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Serial or parallel proactive control of components of task-set? A task-switching investigation with concurrent EEG and eye-tracking

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Abstract

Among the issues examined by studies of cognitive control in multitasking is whether processes underlying performance in the different tasks occur serially or in parallel. Here we ask a similar question about processes that pro-actively control task-set. In task-switching experiments, several indices of task-set preparation have been extensively documented, including anticipatory orientation of gaze to the task-relevant location (an unambiguous marker of reorientation of attention), and a positive polarity brain potential over the posterior cortex (whose functional significance is less well understood). We examine whether these markers of preparation occur in parallel or serially, and in what order. On each trial a cue required participants to make a semantic classification of one of three digits presented simultaneously, with the location of each digit consistently associated with one of three classification tasks (e.g., if the task was odd/even, the digit at the top of the display was relevant). The EEG positivity emerged following, and appeared time-locked to, the anticipatory fixation on the task-relevant location, which might suggest serial organisation. However, the fixation-locked positivity was not better defined than the cue-locked positivity; in fact, for the trials with the earliest fixations the positivity was better time-locked to the cue onset. This is more consistent with (re)orientation of spatial attention occurring in parallel with, but slightly before, the reconfiguration of other task-set components indexed by the EEG positivity.

Key words: Serial vs. parallel processing, cognitive control, task-set, task switching, EEG, eye-tracking

1. Introduction

Over the last two decades or so, "task-switching" paradigms (e.g., Rogers & Monsell, 1995; Meiran, 1996; for reviews see Monsell, 2003; 2015; Kiesel et al., 2010; Vandierendonck et al., 2010) have gained considerable popularity among those interested in flexible goal-driven control of behaviour in response to changes in the instructed task – "task-set control". In the most commonly used paradigm – "task-cuing" (Meiran, 1996) – participants are required to classify the stimulus on each trial according to the stimulus-response (S-R) rules associated with one of two (or more) simple tasks. The task is cued at a variable interval prior to stimulus onset, thereby allowing for the manipulation of the opportunity for preparation. Most task-set control theorists believe that in a situation where participants must switch between different tasks, if there is opportunity to endogenously adjust ("reconfigure") processing parameters constituting the task-set in advance of the stimulus, motivated participants will generally attempt to do so. This is held to explain why the performance "switch cost" typically reduces as the cue-to-stimulus interval (CSI) increases, reaching an asymptote – the "residual" switch cost – at a CSI of between 0.5 and 1.0 s (e.g., Monsell & Mizon, 2006).

In most task-switching studies, the switch requires the updating of more than one parameter, e.g., which stimulus attribute to attend to, which effector to select for the response, what set of S-R rules to select, etc. Hence, many theoretical conceptions of task-set implementation distinguish between reconfiguration of perceptual selection and response selection components (e.g., Meiran, 2000; Meiran & Marciano, 2002; Meiran et al., 2008; Logan & Gordon, 2001; for extensive coverage of this distinction, see Rushworth et al., 2002; Kieffaber et al., 2013; Elchlepp et al., 2015, 2017). The question we ask is: when multiple task-set parameters must be reconfigured proactively,

do these adjustments occur in parallel or serially and, if serially, in what order? This issue has received surprisingly little scrutiny.

At first glance it may seem that an analogous serial vs. parallel processing question has been posed in other paradigms in the broad domain of "attention and performance", most notably in the Psychological Refractory Paradigm (PRP) – where participants are required to categorize each of two stimuli (S1 & S2) presented in rapid succession. The key PRP observation is that reducing the interval between them tends to prolong the response time to S2, suggesting that at least some processes underlying the two categorizations do not (or cannot) run in parallel (e.g., Pashler, 1984, 1994; Lien et al., 2010). However, PRP research is concerned with the seriality of processes from consecutive task-sets (in most PRP studies S1 and S2 are associated with distinct categorization tasks), whereas we are concerned with serial vs. parallel processing within a task-set. We illustrate this distinction using Logan and Gordon's (2001) ECTVA model, developed as an account of PRP performance, but also proposed to explain the task-switch cost. To implement a task-set the model's Executive Control (EC) module "transmits" parameters for stimulus selection and response selection from Working Memory to a task execution module (TVA). Gordon and Logan examined PRP performance of a "serial" version of the model, where the initially transmitted stimulus selection parameter biases the selection of S1 over S2; then, after the onset of S1, a stimulus selection parameter is transmitted that reverses the bias. This model was compared with a "parallel" model, where the stimulus selection parameters transmitted throughout the stimulus sequence were equally biased towards S1 and S2. Perhaps unsurprisingly, only the serial model was capable of generating (like human participants) the response to S1 before generating the response to S2, as the PRP paradigm usually requires. However, crucially for the present context, in both models the transmission of stimulus selection and response selection parameters relevant for

one stimulus occurs in parallel. Thus, the "serial" instantiation of ECTVA is in fact parallel with regard to the reconfiguration ("transmission") of parameters within a task-set.

Although the relative time-course of reconfiguring the stimulus selection and response selection components of task-set has received very limited scrutiny, serial alternatives to the ECTVA assumption of parallel transmission have been developed as part of the CARIS computational framework of Meiran and colleagues (Meiran, 2000; Meiran et al., 2008). This class of models has at its core the notion that during a change of task the reconfiguration of some task-set components can be done in advance of stimulus onset, whereas the reconfiguration of other components requires the presence of the stimulus (consistent with an earlier proposal by Rogers & Monsell, 1995, that task-set reconfiguration cannot be completed in advance of the stimulus) and/or generation of the response. In Meiran and colleagues' framework, the reweighting of perceptual and response selection parameters is done serially, in distinct processing stages. However, the order of these stages has changed from the first to the more recent version of the framework. According to Meiran (2000), if opportunity for preparation is provided, perceptual selection parameters are re-set in advance of stimulus onset, but response selection parameters can be reset only after the stimulus is encoded: hence the residual cost. Meiran et al.'s (2008) CARIS model reversed this order: response selection can be reconfigured before stimulus onset, perceptual selection parameters only after a response: hence the residual cost. The change was motivated by observations such as that of Meiran and Marciano (2002) that increasing the preparation interval did not reduce the cost of switching attention between dimensions in a same-different matching task, but it did reduce the cost of reversing the S-R rules. Thus, both versions of this modelling framework have assumed serial reconfiguration of the two types of task parameter (perceptual vs. response selection).

So far, there has been no direct empirical evidence to suggest that task-set components are reconfigured serially, or indeed in parallel. The aim of the present study was to acquire such evidence. To examine whether different task-set components are (re)configured serially or in parallel, we need independent indices of their reconfiguration. We took advantage of two such indices – one derived from eye-movement recordings, the other from the electroencephalogram (EEG). The eye-tracking measure has been documented in recent studies from our laboratory which explore the dynamics of spatial attention in task-switching (e.g., Longman et al., 2013, 2014, 2016, 2017; for an analogous use of eye-tracking for examining shifts of attention between visual dimensions see Mayr et al., 2013, and Kikumoto et al., 2016). Longman et al. (2014) required participants to classify one of three digits presented simultaneously at different locations (see Figure 1) according to one of three semantic criteria (parity, magnitude, and inner/outer position along an imaginary number line, see Method), as specified by a task cue. Crucially, each of the three classification tasks was consistently associated with one of the three locations; for instance, for some participants, the cue "ODD?" meant that they had to classify the digit at the top as odd or even, and the cue "HIGH?" meant that they had to classify the digit on the left as ≤5 or >5. Switching tasks substantially delayed the orienting of spatial attention to the task-relevant location and resulted in a tendency to attend to the location associated with the previously relevant task even when the preparation interval was a generous 1400 ms – we termed this effect "attentional inertia". In an experiment that included a control condition in which the location changed but the classification task remained constant throughout the experiment, both the attentional delay and attentional inertia were considerably smaller for 'location switching' (mean delay in orienting = 9 ms) than for 'task switching' (mean delay in orienting = 35 ms). Thus, Longman et al. (2014) concluded that the latency of fixating the task-relevant location during a task switch

provided a close-to-online[1] measure of the reconfiguration of an attentional component of task-set.

Another online measure of task-set reconfiguration is provided by a switch-induced posterior positive-polarity brain potential in the EEG, typically observed from ~400 ms following the onset of a task cue when the sequence of tasks is unpredictable and the CSI relatively long (≥800 ms, e.g., Astle et al., 2006; Jost et al., 2008; Kieffaber & Hetrick, 2005; Lavric et al., 2008; Rushworth et al., 2002), but earlier with a shorter CSI (e.g. Karyanidis et al., 2011, Nicholson et al., 2006). In task sequences that are predictable, so that preparation can begin immediately after initiation of the previous response, the positivity emerges at around 200-300 ms after the previous response when the response-stimulus interval (RSI) is short, but later and with a lower amplitude and greater spread when the RSI is long (Karayanidis et al., 2003; for reviews see Karyanidis et al, 2010, Karyanidis & Jamadar, 2014), indicating that the positivity is to some extent sensitive to the anticipation of the stimulus onset. This posterior positivity is not the only EEG feature that differentiates between switches and repeats during the preparation interval (see Astle et al., 2006; Karayanidis et al., 2010, and Lavric et al., 2008), but it is by far the most consistently reported correlate of preparation for a task-switch; recently, the posterior positivity has also been found when bilinguals prepared to switch the language for production (Lavric et al., 2019). It also shows the clearest relation to performance: its magnitude is positively correlated over participants with the reduction in RT switch cost with preparation (e.g., Elchlepp et al., 2012; r=0.77), and negatively correlated with the switch cost observed with a long CSI (e.g., Kieffaber & Hetrick, 2005; r=-0.39); it is larger on those trials that have fast responses and small switch costs, and is virtually absent during the CSI (and delayed until post-stimulus) on trials with slow responses and large switch costs (Karayanidis et

[1] "Close to" because there is a lag of around 120-150 ms between attention being oriented and the onset of the associated eye-movement, e.g. Rayner (1998).

al., 2011; Lavric et al., 2008; 2019). Inasmuch as EEG features/components can be "signatures" of psychological processes, the positivity is our best candidate for an electrophysiological signature of advance task-set reconfiguration (e.g., Lavric et al., 2008).

What aspect or component of reconfiguration is indexed by the posterior positivity? Not, it is clear, cue processing per se. As already noted, the positivity is observed not only with explicit cuing paradigms but also with predictable task sequences cued only by stimulus position. Its latency and spread are sensitive to when the stimulus is expected, not simply locked to cue onset; when there is plenty of time to prepare for a change of task it occurs quite late after cue onset. With more than one cue per task, it reflects a task change not a cue change; studies which compared task repetitions where the cue was repeated with task repetitions where the cue changed found a distinct (earlier) ERP effect of cue change (Jost et al., 2008, Nicholson et al., 2006). Hence the positivity seems to reflect some aspect of the work of proactive task-set reconfiguration rather than mere registration of the need to reconfigure. But which aspect?

The positivity is unlikely to reflect attentional (perceptual) reorientation per se. Although it has been found when switching tasks involved a change in perceptual attributes (e.g., Rushworth et al., 2005; Lavric et al., 2008; Kieffaber et al., 2013), it is also found when switching between semantic categorizations of digits (e.g., Nicholson et al., 2006). A posterior positivity has been reported when only the response set changes, as when a binary S-R mapping is reversed (Rushworth et al, 2002; Astle et al., 2012), or in the Stop signal task when the rule regarding the signal changes (Elchlepp et al., 2016), but also when only the relevant stimulus attribute changes and the response set is constant – e.g., switching between same-different judgements on different stimulus attributes or modalities (Kieffaber & Hetrick, 2005). West et al. (2009)

manipulated stimulus set (colour versus word in Stroop stimuli) and response hand, and found that switches in either or both had about the same effect on an early (400-600 ms) part of the posterior positivity, while a later part had a smaller amplitude when only the response hand changed. It is possible that the posterior positivity can be decomposed into components corresponding to different components of reconfiguration (cf. Karyanidis et al., 2010, 2014), and/or that it reflects in part a global intention-activation process (Goschke, 2000). However, to our knowledge there is no evidence linking the positivity to preparatory shifts of spatial attention outside a task-switching context.

1.1 The present study

The current experiment therefore used a paradigm closely modelled on that of Longman et al. (2014) to examine the temporal relation between two observable indices of task-set preparation: a saccade to the task-relevant location, which we take to mark the end-result of a preparatory process leading to a spatial *attention shift* (AS), and the ERP posterior positivity, which we take to be an on-line index of a temporally extended process of configuring other aspects of task set; as a working assumption we label the latter process *rule configuration* (RC). On task-switch trials more configuration work is required (*re*-configuration), resulting in the difference in average neural activity between switch and repeat trials – the posterior positivity. We ask two questions about the temporal relationship between these two indices. In what order do they occur? And how closely coupled is their timing? The latter we assess by comparing the average posterior positivity for cue-locked ERPs and for fixation-locked ERPs (that is, ERPs time-locked to the onset of a fixation on the relevant location), in analyses limited to trials on which the first location fixated is the task-relevant location.

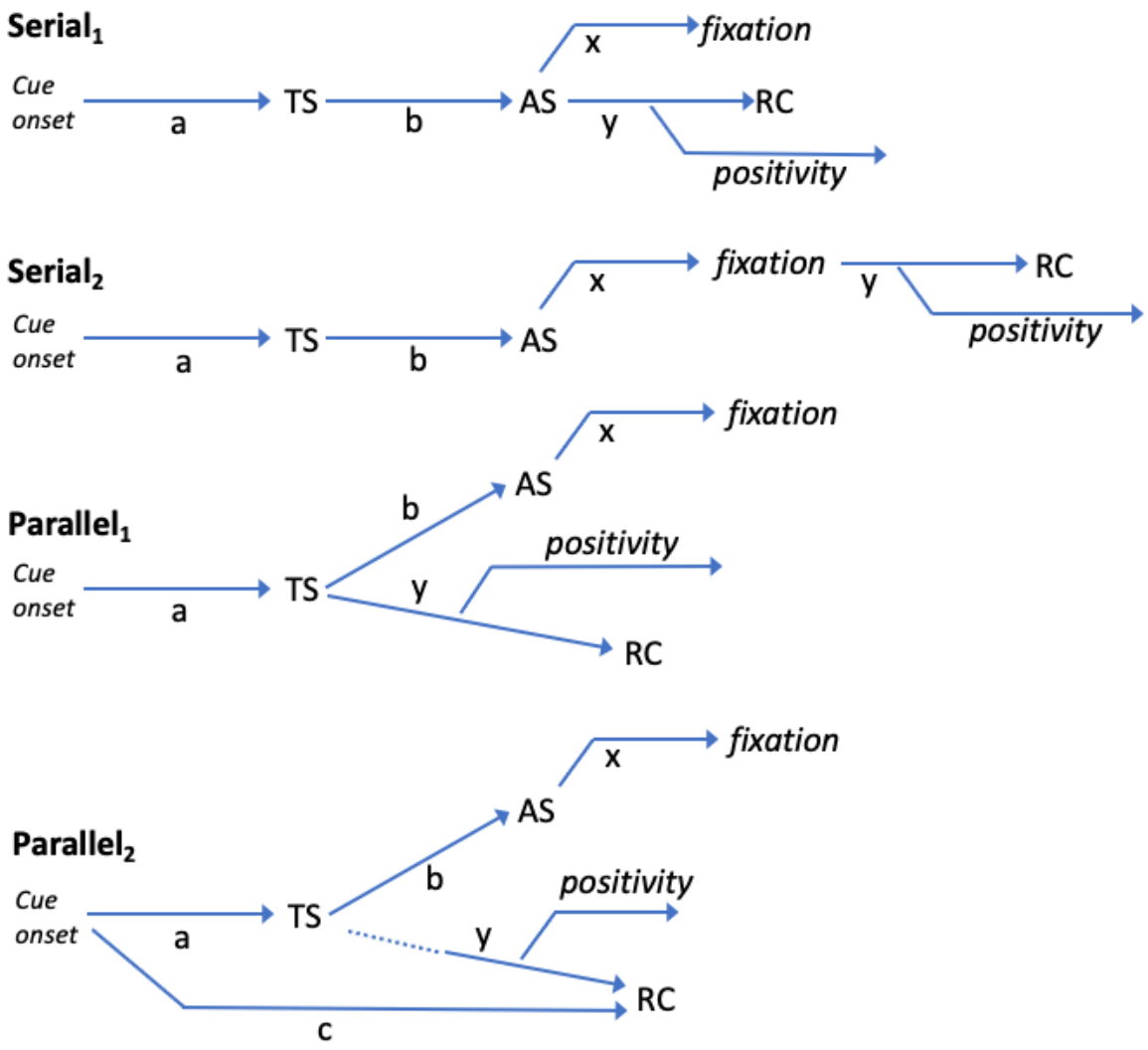

Figure 1. All models assume that cue onset triggers a process (duration *a*) decoding the cue to determine task selection (TS). This in turn triggers two components of task-set preparation. One (duration *b*) leads to an attention shift (AS), resulting in the observed saccade after a delay *x*, and fixation of the task-relevant location. A second process leads to rule configuration (RC); we allow for a delay *y* in the time taken for the extra processing required on task-switch trials to manifest detectably in the ERP posterior positivity. In the Parallel$_2$ model, duration *c* is that of a separate process triggering RC based on when the stimulus is expected.

Figure 1 sketches four possibilities. All assume that the cue onset triggers an encoding process that results in global task selection (TS). This in turn enables the two component processes of task preparation, AS and RC, to proceed, each generating their observable consequences: fixation of the task-relevant location and the ERP positivity. Process durations are labelled with single letters in Figure 1; each duration *i* has a mean *Mi* with variance *V*i over trials. The attention shift results, after a delay (*x*) for motor

programming and execution of the saccade, in the observed fixation on the relevant location.

What do we know about *x*, the lag between a covert shift of attention and the onset of the corresponding fixation? In saccadic latency experiments, mean latencies between onset of a target and onset of a saccade are typically around 150-200 ms (Rayner, 1998), but vary somewhat with the temporal and spatial predictability of the target. For a 4^{o} fixed-distance saccade to a random left or right target, with a warning interval between 1.0 and 1.5 sec, and the fixation display present until target onset, Wenban-Smith & Findlay (1991) obtained mean launch latencies of ~160 ms. Saccades over this sort of distance take ~30 ms to reach the target (Rayner, 1998). Allowing ~90 ms for cortical registration of the cue (Amassian et al, 1989), the duration of the lag between the target location being "known" and landing on the target fixation must be no more than ~100 ms (of which at least 30 ms is required for neural transmission to eye muscles, Robinson, 1972). Our experimental paradigm is somewhat different: the saccade is a predictable 2.7^{o}, with the three possible target locations already visible, and the choice between them specified by the TS and AS processes, but ~100 ms seems a reasonable ball park estimate of *Mx*.

We also allow for the possibility of a delay (*y*) in the onset of the observed ERP positivity relative to the rule configuration process that generates it. This delay may include (i) time taken for the ERP difference to become detectable relative to onset of the process generating it, and (ii) any transmission delay between the brain region where the AS process happens and the cortical activity we measure on the scalp. (As an example of the latter kind of delay, the N2pc – commonly taken to mark a shift in spatial attention – has been attributed to an enhancement in processing in the retinotopically appropriate region of posterior visual cortex triggered by an earlier attention shift in more anterior cortex; see Luck & Hillyard, 1994; Zivony et al, 2018).

However, given the 170-200 ms latency of the N2pc, and again allowing time for initial registration of retinal input in visual cortex, this transmission delay must be small. So while *My* may be non-trivial, it seems unlikely to be more than ~100 ms or so.

The variability of *a* (the duration of the process resulting in task selection and initiation of preparation, is likely to be substantial. It may have two sources. One is the intrinsic variability in how long it takes to identify the cue as specifying one or the three tasks. In addition, with a fixed and relatively generous 1000 ms CSI (as in the critical condition of our experiment), the incentive is to complete preparation (or at least fixation) by the stimulus onset, not as fast as possible. Thus *a* may include some (variable) waiting time as well as (variable) processing time. Bearing these estimates in mind:

- The $Serial_1$ model assumes that the AS and RC processes unfold as successive stages triggered by TS.[2] As a consequence (i) unless $My<Mx$, which seems unlikely, we expect the positivity to follow the fixation, and (ii) we expect to see relatively tight time-locking between the fixation and the evolution of the positivity. In particular, time-locking the ERP to the fixation should produce a well-defined average posterior positivity relative to time-locking to the cue onset, as it is likely that *Vx* is considerably smaller than *Va* + *Vb*.
- In the $Serial_2$ model, we entertain the possibility that RC process is triggered only after fixation on the relevant location has been achieved, perhaps because orienting to this location triggers retrieval of the associated task rules.[3] Now (i) the positivity *must* follow the fixation after some lag and (ii) the observed average positivity time-locked to fixation should be particularly well-defined compared to that time-locked to cue-onset, as *Va* + *Vb* + *Vx* are removed from the former's variability of timing.

[2] We do not assume successive processes to be strictly discrete processing stages in the sense of Sternberg (1969); there may be some degree of temporal overlap and non-independence.
[3] We thank Eric Ruthruff for suggesting this possibility.

- The Parallel$_1$ model assumes that AS and RC result from parallel processes (with independent durations) triggered by TS. In this model, the temporal relation between the fixation and the positivity will depend on the means and trial-to-trial distributions of durations *b*, *x* and *y*. The positivity will (i) follow the fixation only if *My*>(*Mb*+*Mx*) and (ii) time-locking the ERPs to the fixation will smear out the posterior positivity relative to time-locking to the cue onset unless *Va* is large relative to *Vb*+*Vx*.
- We raised the possibility that the point at which task-set preparation begins may reflect temporal anticipation of stimulus onset as well as time taken to decode the cue. The Parallel$_2$ model supposes that although the choice of rules to prepare must depend on the TS process being completed, the timing of the RC process may be triggered quite separately from that of the AS process. (Using predictable switching with a predictable response-stimulus interval, Karyanidis et al, 2003, found that the average posterior positivity was smeared out and reduced in amplitude when the response-stimulus interval was long (1200 ms), suggesting much more variability in the timing of reconfiguration when a long interval was available to get it done.) Hence this model assumes that, although the TS process tells the RC process *what* rules to prepare (dotted line), the timing of *when* RC occurs is determined by a separate process (duration *c*), based on experience of the CSI and previous preparation attempts. This model (i) places even less constraint than the Parallel$_1$ model on the order of the fixation and ERP positivity, and (ii) even though *Vc* may be large, time-locking the ERP to the fixation must add considerable variability to the temporal localisation of the positivity and smear out its average amplitude relative to the cue-locked ERP.

Doubtless there are other possibilities (such as serial processing with a variable order of processing), but these will serve to motivate our analyses. Although the history of

mental chronometry is rich in serial and parallel processing accounts that mimic aspects of each others' behaviour, choosing between them often depends on consideration of the plausibility of the assumptions made to achieve that mimicry. As already detailed above, we will assess the plausibility of the models' assumptions vis-à-vis two criteria in our empirical tests: (1) the temporal order of the onset of the fixation on the task-relevant location and the ERP positivity and (2) the time-locking of the ERP positivity to the task cue vs. the fixation (i.e. how clearly the posterior positivity is defined in the cue- vs. fixation-locked ERPs). The serial models generally require a successive ordering of the fixation and the positivity and a more defined positivity in the fixation-locked ERP.

2. Method

2.1 Participants

Twelve undergraduate students (8 female, mean age = 21.5 years) participated in the study, having provided informed written consent for their participation and for their data to be used once the aims of the study had been explained to them. Participants received course credits plus a ≤£2 performance-related bonus (see next section).

2.2 Tasks, Stimuli and Procedure

The stimuli were presented using E-Prime (Psychology Software Tools Inc., Sharpsburg, USA) on a 17" zero-curvature CRT monitor. Each trial (see Figure 2) started with a blank screen which was followed by the presentation of a central fixation cross (subtending 0.4°) and three light blue dots (0.3° in diameter) at the parafoveal locations where the three digits would eventually appear. After 300 ms, the fixation cross was replaced with a word cue ('ODD?', 'EVEN?', 'LOW?', 'HIGH?', 'INNER?' or 'OUTER?') subtending up to 0.8° x 0.3° displayed for the entire CSI, which specified

one of three classification tasks (odd vs. even; low [≤5] vs. high [>5], inner [4, 5, 6, 7] vs. outer [2, 3, 8, 9]), each mapped to a single location throughout the experiment for all participants: odd/even task = top digit, low/high = bottom left digit, inner/outer = bottom right digit. The cue, which changed on every trial to unconfound task switches from cue switches (e.g., Monsell & Mizon, 2006), was followed by the stimulus at one of two CSIs: 100 ms or 1000 ms. To unconfound the effects of endogenous preparation from those of passive decay of task-set inertia (Meiran, 1996), the response-stimulus interval was 2100 ms regardless of CSI, except following an error when "ERROR" was presented for a further 1000 ms. The CSI was constant throughout a 74-trial block but changed over blocks to provide an estimate of the reduction in the behavioural switch cost with preparation. Given the present focus on events during a preparation interval, 9 out of the 12 blocks had a long CSI. Three short CSI blocks were interspersed among long CSI blocks at regular intervals (one in every four blocks); the four possible resulting sequences (where the first short CSI block was the 1st, 2nd, 3rd or 4th in every four blocks) were equally represented over participants.

The stimulus comprised three digits (0.4° x 0.5°) presented at the corners of an invisible equilateral triangle (so that they were 5° from each other and 2.7° from the centre) until one of two keys ('c' or 'm' on a standard 'QWERTY' keyboard) was pressed with either the left or right index finger respectively. Stimuli were generated by first selecting the response category (e.g., odd, inner) for each digit, then randomly selecting a digit from the appropriate set with two constraints: the three digits in each stimulus were different, and there could be no exact repetition of the entire stimulus from the previous trial (i.e., all three digits in the same locations). The combinations of the three categories (e.g., even, low, outer) were equiprobable for each task and transition type. The tasks were equiprobable (resulting in a 2:1 switch:repeat ratio).

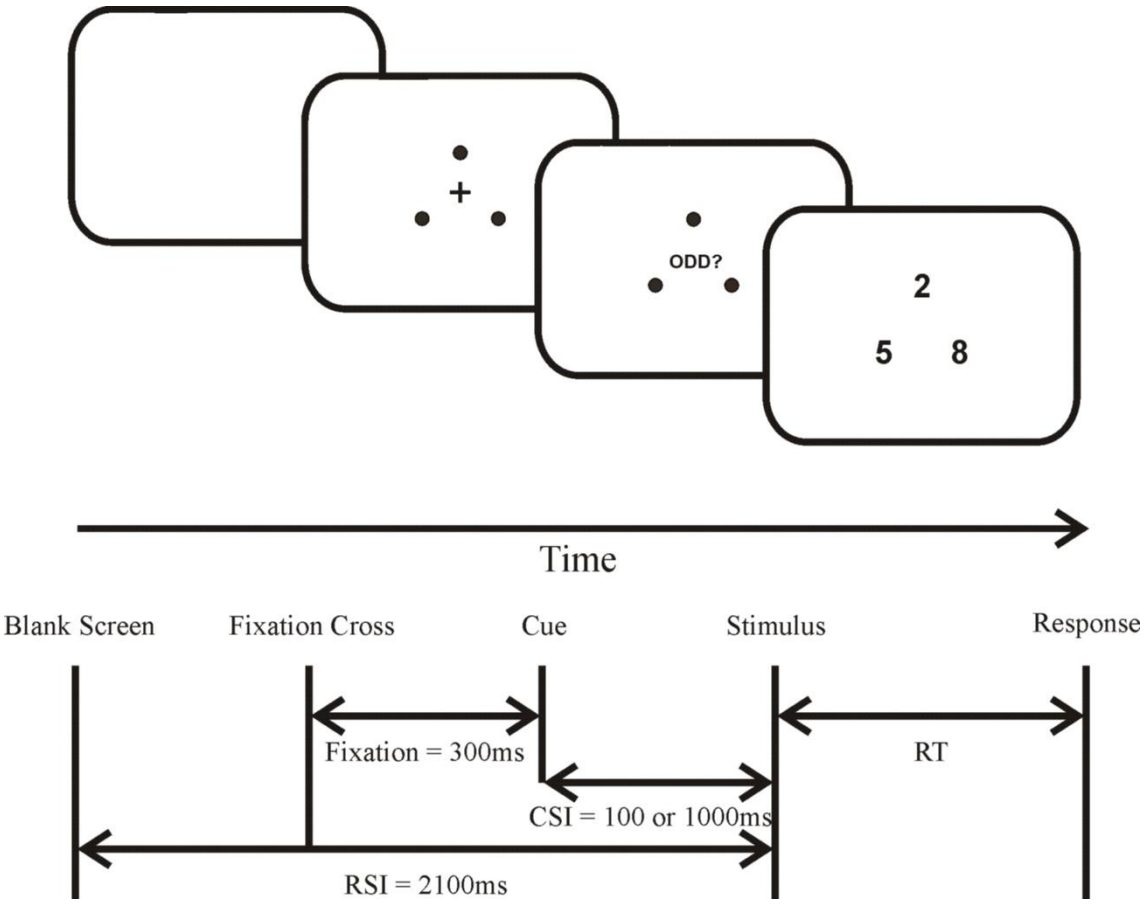

Figure 2. The time course of one trial with example displays. The dots where the digits would eventually appear were presented in light blue. The cue (and fixation cross) was presented in a smaller font which made it difficult to read without fixating it. Both are enlarged here for clarity.

The CSI was displayed before each block of trials. The mean correct RT, number of errors, a score for the block (a weighted combination of mean RT, and error rate), the target score for the block (mean score from previous blocks with the same CSI) and bonus points when the score was less than the target score (used to calculate bonus payments) were displayed at the end of each block. The experiment started with a practice run comprising three 8-trial single-task blocks each requiring one of the three classifications of single digits presented centrally; a task-switching block (74 trials) with single digits presented centrally; and (following the introduction of the task-location mappings) two task-switching blocks equivalent to the test blocks described above.

2.3 Data acquisition

2.3.1 Eye-tracking. An EyeLink 1000 eye-tracker (SR Research, Ottawa, Canada) recorded the movements of the right eye at a 500 Hz sampling rate, with calibration before each block.

2.3.2 EEG/ERP. The EEG was sampled continuously at 500 Hz (bandpass 0.016-100 Hz, reference Cz, ground AFz) using 64 Ag/AgCl active electrodes in a 10-10 configuration (ActiCap and BrainAmp, Brain Products, Munich, Germany). All impedances were kept below 10kΩ.

2.4 Data analysis

All raw data files are available to download from the Open Science Framework data repository: https://osf.io/bpq5c/. The first two trials in each block, trials following an error, trials with RT>2500 ms, and trials with no fixations on the cue for 1000 ms following cue onset were discarded from all analyses. Error trials were omitted from RT, eye-tracking and ERP analyses.

Significance levels were corrected using the Huynh-Feldt correction for violations of sphericity, but for transparency degrees of freedom are reported uncorrected.

2.4.1 RT and errors. The mean RTs and proportion of errors were subjected to Switch by CSI by Task ANOVAs. Follow up Switch by Task ANOVAs were performed on the data from each CSI individually to determine whether the switch cost was reliable at each CSI.

2.4.2 Eye-tracking. Fixations in four square regions (side = 2°) centred on each of the three digits and the cue were analysed; 92.80% (repeat trials) and 92.43% (switch trials) of fixations occurred in these regions[4]. Fixation data were first partitioned into 20

[4] For one participant, a single block with >20% of trials containing no fixations in any of these regions (indicating poor calibration) was discarded.

ms time-bins for the entire duration of the trial (see Figure 4). This measure of "dwell time" is equivalent to the probability of fixating a given region in a 20 ms period, which can be calculated by dividing each dwell time value by 20. The effects of a task-switch on the pattern of fixations were tested statistically in a 200 ms window selected to reflect the maximal rise in dwell-time: for each CSI the window started from the bin where dwell-time for the currently-relevant region on repeat trials (averaged over participants) exceeded 2 ms (10% of the maximum).

To capture the switch-induced delay in orienting to the currently relevant region, we estimated the temporal separation between the switch and repeat dwell-time curves for every time-point (2 ms) and averaged the estimates for the 200 ms analysis window. For each participant and each time-point on the dwell-time curve within the 200 ms analysis window for repeat trials, we estimated the time at which the dwell-time for the switch curve reached the same value. The procedure uses non-linear temporal interpolation; details are provided in Longman et al. (2014). One-sample t-tests were used to determine whether the switch-induced delay in fixating the currently relevant region was significant for each CSI. A one-way ANOVA with the factor CSI was also run in order to assess the effect of preparation interval on the estimated delay.

Dwell time on the currently irrelevant regions was subjected to a Switch by CSI by Task ANOVA. The results (see Section 3.2) suggested that the delay in fixating the relevant region on switch trials may be at least in part due to the gaze being drawn toward the irrelevant digits during a task-switch. To determine whether a task switch delays the fixation on the relevant digit even on trials where this fixation is not preceded by (inappropriate) fixations on the irrelevant digits, we analysed the mean onset time of the first fixation on the relevant digit limited to trials on which the first eye movement away from the cue was to the relevant region with a further Switch by CSI by Task ANOVA.

To examine the tendency to fixate the previous task's location on switch trials ("attentional inertia", see Introduction) we compared, for switch trials only, dwell time on the previously (but no longer) relevant region with dwell time on the other irrelevant region in a Previous Relevance (previously relevant, previously irrelevant) by CSI by Task ANOVA. Follow-up Previous Relevance by Task ANOVAs performed on the dwell time data from each CSI individually were performed to determine whether this measure of attentional inertia was evident in each preparation interval.

2.4.3 EEG/ERP. Following offline filtering with a 20 Hz low-pass filter (24dB/oct), EEG data were first subjected to an Independent Component Analysis (ICA, Bell & Sejnowski, 1995) to correct for ocular artefacts. Note that eye movements are typically discouraged during the interval of interest in ERP studies in order to avoid ocular artefacts. This was not possible in the current experiment because eye movements during that interval were also of interest. Using ICA to correct for ocular artefacts meant that, although some trials were omitted from further analysis due to other (residual) artefacts, none were omitted due to eye-movements. Following the removal of ICA components containing eye-blink and eye-movement artefacts, the EEG was re-referenced to the averaged earlobes. Only long CSI trials (75% of all trials) were submitted to the ERP analyses; the short CSI trials were included in the experiment to confirm the reduction in switch cost with preparation (in the behavioural data) and reduction in the "attentional inertia" (in the fixation data), which we have previously documented (Longman et al., 2013; 2016; 2017; Longman et al., 2014).

2.4.3.1 ERP Analysis 1. The EEG for long CSI trials was then segmented into 1000 ms epochs time-locked to cue onset plus a 100 ms pre-cue baseline epoch. Following baseline correction, the segments were inspected for residual (muscle, head movement, skin and other) artefacts, and those free of artefact were averaged for every participant/condition. For statistical analysis, electrodes were averaged for 4 anterior-to-

posterior regions, each containing 3 levels of laterality (left, middle, right; see Figure 3), this averaging along two spatial dimensions was reflected in Region and Laterality factors in ANOVAs.

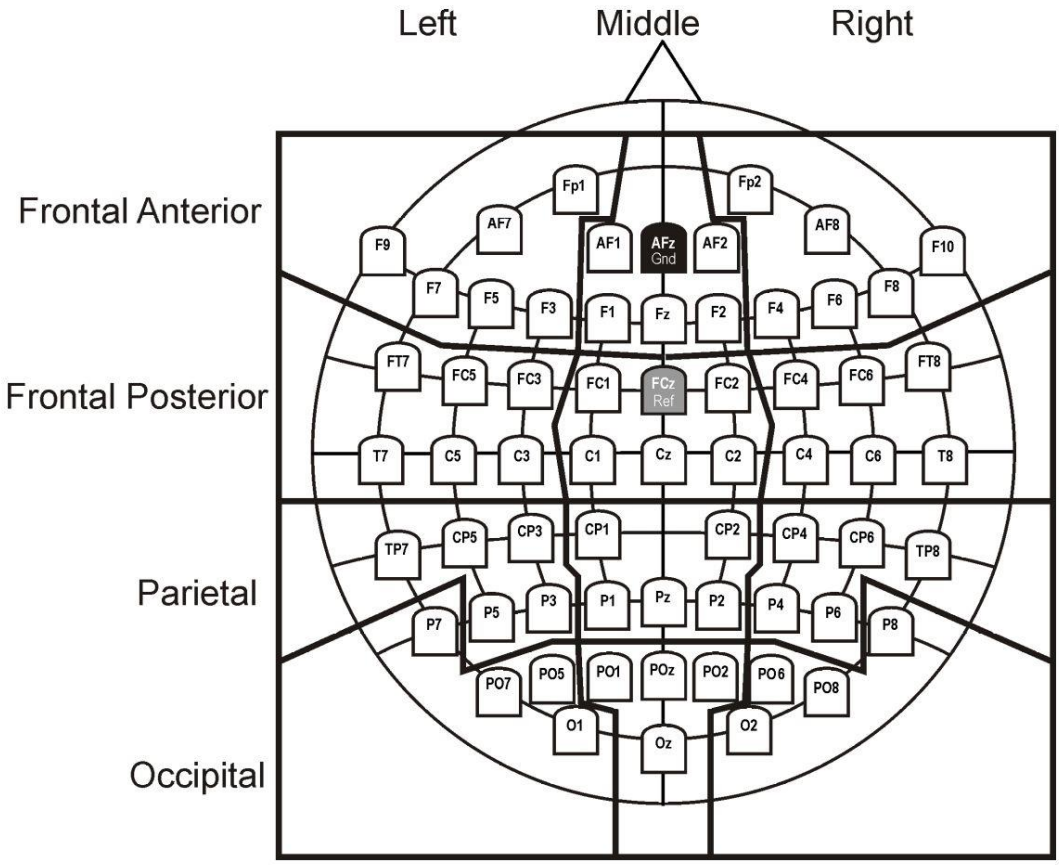

Figure 3. Distribution of electrodes and regions used for statistical analysis.

We started by analysing the ERPs without relating them to fixations. Switch by Region by Laterality ANOVAs were run on ERP amplitudes averaged for the 300-500 ms and 600-800 ms windows following the cue to measure the switch-induced early negativity and late positivity observed in the ERP topographies (see Figure 6) respectively.

2.4.3.2 ERP Analysis 2. However, the primary aim of the current investigation was to relate the time-course of (re)orienting spatial attention during a task-switch to the brain potentials induced by preparation for a switch (the posterior switch positivity).

Hence, in our second analysis we examined the positivity (and the preceding negativity) in ERPs time-locked to the onset of the first fixation on the task-relevant location (rather than to the onset of the task cue, as in the analysis above). We started by segmenting cue-locked EEG epochs separately for thirds (terciles) of the distribution of onset times of the first fixation on the region associated with the relevant task-set (the task-set specified by the cue). To rule out any effects due to fixations on the regions associated with the irrelevant task-sets prior to fixating the relevant region, this analysis was limited to trials where the first saccade to leave the cue landed directly on the relevant region. The aim was to obtain from these cue-locked EEG epochs shorter epochs time-locked to the fixation onset yet baseline-corrected relative to the pre-cue-onset baseline – thereby avoiding contamination of the baseline with the switch-repeat difference in the cue-to-fixation interval. Hence, we segmented long cue-locked EEG epochs which included even the fixations with the longest onsets. For each tercile, the length of the epoch was calculated as the longest fixation onset latency (over all trials for the given tercile from all participants for the first fixation on the relevant region) plus 600 ms – the intended portion of the ERP following fixation onset. This resulted in epoch lengths (where 0 ms is the cue onset) of -100 to 1350 ms (fastest tercile); -100 to 1800 ms (medium tercile); and -100 to 3270 ms (slowest tercile). Following pre-cue baseline-correction (-100 to 0 ms), we cut out from these long EEG epochs shorter (900 ms) epochs time-locked to the onset of the first fixation to land directly in the currently relevant region (-300 ms to 600 ms). These were then averaged (without further baseline-correction) for each participant/condition. If the posterior positivity followed the (re)orienting of attention, one would expect the positivity to be confined to the interval following the fixation onset. This was tested statistically by t-tests run on the ERP amplitudes for the scalp regions in which the negativity and positivity were

maximal[5]. Note that t-tests were not corrected for multiple comparisons to ensure that the non-significance of the positivity before the fixation onset and of the negativity following the fixation onset could not be due to reduced sensitivity (increased likelihood of type 2 error). The primary aim of this analysis was not to ascertain the overall significance of the switch-induced ERP components (positivity and negativity) – as in the ERP amplitude analysis described above – but to examine their time-course. It therefore seemed more appropriate to err on the side of sensitivity than on the side of caution.

2.4.3.3 ERP Analysis 3. In our third (and final) ERP analysis we asked whether the posterior positivity is better coupled to the onset of the fixation on the task-relevant region than the onset of the task cue. Our approach to answering this question was to compare the amplitude of the positivity at its maximum in the cue-locked ERP segmentation vs. in the fixation-locked segmentation. A larger positivity in either segmentation would be indicative of a greater temporal coupling of the positivity to either the fixation or the cue – such a difference might prove diagnostic in deciding between the temporal processing models outlined in the introduction. The fixation-locked ERPs were those obtained for ERP Analysis 2 above; we had to ensure that they were contrasted with cue-locked ERPs based on the same experimental trials[6]. Hence, we obtained from the long cue-locked EEG epochs created for ERP Analysis 2 above (which were already baseline-corrected) 1100 ms-long cue-locked epochs whose average (cue-locked ERP) was compared to the fixation-locked ERP. For each tercile and segmentation (cue-locked and fixation-locked), a 150-ms long window (see Table

[5] One participant's ERP had to be discarded from the analysis due to an insufficient number of epochs in the average.

[6] The fixation-locked analysis (ERP Analysis 2) was limited to trials where the first saccade to leave the cue landed directly on the region associated with the relevant task (to rule out possible confounding effects of earlier fixations on the fixation-locked ERPs), whereas the original cue-locked analysis (ERP Analysis 1) included all artefact-free trials, including trials where before fixating the region associated with the relevant task the participant fixated other (irrelevant) regions.

3) was selected where the posterior switch positivity reached maximal amplitude in the grand-average (average over participants).We then subjected the mean amplitude of this time-window for four scalp regions where the positivity was maximal in ERP Analyses 1 and 2 (parietal left, parietal medial, occipital left, occipital medial) to a Switch (2) by Tercile (3) by Segmentation (2: cue-locked, fixation-locked) by Region (4) ANOVA.

3. Results

3.1 RT and Errors

The ANOVA on the RTs found the 107 ms RT switch cost (main effect of Switch) to be significant, $F(1,11)=41.41$, $p<0.001$ (see Figure 4). It reduced reliably (Switch by CSI interaction: $F(1,11)=8.97$, $p=0.012$) from 135 ± 22[7] ms at the short CSI to 80 ± 16 ms at the long CSI (a 41% reduction), but remained significant at the long CSI (main effect of Switch for this CSI), $F(1,11)=25.23$, $p<0.001$. No effects involving Switch were significant in the ANOVA performed on the error rates ($Fs<1$). There were no reliable effects or interactions involving the factor Task for either RTs or errors.

[7] Standard error of the contrast.

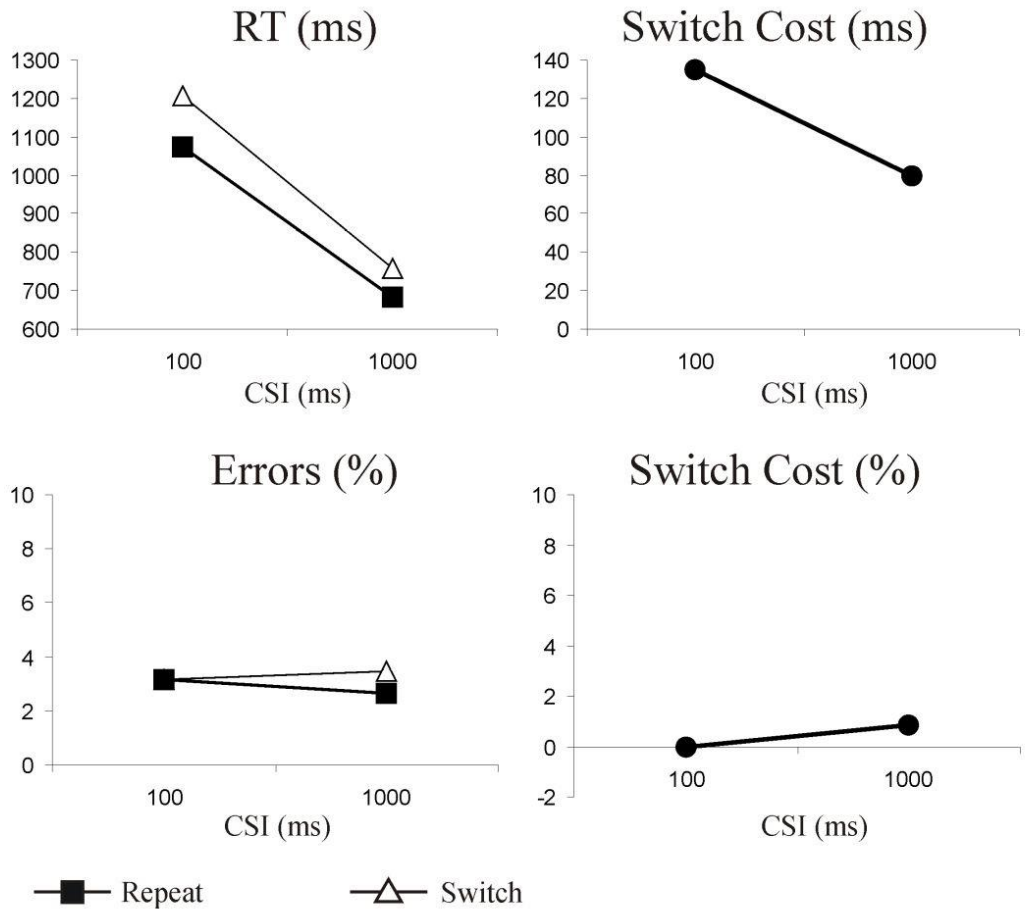

Figure 4. Mean RT (top), error rates (bottom) and switch costs (right panels) as a function of cue-stimulus interval (CSI) and transition (switch, repeat).

3.2 Eye-tracking

Table 1 presents the summary statistics for the first fixation following the fixation on the cue (these statistics were restricted to trials which were included in the RT and eye-tracking analyses, for the trial inclusion criteria see Section 2.4). The vast majority of the fixations immediately following the fixation on the cue were on the task-relevant region, though a non-trivial proportion were on the irrelevant regions. The latency of the gaze reaching the task-relevant region and the relative proportions of fixations on the two irrelevant regions was modulated by switch and CSI.

Table 1: *Mean (Standard Deviation) Proportion of the First Fixation Immediately Following Fixation on the Cue to Land in each Analysis Region or None of the Regions (Miss) as a Function of Cue Stimulus Interval (CSI) and Transition.*

	CSI = 100 ms		CSI = 1000 ms	
Region	**Switch**	**Repeat**	**Switch**	**Repeat**
Relevant	66.8% (14.1)	83.3% (9.0)	77.4% (11.4)	88.2% (5.8)
Irrelevant	10.3% (5.2)	11.5% (6.5)	7.5% (3.9)	5.8% (3.4)
Previously relevant	16.1% (9.0)	N/A	7.8% (6.4)	N/A
Miss	6.8% (4.8)	5.2% (5.4)	7.3% (4.6)	6.0% (4.1)

One-sample t-tests on the estimated delay between cue onset and orientation to the relevant region (estimated as specified in Section 2.4.1; see Figure 5) showed the switch-induced delay to be significant for each CSI: CSI=100 ms, mean delay = 107 ± 31 ms, $t(11)=3.71$, $p=0.003$; CSI=1000 ms, mean delay = 77 ± 22 ms, $t(11)=3.32$, $p=0.007$. The one-way ANOVA with the factor CSI found that the reduction (from 107 ms at the shorter CSI to 77 ms at the longer) in the delay with CSI did not approach significance, $F(1,11)<1$.

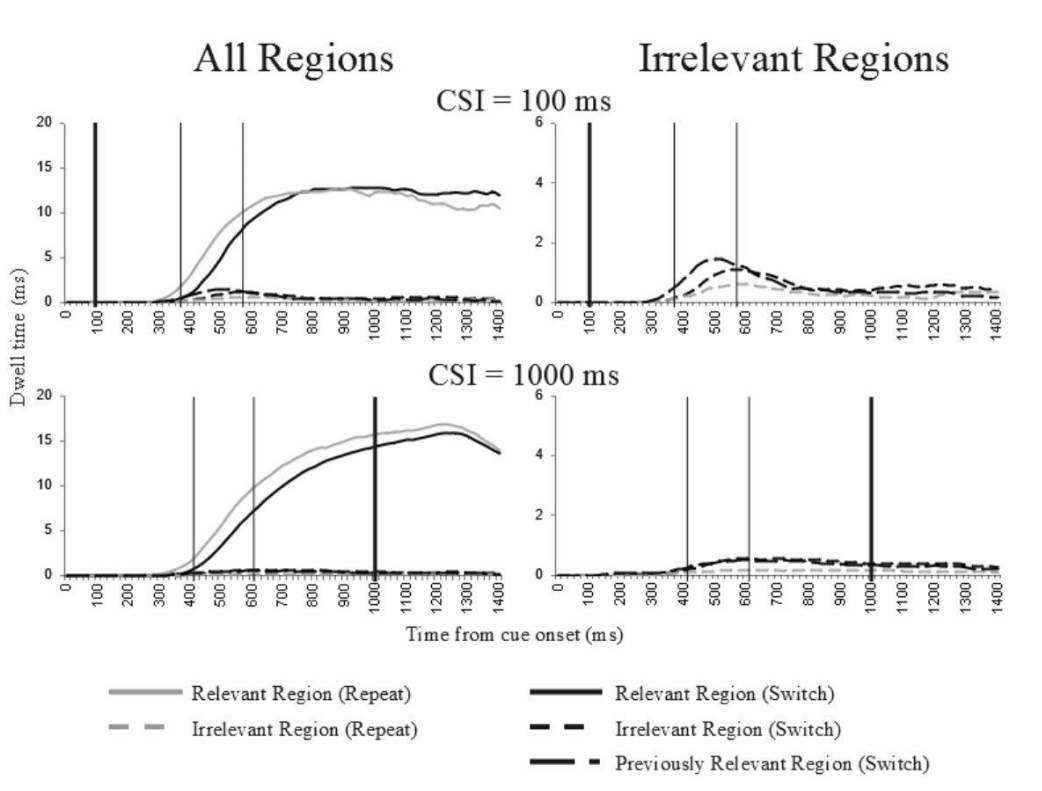

Figure 5. Dwell time per 20 ms bin for 1420 ms following cue onset as a function of CSI, transition (switch, repeat) and task-relevance of stimulus region. Thick vertical

lines indicate the stimulus onset time, thin vertical lines show the time-windows used for statistical analysis.

The ANOVA on the dwell time on the currently irrelevant regions found that participants tended to fixate the irrelevant regions more on switch than repeat trials (main effect of Switch: $F(1,11)=12.38$, $p=0.005$; see Figure 5, right panels)[8]. There were also reliable interactions between Task and Switch, $F(2,22)=10.98$, $p=0.001$, and CSI, Task and Switch, $F(2,22)=5.53$, $p=0.011$, reflecting larger differences found for low/high (bottom left) task trials.

The ANOVA conducted on the dwell time on the currently irrelevant regions on switch trials (assumed to measure "attentional inertia", see Introduction) found a reliable interaction between Previous Relevance and CSI, $F(1,11)=18.13$, $p=0.001$. Follow-up analyses revealed a clear preference for the previously relevant region when CSI = 100 ms (the mean difference in dwell time between previously relevant and irrelevant regions was 5.6 ± 2.3 ms, $F(1,11)=6.28$, $p=0.02$), but not when CSI = 1000 ms (mean difference -0.2 ± 1.4 ms, $F<1$); see Figure 5, right panels.

When onsets of the first fixation on the currently relevant digit were limited to trials on which the first eye movement away from the cue moved directly to the relevant region, the ANOVA revealed a switch-induced delay of 55 ms in appropriate orienting, $F(1,11)=14.40$, $p=0.003$. The mean fixation onset latencies for each CSI (CSI=100 ms: switch = 594 ms, repeat = 554 ms; CSI=1000 ms: switch = 711 ms, repeat = 640 ms) show that the switch-induced delay increased numerically (but non-significantly, $F(1,11)=2.64$, n.s.) from the shorter to the longer CSI (from 39 ms to 71 ms), suggesting that on short CSI switch trials fixations were faster but more prone to attentional inertia (as shown by the irrelevant regions dwell-time analysis above). This analysis demonstrates that the switch-induced delay in orienting was not due entirely to

[8] Only ANOVA effects involving the switch factor are presented.

(additional) fixations on the irrelevant regions prior to fixating the relevant region, and that when the gaze went directly from the cue to the relevant digit, this eye-movement was also delayed by a task switch.

3.3 ERPs

3.3.1 ERP Analysis 1

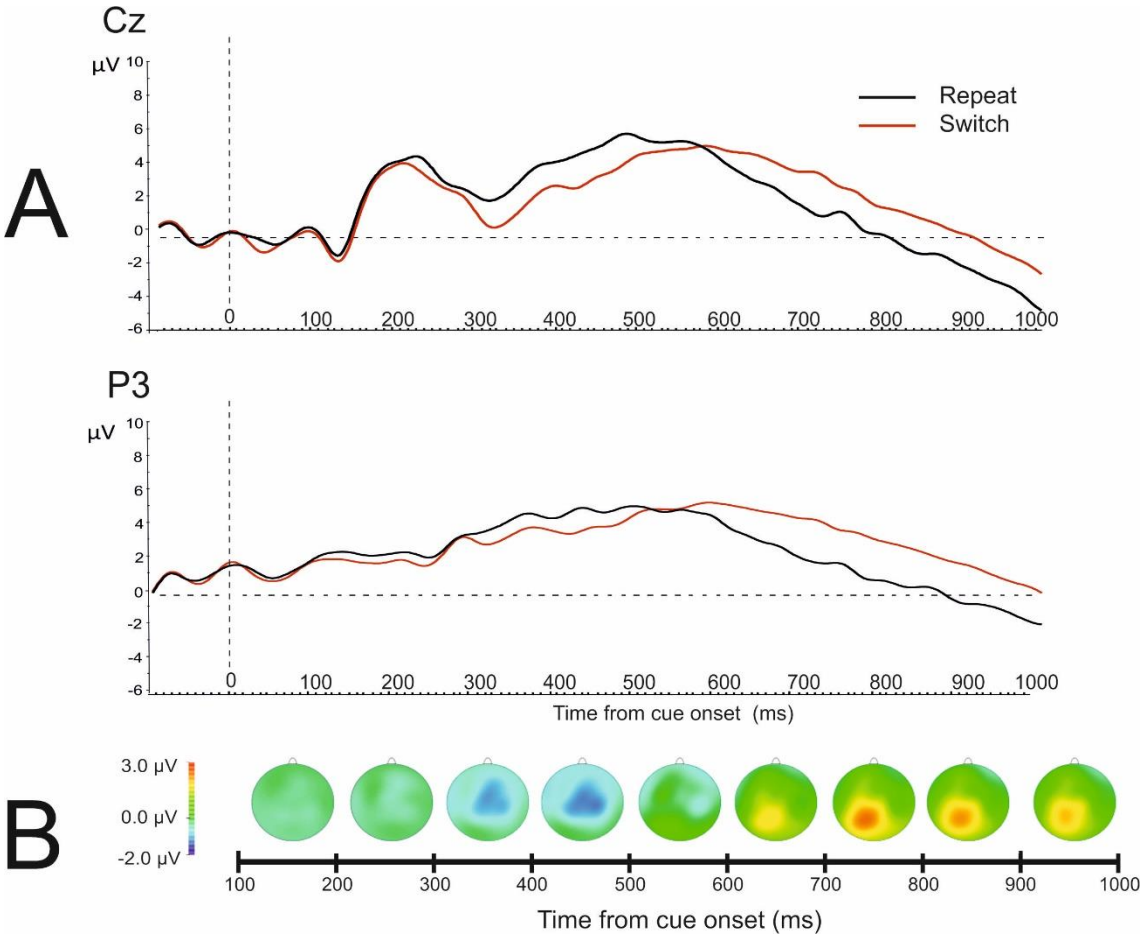

Figure 6. (A) Mean switch and repeat cue-locked waveforms from two example electrodes showing the extent of the early negativity (Cz) and late positivity (P3). (B) Cue-locked switch minus repeat ERP topographies.

An inspection of the cue-locked ERP waveforms (see Figure 6A) and topographies (see Figure 6B) revealed the familiar and substantial posterior positivity induced by a task-switch (see Introduction) starting from ~600 ms following the cue (400 ms before stimulus onset). The ANOVA run on ERP amplitudes averaged for the

600-800 ms window found a reliable main effect of Switch, $F(1,11)=16.77$, $p=0.002$. Reliable interactions between Switch and Region, $F(3,33)=6.09$, $p=0.019$, and Switch and Laterality, $F(2,22)=10.18$, $p=0.001$, indicated the expected localization of the positivity in posterior electrodes towards the left of the scalp (in many previous studies, particularly those using word cues, the positivity has been somewhat left-lateralized, e.g., Elchlepp et al., 2012; Lavric et al., 2008). Intriguingly, in addition to the posterior positivity, there was an earlier switch-related negative-polarity deflection maximal over the centro-parietal scalp, confirmed in the analysis of the 300-500 ms time-window by the significant main effect of Switch, $F(1,11)=8.96$, $p=0.012$.

3.3.2 ERP Analysis 2

The fixation-locked analyses revealed that for each tercile the positivity emerged after the mean onset of the first fixation on the relevant attribute of the stimulus (see Figure 7). In contrast, the central negativity emerged, and tended to return to baseline, prior to the mean onset of the fixation landing on the relevant attribute. (For the medium tercile, the negativity seemed to have returned to baseline somewhat later). This pattern of observations was confirmed statistically by the t-tests run on ERP amplitudes for the scalp regions in which the negativity and positivity were maximal: the tests corresponding to the negativity were only significant prior to the onset of the fixation and the tests corresponding to the positivity were only significant following the fixation onset (see Table 2).

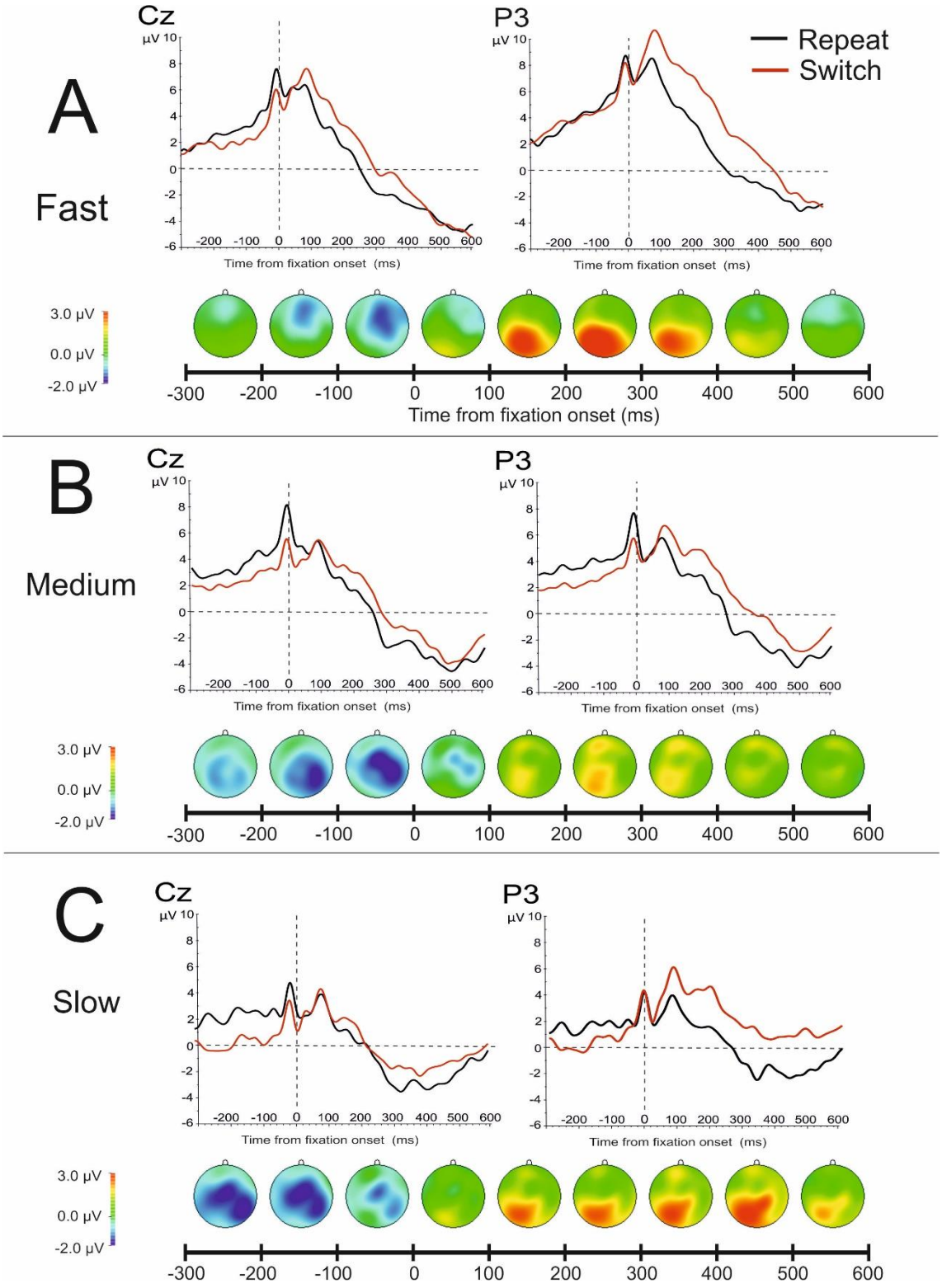

Figure 7. Mean switch and repeat fixation-locked waveforms from two example electrodes showing the extent of the early negativity (Cz) and late positivity (P3), as well as the fixation-locked switch minus repeat ERP topographies corresponding to terciles of the distribution of onset times of fixations on the task-relevant region – the fast (A), medium (B) and slow (C) fixations (see text for description).

Table 2: *Mean ERP Amplitude Difference (Switch-Repeat) and Switch vs. Repeat T-test Statistics as a Function of Speed of Fixating the Relevant Region for the Parts of the Scalp Where the ERP Effects Were Maximal: Middle Central Region (Negativity) and the Average of the Left and Middle Parietal and Occipital Regions (Positivity).*

		Window (ms)					
		Pre-fixation			Post-fixation		
		300-200	200-100	100-000	000-100	100-200	200-300
		Middle Frontal Posterior					
Fast	**Mean**	-0.570	-1.043	-1.400	-0.396	1.489	1.584
	SE	0.363	0.383	0.736	0.643	0.789	0.910
	t	1.570	2.725	1.902	0.615	1.886	1.740
	p	0.131	0.017*	0.074	0.533	0.076	0.098
Medium	**Mean**	-0.495	-1.234	-1.819	-0.403	1.017	1.459
	SE	0.485	0.597	0.782	0.861	0.882	0.971
	t	1.021	2.066	2.327	0.468	1.153	1.503
	p	0.309	0.056	0.035*	0.634	0.254	0.146
Slow	**Mean**	-0.865	-1.792	-1.165	0.419	1.100	0.883
	SE	0.856	0.885	0.943	0.907	1.193	1.090
	t	1.010	2.026	1.236	0.462	0.922	0.810
	p	0.314	0.060	0.224	0.638	0.356	0.416
		Left and Middle Parietal and Occipital					
Fast	**Mean**	0.577	0.182	-0.247	1.100	2.608	3.112
	SE	0.284	0.232	0.569	0.597	0.615	0.946
	t	2.032	0.783	0.434	1.841	4.243	3.290
	p	0.059	0.430	0.658	0.082	0.001**	0.006**
Medium	**Mean**	-0.866	-1.025	-0.861	0.135	1.409	1.842
	SE	0.436	0.483	0.699	0.802	0.704	0.848
	t	1.985	2.121	1.233	0.169	2.002	2.173
	p	0.064	0.050	0.225	0.863	0.062	0.046*
Slow	**Mean**	-1.213	-1.074	-0.355	1.101	2.215	2.229
	t	0.725	0.769	0.520	0.616	0.670	0.901
	p	1.674	1.397	0.681	1.788	3.305	2.473
	P	0.110	0.174	0.491	0.090	0.006**	0.027*

Note: * $p<0.05$, ** $p<0.01$

3.3.3 ERP Analysis 3

The aim of our final analysis was to determine whether the switch positivity was better coupled (time-locked) to the fixation onset or to the cue onset by comparing the amplitude of the positivity in a 150-ms time-window spanning its maximal amplitude for each segmentation (cue-locked vs. fixation-locked). The switch by tercile by segmentation by region ANOVA revealed a significant switch by segmentation by

tercile interaction, F(2,22)=6.27, p=0.014, indicating that the pattern of differences between the cue-locked and fixation-locked positivity varied over terciles. The follow-up ANOVAs separately for each tercile found that in the fast tercile the positivity had a significantly larger amplitude in the cue-locked ERPs than in the fixation-locked ERPs, F(1,11)=15.82, p=0.002 (see Table 3 and Figure 8). The same numerical pattern was observed in the medium tercile, but the difference was smaller and did not approach significance (F=1.1). In the slow tercile, the difference was reversed numerically (slightly larger positivity in the fixation-locked ERPs), but it too did not approach significance (F<1). Thus, for fast fixation trials, the positivity was better time-locked (coupled) to the onset of the task cue than to the onset of the fixation on the relevant region. This difference in time-locking disappeared in the medium and slow terciles.

Table 3. The mean amplitude of the positivity in the 150-ms window where it reaches maximum as a function of time-locking of ERPs: to the onset of the task cue vs. time-locked to the onset of the fixation on the region of the relevant task. The boundaries of the time-window are given in parentheses.

Tercile	Cue locked	Fixation locked
Fast	4.4 μV (625 – 775 ms)	2.9 μV (150 – 300 ms)
Medium	1.9 μV (750 – 900 ms)	1.5 μV (175 – 325 ms)
Slow	2.2 μV (1000 – 1150 ms)	2.7 μV (200 – 250 ms)

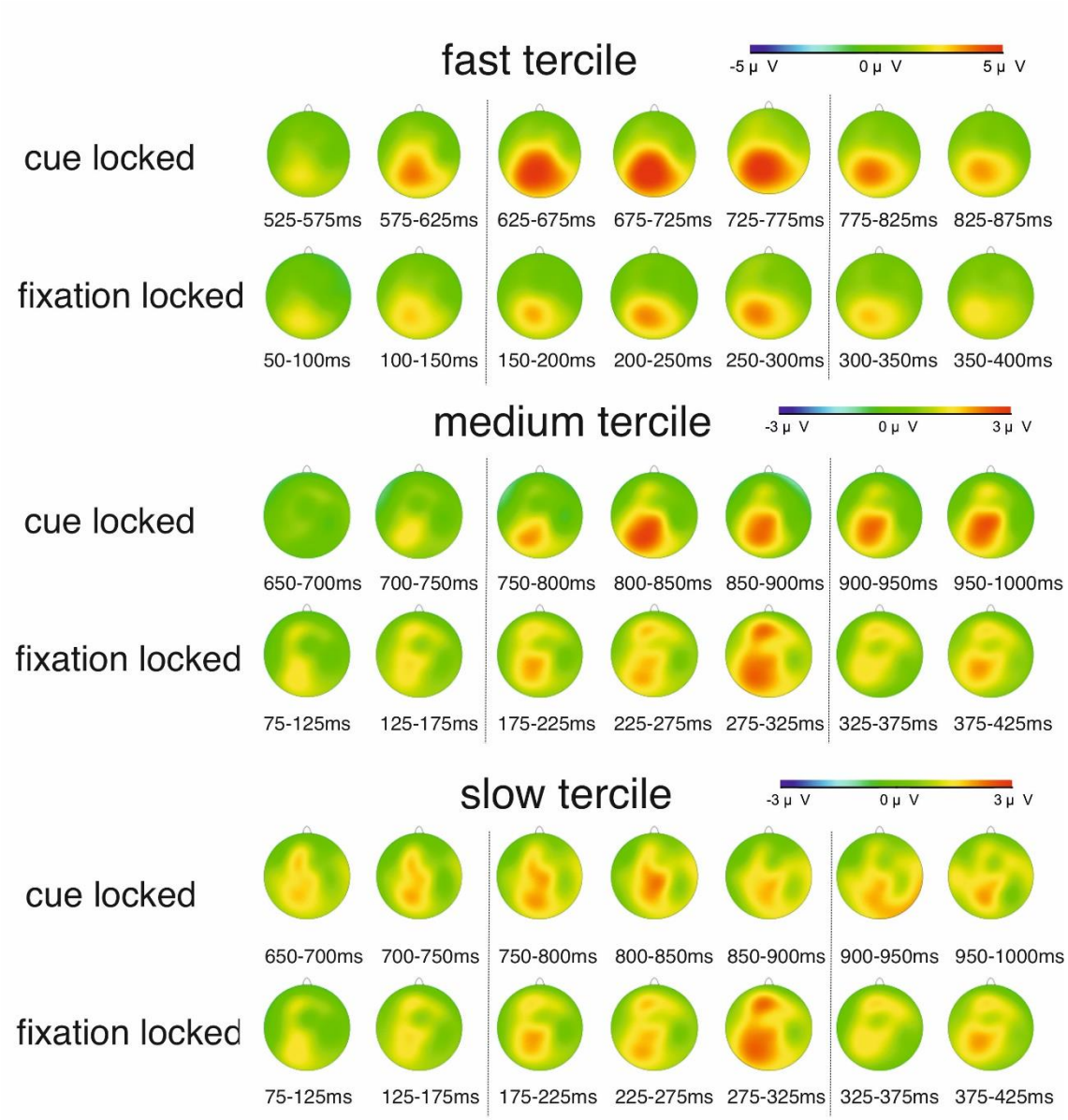

Figure 8. Switch-minus-repeat topographies as a function ERP time-locking and tercile. The vertical bars delineate the 150 ms time-window where the switch-related positivity reached maximal amplitude and for which ERP amplitudes were subjected to statistical analysis.

4. Discussion

We observed the two indices of task-set preparation we expected: an eye movement from the central location of the task cue to the task-relevant para-foveal location, and the switch-related positivity in the ERP. ERP analysis time-locked to the cue onset (ERP Analysis 1) revealed a robust positivity with the time-course and scalp distribution seen in many prior studies: a protracted switch-repeat difference emerging

over (in this case) the last 400 ms of the 1000 ms CSI, maximal over the parietal-occipital scalp and somewhat left-lateralized (see Figure 6). The fixation data also indicated an anticipatory shift of attention to the task-relevant region, delayed on switch trials, as in our previous studies (Longman et al., 2013, 2014, 2016, 2017). The primary goal of the experiment was to examine the temporal relationship between these two indices, one discrete and one temporally extended, on the assumption that they reflect distinct components of task-set preparation: orientation of spatial attention, and (most likely) reconfiguration of S-R rules. ERP analysis time-locked to the arrival of the gaze to (onset of fixation on) the relevant location (ERP Analysis 2) revealed substantial temporal coupling of the positivity to the orientation of attention (see Figure 7): for fixations with fast, medium and slow latencies, the positivity emerged with a similar time-course in the 0-200 ms interval following the fixation, even though the timing of the fixation relative to the cue was highly variable: mean latency of the *fast* fixations was 499 ms, of the *medium* fixations 650 ms, and of the *slow* fixations 1048 ms. (The switch-related negativity seen in the cue-locked ERPs preceding the positivity also terminated at about the fixation onset in all three terciles.)

The analysis that directly compared the coupling of the positivity to the cue vs. its coupling to the fixation onset (ERP Analysis 3) revealed that this coupling was modulated by tercile. In the *fast* tercile (comprising trials with the earliest eye-movements from the cue to the relevant region) the positivity at its maximum had substantially (and significantly) larger amplitude in the cue-locked analysis than in the fixation-locked analysis – which indicates that it was better time-locked to the cue than to the fixation (see Figure 8). This difference between the cue-locked and the fixation-locked analysis was much smaller in the *medium* and *slow* terciles (it was non-significantly reversed in the latter), suggesting comparable time-locking of the positivity to the cue onset and the fixation onset in these two terciles.

What are the implications for the processing architecture? In the introduction we sketched models in which a task-selection process TS (including cue interpretation) is followed by an attention shift process AS and a rule configuration process RC that requires more processing on switch trials. The AS and RC processes occur serially or in parallel. Completion of the AS process results in the observed fixation after a delay of *x* ms (comprising motor programming, neural transmission to eye muscles, and the duration of the saccade). The effect of switching on the RC process manifests, with a possible lag of *y* ms, as the positivity. The consistent ordering and substantial time-locking of the two indices, in spite of the large variability in fixation onset time, argues against them being generated by two parallel processes with largely independent durations and variance, as in the $Parallel_2$ model. On the other hand, the time-locking to fixation onset is far from perfect – and in fact inferior to the time-locking to the cue onset for the third of trials with the fastest eye-movements to the relevant location; for the remaining trials the positivity reached comparable amplitudes in the fixation-locked and in the cue-locked ERPs. Hence, we can reject the $Serial_2$ model, whose strict requirement is that the positivity reaches larger amplitude when time-locked to the fixation onset, because fixation on the relevant location must be achieved before the RC process begins.

This seems to leave in contention two models: $Serial_1$, in which the AS and RC processes unfold sequentially, following TS, and $Parallel_1$, in which completion of the TS process triggers parallel AS and RC processes. What assumptions does each have to make, given the ordering of the two indices, their temporal coupling to one another and to the cue, and the large variability of the fixation onset times?

Of the two models, $Serial_1$ may seem more consistent with the observed order of the fixation and the positivity; its core tenet is: first AS then RC. In all models, fixation is assumed to follow the achievement of AS (and the onset of RC) by some delay *x*.

Close inspection of Figure 7 shows that the positivity emerges at 20-40 ms following fixation onset in the fast and slow terciles, and at 50-70 ms following fixation onset in the medium tercile[9]. Thus if, as estimated in the Introduction, *Mx* is ~100 ms, $Serial_1$ requires a lag between the onset of the RC process and the emergence of the positivity of ~100-140 ms. A potential source of such a lag is the overlap between the scalp distribution of the positivity and the earlier switch-related negativity in central and posterior scalp regions – the negativity must return to baseline and/or the positivity must overcome it to be detected.

In the $Parallel_1$ model, RC does not follow but is initiated simultaneously with AS, so this model has to assume an even longer lag between the onset of the RC process and the emergence of the positivity – to account for an extra delay in the production of a fixation equal to *Mb* (see Figure 1). If, following Logan (2005), we estimate Mb as ~70-100 ms, that would require a lag of ~170-240 ms between the onset of RC and the onset of the positivity. Moreover, if the preceding negativity over the fronto-parietal scalp regions reflects AS and/or the transition from AS to an eye-movement (as we suggest below in more detail), $Parallel_1$ will also have to explain why the negativity precedes (or reaches maximum before) the positivity. This is not an issue for $Serial_1$ because AS necessarily precedes RC and its correlate – the positivity. Thus, $Parallel_1$ would presumably need to assume that RC simply takes much longer to "get going" and generate its observable correlate than AS.

Hence both $Serial_1$ and $Parallel_1$ can deal with the observed order of fixation and positivity, but need extra assumptions to account for the observed delays between fixation and positivity (and, on one interpretation, the timing of the preceding

[9] Although in Table 2 the positivity is statistically significant only starting from 100-200 ms following fixation onset – however the positivity already had to "ramp-up" to that point to reach the significance criterion, so it would be too conservative to use the time to reach the significance threshold as an onset estimate. We also note that the positivity approached significance in two terciles (fast and slow) even in the earler, 0-100 ms, time-window (see Table 2).

negativity), So far, these assumptions appear somewhat less plausible for the $Parallel_1$ model. But the situation changes when we consider another criterion: the degree of temporal coupling (or "time-locking" in ERP-speak) between the positivity and the task cue compared to that between the positivity and the fixation onset. Our analyses suggest that for the fast tercile the positivity is more coupled to the cue than to the fixation onset; for the intermediate and slow terciles this difference largely disappears (and may even be numerically, though non-significantly, reversed in the slow tercile). Since in $Serial_1$, the RC process underlying the positivity is directly triggered by the AS process, we would expect much tighter time-locking of the positivity to the fixation onset than to the cue onset (or the anticipated stimulus onset, for that matter). More formally, in terms of the durations in Figure 1, the variance of the time taken to accomplish a fixation following determination of its target has to be greater (for the shortest tercile) or approximately equal (for the other terciles) to the summed variances of the TS and AS processes: $Vx \geq Va + Vb$. As the process underlying x is both brief (~100 ms) and relatively ballistic, whereas the process durations a+b are much longer and highly variable (consider the 549 ms difference between the mean fixation latencies in the fastest and slowest terciles), this assumption seems highly implausible.

In contrast, the $Parallel_1$ model places much less constraint on the temporal coupling of fixation and positivity, as they are generated by processes with independent durations. It is likely that the processes preceding TS have a shorter duration and are less variable in the fast tercile than in the remaining terciles. Hence, in the fast tercile, the variance of TS may well be less than the summed variances of AS and fixation (or $V\mathit{a} < V\mathit{b} + V\mathit{x}$). As the duration and variability in TS increases, for the *medium* and *slow* terciles, its variance becomes comparable ($V\mathit{a} \approx V\mathit{b} + V\mathit{x}$), or even greater than, for the *slow* tercile, the summed variances of AS and fixation ($V\mathit{a} > V\mathit{b} + V\mathit{x}$). Essentially, the overarching assumption here is that the substantial variance in the

distribution of fixations (see above the mean fixation onsets for the three terciles) are largely driven by variability in the duration of the initial TS process (including any optional waiting time – see Introduction).

In conclusion, although $Parallel_1$ seems somewhat less parsimonious in accounting for the lag between the onset of the positivity and the fixation onset, $Serial_1$ struggles badly when it comes to the temporal coupling of the positivity; essentially, it cannot offer a plausible account for the observation that the positivity was equally (or better) time-locked to the task cue than to the fixation. We therefore tentatively favour the $Parallel_1$ model. With regard to the theoretical accounts of task-set control outlined in the Introduction, this conclusion is more consistent with Logan and Gordon's (2001) application of their ECTVA model to task switching, which assumes that all task-set parameters are configured ("transmitted" from WM to the TVA) in parallel, than with Meiran and colleagues' CARIS framework (2000, 2008), where processing of task-set components is serial – though we need to note that attentional selection in CARIS did not include a spatial parameter; the perceptual selection parameters it modelled were non-spatial dimensions such as shape and colour.

Might the current experiment be construed as a PRP paradigm with two distinct tasks: shift spatial attention to the task-relevant location, then perform the relevant number classification task[10]? Such a construal, coupled with a classic response selection bottleneck account of the PRP effect (Pashler, 1984, 1994) provides a rationale for the positivity following the fixation, but in terms of the detailed timing would appear to make the same predictions as the Serial models we have already considered. The appeal of any such account is further reduced by two kinds of consideration. First, in PRP paradigms, participants are explicitly instructed (a) what the responses in the two tasks are and (b) in what order the tasks must be performed. Neither of the above was the case

[10] We thank an anonymous reviewer for bringing this interpretation to our attention.

in the current experiment: we neither (a) instructed participants to move their eyes to one of the dots during the CSI (before the digits appeared), nor (b) told them to first make an eye-movement and only then think of other aspects of the task, such as the relevant number categories and the corresponding responses. Second, when one of the concurrent tasks used in a PRP experiment has high S-R compatibility, the PRP effect is eliminated. One such task is making a saccadic movement towards a spot (Pashler et al., 1993) – which is, of course, what our participants had to do, the only difference being that the target spot was one of three, with the relevant spot changing on switch trials.

The current analysis revealed another switch-repeat difference in the ERP – a switch-related negativity over the central frontal and parietal scalp, which has not been reported hitherto in task-switching experiments, possibly because almost no ERP task-switching studies to date have used a paradigm where tasks are bound to spatial locations, as it was done here and in other eye-tracking studies from our laboratory (Longman et al., 2013, 2014, 2016, 2017). As far as we are aware, only one other ERP task-cuing study, by Astle et al. (2008) has included a condition with tasks consistently bound to distinct locations on the display. Astle and colleagues did not find a switch-related fronto-central negativity. However, they made efforts to prevent participants from overtly shifting spatial attention by instructing them to maintain central fixation and excluded from the analysis trials containing eye-movements. Our negativity, like the positivity, had its timing tightly coupled to the latency of fixation but, unlike the positivity, which always followed the fixation, the negativity always preceded it, consistent with the eye-tracking evidence that attention was shifted first. Taken together with the absence of the negativity in Astle et al.'s (2008) study, this suggests that the negativity is plausibly an electrophysiological correlate either of overt reorienting of spatial attention, or of the reconfiguration of eye-movement programs resulting from such reorienting during a task-switch in the current paradigm, in which tasks were

associated with locations and early (preparatory) eye-movements to these locations were not discouraged. Given the scalp distribution of the negativity, its anatomical substrates might be in the superior parietal lobule and the frontal eye-fields (and/or supplementary eye-fields), both regions involved in spatial orienting and programming of eye-movements.

In conclusion, our data suggest that advance reconfiguration of at least some key components of task-set – can occur in parallel. In particular, when stimulus location is an essential parameter of the task-set, it does not seem that other task-set components (such as the relevant categorisation or S-R mappings) has to wait for spatial attention to be shifted in order for their preparatory reconfiguration to proceed.

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Data Repository: All raw data files are stored on the Open Science Framework data repository (https://osf.io/bpq5c/).

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