.6 ms, consistent with more successful preparation for a task-change on the Fast trials. The $t$-anova for the Fast trials identified a window of significant switch–repeat difference from 594 to 800 ms (Fig. 4c), albeit marginally reliable from 628 to 696 ms. For the Slow trials, however, the $t$-anova identified no time-point with a reliable switch–repeat contrast after 450 ms, only the series corresponding to the early positivity at 202–226 ms.

As expected from the analysis of all trials, the temporal PCA performed on the Fast and Slow ERPs found the extended late PCA component (400–800 ms, with the highest loadings in the 600–800 ms range; PP-AN). ANOVA on its scores found a significant effect of switch ($F_{1,13} = 10.58$, $P = 0.006$). Importantly, response speed (fast, slow) interacted with switch and region ($F_{4,52} = 11.19$, $P = 0.001$). Separate ANOVAs on the Fast and Slow scores found, for the Fast trials, a reliable effect of switch ($F_{1,13} = 5.67$, $P = 0.033$) and a switch $\times$ region interaction reflecting the dipolar PP-AN topography ($F_{4,52} = 20.84$, $P < 0.001$) but, for the Slow trials, only a marginally reliable effect of switch ($F_{1,13} = 4.60$, $P = 0.051$). Pairwise switch vs. repeat $t$-tests for all regions were run separately for the Fast and Slow factor scores. For the Fast trials, five regions showed reliable differences: frontal anterior left and right ($t_{13} = 4.27$, $P = 0.02$; $t_{13} = 6.85$, $P < 0.05$), parietal left and right ($t_{13} = 9.06$, $P < 0.01$; $t_{13} = 4.04$, $P = 0.02$) and parietal–occipital left ($t_{13} = 4.15$, $P = 0.02$). For Slow trials, no individual region yielded significant contrasts.

LORETA switch–repeat contrasts were run separately for the Fast and Slow ERPs in the 500–600 and 600–800 ms time-windows (Fig. 4c, right panel). For the Fast trials, these revealed widespread extra activity during preparation for a switch: the 500–600 ms window was dominated by frontal, and the 600–800 ms window more by temporoparietal, activations. For the Slow trial LORETA, the 500–600 ms window revealed no reliable extra activity on switch trials whereas in the 600–800 ms window the areas of surplus switch activity were restricted to the left dorsolateral frontal region, which also showed differential switch–repeat activity in the 500–600 ms range on the Fast trials.

Fig. 5. Poststimulus ERPs (0–490 ms after onset). Panel (a) contrasts vertex task-switch and -repeat ERPs following long and short CSIs, and shows $t$-anova windows of difference; corresponding difference waves are shown in the top of Panel (c); see Fig. 6 for additional electrodes. After a long CSI the switch waveform was more negative over the whole interval, but after a short CSI a positive difference (marked by an arrow) was superimposed, peaking at $\sim$300 ms. The partitioning of long-CSI trials into Fast and Slow responses in panel (b), and the corresponding difference wave at the bottom of panel (c), reveal a similar differentiation. The $\sim$300 ms positivity appears to be associated with either inadequate time for prestimulus preparation (short CSI) or ineffective preparation (long CSI and slow response). Panel (d): LORETA switch vs. repeat contrasts for the positivity in the short CSI condition and the slow-response long-CSI trials show overlapping areas of activation in left PFC; to capture subtle effects, results both corrected and uncorrected for multiple comparisons are presented.
Given the behavioural evidence that word and picture cues differed in efficacy, we conducted separate analyses of switch–repeat ERPs following each cue type. TANOVAs found broad windows of switch–repeat difference in the 600–800 ms (PP-AN) range for both cues, but for word cues there was also an earlier window of difference (454–544 ms). The most striking way in which switch-related activation depended on cue type was in its lateralization. Separate LORETA switch–repeat contrasts for word and picture cues (Fig. 4b) showed switch-related temporal lobe activation strongly lateralized to the right for word cues and to the left for picture cues; the inferior frontal activation was also right-lateralized following a word cue. This difference in lateralization for word and picture cues was also reflected in a significant cue × switch × hemisphere interaction in the ANOVA on the extended PCA component that showed the PP-AN effect in the analysis of all trials above ($F_{1,14} = 4.71, P = 0.048$).

**Preparatory effects: summary**

Our prestimulus analyses showed switch-induced ERP effects both early and late in the 800-ms interval preceding the stimulus (long CSI condition). The temporal PCA suggests that the two late ERP effects with overlapping latencies (PP-AN) are facets of the same underlying activity. Unlike the early (200 ms) switch-related ‘anterior positivity’, the PP-AN effect shows a meaningful relationship with behavioural measures of effective preparation, which makes it a probable correlate of an anticipatory task-set reconfiguration process.

**Poststimulus ERPs**

The general pattern, visible in the stimulus-locked ERPs and the switch–repeat difference waveforms in Figs 5 and 6, is that, after a long CSI, ERPs were more negative on switch trials over frontocentral and posterior electrodes over the 490-ms epoch analysed following the stimulus, with significant TANOVA windows at 42–58 and 82–490 ms. However, with a short CSI (only 200 ms to prepare), this negativity was reduced (significant only in the 46–64 ms interval) and then largely reversed in polarity over the 292–354 ms interval such that there was greater positivity on switch trials peaking at ~300 ms poststimulus, i.e. ~500 ms postcue. We tentatively identify this poststimulus positivity following a short CSI with the positivity that developed ~500 ms after the cue during the long CSI, and interpret it as a correlate of task-set reconfiguration now performed after the stimulus because the short CSI afforded no earlier opportunity. This is consistent with a LORETA switch–repeat contrast on the poststimulus 292–354 ms window; it showed greater activation mainly in left dorsolateral PFC (Fig. 5d), a subset of the regions differentially activated over the 500–600 ms window during the long CSI (Fig. 4c, right panel). However, neither the main effect of, nor interactions with, a switch–repeat were reliable for the PCA component whose maximal amplitude was in the 292–354 ms window.

**Fast vs. slow trials**

We separated Fast and Slow trials in the long-CSI analysis above on the grounds that the Fast trials should contain more cases of successful prestimulus preparation. It follows that, after a long CSI, we should find more evidence of delayed, poststimulus TSR on Slow trials: these should look more like short-CSI trials, which allowed insufficient time for prestimulus preparation. The ERPs for Fast and Slow long-CSI trials were largely consistent with this expectation (Figs 5 and 6). For

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**Fig. 6.** Poststimulus difference waves (task-switch minus repeat) for representative electrodes. Top panel: short- vs. long-CSI trials. Bottom panel: Fast-response (well-prepared) vs. Slow-response (poorly prepared) trials with long CSI.
Fast trials, TANOVA found significant windows of switch–repeat difference in the ranges 26–88 and 150–490 ms, and these were more negative for switch over most electrodes. However, for Slow trials there were only brief windows of negative difference (between 142 and 178 ms), and there was a 218–290 ms window of greater positivity on switch trials, though its scalp distribution was more anterior than that of PP-AN and of the poststimulus positivity in the short CSI (see Figs 3 and 6). A marginally reliable switch–repeat difference \( F_{1,12} = 7.83, P = 0.081 \) was found for Slow trials in an ANOVA on the PCA scores for the component overlapping this time-range and accounting for 9.2% of the variance. A LORETA switch–repeat contrast over this window (Fig. 5d) showed greater activation on switch trials in left-lateral PFC regions similar to those activated in the 292–354 ms window for short-CSI trials, albeit not surviving whole-brain correction for multiple comparisons. For the Fast trials, this component did not show reliable switch effects or interactions.

In summary, the poststimulus ERPs for trials with slow responses following an opportunity for prestimulus preparation resembled those for trials with no opportunity for preparation; the poststimulus positivity shared at least some of its features with the prestimulus positivity seen when prestimulus preparation was both available and effective.

**Conventional contrasts on ERP amplitudes**

To facilitate comparison with previous ERP studies of task-switching, ANOVAs were run on ERP amplitudes averaged within time-windows suggested by TANOVA and PCA. ANOVAs run on two time-windows corresponding to the range of the PP-AN effect found a reliable main effect of switch and a reliable switch × region interaction (reflecting the different polarity of the switch vs. repeat difference in the anterior relative to the other scalp regions) for both time-windows (500–600 ms: \( F_{1,13} = 6.48, P < 0.05 \); \( F_{4,60} = 4.37, P < 0.05 \); 600–800 ms: \( F_{1,15} = 5.32, P < 0.05 \); \( F_{4,60} = 9.82, P = 0.001 \) ). ANOVAs contrasting the terciles of trials with the fastest and slowest responses found the critical switch × response speed interaction reliable in the 600–800 ms window (\( F_{1,13} = 10.75, P < 0.01 \)); in the 500–600 ms window it failed to reach significance (\( F_{1,13} = 2.42, P = 0.14 \)). In the analyses that compared the two cues (word, picture), the interaction of interest between switch, cue and hemisphere was reliable in the 500–600 ms range (\( F_{1,14} = 4.69, P < 0.05 \)) and marginally reliable in the 600–800 ms range (\( F_{1,14} = 4.07, P = 0.063 \)).

In the poststimulus ERPs, ANOVAs on two time-windows spanning the protracted switch-induced negativity in the long CSI trials found a reliable main effect of switch for both windows (100–300 ms: \( F_{1,13} = 4.72, P < 0.05 \); 300–490 ms: \( F_{1,13} = 11.45, P < 0.01 \)). In the time-window of the switch-induced positivity in the short CSI trials, identified by TANOVA and further analysed with LORETA (275–350 ms), a reliable main effect of switch was also found (\( F_{1,13} = 8.51, P = 0.01 \)). A similar positivity identified by TANOVA in the long CSI trials associated with the slowest responses in the 225–300 ms range was also examined by an ANOVA on the ERP waveform amplitudes averaged within this time-window. Although no reliable main effect of switch was found, the switch × region interaction was reliable (\( F_{4,48} = 10.43, P < 0.001 \)) and the switch × hemisphere interaction approached significance (\( F_{1,12} = 4.48, P = 0.056 \)).

**Discussion**

The primary aim of this task-cuing experiment was to identify which (if any) of several ERP effects previously associated with preparation for a task switch is associated with advance task-set reconfiguration by identifying switch-sensitive modulations of ERP associated with effective preparation, as assessed behaviourally. We also aimed to further characterize the ERP effects under scrutiny by examining their functional anatomy with distributed source localisation (LORETA) and by assessing their relationship with other well-documented ERP components (e.g. P3, CNV). Furthermore, we took the opportunity to examine differences in the behavioural effects and brain activity triggered by verbal and pictorial task cues, prompted by evidence that verbal cues seem particularly effective (e.g. Monsell & Mizon, 2006) and the idea that linguistic self-instruction can support task-set reconfiguration (Goschke, 2000; Miyake et al., 2004). Importantly, the paradigm we employed to address these issues was optimized on the basis of recent behavioural research (Monsell & Mizon, 2006) to avoid confounds (i.e. cue change and task change) that complicate theoretical interpretation and limitations (e.g. high probability of a task switch) that reduce the switch–repeat contrast.

**Previous reports of ERP effects associated with task-set preparation**

As mentioned in the Introduction, at least four switch–repeat differences observed in the ERP preceding stimulus onset have been proposed to reflect preparation for a task switch:

(i) An early switch-induced positivity with anterior topography was reported by Rushworth et al. (2002b), with onset at ~200 ms following a cue indicating response remapping (exchange of left and right responses), and dipole sources in the medial frontal cortex. (Rushworth et al., 2005; Tiegges et al., 2007; and Astle et al., 2008; reported similar anterior positivities.) In an IMRI study of the same rule reversal, Rushworth et al. (2002a) also found switch-related extra activation in the medial frontal region (pre-supplementary motor area); TMS stimulation of this region between cue and stimulus slowed RT on switch, but not repeat, trials. Based on the requirements of their paradigm, Rushworth and colleagues (Rushworth et al., 2002a, b) proposed that the anterior positivity reflects anticipatory reorganization of stimulus–response mappings on switch trials.

(ii) Most ERP studies of prestimulus activity in task-switching report an extended positivity with a posterior topography from ~500 ms following the cue in task-cuing studies, or following the previous response when a task-switch is predictable (Astle et al., 2006, 2008; Hsieh & Chen, 2006; Karayamidas et al., 2003; Kieffaber & Heitrick, 2005; Minussi et al., 2005; Moulden et al., 1998; Nicholson et al., 2005, 2006a, b; Rushworth et al., 2002b, 2005; Swainson et al., 2003, 2006; Tiegges et al., 2007; Wylie et al., 2003). Some investigators have seen this as a modulation of the P3 component of the ERP (Kieffaber & Heitrick, 2005; Tiegges et al., 2007) and interpreted its functional significance in accordance with the P3 literature: for example, as reflecting either the updating of task-set in working memory, or increased difficulty on switch trials (Tiegges et al., 2007).

(iii) Some of the studies that reported the posterior positivity also reported an extended switch-induced negativity in the anterior frontal electrodes (Moulden et al., 1998; Wylie et al., 2003; Astle et al., 2006, 2008; Gladwin et al., 2006). (Among studies that did not report this negativity, some lacked appropriate electrodes to detect it.) Although this anterior negativity overlapped in time with the posterior positivity, Astle et al. (2008) argue that they are dissociated, for reasons we return to below.
A further, longer-latency switch-induced negativity has also been reported (Karayanidis et al., 2003; Tieges et al., 2006, 2007). Although the relationship between this negativity and the shorter-latency anterior negativity mentioned above is not clear, we distinguish between them on two grounds. The longer-latency negativity seems to start only after the posterior positivity is resolved (no earlier than after 800 ms of preparation; Karayanidis et al., 2003; Tieges et al., 2007) and its scalp distribution is more broad and posterior than that of the anterior negativity in the 500–1000 ms range. Tieges et al. (2006, 2007), who found caffeine to enhance this negativity and reduce switch costs, have proposed that it reflects ‘active maintenance’ of task-set.

Although it is possible that all of the above ERP features are manifestations of advance task-set control, it is also likely that switch trials are different from repeat trials in overall difficulty, allocation of resources, conflict processing, subjective salience etc. ERPs are sensitive to such nonspecific processing differences. For example, the amplitude of components from the P3 group is modulated by stimulus probability, salience, motivational state and other factors whereas the latency of P3 components is sensitive to task difficulty. It is, therefore, important to distinguish between such modulations of ERP and components specifically associated with task-set control. For this reason, we focus on the relation between ERP modulations and behavioural indices of effective preparation.

**PP-AN: a neurophysiological signature of effective task-set preparation**

The robust reduction in the behavioural cost of a task change at the long CSI demonstrated that subjects effectively prepared for a task change given sufficient time between task-cue and stimulus. The more persistent feature of the differential activation during the long CSI on switch trials [a late posterior positivity (PP) concurrent with an anterior negativity (AN)] evolved steadily from ~500 ms after the cue (see Fig. 3). As both the PP and AN were well accounted for by only a single component in the temporal PCA (see Fig. 4a), we identified a ‘PP-AN’ complex. As already mentioned, similar late positivities and/or anterior negativities have been reported in prior ERP studies of task-set preparation. For these waveform features to be viewed as reflections of anticipatory control, they must relate to behavioural measures of successful preparation. Hitherto, the evidence for such a relationship has been weak. A recent ERP study that employed three tasks and contrasted the effects of using switch-cue cues that did or did not specify the identity of the task to be performed (‘switch-to’ vs. ‘switch-away’ cues; Nicholson et al., 2006b) found that only the former resulted in a reliable reduction in switch cost. Finding that trials with ‘switch-to’ cues were also associated with a greater switch-related positivity in the cue interval than trials with ‘switch-away’ cues is consistent with this component being a reflection of effective preparation. However, it is difficult to determine whether ‘switch-away’ cues were associated with any switch-related positivity, because their contrast to the baseline (task-repeat trials) was confounded with the effects of cue change (the cue remained the same on repeat trials).

Our approach to examining the relationship between PP-AN and preparation was twofold. First, we showed that the PP-AN amplitude was much larger for trials with fast responses, for which better preparation was presumably achieved and for which the long-CSI switch cost was smaller, consistent with trial-to-trial variation in the efficacy of task-set reconfiguration (Fig. 4c). For these fast-response trials LORETA indicated widespread frontal and temporoparietal activation, with the former leading, while on the slow response trials all that could be detected was later and weaker left frontal activity. Second, we examined correlations over subjects. Previously, Kieffaber & Hetrick (2005) correlated the difference in a switch-sensitive PCA-identified ERP component with RT task-switch cost over subjects, and found a reliable association only for one of three kinds of switch trials (transitions between two visual tasks, not between auditory and visual tasks). However, as RT switch cost varies over subjects for many reasons, including the fact that it tends to scale with mean RT, a more meaningful correlate than the switch cost (main effect) is the extent to which it reduces with an opportunity for preparation (the CSI × switch–repeat interaction). Our study included a CSI manipulation (unlike Kieffaber & Hetrick, 2005), and we found that an index of this reduction was reliably correlated with the amplitude of the PP-AN effect in the right anterior frontal region.

Temporal PCA allowed us to examine the relationship between the PP and the concurrent AN we and others have observed. Astle et al. (2006) distinguished between two ERP effects in the CSI: a frontal negativity concurrent with a left parietal positivity and a parietal positivity maximal at midline sites. They claimed these effects could be dissociated: unlike the latter effect, the former was reduced or eliminated when the response on the previous trial had to be withheld (a ‘no-go’ trial). They suggested that the frontal negativity (and the associated left parietal positivity) may reflect the process of overcoming task-set inhibition: on a no-go trial less inhibition is applied to the competing task-set, hence on the subsequent trial there is less need to overcome this inhibition. Of two more recent studies by the same group, one reported an apparent association: Mueller et al. (2007) detected both AN and PP modulations when responses in both tasks were mapped onto the same effectors and neither when responses were mapped onto separate effectors. The other study (Astle et al., 2008) reported an apparent dissociation: a PP but no AN when responses were covert. These conclusions were based on analyses of local amplitude contrasts in average-referenced ERPs (interactions with topographic factors such as anterior–posterior and left–right were not apparently assessed statistically). Because average-referencing is the subtraction from each electrode of the average voltage over all electrodes, local voltage modulations are reflected in all channels and can lead to different conclusions about the location and timing of differences than the local, more commonly used, (e.g. mastoid) referencing, though the latter has its limitations. For this reason, analytic procedures such as PCA provide a better way of assessing the independence of temporally overlapping ERP effects in different scalp regions. In our analysis, the PP and the AN showed statistical interdependence in that they were accounted for by the same PCA component (see Fig. 4) in the analyses both of all trials and of the trials with fastest responses. Although one cannot exclude the possibility that the PP and the AN may reflect processes that are correlated in some conditions (hence our PCA result) and independent in others, our results favour a single-component interpretation.

We also observed an early positivity on long-CSI switch trials in a 140–220 ms window following the cue (see Fig. 3). While the earliness of this effect is consistent with cue-related activity, the LORETA localization in medial frontal cortex (Fig. 4a, left panel) is also reminiscent of the positivity observed by Rushworth et al. (2002b) following a cue indicating a response remapping (exchange of left and right), with dipole sources in the medial frontal cortex. The switch between colour and shape classification that we required of our subjects involves both a change in the stimulus attribute attended to and remapping of responses to stimuli; the medial frontal activation we observed could be associated with a response-remapping process of the kind suggested by Rushworth et al. (2002a, b). However, its short latency following the cue is perhaps more compatible with early
registration of the need for response remapping rather than the remapping process itself. Furthermore, the PCA in this range found switch-sensitive components in the analysis of slow- as well as fast-response trials (Fig. 4c, left panel), consistent with detection of the need to re-map rather than its effective accomplishment. Alternatively, the early medial frontal activity might reflect the early detection of conflict between the currently cued task-set and the previous one, consistent with the role often attributed to medial frontal lobe in conflict monitoring (Botvinick et al., 1999).

Our 800-ms CSI, chosen on the basis of evidence suggesting that the reduction in switch cost with increasing CSI is usually asymptotic at or before that value (e.g. Monsell & Mizon, 2006), did not allow us to look for a later broadly-distributed switch-related negativity that some have reported using longer CSIs (Karayanidis et al., 2003; Tieges et al., 2006, 2007). One possibility is that, given a predictable and long preparation interval, subjects delay preparation until later in the interval. (Tieges et al., 2006; do report a significant reduction in switch cost as they increased CSI from 600 to 1500 ms, though this is partly due to an increase in repeat RT). Moreover, there is evidence in the data of Karayanidis et al. (2003) that the timing of preparatory activity becomes more variable with a longer fixed CSI. However, a preparation interval longer than that required to complete preparation may also evoke additional processes required to maintain that preparatory state. The evidence suggests that intervals of well under a second are sufficient for asymptotic preparation both with the predictable alternating-runs paradigm using letter or digit classification (Rogers & Monsell, 1995; Karayanidis et al., 2003) and in the task-cuing paradigm using other tasks (Monsell & Mizon, 2006). Hence, the functional significance of the negativity sometimes seen at longer intervals remains ambiguous.

Cortical substrates of anticipatory task-set control: fMRI vs. ERP

As well as the ERP studies we have reviewed, a number of fMRI studies, motivated by much the same rationale, have looked for additional activity in control-relevant brain regions associated with preparation for a task-switch. It is difficult to separate effects of a task-switch on pre- and poststimulus activation with haemodynamic measures when one uses relatively short CSIs similar to those employed in behavioural paradigms (Brass & von Cramon, 2004). In other fMRI studies, which used preparation intervals of many seconds to achieve such separation (Barber & Carter, 2005; Kimberg et al., 2000; Sohn et al., 2000), extra activation seen during preparation for a switch (in the lateral prefrontal and posterior parietal regions and the precuneus) might have reflected maintenance rather than preparatory processes per se. Several task-cueing fMRI studies with shorter CSIs have either varied CSI from trial to trial or included some cues that are not followed by stimuli in order to deconvolve cue- and stimulus-related blood oxygen level dependent (BOLD) activation (Brass & von Cramon, 2002; Luks et al., 2002; Ruge et al., 2005; Gruber et al., 2006; Slagter et al., 2006). Of these, all except Slagter et al. (2006) have failed to detect any difference between preparation for a switch and preparation for a task repeat and, as a result, have questioned whether preparation for a change of task differs from preparation for a task-repeat.

In contrast, as we have seen, ERP studies routinely report switch–repeat differences in the CSI, even though there is not yet consensus on their characterization and interpretation. Moreover, where source localization has been done, the results, like ours, consistently show intracerebral activity surpluses on switch trials (Rushworth et al., 2002b, 2005; Brass et al., 2005b). A larger number of reliably activated dipole sources was also found on switch trials in the inferior frontal region and the anterior cingulate and supramarginal gyri in a recent MEG study (Perianez et al., 2004). This is consistent with additional processing and perhaps qualitatively different processing during preparation for a task change. It remains unclear why such differences have been readily detected by ERP (and MEG) but not by fMRI studies. Inasmuch as advance preparation is an optional and effortful strategy, it may easily be discouraged by the experimental strategies used to deconvolve cue- and stimulus-related BOLD signals (e.g. unpredictable CSIs, cueing task-preparation for stimuli that then do not occur), or indeed by the stress of being tested in the scanner. Another possibility is that anticipatory task-set reconfiguration is realized not as a gross increase in neural activity but as an increase in coherent activity, which may have limited metabolic consequences yet be detectable with EEG and MEG. It is also possible that frontal systems apply as strong a top-down bias following the task cue regardless of whether the task changes or repeats (and it is this ‘control effort’ that fMRI primarily measures) but, as the network is already in or near an optimal state on task-repeat trials, the effect on processing in the lower-level systems that are the targets of this signal is much greater on task-switch trials (and ERP and MEG are sensitive to these effects).

The regions of surplus current density found on switch trials in our LORETA analyses were widely distributed over PFC, among other regions, consistent with existing evidence and theory on the role of PFC in task set control (e.g. Miller & Cohen, 2001). Extra left-lateral PFC activity has previously been found during preparation for the less habitual of the two tasks afforded by a Stroop stimulus: colour naming (MacDonald et al., 2000). Left-lateral PFC damage has been found to impair task-switching (Rogers et al., 1998; Aron et al., 2004a). The region of LORETA activation that emerges most consistently in our switch–repeat contrasts (following the cue in both Fast and Slow trials; Fig. 4c; following the stimulus in the short CSI and, less robustly, in the Slow trials in the long CSI; Fig. 5) is a broad region of left lateral PFC, including possibly the left inferior frontal junction (IFJ) area, which has shown switch-related activity in fMRI studies (Brass & von Cramon, 2002, 2004) and has been implicated in several cognitive control operations (Brass et al., 2005a). Interestingly, a recent task-switching ERP study showed that a dipole positioned at the IFJ provided a good fit of the ERPs in the CSI, together with a parietal dipole (Brass et al., 2005b). However, the switch–repeat contrast in that study was defined not relative to the previous trial in the sequence but relative to the first of two cues presented on the same trial (which could signal the same or different tasks) which makes it difficult to compare to other results.

Right-PFC activation has also been reported during preparation for a task-switch (Sohn et al., 2000), right-PFC lesions have been shown to result in task-switching deficits (Aron et al., 2004a), and our data are compatible with neuropsychology in that the right activations were of relatively inferior right-PFC compared to the broader lateral activation of left-PFC. The right inferior frontal gyrus has been associated with inhibitory processes (Aron et al., 2004b; Lavric et al., 2004), including task-set inhibition (Aron et al., 2004a). The fact that we saw more right inferior frontal activation with the somewhat more effective verbal cues may be suggestive of more effective inhibition of the inappropriate task-set with these cues.

The PP-AN complex in relation to P3 and CNV

An important issue in the interpretation of the PP-AN effect is its relation to two well-documented ERP components that occur in the
same temporal range: P3 and CNV. For example, Kieffaber & Hetrick (2005) interpreted the posterior switch-induced positivity they observed as a modulation of the P3b component (late part of the P3 complex, with posterior topography), on the grounds that they saw switch vs. repeat differences in a temporal PCA component corresponding to the P3b peak in the ERP waveforms. (See Tieges et al., 2007; for a similar proposal and Barcelo, 2003; for a related account of ERP positivities preceding rule-switching in card-sorting tasks). However, neither Kieffaber & Hetrick (2005) nor Tieges et al. (2007) distinguished task-change from cue-change, so the functional significance of the switch-induced ERP effects they observed is somewhat ambiguous. Furthermore, Kieffaber & Hetrick (2005) show a distinct temporal PCA component with steadily increasing loadings in the later part of the CSI but do not report its specificity to a task-switch, although it overlapped substantially with the switch-related positivity in the raw ERPs and accounted for more of the total variance than the P3b-like PCA component.

In our own data, the posterior positivity part of the PP-AN complex was clearly distinct from any member of the P3 family. The positivity increased monotonically up to the end of the CSI, whereas P3 tends to return to baseline at ~500–600 ms. Moreover, our PCA analyses also yielded a substantial P3-like component (Fig. 4) but it was not switch-sensitive. An important theoretical implication of this distinction between P3 and the PP-AN effect is that the latter is unlikely to be interpretable in terms either of the generic ‘difficulty’ of processing on switch trials or of the relative ‘novelty’ of a cue signalling a switch (one in three trials), as both difficulty and novelty typically do modulate P3.

Other authors have characterized the posterior positivity as a reduction (Hsieh & Chen, 2006; Lorist et al., 2000) or delay (Brass et al., 2005b) in CNV, a negative-going wave observed in anticipation of a stimulus preceded by a warning signal (in the S1–S2 paradigm; Walter et al., 1964). CNV is believed to reflect ‘readiness’ for the upcoming stimulus, so a more negative-going wave on the task-repeat trials than on the task-switch trials could result from a larger or earlier CNV in the repeat condition. On both switch and repeat trials, we did observe a negative-going CNV-like wave in the late part of the long-CSI ERPs. Could the PP-AN effect thus reflect (merely) greater stimulus anticipation on repeat trials rather than a process of active reorganisation of task-set? We think not. First, the unequivocal finding from source estimation studies of CNV (e.g. Hultin et al., 1996), including some using LORETA (Gomez et al., 2003), is that CNV reflects an increase in intracortical current density whereas our analyses show substantially less current density (and global field power across the scalp) during the CSI on repeat than on switch trials. Secondly, the behavioural switch cost was greater on the slow trials than on the fast trials, suggesting that the discrepancy in ‘readiness’ between repeat and switch conditions was greater for slow trials. If our PP was a CNV increase on repeat trials it should have been larger on slow trials, contrary to what we found. Hence, while generic preparation for a stimulus onset may well be generating the CNV-like pattern in our data, the posterior positivity on switch trials appears to be a distinct phenomenon, not just a modulation of CNV.

Astle et al. (2006, 2008) noted similarities between the anterior negativity they observed concurrently with a posterior positivity and CNV, a parallel they relate to the previous finding of an enhanced CNV on trials associated with particular ‘effort’ (Falkenstein et al., 2003). However, the frontal–polar distribution of our AN (as well as the presence of the concurrent, widespread and highly correlated PP in its time range) is not consistent with the frontal–central or posterior–central topography of CNV. Furthermore, at the neurophysiological level the frontal CNV is thought to reflect early activation of premotor and motor areas involved in the generation of the motor response (Brunia & Van Boxtel, 2001); if this were to occur primarily on switch trials one would expect a switch benefit rather than cost.

**The role of linguistic processing in task-set reconfiguration**

Our study compared word and picture cues. Consistent with earlier data, the word cue seemed more effective: it was associated with faster RTs and fewer errors overall and, after a long CSI for preparation, a smaller switch cost (though the relevant interaction was marginally reliable only for errors). Recent behavioural work that compared verbal and spatial cues also found verbal cues to be associated with smaller switch costs (Arbuthnott, 2005). We also found a marked difference between cues in the lateralization of the scalp distribution of switch–repeat ERP differences, and in the frontal and temporal activation found by LORETA, with more right-side activation following a word cue and more left-side activation following a picture cue. We suggest that the greater left-temporal and left-frontal activation seen following a pictorial cue is attributable to the self-generation of a verbal instruction when it is not supplied directly by the cue. This is consistent with the idea that a basic context-sensitive task-set control network (Miller & Cohen, 2001) present in both humans and infrahumans (with cortical components primarily in PFC and parietal cortex) is, in humans, supplemented by verbal self-instruction (Goschke, 2000; Gruber & Goschke, 2004; Miyake et al., 2004) and with the observation that the impact of left hemisphere damage on task-switching varies with the extent of language disorder (Mecklinger et al., 1999). As for the greater right-temporal activation following a verbal cue, we speculate that it reflects non-verbal rehearsal and/or retrieval of possible target stimuli which the pictorial cue supplies directly.

**Poststimulus dynamics of task-set control**

Our prestimulus analyses converge on the PP-AN complex, among ERP deflections previously associated with advance task-set control, as the probable candidate for a specific neurophysiological signature of anticipatory task-set reconfiguration. That this component is associated with a task-set reconfiguration process which, if not done before the stimulus onset, must be done after it, was also supported by the poststimulus ERPs. On short-CSI trials a positive switch–repeat difference developed ~300 ms following the stimulus, i.e., ~500 ms following the cue, similar to the onset latency for the late positivity during the long CSI (see Karayanidis et al., 2003 and Nicholson et al., 2005, for similar findings). We observed a similar poststimulus positivity on long-CSI trials with slow responses (which presumably include a high proportion with ineffective prestimulus preparation), reinforcing the suggestion that when task-set reconfiguration does not, or cannot, occur before the stimulus, it must occur after it.

This poststimulus positivity appeared to be superimposed on a more protracted negativity, which developed shortly after the stimulus on long-CSI switch trials and persisted through the half-second epoch analysed. A protracted switch-related negativity following the stimulus (also referred as repeat-related positivity) has been reported in other ERP studies (Rushworth et al., 2002b; Karayanidis et al., 2003; Kieffaber & Hetrick, 2003; Nicholson et al., 2005; Poulsen et al., 2005; Swainson et al., 2006), albeit with somewhat variable latencies. It may reflect enhanced conflict due to carry-over of the previous task-set, manifest also in the ‘residual’ switch cost seen in
RTs despite ample opportunity for preparation (Monsell, 2003). This conflict-interpretation of the switch-related poststimulus negativity is also supported by the finding that a similar poststimulus negativity is observed when stimuli which afford only one task are compared to stimuli which afford two or more tasks (Poulsen et al., 2005). Swainson et al. (2006) proposed that this poststimulus switch–repeat difference reflects ‘active consolidation’ of the task-set on repeat trials (hence the term ‘repeat positivity’). Their rationale was that they detected this difference only when the task sequence was fixed and predictable (e.g. AABB…), not unpredictable, as in the task-switching paradigm, and that behavioural studies have shown that in predictable switching the first task repetition is sufficient to recover fully from the preceding switch, whereas unpredictable switching produces a more gradual approach to asymptotic performance (Monsell et al., 2003; Swainson et al., 2006). However, as the same group (Astle et al., 2006), we and others (Nicholson et al., 2005, 2006b) did observe this poststimulus ERP effect with task-cuing, the extent to which it is modulated by sequence predictability remains an open issue. Moreover, ‘active consolidation’ seems a surprising interpretation of a process that, on a task-repeat trial in a predictable sequence, does not detectably improve performance on the following trial. Rather, the effect of predictability seems likely to reflect some difference in ‘consolidation’ of the task set on or immediately after the previous trial (cf. Monsell et al., 2003).

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Abbreviations

AN, anterior negativity; CNN, contingent negative variation; CSL, cue–stimulus interval; ERP, event-related potentials; fMRI, functional magnetic resonance imaging; LORETA, low-resolution electromagnetic tomography; PCA, principal components analysis; PFC, prefrontal cortex; PP, posterior positivity; PPAN, posterior positivity concurrent with anterior negativity; RT, reaction time; TANOVA, topographic analysis of variance.

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