

Dissociable Neural Correlates of Intention and Action Preparation in Voluntary Task Switching

Edita Poljac and Nick Yeung

Department of Experimental Psychology, University of Oxford, Oxford, UK

Address correspondence to Edita Poljac, Department of Experimental Psychology, University of Oxford, South Parks Road, Oxford OX1 3UD, UK. Email: edita.poljac@psy.ox.ac.uk

This electroencephalographic (EEG) study investigated the impact of between-task competition on intentional control in voluntary task switching. Anticipatory preparation for an upcoming task switch is a hallmark of top-down intentional control. Meanwhile, asymmetries in performance and voluntary choice when switching between tasks differing in relative strength reveal the effects of between-task competition, reflected in a surprising bias against switching to an easier task. Here, we assessed the impact of this bias on EEG markers of intentional control during preparation for an upcoming task switch. The results revealed strong and varied effects of between-task competition on EEG markers of global task preparation—a frontal contingent negative variation (CNV), a posterior slow positive wave, and oscillatory activity in the alpha band (8–12 Hz) over posterior scalp sites. In contrast, we observed no between-task differences in motor-specific task preparation, as indexed by the lateralized readiness potential and by motor-related amplitude asymmetries in the mu (9–13 Hz) and beta (18–26 Hz) frequency bands. Collectively, these findings demonstrate that between-task competition directly influences the formation of top-down intentions, not only their expression in overt behavior. Specifically, this influence occurs at the level of global task intention rather than the preparation of specific actions.

Keywords: cognitive control, EEG, intentions, task switching, voluntary action

Introduction

Understanding the neurocognitive processes supporting flexible human cognition is a long-standing challenge in psychology and neuroscience. According to an influential framework, cognitive flexibility depends on dedicated control mechanisms that serve to guide thought and action in accordance with current intentions. In Norman and Shallice's (1986) attention to action theory, for example, a supervisory attention system is called upon when required actions are novel, non-routine, or complex. Miller and Cohen's (2001) guided activation model proposes a cognitive control system with very similar functions and identifies these functions primarily with the prefrontal cortex. Both of these theories view cognitive control as providing a biasing input that influences competition among stimulus–response pathways (termed “schemas” by Norman and Shallice) for the control of behavior. In the absence of this top-down bias, behavior will be governed by habitual or recently activated pathways—that is, it will be governed by past experience rather than explicit representations of current intentions. Even with top-down input, performance will be less efficient if those current intentions conflict with habitual patterns of behavior.

Participants' performance in the task-switching paradigm exemplifies these interactions between current intentions and past experience. In this paradigm, participants are required to switch between tasks (such as classifying stimuli according to their shape or their location) across trials. In some experiments, participants are told which task to perform on each trial (e.g., Rogers and Monsell 1995; Meiran 1996); in others, they are given some freedom to choose (e.g., Arrington and Logan 2004). In both cases, intentional control of behavior is evident in participants' ability to make rapid, flexible switches of task according to instruction or whim and to do so more efficiently when given time to prepare for each switch (e.g., Rogers and Monsell 1995; Meiran 1996; Arrington and Logan 2005). However, task switching equally shows strong influences of past experience: Switching is associated with a performance cost—slowed RTs and increased error rates—that at least partly reflects competitive interactions between current and previous tasks (Allport et al. 1994). Thus, switch costs are increased by the presence of distracting stimulus information associated with previous tasks (Rogers and Monsell 1995; Yeung et al. 2006), are greater if the task now required was recently switched away from (Mayr and Keele 2000), and are increased if the current stimulus was previously associated with a competing task (Waszak et al. 2003; Koch and Allport 2006).

It is now widely accepted that task-switching performance reflects a complex interaction between current intentions and past experience (e.g., Kiesel et al. 2010; Vandierendonck et al. 2010). However, the nature of the interaction remains unclear. Consider the case of a participant who has switched their attention from the shape to the location of a presented stimulus, but in doing so has experienced a typical switch cost. One possibility is that the participant has formed a clear intention to perform the new task—attending to the location—but nevertheless responds slowly because there is residual attention to the stimulus shape that interferes with selecting an appropriate response. On this view, the intention is unambiguous; the observed cost simply reflects imperfect implementation of that intention. However, it could also be that the participant's ability to form an effective intention is itself impaired during task switching and that the observed cost of switching reflects this failure of intention.

The aim of the present study was to evaluate these contrasting interpretations of the relationship between intention and action in task switching. This question bears on the broader relationship between top-down intentional control and between-task competition. Many theories suggest that this relationship is asymmetrical, with intention influencing between-task competition but not vice versa. This is true, for example, in Norman and Shallice's (1986) theory, in which

the supervisory attention system modulates the activity of competing schemas, but in which there is no pathway of influence running in the opposite direction. Similarly, in Cohen et al.'s (1990) connectionist model of the Stroop task, "task demand" units exert a unidirectional influence over the activation levels of competing word reading and color naming pathways (but see Cohen and Huston 1994). In these models, then, top-down intentions may not always be followed—for example, when those intentions fail to overcome entrenched habits—but these intentions are not themselves contaminated by between-task competition.

A division between intention and action is also consistent with key findings from voluntary task-switching experiments, in which participants are asked to choose which task to perform on each trial (within the broad constraint of performing each task equally often and in a random order). These experiments have revealed dissociable influences on participants' task choices—thought to index their top-down intentions—and their performance of the chosen task—which is subject to the influences of between-task competition. For example, individual differences in biases toward repeating tasks over switching do not correlate with individual differences in the performance costs associated with task switching (Mayr and Bell 2006). Meanwhile, Butler et al. (2011) have shown that individual differences in working memory capacity significantly interact with switch costs but correlate weakly, if at all, with task choices.

However, there is not unanimous theoretical or empirical support for a clean dissociation between task choice and task performance. In their parallel distributed processing model of task switching, for example, Gilbert and Shallice (2002) included associatively learned links between stimulus and task demand units, implying a bottom-up influence on top-down intentions. This feature of their model allowed them to account for the observation that switch costs increase if the current stimulus was last seen in the context of a competing task (Waszak et al. 2003), a finding which suggests that stimuli can activate associated high-level intentions to perform competing tasks. Consistent with this interpretation, prior associations between stimuli and tasks have been shown to influence participants' choice of tasks in voluntary task-switching experiments (Arrington et al. 2010).

A striking demonstration of between-task competition affecting task choice comes from studies of voluntary switching between tasks differing in their relative strength (Liefoghe et al. 2009; Yeung 2010). Given a pairing of an easy and a hard task, one would intuitively expect participants to exhibit a preference for the easier of the 2 tasks, just as they prefer easy task repetitions over more difficult task switches (Arrington and Logan 2004). In fact, the opposite result is observed. For instance, participants in Yeung's study chose on each trial between an easy (compatibly mapped) location task and a relatively hard (arbitrarily mapped) shape classification task. Although participants found the shape task generally more effortful—reflected in slower and less accurate performance—they exhibited a small but consistent bias toward performing this difficult task over the easier location task. This surprising bias can be explained in terms of the influence of between-task competition on participants' task choices: Performing a difficult task requires a strongly imposed task set, which may then be difficult to switch away from—even when switching to

an easy, well-practiced task—resulting in a large switch costs and a tendency to get "stuck" performing that difficult task (Allport et al. 1994; Yeung 2010).

Participants' task choices are evidently influenced by between-task competition. However, it remains unclear whether this influence is a direct one, with participants' actual intentions varying according to past choices, or an indirect one, with participants' intentions remaining pure but with the expression of these intentions corrupted by residual activation of recently performed tasks (particularly when those tasks are relatively difficult). Addressing this question is not straightforward using standard behavioral measures, because they typically confound participants' intentions with the execution of corresponding actions. In voluntary choice paradigms, for instance, each of the 2 tasks is usually mapped to one of the hands, meaning that participants indicate their task choice (intentions) by the hand they use to respond (actions).

The present study therefore used electroencephalographic (EEG) to tease apart the preparation of task intentions and task performance in voluntary task switching. Specifically, we used EEG measures to index the behaviorally silent processes of task preparation that are the hallmark of top-down intentional control (Rogers and Monsell 1995; Lavric et al. 2008). Previous research has identified various EEG markers of task preparation (see Karayanidis et al. 2010 for a review). Of interest here was whether these EEG markers would be sensitive to the effects of between-task competition, specifically when switching between tasks differing in their relative strength, for which a surprising bias is observed toward performing the more difficult task of the pair. Evidence for such sensitivity would indicate that top-down intentions are directly influenced by between-task competition, rather than only indirectly via their expression in task performance.

Using EEG measures additionally enabled us to dissociate 2 distinct levels of task preparation. First, general task preparation, independent of the specific responses to be produced, is reflected in at least 3 EEG components: A frontal negative slow wave (Falkenstein et al. 2003), an accompanying slow positive potential over posterior scalp sites (Lavric et al. 2008), and oscillatory activity in the alpha (8–12 Hz) range over parieto-occipital areas (Gladwin and De Jong 2005). Secondly, response-specific preparation can be measured as lateralized activity over the motor cortices when 2 tasks are mapped to different hands. Again, we focused on 3 separate markers: The lateralized readiness potential (LRP; Coles 1989), and oscillatory activity in the mu (9–13 Hz) and beta (18–26 Hz) ranges, referred to as motor-related amplitude asymmetries (mu- and beta-MRAAs, respectively; De Jong et al. 2006). Together, these 6 separate EEG markers provide a rich source of information about task preparation with which to assess the impact of between-task competition.

The frontal contingent negative variation (CNV; Lorist et al. 2000; Astle et al. 2006, 2008; Mueller et al. 2007; Vandamme et al. 2010) and posterior positivity (e.g., Kieffaber and Hetrick 2005; Goffaux et al. 2006; Lavric et al. 2008; Karayanidis et al. 2011) are both enhanced when the task switches compared with when it repeats. In addition, both components show a degree of lateralization: Whereas the CNV is often observed to be more right lateralized, the slow posterior positivity tends to maximal over left-lateralized scalp locations (Astle et al. 2006; Lavric et al. 2008). Some studies associate the posterior positivity with the effectiveness of task-specific preparation

(Goffaux et al. 2006), mainly driven by fast switch trials (Lavric et al. 2008; Karayanidis et al. 2011). For successfully prepared (i.e., fast response) trials, Lavric et al. observed a posterior positivity accompanying a CNV-like component (which they referred to as a right anterior negativity). They suggested that these 2 concurrently occurring event-related brain potential (ERP) components are facets of the same underlying processes of anticipatory task preparation.

Parieto-occipital alpha power, meanwhile, provides a complementary index of general task preparation, with alpha suppression observed during periods of high cognitive effort and task engagement (Klimesch et al. 2007; Snyder and Foxe 2010; Macdonald et al. 2011). In task-switching studies, alpha power is reduced when participants prepare for effortful task switches compared with easier task repetitions (Gladwin and de Jong 2005). Greater alpha suppression is also observed in individuals with fast, accurate, and stable task performance compared with inaccurate performers (Verstraeten and Cluydts 2002), possibly reflecting a more successful goal shielding from task-irrelevant information (cf. Dreisbach and Haider 2008). Thus, effective intentional preparation is reflected in increased amplitude of the CNV and posterior positivity, together with reduced amplitude of oscillatory alpha power over parieto-occipital areas.

Previous studies have meanwhile used lateralized motor activity to measure the preparation of specific motor sets in task switching (De Jong et al. 2006; Gladwin et al. 2006; Steinhäuser et al. 2009; Vandamme et al. 2010). In addition to the widely used LRP, which takes the difference between negative-going slow-wave potentials over the left and right motor cortex to isolate hand-specific preparation, De Jong et al. (2006) used 2 time–frequency LRP-like measures of motor-specific task preparation, the mu- and the beta-MRAA: Both frequency bands exhibit desynchronization (power reductions) contralateral to the responding hand (Pfurtscheller and Lopes da Silva 1999). Interestingly, the LRP and MRAA measures dissociated: Whereas the MRAA measures showed preparatory changes in advance of an upcoming change of task (and therefore, in this study, of response hand), the LRP only switched to reflect the changes of task and hand after stimulus onset. These findings suggest that mu- and beta-MRAAs provide an index of motor preparation, while the LRP reflects the subsequent translation of motor goals into performance of the required task (De Jong et al. 2006). Consistent with this distinction, switch-related changes in the LRP have been suggested to reflect the inhibition of specific responses rather than the more global inhibition of previous tasks (e.g., Steinhäuser et al. 2009). Of interest in the present study was the degree to which these distinct aspects of motor preparation and action selection might be sensitive to between-task competition.

In summary, our study investigated whether between-task competition influences the formation of intentions and the preparation of tasks in voluntary switching. Specifically, we assessed whether EEG markers of general task preparation (CNV, slow posterior positivity, and parieto-occipital alpha power) and motor-specific preparation (LRP, mu-MRAA, and beta-MRAA) are sensitive to the asymmetrical costs and biases that are associated with switching between tasks differing in their relative strength. In the study, participants voluntarily switched between an easy location task and a relatively hard shape classification task, which have previously been shown to produce markedly asymmetrical voluntary switching costs

(Yeung 2010). Our analyses focused primarily on preparatory activity related to intentional and motor-specific task preparation observed before the presentation of the imperative stimulus and ensuing task performance on each trial; of interest was whether this preparatory activity would differ across the 2 tasks. Preparatory activity was further analyzed in relation to response speed, which is often taken as an index of effectiveness of task preparation (e.g., Lavric et al. 2008; Karayanidis et al. 2011). For completeness, we also report analyses of poststimulus EEG activity, focusing in particular on the stimulus-evoked P3, a component that is broadly associated with the subjective probability and motivational significance of the eliciting stimulus (Duncan-Johnson and Donchin 1977). This component seems to be specifically related to the processing of the stimulus features that are relevant to the task at hand (e.g., McGinnis and Keil 2011). Previous task-switching studies have revealed attenuation of the P3 peak on switch trials compared with task repetitions (e.g., Kieffaber and Hetrick 2005; Poulsen et al. 2005; Mueller et al. 2007; Vandamme et al. 2010). We expected this switch-related P3 difference to be particularly marked for the easier task of the pair, mirroring the asymmetry of switch costs that is observed behaviorally.

Materials and Methods

Participants

Sixteen participants (7 women), aged 18–34 years, took part in the study. All had normal or corrected-to-normal vision, received payment or course credit for participating, and gave written informed consent at the start of the session.

Stimuli and Tasks

On each trial, participants were presented with 1 of 3 shapes (triangle/square/circle) inside a grid of 3 adjacent boxes and responded either to the shape of the stimulus or to its location within the grid (Fig. 1). Participants were required to choose voluntarily which of the 2 tasks to perform in each trial, with additional instructions (based on those used by Arrington and Logan (2005)) to make their choice in such a way that both tasks are chosen equally often and in a random order. The 2 tasks were mapped separately to the 2 hands: Half of the participants responded to the stimulus shape by pressing keys with their left hand and to the stimulus location by pressing keys with

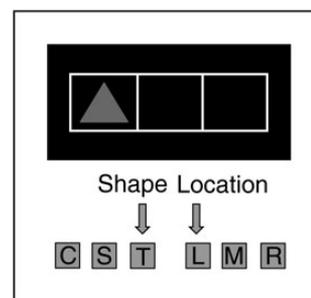


Figure 1. Schematic overview of stimulus presentation. The critical features of stimuli were related to the 2 tasks used: Shape (circle/square/triangle) and location (left/middle/right). The tasks were mapped separately to the 2 hands and the participants responded by pressing a key. In the example illustrated here, the left hand is used to respond to the shape (C = circle, S = square, T = triangle) and the right hand to the location of the stimulus (L = left, M = middle, R = right), with arrows indicating the correct response to the presented stimulus according to the 2 tasks.

their right hand. This mapping was reversed for the other half of the participants. The actual response was given by pressing a key with the index, middle, and ring fingers of the 2 hands. To indicate the shape of the stimulus, participants used their leftmost, middle, and rightmost fingers of the appropriate hand for circle, square, and triangle, respectively. The location of the stimulus was mapped compatibly to corresponding responses: Leftmost, middle, and rightmost fingers were used to indicate the left, centre, and right box, respectively. The shape and location varied randomly from trial to trial.

These tasks were designed to induce asymmetric between-task competition, with the location task expected to be the stronger task of the pair. This design was critical to our aim of investigating how between-task competition—as reflected in asymmetries in patterns of behavior—influences neural processes involved in task preparation. Previous studies have shown that task competition arises between tasks differing in relative strength (Liefvooghe et al. 2009). The difference in relative strength between one task with direct stimulus–response associations (location) and another with arbitrary stimulus–response associations (shape) is assumed to arise from differences in response congruency (e.g., Kornblum et al. 1990). This was expected even though the tasks have nonoverlapping response sets (a feature needed here to determine which task was actually performed during voluntary task switching), because previous findings have established that bimanual responding typically makes use of shared spatial response codes (Campbell and Proctor 1993), particularly when the stimuli have spatial features (Druey and Hubner 2008). Consistent with this expectation, the 2 tasks used in our study show robust spatial congruence effects that are reliably greater for the weaker shape task (Yeung 2010).

Procedure

Participants first practiced 30 trials of each task separately, then practiced switching between the 2 tasks for 2 blocks of 50 trials each. A block of trials started with the presentation of the grid, which then remained on the screen during the whole block. Each trial began with the shape stimulus appearing at one location within the grid. The presented shape approximately filled the specific box within the grid, which was 2.6° high and 7.4° wide at a viewing distance of approximately 1 m. The stimulus remained on the screen until a response was given, which initiated a cleared grid for a short (250 ms) or a long (1150 ms) response-stimulus interval (RSI). After the RSI, the next stimulus appeared. Participants were encouraged to use the time before the stimulus on each trial to decide which task to perform.

After practice, participants completed 16 task-switching blocks of 90 trials each, with RSI varying across blocks. For each participant, RSI varied according to a repeating ABBA order, with RSI in the first block counterbalanced across participants. At the end of each block, brief feedback was provided to encourage the participants to respond quickly and accurately and to follow the instructions about “random” switching and equal task distribution as described above. Feedback indicated the average response time (RT), error rate, counts of the number of times each of the 2 tasks was performed and counts of the number of switch and repeat trials. Participants were encouraged to use the time between blocks to rest if needed.

EEG Data Acquisition

EEG was recorded using 32 Ag/AgCl electrodes embedded in a fabric cap (Neuroscan, El Paso, TX, United States of America), from channels FP1, FPz, FP2, F7, F3, Fz, F4, F8, FT7, FC3, FCz, FC4, FT8, T7, C3, Cz, C4, T8, TP7, CP3, CPz, CP4, TP8, P7, P3, Pz, P4, P8, POz, O1, Oz, and O2. Additional electrodes were placed on the right mastoid, above and below the left eye, and on the outer canthi of both eyes. The ground was placed at location AFz. All electrode recordings were referenced to the left mastoid and offline re-referenced to linked mastoids. Electrode impedances were kept <10 k Ω . EEG and electro-oculographic data were continuously recorded from 0.1 to 200 Hz, using SynAmps2 amplifiers (Neuroscan) at a sampling rate of 1000 Hz, with a resolution of 29.8 nV, and amplified with a gain of 2816.

Data Analysis

EEG analysis focused on the period before stimulus onset for trials with a long RSI, in which advance preparation was possible. In voluntary task-switching paradigms, participants can in principle start to prepare for the upcoming task immediately after responding on the preceding task. We therefore analyzed task preparation beginning at the time of the response in the previous trial and lasting until the stimulus onset in the current trial. The results presented below indicate that this approach, though necessarily somewhat arbitrary given that the onset of preparation is not fixed, captures key features of the empirical data.

For our analyses, the identity of the chosen task was determined by the hand the participant used to respond. Accordingly, we considered a trial as an error when the participant responded with the wrong finger of that hand. Furthermore, the transition type (switch or repeat) on a given trial was defined according to the current and previous tasks. To investigate possible interactions of between-task competition and effective advance preparation—with the latter characterized by fast responses (e.g., Lavric et al. 2008)—correct trials were divided into fast and slow bins based on an RT median split separately for each condition of the factorial combination of task and transition type.

The continuous EEG data were preprocessed with the correction of ocular artifacts using a regression approach (Semlitsch et al. 1986). The extracted epochs started 1000 ms before until 1500 ms after the response on trial $n - 1$. Trials with voltage differences larger than 100 μ V were discarded. We also excluded the first trial of each block and trials with errors or following errors. Epochs from each channel were then baseline corrected relative to the period between 1000 and 800 ms prior to RSI onset (i.e., prior to the response on trial $n - 1$), with this baseline being applied prior to ERP averaging and EEG filtering on all prestimulus EEG epochs. This specific baseline was chosen to prevent any confounding of the baseline period with events taking place at or around the response on trial $n - 1$ (which are clearly evident in the ERP waveforms from posterior electrode sites in Fig. 2B). Our choice of baseline was effective in avoiding these confounds, as is evident in the figures below in which the critical effects of interest were restricted to particular components and timepoints of interest rather than in overall shifts in the waveforms. In a final preprocessing step, the data were down-sampled to 100 Hz.

We applied the same data preprocessing on the poststimulus EEG data, with the following 3 differences. First, the epochs were extracted from -200 ms before until 1200 ms after stimulus onset. Secondly, we analyzed the stimulus-locked data for both long and short RSI conditions. Thirdly, baseline correction for the stimulus-locked data was applied on epochs from each channel relative to the period between 100 and 0 ms before stimulus onset.

For all ERP components (CNV, slow posterior positivity, and P3), statistical analysis focused on channels and time windows identified from the results of prior studies and from descriptive analysis of the present data. To establish the existence of a frontal negativity (CNV) and a parietal positivity (slow posterior positivity) in the preparation-locked data, we first compared the data collected at 9 electrodes in an anterior region with the data collected at 9 electrodes in a posterior region of the scalp. We quantified the CNV as a switch-related slow frontal negativity in the 600-ms leading up to stimulus onset (cf. Vandamme et al. 2010). During the same interval, we quantified the slow posterior positivity as the difference between the switch and repeat trial waveforms for both tasks in the posterior region. The anterior and the posterior electrodes were grouped in left (F3, FC3, C3; and CP3, P3, O1, respectively), medial (Fz, FCz, Cz; and CPz, Pz, POz, respectively), and right (F4, FC4, C4; and CP4, P4, O2, respectively) lateralized clusters. This spatial clustering enabled us to detect lateralization in the CNV and the slow posterior positivity, as has been previously reported in the literature on instructed task switching (Astle et al. 2006; Lavric et al. 2008). We quantified the poststimulus P3 as a positive wave at Pz in the time window of 300–450 ms after stimulus onset.

Further components of interest in the preparation-locked data were the LRP, MRAAs, and parieto-occipital alpha power. Preparatory mu-MRAA (9–13 Hz), beta-MRAA (18–26 Hz), and alpha power (8–12 Hz)

were quantified for each trial by band-pass filtering the EEG epochs from C3 and C4 channels for mu- and beta-MRAA and from parieto-occipital channels P7, P3, PZ, P4, P8 and POZ for alpha power. After filtering, the mu-, beta-, and alpha oscillations were quantified using the Hilbert transform (“Hilbert” function in Matlab), which discards phase information and reveals oscillatory power fluctuations over time. Data from the first 500 ms and last 300 ms of each epoch were discarded to avoid contamination from edge artifacts after filtering. The LRP and mu- and beta-MRAA were then computed using averaged EEG amplitude at C3 and C4 using the following equation (Coles 1989):

$$\frac{(C3 - C4) \text{ right} + (C4 - C3) \text{ left}}{2}$$

EEG analyses were computed separately for each participant and each condition before being subjected to analyses of variance (ANOVA), with task (location/shape), transition type (switch/repeat), and for preparation-locked data, speed (fast/slow), and for stimulus-locked data, RSI (short/long) as independent factors. In addition, the CNV and the slow posterior positivity also included anterior–posterior (frontal/parietal) and lateralization (left/medial/right) as independent factors. ANOVAs for the ERP components of interest focused on the specific time windows described above. ANOVAs for the time-evolving EEG power data (parieto-occipital alpha power, mu- and beta-MRAA) were divided into 3 time windows, because previous studies have suggested that preparatory effects in oscillatory data unfold across the preparation interval (De Jong et al. 2006). Specifically, we focused on the interval from 100 ms after the onset of the RSI until stimulus presentation and divided this into 3 successive intervals of 350 ms. Accordingly, an additional within-subject factor of time window (early/middle/late) was included in analyses of oscillatory EEG activity.

Results

Detailed analyses of the behavioral RT, error rate, and task choice data are reported in Yeung (2010, Experiment 1a). Briefly, these analyses confirmed that the location task was easier and stronger than the shape task, being performed more quickly (552 vs. 683 ms mean RT), more accurately (2.8% vs. 7.0% error rate), and with less interference from irrelevant stimulus attributes (20 vs. 63 ms). However, switch costs were greater for the easier location task (144 vs. 49 ms), and participants exhibited a small but reliable bias toward performing the more difficult shape task (on 52.5% of trials). Comparing the short and long RSI conditions, switch costs reduced from 121 to 74 ms, and between-task asymmetries from 116 to 63 ms, demonstrating that participants made effective use of long RSIs to prepare for their voluntary task switches. Moreover, in the comparison of trials divided into fast and slow RT bins, switch costs were reliably lower in fast RT than slow RT trials (51 vs. 144 ms), demonstrating that response speed provides a useful index of effective task preparation.

Asymmetries in voluntary switching costs and task choice have been taken to reflect the effects of between-task competition (Yeung 2010), which is enhanced when switching away from a difficult and, hence, strongly imposed task. Of critical interest in the present study was whether these asymmetries are reflected in EEG indices of intentional task preparation. We therefore first report analyses of prestimulus ERPs and oscillatory EEG power during the long RSI, reflecting preparatory processes at the level of global intentions (CNV, slow posterior positivity, and parieto-occipital alpha power) and corresponding motor actions (LRP and mu- and beta-MRAA). In analyses not reported in detail here, we confirmed that the effects described below were robustly observed throughout

the course of testing, reflecting the stable differences in task strength that are created by pairing the arbitrarily mapped shape classification with a highly stimulus–response compatible location task.

General Task Preparation

The CNV, the slow posterior positivity, and oscillatory alpha power all exhibited the crucial interaction between task and transition type (Figs 2, 3, and 4), but did so in importantly different ways. Figure 2 plots ERPs for anterior and posterior electric clusters. In what follows, we first address the preparatory components of interest—the CNV and the posterior positivity—which are evident in Figure 2 as slow-wave potentials that develop in the period leading up to the stimulus on trial n . Figure 2 also reveals ERP differences around the response on trial $n - 1$, particularly over posterior scalp locations, which are discussed in detail later in this section.

To quantify the CNV and slow posterior positivity, data from anterior (F3, Fz, F4, FC3, FCz, FC4, C3, Cz, and C4) and posterior electrodes (CP3, CPz, CP4, P3, Pz, P4, POz, O1, and O2) were averaged across the 600-ms interval prior to stimulus onset, then submitted to a $2 \times 2 \times 2 \times 3$ (task \times transition type \times anterior–posterior \times lateralization) repeated-measures ANOVA. The first step was to examine the existence of switch-specific differences in the anterior and posterior clusters. The analysis indeed revealed a significant interaction between anterior–posterior location and task transition, $F_{1,15} = 14.75$; $P < 0.002$, which is in line with the expected switch-related frontal negativity and parietal positivity. Furthermore, a significant 3-way interaction between anterior–posterior signal distribution, lateralization, and task transition, $F_{1,15} = 5.05$; $P = 0.022$, demonstrated that the frontal negativity and parietal positivity were differently lateralized: While the frontal negativity was more right lateralized, the switch-specific posterior positivity was more left lateralized (Fig. 2C).

We next looked into the frontal CNV and slow posterior positivity in more detail using separate analyses focused on the anterior and posterior electrode clusters, respectively. The CNV is apparent in Figure 2A as a slow-going negativity that is enhanced on switch trials in the period preceding stimulus onset, whereas the slow posterior positivity (Fig. 2B) is apparent as a prolonged slow wave that is likewise enhanced on switch trials. During this preparatory time window, no main effects of task, transition, or lateralization were observed for either the CNV or the slow posterior positivity, $F_{1,15} < 2.45$; $P > 1.38$.

Importantly, a significant interaction between task and transition type was observed for both the CNV, $F_{1,15} = 10.30$; $P = 0.006$, and the slow posterior positivity, $F_{1,15} = 9.17$; $P = 0.008$, indicating the sensitivity of both components to between-task differences in switching. However, whereas the switch-specific CNV effect was significant only for the location task, $F_{1,15} = 8.83$; $P = 0.010$ (for the shape task, $F < 1$), the reverse pattern was observed in slow posterior positivity, with a switch-specific enhancement reliable only for the shape task, $F_{1,15} = 7.25$; $P = 0.017$ (for the location task, $F < 1$). Furthermore, a significant interaction between task transition and lateralization was observed for both CNV, $F_{2,14} = 18.02$; $P < 0.001$, reflecting its lateralization to the right, and slow posterior positivity, $F_{2,14} = 33.39$; $P < 0.001$, reflecting reliable left lateralization for this component. Specifically, the CNV

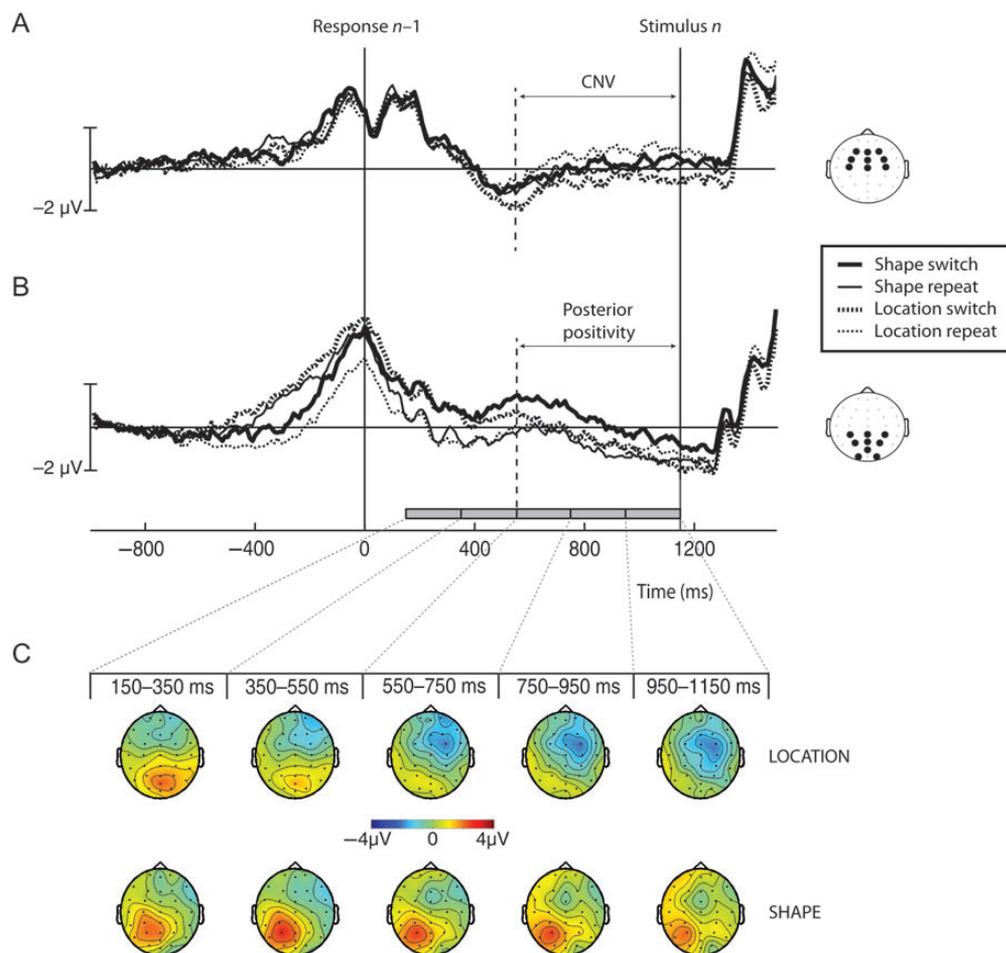


Figure 2. Grand average ERPs for switch and repeat trials of the location and the shape classification task during the long RSI. (A) The CNV as measured at the electrodes F3, Fz, F4, FC3, FCz, FC4, C3, Cz, and C4 and (B) the posterior slow wave as measured at the electrodes CP3, CPz, CP4, P3, Pz, P4, POz, O1, and O2, both time-locked to the onset of the response on trial $n - 1$. (C) The scalp topography of the average signal differences between switch and repeat trials for the 2 tasks in steps of 200 ms starting from 150 ms after the response on $n - 1$ trial.

effect was of similar magnitude across the medial and the right anterior electrodes, $F < 1$, but was significantly smaller in the left anterior electrodes than in either medial, $F_{1,15} = 38.52$; $P < 0.001$, or the right electrodes, $F_{1,15} = 14.29$; $P = 0.002$. The switch-specific posterior positivity, on the other hand, was larger across the left posterior sites than either across the medial, $F_{1,15} = 31.05$; $P < 0.001$, or right posterior electrodes, $F_{1,15} = 33.73$; $P < 0.001$, and reduced even further from medial toward the left posterior electrodes, $F_{1,15} = 9.54$; $P = 0.007$.

Our analysis further divided trials into fast and slow bins to investigate the possible influence of the effectiveness of task preparation. This contrast revealed a significant interaction between location and speed for both the CNV, $F_{2,14} = 4.721$; $P = 0.027$, and the slow posterior positivity, $F_{2,14} = 4.54$; $P = 0.030$. Again, however, as Figure 3 illustrates, the patterns were reversed for the 2 components: Whereas CNV amplitude tended to be greater on fast trials (Fig. 3A, left), consistent with it being a measure of effective task preparation (cf. Lavric et al. 2008), the slow posterior positivity showed increased amplitude on slow RT trials (Fig. 3B, right).

The preceding analyses of global task preparation focused on slow-wave potentials developing in the period prior to stimulus onset—motivated by our key hypotheses and recent

evidence about the timing of this preparatory activity in voluntary task switching (Vandamme et al. 2010). However, inspection of Figure 2B makes clear that between-condition differences are apparent over posterior sites well before the time window chosen for our main analyses. Differences first become apparent in the period leading up to the response on trial $n - 1$. These effects relate to the stimulus-locked P3 from trial $n - 1$, which is larger when the shape task was performed on that trial (i.e., when trial n is a shape repeat or location switch trial) than when the location task was performed (i.e., when trial n is a location repeat or shape switch trial). These P3 differences are discussed in more detail below in the stimulus-locked data analyses. For now, the critical point to note is that signal differences apparent prior to $n - 1$ response do not reflect an interaction between task and transition type ($F < 1$), thus clearly distinguishing these trial $n - 1$ effects from the switch-specific CNV and slow posterior positivity discussed above.

Furthermore, ERP differences develop early in the RSI, in the period following the trial $n - 1$ response. To investigate the functional significance of these effects, and their relation to the slow posterior positivity discussed above, we analyzed the earlier part of the RSI in steps of 200 ms prior to our main

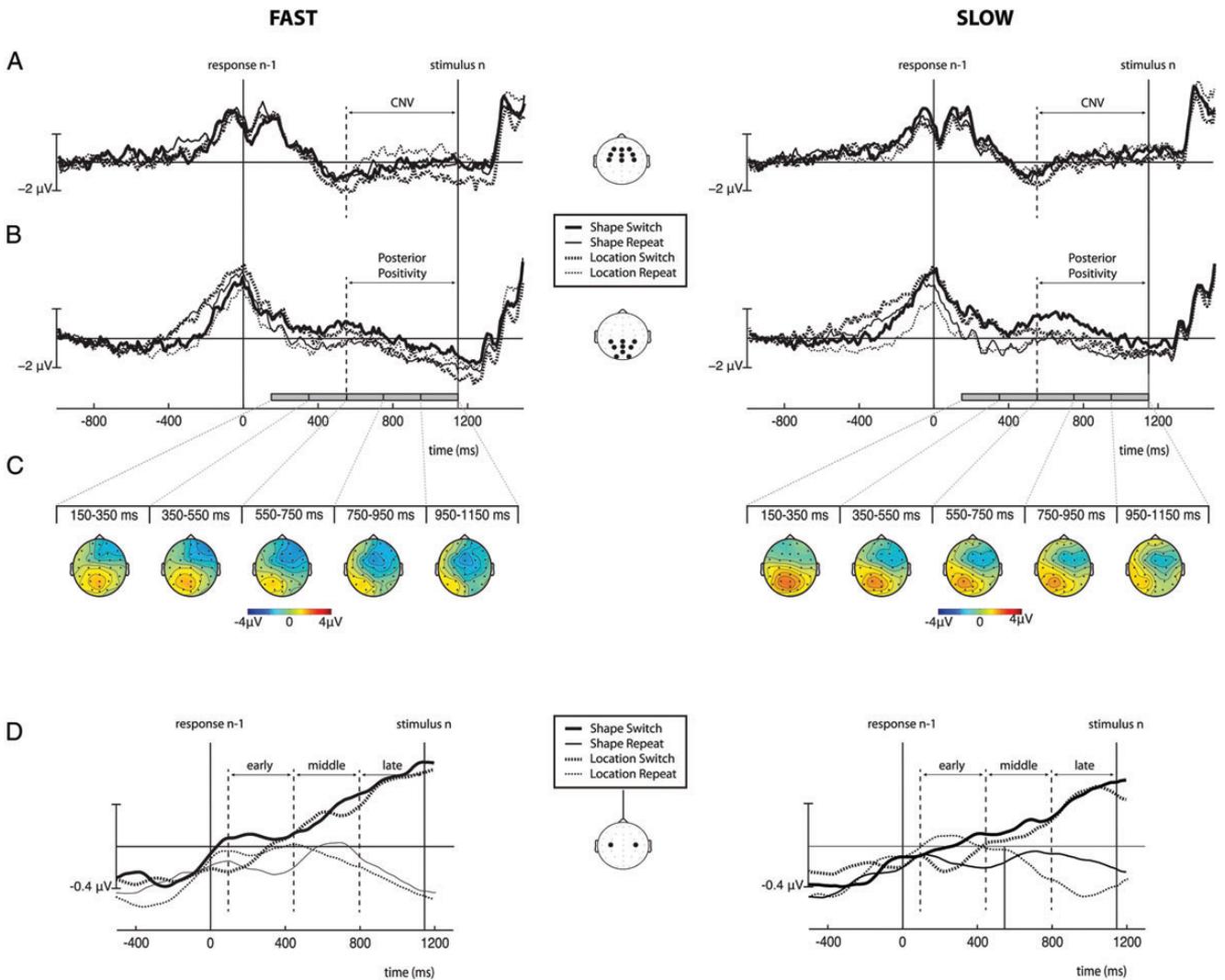


Figure 3. Modulation of the CNV, posterior positivity, and mu-MRAA by response speed. On the left, the CNV (A), the posterior positivity (B), and the mu-MRAA (D) are illustrated for trials with fast responses, and on the right the same components are illustrated for trials with slow responses. (C) The scalp topography of the average signal differences between switch and repeat trials. The distributions are presented in steps of 200 ms starting from 150 ms after the response on $n - 1$ trial, separately for the fast (left) and slow (right) trials.

analysis window (i.e., in an early window from 150 to 350 ms and a middle window from 350 to 550 ms after the onset of the RSI). This analysis revealed significant main effect of transition type in both the early, $F_{1,15} = 21.54$; $P < 0.001$, and middle windows, $F_{1,15} = 11.40$; $P = 0.006$, confirming that switch-related positive potentials developed early in the RSI. This observation is in line with previously reported posterior positive differences in task switching that also emerge prior to our main analysis window (and prior to the onset of our frontal CNV): From around 300 ms into the preparation interval (e.g., Karayanidis et al. 2003, 2011; Tiegues et al. 2006) or slightly later (Lavric et al. 2008; Elchlepp et al. 2012). However, in contrast to the later slow posterior positivity, earlier switch-related activity was not reliably modulated by the task, $F_s < 1$, or by the response speed, $F_s < 1$, in either the early or middle time windows. Altogether, these observations suggest that activity early in the RSI reflects functionally different mechanisms in voluntary task switching than the slow posterior positivity that is the main focus of the present study. Further investigation of these early posterior effects in

voluntary procedures might benefit from the use of designs that more precisely indicate the start of preparation. For example, in the double registration procedure, participants make a separate response indicating their task choice prior to performing the chosen task (e.g., Arrington and Logan 2005; Millington et al. submitted for publication). This design might help to minimize overlap between early preparatory activity and activation carried over from previous trials, thus allowing further investigation of the relationship between early preparatory activity and the slow posterior positivity studied here.

Turning now to oscillatory EEG measures, our final analysis of general task preparation focused on alpha power over posterior scalp sites. As described above, parieto-occipital alpha power typically varies inversely with effective engagement in the task at hand (Macdonald et al. 2011). Figure 4 plots grand-averaged alpha power at posterior scalp sites in the present study. A $2 \times 2 \times 3$ (task \times transition type \times time window) ANOVA revealed significant main effects of task, $F_{1,15} = 6.66$; $P = 0.021$, and transition type, $F_{1,15} = 7.86$; $P = 0.013$.

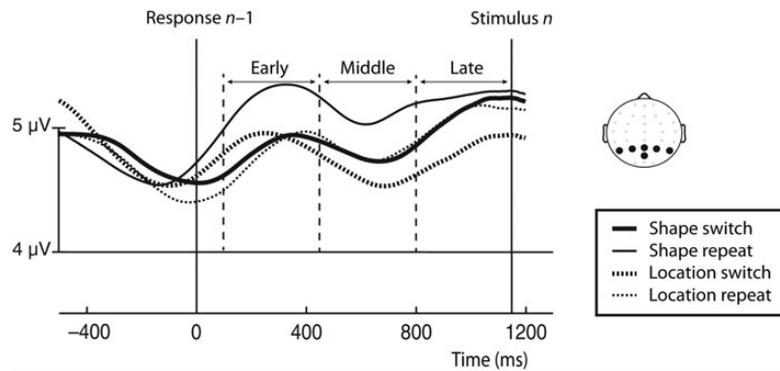


Figure 4. Grand average amplitude-modulated EEG signal after band-pass filtering at alpha frequencies, time-locked to the onset of the response on trial $n - 1$. The signal is depicted for switch and repeat trials of the location and the shape classification task during the long RSI. Arrows indicate the 3 time intervals of interest (early, middle, and late). The scalp plot indicates the locations of the electrodes included in the analyses.

Specifically, higher prestimulus alpha was observed in the weaker shape task and, consistent with previous findings (Gladwin and De Jong 2005), in repeat trials. Furthermore, a marginally significant 3-way interaction between time window, task, and transition type was observed, $F_{1,15} = 3.36$; $P = 0.064$. This 3-way interaction was driven by the 2-way interaction between task and transition type being significant early in the RSI, $F_{1,15} = 6.30$; $P = 0.024$, but not in the middle or late time window ($F < 1$). Alpha power in the early time window was significantly higher in repeat trials when compared with switch trials in the shape task only, $F_{1,15} = 23.48$; $P < 0.001$, and not for the location task, $F < 1$. Hence, parieto-occipital alpha power was modulated by the task and transition type early in the RSI, being selectively stronger in repeat trials of the weaker task. Response speed had no reliable effect on alpha power: Neither the main effect of speed nor its interactions with other factors reached significance, $F < 2.01$; $P > 0.18$.

Collectively, these findings demonstrate the strong and varied influences of between-task competition on intentional task preparation. The somewhat right-lateralized CNV bore the clearest hallmarks of this intentional preparation: Switch-specific modulations of this component were restricted to the location task, mirroring the greater cost of switching to this task, and increases in its amplitude tended to be associated with improved performance. In contrast, the concurrent slow posterior positivity (which was somewhat left lateralized) increased in amplitude on trials with the longest RTs, both when comparing across conditions (where it was maximal on shape task switch trials) and when comparing fast and slow trials within conditions. Finally, parieto-occipital alpha power was selectively increased during preparation for shape task repetitions. Given that parieto-occipital alpha suppression typically signifies increased cognitive effort, this finding indicates that preparation for shape repetitions was less cognitively demanding than for other trial types—consistent with the observation that shape repeat trials were the most commonly selected trial type by participants in this study.

Motor-Specific Task Preparation

Our analyses of motor-specific preparation made use of the fact that the 2 tasks were mapped to separate hands, enabling us to measure preparation for a particular task in terms of the lateralization of cortical motor activity (De Jong et al. 2006;

Gladwin et al. 2006). In contrast to the indices of global task preparation analyzed above, our measures of motor-specific preparation showed no switch-related asymmetries across the 2 tasks.

Figure 5 presents grand-averaged LRPs, with the data plotted differently in the 2 panels to draw out separate critical features of the waveforms. Figure 5A plots the waveforms so that negative values correspond to the selection of the task/hand relevant on the current trial (such that all waveforms are negative going at or following stimulus presentation on trial n). This plot reveals that the LRP shows an early peak around 400 ms into the RSI that follows the lateralization of the response just selected on trial $n - 1$, such that the peak has opposite polarity when the task switches versus repeats on the subsequent trial n . This difference, reliable in a window from 200 to 600 ms into the RSI, $F_{1,15} = 9.20$; $P = 0.008$, replicates a finding first reported by Vandamme et al. (2010). Vandamme et al. interpreted the result as evidence of an automatic bias to repeat the previous task that contributes to observed costs of voluntary task switching. Our data do not directly challenge this interpretation, but they do show that the effect does not correlate with behavioral switch costs in 2 key respects. First, we found no hint that the repetition bias differed across the 2 tasks, $F < 1$, despite switch cost and task choice effects indicating that participants were biased toward repeating the more difficult shape task. Secondly, we found no association between this early LRP lateralization and subsequent response speed, $F < 1$. These findings are perhaps consistent with the view that this early LRP effect reflects the decay of motor activity and activity from reafferent processes (Leuthold and Jentzsch 2001, 2002; Steinhauser et al. 2009).

Figure 5B replots the LRP waveforms with negative values now corresponding to the selection of the task/hand relevant on the previous trial (such that all waveforms are negative going at and around the time of the response on trial $n - 1$). This plot reveals the development of hand-specific motor activity on the current trial, apparent as separation between the LRP waveforms for switch and repeat trials. Immediately striking in Figure 5B is that this switch/repeat separation does not occur until after stimulus onset on the current trial: Analysis of LRP amplitude in a “late” 300-ms period just prior to stimulus onset revealed no reliable modulation by the transition type, $F < 1$. There was, however, a reliable main effect of task, $F_{1,15} = 4.99$; $P = 0.041$ with more positive LRP values

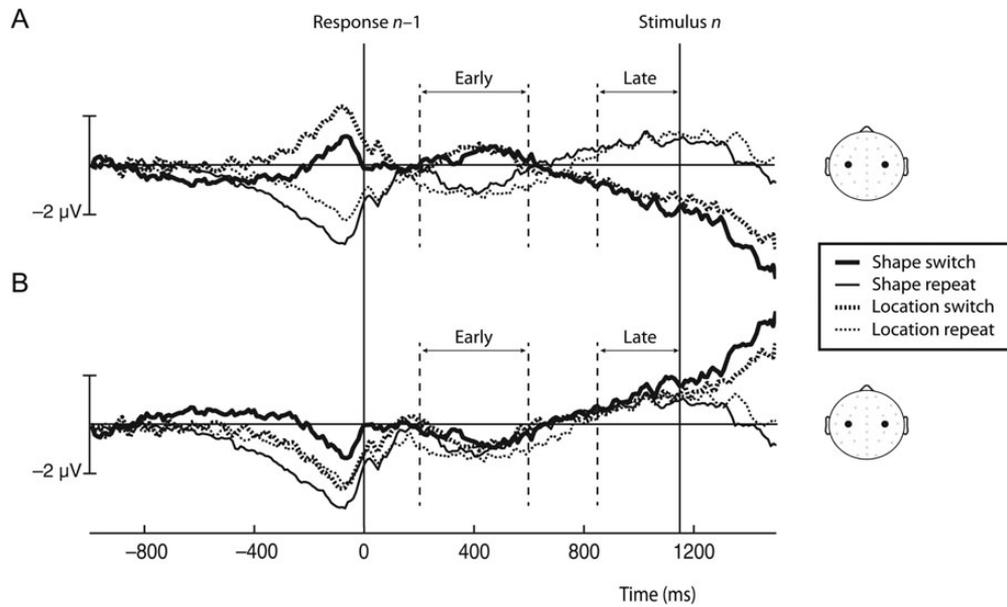


Figure 5. LRP for switch and repeat trials of the location and the shape classification task during the long RSI. The signal is time-locked to stimulus presentation, plotted either according to the hand used for the response on the current trial (*A*) or according to the hand used for the response on the previous trial (*B*). Arrows indicate the 2 time intervals of interest (early and late LRPs).

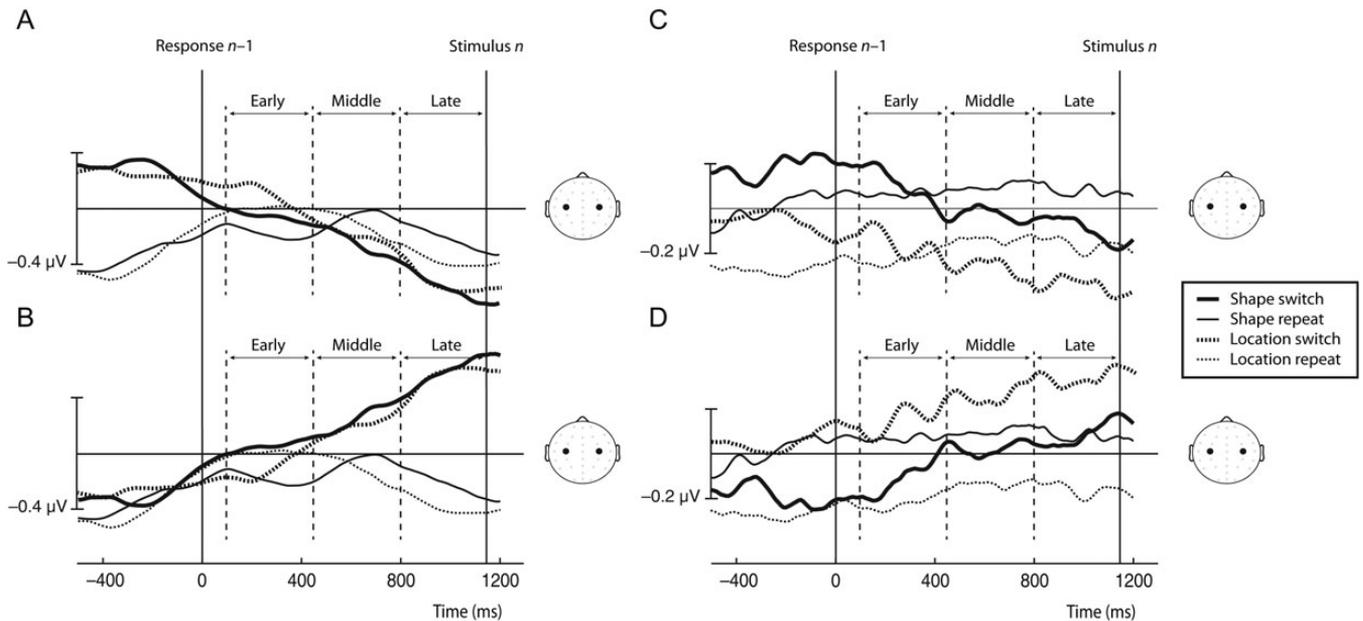


Figure 6. Motor-related amplitude asymmetries (MRAAs) for switch and repeat trials of the location and the shape classification task during the long RSI. (*A*) and (*B*) show MRAA in the mu band (9–13 Hz, mu-MRAA) and (*C*) and (*D*) in the beta band (18–26 Hz, beta-MRAA). The signal is time-locked to stimulus presentation, plotted either according to the hand used for the response on the current trial (*A*, *C*) or according to the hand used for the response on the previous trial (*B*, *D*). Arrows indicate the time intervals of interest (early, middle, and late).

for the shape task than for the location task in this late window. Nevertheless, this task effect was not modulated by the transition type, $F < 1$, indicating that for both tasks, LRP activity favoring the to-be-produced task occurred only after the presentation of the imperative stimulus.

Figure 6 presents corresponding grand-averaged waveforms for the mu- and beta-MRAAs (in the left and right panels, respectively). As with the LRP data, the waveforms are plotted differently in the upper and lower panels. In the upper panels, negative values indicate greater activation in

the response hand/task selected on trial n ; in the lower panels, negative values indicate greater activation in the hand/task selected on trial $n - 1$. Although there are superficial differences between the mu- and beta-MRAA waveforms, key features of the 2 are very similar. Thus, in both upper panels, there is little evidence of the repetition bias—that is, postresponse lateralization toward the response selected on trial $n - 1$ —that was apparent in the LRP data (cf. Vandamme et al. 2010). More relevant to the present concerns, both of the lower panels reveal consistent, early-onset lateralization

toward the task/hand chosen on trial n during the RSI, indicative of effective motor preparation that is not revealed in the LRP analysis (cf. De Jong et al. 2006).

Thus, for the mu-MRAA data, Figure 6B indicates that the separation of switch and repeat trial waveforms emerged in the first half of the RSI, increased throughout the RSI, and finally reached its peak around stimulus presentation on trial n . Statistical analysis confirms these impressions, revealing a significant main effect of the time window, $F_{2,14} = 4.98$; $P = 0.023$, and transition type, $F_{1,15} = 29.37$; $P < 0.001$; and a significant interaction between these 2 factors, $F_{2,14} = 13.14$; $P < 0.001$. Separate 1-way ANOVAs showed a linear trend for both switch trials, $F_{1,15} = 5.91$; $P = 0.028$, and repeat trials, $F_{1,15} = 8.47$; $P = 0.011$, though in the opposite direction for the 2 transition types. Crucially, however, these preparatory shifts in motor activity did not differ reliably for the 2 tasks, $F_{1,15} = 2.64$; $P = 0.125$. Instead, analysis of the waveforms in terms of response speed revealed a significant interaction between the speed and transition type, $F_{1,15} = 12.04$; $P = 0.003$, indicating that switch-repeat differences in mu-MRAA amplitude were more pronounced in fast trials than in slow trials (0.46 vs. 0.33 μV , respectively, Fig. 3D).

Inspection of Figure 6D reveals corresponding evidence of advance motor preparation in the beta-MRAA data, with separation between switch- and repeat-trial waveforms becoming evident early in the RSI and growing steadily throughout. Thus, there was a significant main effect of the time window, $F_{2,14} = 15.60$; $P < 0.001$, and transition type, $F_{1,15} = 24.60$; $P < 0.001$; and a significant interaction between these 2 factors, $F_{2,14} = 6.01$; $P = 0.013$. A 1-way ANOVA revealed a general linear increase in amplitude for switch trials, $F_{1,15} = 30.14$; $P < 0.001$, but not for repeat trials, $F_{1,15} = 2.38$; $P = 0.144$. Once again, however, this preparatory motor activity did not differ for the 2 tasks, $F < 1$, or between trials associated with fast and slow RTs, $F < 1$.

Taken together, the LRP and MRAA analyses paint a nuanced picture of motor-specific preparation in voluntary task switching. The mu- and beta-MRAA results provide clear evidence that participants began to prepare their motor responses in advance of stimulus onset. However, this preparatory activity did not differ across the 2 tasks, despite large task asymmetries in behavioral switch costs and subtle but consistent biases in task choices. The contrast between LRP and MRAA results, with only the latter showing evidence of preparatory activity, provides further support for the notion that these measures index dissociable aspects of action selection in task switching (De Jong et al. 2006; Steinhäuser et al. 2009).

Poststimulus P3

Previous studies have reported modulations of poststimulus ERP components, particularly the P3, in task switching (Karyanidis et al. 2003; Kieffaber and Hetrick 2005; Poulsen et al. 2005; Mueller et al. 2007; Vandamme et al. 2010). We aimed to replicate and extend these findings to the case of switching between tasks differing in relative strength. To this end, Figure 7 presents stimulus-locked grand-average ERPs for switch and repeat trials in both tasks, separately for short and long RSI blocks.

Poststimulus P3 amplitude, quantified as the average voltage in a time window from 300 to 450 ms poststimulus,

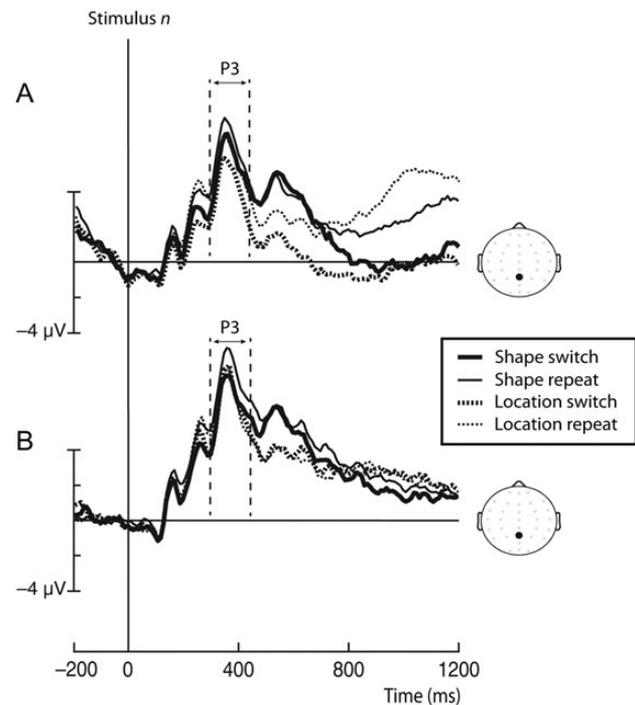


Figure 7. Grand average ERPs for switch and repeat trials of the location and the shape classification task during the short (A) and the long (B) RSI. The signal is time-locked to stimulus presentation and measured at electrode Pz.

was analyzed using a $2 \times 2 \times 2$ (RSI \times task \times transition type) repeated-measures ANOVA. This analysis revealed that P3 was reduced at the short RSI compared with the long RSI, $F_{1,15} = 7.79$; $P = 0.014$, for the stronger location task compared with the more difficult shape task, $F_{1,15} = 7.27$; $P = 0.017$, and on switch trials compared with repeat trials, $F_{1,15} = 5.32$; $P = 0.036$.

A marginally significant interaction was observed between RSI, task, and transition, $F_{1,15} = 4.45$; $P = 0.05$. This interaction was driven by a difference in the task \times transition type interaction observed at the short and long RSIs: Whereas task and transition type did not reliably interact when the RSI was short, $F < 1$, at the long RSI, the switch-specific attenuation of the P3 was especially marked for the weaker shape task, $F_{1,15} = 6.99$; $P = 0.018$, contrary to our expectation that the effect would be more marked for the location task (to mirror the increased behavioral switch cost observed for this task). A 1-way ANOVA indicated a significant attenuation in switch trials relative to repeat trials for the shape task, $F_{1,15} = 5.74$; $P = 0.03$, but not for the location task, $F < 1$. Thus, the specific interaction of interest, between task and transition type, was selectively observed for the long RSI condition. Here, the switch-specific attenuation of P3 was observed for the shape task only.

Discussion

The present study investigated the impact of task difficulty on EEG markers of intentional preparation in voluntary task switching. Previous behavioral studies have revealed a surprising bias toward performing the weaker task of a pair, evident as decreased switch costs for this task and a bias in voluntary task choices toward performing this weaker task.

The present results demonstrate that this bias not only manifests during active task performance, but is also reflected in modulations of neural activity related to effective preparation for an upcoming task. These modulations were restricted to markers of global task preparation—the CNV, slow posterior positivity, and oscillatory alpha power over posterior scalp sites—and were absent in EEG measures of motor-specific preparation. Task asymmetries in switch costs and voluntary choice have typically been interpreted as evidence for the effects of between-task competition: Weak tasks must be strongly imposed and are therefore difficult to switch away from, resulting in high levels of competition and correspondingly poor performance on subsequent trials. Our findings demonstrate that these effects of between-task competition extend to the formation of intentions prior to task performance.

Intention and Between-Task Competition

Previous research has identified switch-related modulations of 3 markers of global (i.e., nonmotor-specific) task preparation: A frontal CNV-like slow wave (Lorist et al. 2000), an accompanying posterior positivity (Lavric et al. 2008), and oscillatory alpha power (Gladwin and de Jong 2005). All 3 of these markers were modulated by task difficulty in the present study, but in importantly different ways. Taking first the CNV, we observed a slightly left-lateralized signal that was stronger on switch trials only for the easier location task, mirroring the greater cost associated with switching to this task. Taken with the finding that CNV amplitude in our study tended to be increased on trials with faster RTs (cf. Lavric et al. 2008), these results suggest that the CNV provides an index of active intentional control and that advance preparation of the stronger task requires more intentional control than advance preparation of the weaker task.

These CNV findings complement and extend existing theoretical accounts of switching asymmetries observed behaviorally, which have typically been taken to show that execution of the weaker task makes the switch toward the stronger task more difficult (Gilbert and Shallice 2002; Yeung and Monsell 2003). Specifically, performing a weak task is thought to require a strongly imposed task set, which is then difficult to overcome when switching away from this task, resulting in large performance costs (Allport et al. 1994) and a tendency to perform competing tasks less often (Yeung 2010). However, despite general agreement on this broad theoretical account, it has remained unclear whether between-task competition occurs solely at the level of specific stimulus-response pathways (i.e., between schemas in Norman and Shallice's framework), or whether this competition affects the formation of effective task intentions (i.e., within the supervisory control system itself). Our data support the latter possibility. As such, they support models in which the interaction between intentional control and between-task competition is bi-directional (e.g., Gilbert and Shallice 2002), with switch costs arising at least in part because past experience impairs the ability to form effective new intentions (e.g., reflecting associations formed between the presented stimulus and the now-irrelevant task; Waszak et al. 2003).

An implication of this hypothesis is that repetition of the weaker task becomes, paradoxically, the default voluntary choice when choosing between tasks that differ in relative

strength. The results of our analysis of oscillatory alpha power over posterior scalp sites, which was selectively increased during preparation for shape task repetitions, provide neural evidence for this idea (cf. Gladwin and De Jong 2005). Parieto-occipital alpha power is typically suppressed in association with general increases in cognitive effort and effective task engagement (Klimesch et al. 2007). Thus, our findings indicate that preparation for shape repetitions was less cognitively demanding than preparation for task switches or for repetitions of the stronger task. Altogether, these findings of task-related modulations of the CNV and parieto-occipital alpha power—2 key EEG markers of task preparation—strongly imply that past experience and between-task competition directly influence our intentions about what to do next.

Previous studies using instructed task-switching designs have reported positive waves over posterior scalp regions that accompany frontal negativities like the CNV we observed (Astle et al. 2008; Lavric et al. 2008). Indeed, it has been suggested that these components may reflect the same underlying mechanism of anticipatory task preparation (Lavric et al. 2008). However, in our data from voluntary task switching, we observed a clear dissociation between the CNV and a concurrent, right-lateralized slow posterior positivity: Whereas the CNV was greater during preparation for the stronger location task and for trials with faster RTs, the slow posterior positivity was enhanced when switching to the weaker shape task and on trials with slower RTs. Thus, although both components reflect preparatory, switch-related processes, the 2 ERP markers we observed seem not to be some kind of a dipole reflecting the same preparatory processes. More specifically, whereas the CNV indexes active intentional preparation, the slow posterior positivity we observed seems more closely associated with slow or difficult conditions. This conclusion stands in contrast to previous findings reported in studies using cued procedures (e.g., Lavric et al. 2008; Karayanidis et al. 2011; Elchlepp et al. 2012). It is possible that this discrepancy reflects differences between voluntary and cued procedures as also reported in some other studies (cf. Forstmann et al. 2006).

In previous research, slow posterior positivities have been linked to the retrieval of stimulus-response rules from long-term memory to working memory (Astle et al. 2008; Hsieh and Wu 2011). It is plausible that these retrieval demands are greater for weaker or less familiar tasks, thus accounting for the differences we observed, but it is notable that these additional demands appear not to translate to increased behavioral switch costs (which were low for the weaker shape task). If correct, this interpretation has intriguing implications. On the one hand, it suggests that reconfiguration processes such as retrieving task rules make relatively small contributions to observed performance costs of switching, as we have argued elsewhere (Yeung 2010). On the other hand, it suggests that these important processes may nevertheless be subject to experimental scrutiny through sensitive neural measures such as EEG.

The slow positivity we observed over posterior sites was preceded by superficially similar switch-related differences that developed earlier in the RSI, with an onset at around 150 ms after the response on trial $n-1$. Previous studies using instructed switching procedures have observed switch-related positivities over frontal rather than posterior scalp sites at this latency (e.g., Rushworth et al. 2002; 2005; Lavric

et al. 2008; Elchlepp et al. 2012), with posterior components developing 150–400 ms later (e.g., Karayanidis et al. 2003; Tiegues et al. 2006; Lavric et al. 2008; Karayanidis et al. 2011). Crucially, in the present study, early switch-related activity differed from the subsequent slow posterior positivity in important ways. In particular, the early positivity was not task specific and was not modulated by participants' response speed. These findings imply that the early switch-related positivity and the subsequent slow posterior positivity reflect functionally different mechanisms in voluntary task switching. Future research might usefully investigate further the relationship between these components. It remains possible, for instance, that switch-related posterior activity begins early in preparation but lasts more briefly for stronger tasks and on faster trials. Accordingly, later in the preparation interval, switch-related activity would only be detected for weaker tasks and for slower trials—the pattern we observed. The design used in the current study, with no precisely defined onset of preparation for the next trial, makes it difficult to conclusively test this possibility. Specifically, the exact point at which the posterior positivity develops during preparation is difficult to determine in our study due to the temporal overlap with stimulus-locked P3 activity from the previous trial. One way to proceed would be to test the development of the posterior positivity, and its sensitivity to between-task interference, using designs that better specify the start of the preparation interval, such as the double registration procedure (e.g., Arrington and Logan 2005; Millington et al. submitted for publication).

Finally, an important point to address regarding the tasks used in our study is that they not only differ in relative strength, but are also likely to recruit different neural pathways for their execution: While the location task should engage regions within the dorsal (“where”) stream, object identification in the shape task should lead to greater engagement of the ventral (“what”) stream (e.g., Ungerleider and Mishkin 1982; Schwarzlose et al. 2008). It is therefore important to consider whether the observed dissociation between the CNV and posterior positivity reflects the differing content of the 2 tasks (location vs. shape) rather than their differing levels of relative task strength. However, our findings suggest that such an explanation is not sufficient. In particular, the components not only dissociated with respect to the task, but also to the response speed: Whereas the CNV was enhanced on trials with fast responses (as well as for the location task), the slow posterior positivity was enhanced on trials with slow responses (as well as for the shape task). Thus, although the location and the shape task are likely to make use of different neural pathways, our findings seem to reflect functional differences rather than idiosyncratic task-specific processing.

Between-Task Competition and Action

By mapping 2 tasks separately to the 2 hands, we were able to measure the preparation and selection of specific actions corresponding to voluntary task choices in terms of the LRP and mu- and beta-MRAAs. None of these measures were significantly modulated by between-task competition, suggesting that this competition influences global task preparation rather than preparation of specific actions associated with chosen tasks. The mu- and beta-MRAA measures nevertheless demonstrated clear evidence of advance task preparation, apparent

as a prestimulus reversal of lateralization in switch trials. Importantly, a corresponding early reversal of lateralization in switch trials was not observed in the LRP. It was only after the presentation of the stimulus that the LRP showed a reversal of lateralization in switch trials. Thus, the preparatory mu- and beta-MRAA, but not the LRP, tracked motor preparation in our voluntary task-switching procedure.

Similar findings have previously been reported in studies using instructed task procedures (De Jong et al. 2006; Gladwin et al. 2006; Steinhauser et al. 2009). De Jong et al. further observed that the LRP, but not oscillatory MRAAs, showed sensitivity to the probability that an instructed response would eventually be executed. Specifically, the LRP was significantly increased in a condition that always required a response when compared with a condition that included no-go trials half of the time. Based on these observations, De Jong et al. suggested that preparatory mu- and beta-MRAAs reflect the selection of motor goals, whereas the LRP reflects the subsequent translation of motor goals into specific movements. Our findings are in line with this proposal, showing that the mu- and beta-MRAAs reflect preparing for a hand switch as a motor goal early in the preparation interval in voluntary task switching, whereas the LRP indexes the implementation of specific stimulus–response associations during task performance.

Taken together, the mu- and beta-MRAA results provide clear evidence that participants prepared their hands in advance of stimulus onset and did so in a similar way for the 2 tasks. The insensitivity of MRAAs to between-task differences marks a clear dissociation between these measures of motor-specific preparation and our measures of global task preparation—the CNV, slow posterior positivity, and parieto-occipital alpha power. Evidently, the struggle that participants have in switching to the stronger location task did not impair their ability to prepare the corresponding response hand. Conversely, effective motor preparation did not guarantee performance that is efficient and shielded from between-task competition, since subsequent task performance showed large task asymmetries in behavioral switch costs and subtle but consistent biases in task choice. Thus, although selecting an appropriate set of responses must be a core component of implementing an effective task set, the ability to do so appears dissociable from other aspects of task preparation and execution that are reflected in key neural and behavioral measures of task switching studied here.

This discussion highlights the important consideration that voluntary task-switching procedures, as adopted here, leave ambiguous the exact moment and mechanism of decision-making during the RSI. Participants are instructed to make random choices (within the broad constraint that these choices are equally distributed over the 2 tasks) and participants presumably engage in complex choice processes prior to preparing and performing the chosen task on each trial. From the behavioral data, we know that people find it difficult to follow the experimental instructions accurately, because they show a tendency to repeat tasks—in particular the harder task of the pair—more than to switch between tasks (Arrington and Logan 2004; Mayr and Bell 2006). However, conditions in which people are given some freedom to choose tasks make it difficult to disentangle decision processes from the control processes involved in voluntary task switching. It is possible that some of the switch-related

differences we observed (e.g., over posterior sites early in the RSI) reflect early decision processes rather than the mechanisms of task switching per se. Future research might usefully attempt to distinguish these processes, for example, by implementing a double registration procedure (e.g., Arrington and Logan 2005; Millington et al. submitted for publication). Since this procedure separates task choice and task performance, it would allow for a more detailed investigation of decision-making and cognitive control processes during the preparation interval.

Poststimulus Effects of Between-Task Competition

The stimulus-evoked P3 is the most commonly used EEG measure of processes involved in stimulus-related task performance. In common with other studies using instructed (e.g., Karayanidis et al. 2003; Kieffaber and Hetrick 2005; Poulsen et al. 2005) or voluntary (Vandamme et al. 2010) task-switching procedures, we observed reduced P3 amplitude for switch trials compared with repeat trials. We furthermore extended these observations, finding P3 attenuation after the short RSI and in the stronger location task when compared with the long RSI and the weaker shape task, respectively.

Contrary to our initial expectation, switch-related decreases in P3 amplitude were more strongly marked in the weaker shape task. Our expectation was that switch-related P3 differences would be greater in the location task, mirroring the stronger behavioral switch costs typically observed in this task. It seems that the P3 switch attenuation in the stronger location task dissolved when ample time was provided to choose and prepare the task at hand. In the weaker shape task, on the other hand, the stimulus-evoked P3 difference between switch and repeat trials was less affected by the time provided to prepare and, hence, more stable over time. Methodologically, these results suggest that the P3 provides more than just a transparent neural correlate of the behavioral switch cost (cf. Elchlepp et al. 2012). In particular, our results demonstrate that the absence of a large behavioral switch cost (as observed for the shape task) is not a reliable indication that the underlying neural processes are unaffected by switching (since we observed robust switch-related P3 attenuation for this task), a dissociation that might productively be pursued in future EEG studies of task switching.

Conclusion

Collectively, the present findings demonstrate the utility of neural measures of task preparation, allowing these behaviorally silent processes to be studied directly and independently of later task performance. Employing this approach, we have presented 3 key findings. First, neural measures of task preparation are sensitive to the effects of between-task competition, indicating that this competition directly affects the formation of intentions, not only the expression of these intentions in overt behavior. Secondly, the influence of between-task competition occurs at the level of global task preparation, independent of the selection of the specific responses associated with the competing tasks. Finally, these differences between measures of global and response-specific preparation indicate that different levels of preparation are at least partly dissociable, with effective preparation of

task-related actions providing no guarantee of task performance that is efficient and shielded from interference from competing tasks.

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