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## **Attentional Inertia and Delayed Orienting of Spatial Attention in Task-Switching**

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**Abstract**

Among the potential, but neglected, sources of task-switch costs is the need to reallocate attention to different attributes or objects. Even theorists who recognize the importance of attentional resetting in task-switching sometimes think it too efficient to result in significant behavioral costs. We examined the dynamics of spatial attention in a task-cuing paradigm using eye-tracking. Digits appeared simultaneously at three locations. A cue preceded this display by a variable interval, instructing the performance of one of three classification tasks (odd-even, low-high, inner-outer) each consistently associated with a location, so that task preparation could be tracked via fixation of the task-relevant location. Task-switching led to a delay in selecting the relevant location and a tendency to misallocate attention; the previously relevant location attracted attention much more than the other irrelevant location on switch trials, indicating ‘inertia’ in attentional parameters rather than mere distractibility. These effects predicted RT switch costs within and over participants. The switch-induced delay was not confined to trials with slow/late orienting, but characteristic of most switch trials. The attentional pull of the previously relevant location was substantially reduced, but not eliminated, by extending the preparation interval to more than 1 sec, suggesting that attentional inertia contributes to the ‘residual’ switch cost. A control condition, using identical displays but only one task, showed that these effects could not be attributed to the (small and transient) delays or inertia observed when the required orientation changed between trials in the absence of a task change.

**Keywords:** task-switching, spatial attention, attentional inertia, eye-tracking.

Purposeful behavior demands appropriate allocation of mental resources to the task and their coherent organization – a ‘task-set’. The control of task-set has been extensively investigated in the laboratory using *task-switching* paradigms (for reviews see Kiesel et al., 2010; Monsell, 2003; Vandierendonck, Liefoghe, & Verbruggen, 2010). On each of a series of trials a stimulus is presented and the participant performs one of two or more tasks. Typically the tasks involve semantic or perceptual categorization or identification (e.g., parity or magnitude classification of a digit), the stimulus is bi-/multivalent (it affords more than one task) and the required task changes from time to time in a predictable (e.g., Rogers & Monsell, 1995) or unpredictable (e.g., Meiran, 1996) sequence. When the sequence is unpredictable, investigators tend to employ *task-cuing* – on each trial, the stimulus is preceded by a cue specifying the task to be performed (e.g., Meiran, 1996; Sudevan & Taylor, 1987).

A change of task results in substantially longer response times (RT) and often higher error rates than a task repetition. This ‘switch cost’ can be reduced by increasing the interval available for preparation for the imperative stimulus (e.g., Meiran, 1996; Monsell & Mizon, 2006; Rogers & Monsell, 1995). This reduction in switch cost with increased preparation time (the ‘RISC’ effect) has been taken as evidence for a time consuming, endogenous process (or set of processes) which must be performed on switch trials – ‘task-set reconfiguration’ (TSR, Monsell, 2003; Rogers & Monsell, 1995). Completing TSR in advance of the stimulus reduces processing demands after stimulus onset, reducing RT and/or the likelihood of an error. Converging evidence for TSR also comes from electrophysiological (ERP) studies of task-switching which report a protracted and substantial switch-induced posterior positive-polarity modulation of brain

potentials during the late part of the preparation interval (see Karayanidis et al., 2010, for a review) often accompanied or followed by frontal negative-polarity modulations (e.g., Astle, Jackson & Swainson, 2006; Lavric, Mizon, & Monsell, 2008). The magnitude of these switch-related brain-potential deflections, particularly the posterior switch-induced positivity, has been shown to correlate with the effectiveness of preparation for a switch within (Karayanidis, Provost, Brown, Paton, & Heathcote, 2011; Lavric et al., 2008) and over (Elchlepp, Lavric, Mizon, & Monsell, 2012) individuals.

However, even ample opportunity for preparation and strong incentives to prepare rarely eliminate the switch cost (e.g., Nieuwenhuis & Monsell, 2002, though see Astle, Jackson, & Swainson, 2008, and Verbruggen, Liefoghe, Vandierendonck, & Demanet, 2007). There are two classes of account of the (asymptotic) ‘residual’ switch cost. According to one class, there is an intrinsic limit to the task-readiness that can be achieved by preparation alone (i.e., without actually performing the task at least once). This limit might reflect some element of reconfiguration that cannot be performed until the stimulus is available (Hübner, Futterer, & Steinhauser, 2001; Meiran, 2000; Rogers & Monsell, 1995; Rubinstein, Meyer, & Evans, 2001) – such as loading of S-R rules into working memory (Rubinstein et al., 2001), or until a response is selected – such as the biasing of response set (Meiran, 2000) or inhibition of the irrelevant S-R rules (Schuch & Koch, 2003). It might also reflect a carry over of the previous task-set parameters – ‘task-set inertia’ (Allport, Styles & Hsieh, 1994; Yeung & Monsell, 2003; Yeung, Nystrom, Aronson & Cohen, 2006) – that cannot be suppressed by preparation, and/or associative reactivation of a previous task-set by the stimulus that cannot be pre-empted by preparation (Waszak, Hommel, & Allport, 2003); the relative contribution of inertia-

like persistence and associative reactivation remains a topic for debate (e.g., Elchlepp, Rumball, & Lavric, 2013; Koch & Allort, 2006; Mayr, Kuhns, & Hubbard, in press; Monsell & Mizon, under revision). According to another class of account (De Jong, 2000; Brown, Lehmann, & Poboka, 2006) optimal task-readiness can be achieved through preparation on *some* trials, it is just that preparation fails on a proportion of trials. The residual cost results from a mixture of some switch trials on which preparation is complete, and some on which it fails.

Theoretical/computational accounts of task-set control assume that activating a task-set has multiple components, including shifting attention to relevant stimulus attributes, activating a goal representation, the task's S-R rules, and effectors, and setting response criteria (e.g., Brown, Reynolds & Braver, 2007; Goschke, 2000; Logan & Gordon, 2001; Meiran, 2000; Monsell, 2003; Rogers & Monsell, 1995). Switch costs might arise from any of these components. Empirical research has tended to focus on response selection as the primary locus of the switch cost. One reason for this may be that, when performing one task, it is harder to respond if the other task(s) maps the stimulus onto a different response, and this congruence effect is often larger on a switch trial (Rogers & Monsell, 1995). There is a substantial literature on the conditions that do/do not result in inertia of the previously-relevant S-R rules (see Kiesel et al., 2010, for a review). Research on task-set preparation has also had a strong focus on S-R rules; for instance it has examined whether the relevant set of S-R rules is activated in advance of the stimulus (Mayr & Kliegl, 2000; Rubinstein et al., 2001), whether certain S-R rules are prepared more than others – perhaps because S-R rules are serially “loaded” (Lien, Ruthruff, Remington, & Johnston, 2005), and on the role of verbal mediation in

representation and preparation of S-R rules (e.g., Liefoghe, Vandierendonck, Muyliaert, Verbruggen, & Vanneste, 2005; Van't Wout, Lavric, & Monsell, 2013). It should be acknowledged, however, that the effect of response congruence is observed long beyond the transient switch cost (e.g., Monsell, Sumner, & Waters, 2003), and that response congruence effects are often not reduced by preparation – whereas preparation does substantially reduce the switch cost (Monsell & Mizon, 2006; Rogers & Monsell, 1995).

A component of task-set that has received less empirical scrutiny is attentional selection. Switching between perceptual categorizations (e.g., color and shape) requires a shift of attention between perceptual dimensions. Switching between semantic categorizations of spatially separable elements of compound stimuli (e.g., vowel/consonant and odd/even classifications of letter-digit stimuli) necessitates orienting attention to the relevant spatial location. Even switching between different semantic classifications of a single symbol (e.g., odd-even versus low-high classifications of a digit) or word can be construed as requiring (internal) attention to different semantic attributes. The role of attention in task-switching has been explicitly captured in some computational models of task-set control. In particular, Meiran and colleagues (Meiran, 2000; Meiran, Kessler, & Adi-Japha, 2008) have distinguished in their models between input selection (i.e., the relative weighing of the relevant perceptual attributes of the stimulus) and response selection (the biasing of S-R mappings). In Logan and Gordon's (2001) ECTVA model, a change of task-set involves deriving in working memory (WM) a set of control parameters from propositional task instructions and transferring these parameters to a stimulus (attentional) selection module and a response selection module. However, these models diverge with regard to how and when attentional selection occurs.

In ECTVA the parameters for perceptual selection and those related to response selection (S-R biasing and response criterion parameters) are all transmitted in parallel from WM to the stimulus selection and response selection modules, and the perceptual selection parameter and S-R biasing parameter influence processing concurrently, as part of the same processing module. In contrast, in the computational framework by Meiran and colleagues, the resetting of parameters governing input (attentional) and output (response) selection occurs at distinct processing stages – though the order in which they are reset has changed between instantiations of this framework. In Meiran's (2000) model the resetting of perceptual selection parameters required by a task-switch can be done early, in advance of the stimulus (the preparation interval permitting), whereas S-R biases can only be reset following response selection – hence the 'residual' switch cost. But in the more recent CARIS framework (Meiran et al., 2008), the model reported to fit the empirical data best contained no advance (pre-stimulus) resetting of perceptual selection parameters on switch trials, though response selection parameters could be reset in advance; the authors suggested that when the task changes the stimulus may need to be physically present for perceptual (attentional) reconfiguring to take place.

Thus, although attentional selection seems relatively common currency in computational accounts of task-set control, there is disagreement with regard to how/when attentional parameters are (re)configured. Meanwhile, empirical evidence that speaks to the issue of attentional (re)configuration in task-switching is scarce. Rushworth, Passingham and Nobre (2005) required participants to switch between attending to the target color or shape of two colored shapes and identify the symbols superimposed on it (e.g., respond via a keypress to the symbol on the red rather than the green shape, or to



the symbol on the rectangle rather than the triangle); the S-R rules remained constant. ERPs acquired during the substantial cue-to-stimulus interval (CSI) of 2000 ms revealed clear switch-repeat differences (including the above-mentioned posterior switch-related positivity), which were interpreted as indexing advance resetting of attention. The presence of a switch cost despite ample opportunity for preparation could be taken to suggest attentional inertia. However, without a shorter CSI condition (allowing a measure of reduction in switch cost with preparation) it is difficult to tell whether preparation was effective and the observed switch cost asymptotic.

Switches of attention between dimensions or between values of the same dimension have also been examined in the visual search literature. In visual search for a singleton popout target, Müller, Reimann, and Krummenacher (2003) have shown that detection RTs are longer if the popout dimension changes – a dimensional switch cost. Verbally cuing the dimension on which the target will pop out (SHAPE, COLOR) reduced this switch cost by about half – a proportional reduction similar in magnitude to the RISC effect in task-switching. Müller et al. attributed this to top-down control of the relative weighting of the dimensions in a “global salience map”, which enables detection of the target and guides attention to it for further processing (as in Found and Müller’s, 1996, Dimension Weighting Account, seen as an extension of Wolfe’s, 1994, guided search model). This account has been challenged on the grounds that dimensional inter-trial effects are very small or altogether absent in ‘compound search’ (Mortier, Theeuwes, & Starreveld, 2005; Theeuwes, Reimann, & Mortier, 2006), when the response is (as in Rushworth et al.’s, 2005, task-switching study) specified by an unrelated property of the singleton target – e.g., all the objects have a superimposed grating, and the participant

must respond to the orientation of the target's grating. Instead, it was suggested that dimensional change effects arise at a post-selection stage when the selected targets are translated into responses. However, Müller and colleagues (Töllner, Grammann, Müller, Kiss, & Eimer, 2008) also examined ERPs in the compound search paradigm and found that a switch in dimension delayed the onset of the N2pc brain potential (contra-lateral to the target hemifield, believed to index the transition between preattentive encoding and attentional selection), whereas a valid cue brought forward N2pc onset. Although the effects were modest in size (perhaps because a singleton target “pops out” without preparation, so there is little incentive to focus on a dimension in advance, especially when the response requires attention to another dimension), they suggest an early attentional locus of the switching and cuing effects. A much larger effect of advance dimension cuing has been shown for conjunction search (Weidner & Müller, 2009) – where the target does not pop out. More recently the Dimensional Weighing account has been extended to account for effects that may arise at later stages of processing, such as response selection (the Multiple Weighting Systems hypothesis, Rangelov, Muller, & Zehetleitner, 2012); this extended account is very much in the spirit of Meiran and colleagues’s earlier modelling framework (see above), in which the task-set comprises distinct weighting systems for perceptual vs. response selection.

The cost of a change in the relevant perceptual attribute and the reduction in this cost with preparation has also been documented for spatial attention (Chiu & Yantis, 2009; Logan, 2005) and auditory attention (selecting the relevant voice in a dichotic-listening paradigm, Koch, Lawo, Fels, & Vorländer, 2011). However, an important characteristic of these studies, as well as Rushworth et al.’ (2005) ERP study and the

visual search investigations above, is that, unlike most task-switching studies, they required no change of categorization/decision criteria and S-R rules: these other key components of the task-set remained (largely) constant over trials. This leaves open the issue whether the more substantial change of task-set required in conventional task-switching experiments may result in greater costs of attentional reorienting than those reported in the visual search literature, including greater attentional inertia.

Lien, Ruthruff and Johnston (2010) argue, to the contrary, that reconfiguring attention as a component of task switching can be highly efficient, resulting in no carry-over to the next trial. Their Experiment 4 combined the *contingent capture* paradigm (Folk, Remington, & Johnston, 1992) with conventional task switching. They asked participants to perform a parity or magnitude judgment for one of four digits two or which were displayed in red and green. The target digit and task were cued on every trial (at a CSI of 1350 ms) by the first letter of the name of one of these two colors, which were consistently associated with the two possible classification tasks (e.g., “R” might cue red and the parity task). The critical feature of the design was the brief (50 ms) presentation shortly before the stimulus of a second, uninformative, ‘cue’ whose color and location did or did not match the color and location of the to-be-attended target. Consistent with the contingent capture literature (e.g., Folk et al., 1992), the uninformative cue captured attention (as indexed by faster responses to targets presented in the same location) only when presented in the task-relevant color. Although switch costs were substantial, Lien et al. found no evidence of capture by the *previously* relevant color on task-switch trials. They concluded (presumably with reference to conditions with generous preparation intervals such as their CSI) that, when task-set changes, attention

can be reconfigured so effectively that there is no carry-over of the previous attentional settings, and hence that attentional inertia is unlikely to contribute to their (residual) switch cost.

Two other studies that recently investigated attentional selection in the context of task-switching reached a rather different conclusion. Mayr, Kuhns and Rieter (2013) presented participants with compound stimuli made of three vertical blue bars, located at the vertices of an imaginary equilateral triangle (rotated from trial to trial so that 12 equally spaced locations on a circle were used). On each trial one bar had a different shade of blue than the other two (the “color singleton”), whilst another bar had a gap above or below its middle (the “gap singleton”). The tasks were to classify either the color of the color singleton (as lighter/darker), or the position of the gap in the gap singleton (as high/low). Each task was specified by one of two word cues presented centrally at one of two CSIs (300 ms or 1000 ms). Fixations recorded as an index of attentional selection revealed that substantial delays in orienting to the relevant bar were caused by a task switch (and hence a switch in the type of singleton that had to be detected) on short CSI trials. Crucially, more opportunity for preparation reduced the handicap on switch trials, but did not eliminate it: there were still fewer fixations of the relevant attribute on switch trials compared to repeat trials.

Mayr and colleagues’ experiments used spatial attention to monitor the dynamics of attention to non-spatial attributes (color, form). A recent investigation in our laboratory (Longman, Lavric, & Monsell, 2012) aimed instead to examine the dynamics of spatial attention per se in switching between two tasks that required attention to different spatial loci. The stimulus on each trial was a photograph of one of four faces with one of four

letters superimposed on the forehead. The task, specified by an auditory word cue (one of two per task) presented at CSIs of 200 ms or 800 ms before the stimulus, was to identify (via a key press) either the face or the letter. The eye movements, recorded from stimulus onset, showed that switching tasks induced a delay in fixation of the relevant stimulus attribute and a tendency to misorient towards the irrelevant attribute (e.g., the letter on the face task trials). These effects of switching were reduced by preparation; nevertheless a ‘residual’ tendency to orient towards the task-irrelevant region remained at the longer CSI. The switch-induced handicap in spatial selection of the relevant attribute predicted the magnitude of the switch cost both within and over participants.

These findings, along with those of Mayr et al. (2013), support the notion that when tasks differ in the attentional parameters required, the resetting of attention during a task-switch is an important contributor to the performance switch cost and, although substantial attentional resetting may be accomplished prior to stimulus onset, even an 800 ms preparation interval does not eliminate the tendency to misallocate attention to the no longer relevant attribute(s) of the stimulus, leaving residual ‘attentional inertia’. Further relevant evidence comes from a recent EEG/ERP study in our lab (Elchlepp, Lavric, & Monsell, under revision) of prepared switching between processing the perceptual and lexical properties of a word stimulus (judging the symmetry of colors over the letters vs. a linguistic task – semantic categorization or lexical decision). We examined the effect of switching from the symmetry task on the onset of the ERP difference between high vs. low frequency words (in a semantic categorization task, Experiment 1) and words vs. pronounceable non-words (in a lexical decision task, Experiment 2). Switching delayed the onset of these differential ERP effects as early as ~200-250 ms following stimulus

onset, consistent with early lexical or pre-lexical processes being prolonged by non-optimal setting of attentional parameters for the relevant dimensions.

However, a number of key questions remain unanswered. First, there has not been an unequivocal demonstration of the effects of switching tasks on spatial attention. Although in Longman et al. (2012) the spatial predictability of the two stimulus attributes (face and letter) evidently encouraged spatial (location-based) selection of the relevant attribute, different features had to be attended to for the two tasks (face features and letter features) and one could not rule out some contribution from non-spatial feature selection to the observed task-switch costs. Second, neither of the above-mentioned eye-tracking investigations documented attentional dynamics during the preparation interval (in advance of the imperative stimulus). In the absence of such a record, the reduction in switch-induced fixation delays with preparation merely suggests, but does not demonstrate, that spatial (Longman et al., 2012) or non-spatial (Mayr et al., 2013) attention is reconfigured during the CSI; indeed, other components of the task-set may be reconfigured in advance allowing for early/rapid attentional reconfiguration and more efficient attentional selection post-stimulus on long CSI trials. These other task-set components include any of: the activation of the task 'goal' (e.g., Goschke, 2000), the activation of the semantic information relevant for the current classification (e.g. the semantics of the relevant categories), the activation of relevant S-R (or category-response) mappings (as in Meiran et al.'s, 2008, simulations), the adjustment of the response threshold. Third, with only two CSIs, as in the previous studies, we cannot be sure that the effects of preparation were asymptotic – and hence estimate a true 'residual' limitation on what preparation can achieve. Fourth, with only two possible task-related

targets of attention (as in the eye-tracking studies to date), we cannot tell whether the irrelevant object pulls attention towards it specifically because of its task-relevance on the previous trial, or because of a general increment in distractibility or difficulty in task-relevant orienting on task-switch trials.

Last but not least, we are interested in attentional orientation as a component of task-set. Hence we need to be sure that the delays and inertia in orienting reported in Longman et al. (2012) are indeed associated with task-sets, not just a general property of spatial attention or inertia in the oculomotor system's settings. Is there prior evidence for a tendency to orient to the same object or location as fixated several seconds before? The literature on spatial orienting might predict, if anything, the opposite. In their pioneering attention-cuing experiments Posner and Cohen (1984) demonstrated a greater difficulty in returning covert attention to a recently attended exogenously cued location – “inhibition of return” – and this was subsequently shown to apply to overt shifts of attention whether exogenously or endogenously cued (Rafal, Calabresi, Brennan, & Sciolto, 1989). Klein (2000) reviewed evidence suggesting that inhibition of return can persist for more than a second. However, a more recent investigation by Chiu and Yantis (2009), which compared left-right shifts of spatial attention to digits presented among letters with switching between categorizations of these digits (odd/even, high/low) found no performance cost associated with attending to the same side of the stimulus as before, as the inhibition of return literature would suggest. On the contrary, as when switching categorization rules, a performance overhead resulted from shifting attention relative to holding it on the same side – but this spatial attention ‘shift cost’ (of ~20 ms) was considerably smaller (by about 50%) than that incurred by a switch of categorization, and

it was not statistically significant. Thus, a critical question that still requires an answer is whether substantial attentional delays and attentional inertia, as in Longman et al. (2012), would be observed if the relevant location changed but the task (categorization, responses) remained the same throughout the experiment.

The present study aimed to answer all these questions. First, our paradigm limited the issue to spatial attention by removing the possibility for non-spatial selection of the task-relevant attribute. We used compound stimuli made of three digits presented at the corners of a fixed equilateral triangle (see Fig. 1). The three digit locations (top, left and right) were consistently associated with three number-classification tasks (e.g., odd vs. even); on each trial the participant was cued to perform one. Second, the design was optimized to reveal preparatory (pre-stimulus) spatial selection in task-switching. A letter cue presented centrally before stimulus onset specified the task (and hence the location) to be selected while three dots were presented in the locations where the three digits would eventually appear, to encourage advance selection of the relevant location. We recorded gaze position throughout the CSI to characterize the effects of a task-switch on this advance orientation. Third, we used four CSIs and extended their range to 1420 ms to chart the preparation function fully and determine whether attentional delays or inertia observed at the longer CSIs were indeed asymptotic. Fourth, by using three tasks, we could, on task-switch trials, compare the tendency to orient to the location fixated on the preceding trial with the tendency to fixate the other irrelevant location, and isolate attentional inertia from general distractibility. Fifth, the compound displays we used afforded a straightforward control condition to estimate how much carry-over, whether positive or negative, from the location fixated on the previous trial could be attributed to



inertia in task-independent oculomotor programs or attentional settings. In the control condition, the stimulus sequence was identical, but the participant performed just one task throughout the experiment; the cue now specified only the location of the relevant digit, not the classification to be performed on it.

### **Experiment 1**

On each trial we presented three different digits equidistant from fixation, as shown in Figure 1, preceded by a letter cue at fixation, displayed briefly in a small font to encourage participants to fixate centrally prior to the cue. In the main task-switching condition the cue specified both the location of the relevant digit and the classification to be performed on it. The three possible classifications were odd/even, high/low (greater than 5 or less than 6) and 'inner/outer' (where 2, 3, 8 and 9 are 'outer' and 4, 5, 6 and 7 are 'inner'). The association between classification task and location was consistent throughout the experiment. The tasks were equiprobable. CSI was constant within a block but varied over blocks to assess effects of preparation. Two cue letters were used per task, and the cue used never repeated from one trial to the next, to avoid confounding task and cue repetition (Logan & Bundesen, 2003; Monsell & Mizon, 2006) and the response-stimulus interval was constant (Meiran, 1996). In the location-switching control condition, the trial sequences were perceptually identical, but the participant performed just one of the three tasks throughout. We monitored eye movements between cue and response to document the effects of switching between categorization tasks on advance re-orientation to the task-relevant stimulus, and any tendency to fixate the previously

relevant location, and to contrast these effects to those of switching the location of the relevant object without a change of task.

Two further details merit consideration. First, the paradigm allows for at least three kinds of response congruence effect. One can examine the congruence of the responses afforded in all three tasks by the digit displayed at the relevant location; this, the response congruence effect typically reported in task-switching, we will refer to as ‘within-location congruence’. One can also look at the congruence with the required response of the responses afforded by the other two digits in the tasks associated with their respective locations (‘cross-location congruence’). Finally, one can investigate what is essentially a “flanker” effect – the compatibility with the required response of the responses to the other two digits according to the relevant task (‘flanker congruence’). The examination of these congruence effects potentially offers insights into the effectiveness of attentional selection. In particular, the presence of cross-location and/or flanker congruence effects would indicate that digits at the irrelevant locations were processed sufficiently to activate responses; conversely, the absence of such effects would suggest effective spatial selection of the relevant digit.

A second feature of the paradigm is that the use of three tasks allows an examination of a sequential effect in task-switching commonly referred to as ‘backward inhibition’ or ‘n-2 repetition cost’ – poorer performance on the third trial of an ABA sequence as compared to CBA, where A, B and C represent three different tasks (e.g., Mayr & Keele, 2000). The n-2 repetition cost is widely viewed as the clearest evidence for task-set inhibition (in the above example returning to task-set A is more difficult, because its inhibition must be overcome). Arbuthnott (2005, 2009) demonstrated that n-2

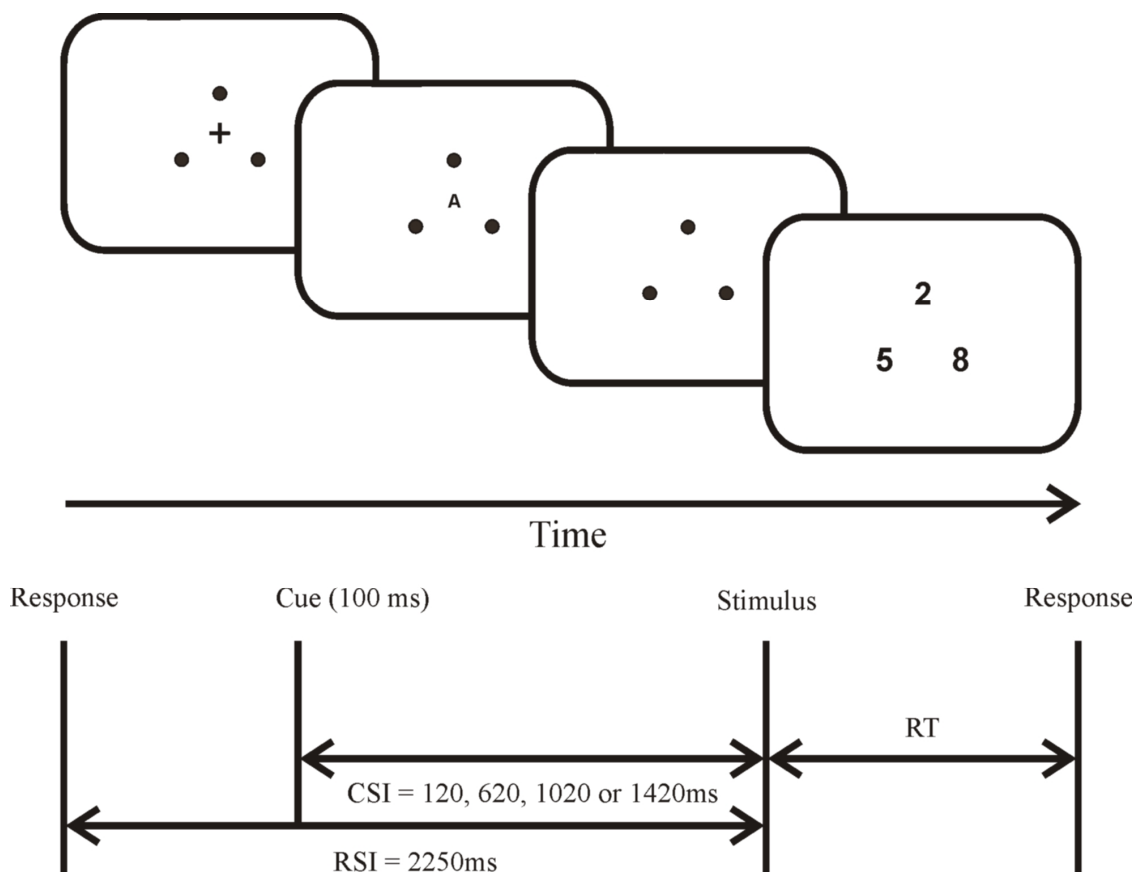
repetition effects can be eliminated when spatial location is used to cue tasks (Arbuthnott, 2005) or when task-cues are presented in unique spatial locations (Arbuthnott, 2009) and attributed this to the possibility that reduced competition from alternative task-sets during task selection eliminates the need for inhibition. Our paradigm offers an opportunity to investigate the  $n-2$  repetition cost when tasks are uniquely, consistently and explicitly associated with locations.

## Method

**Participants.** Forty-eight participants – 24 in the task-switching condition (19 female, mean age, 21.25) and 24 in the location-switching condition (14 female, mean age, 21.54) – provided informed written consent to participate, for which they were paid £10 (£5/hr) plus a performance-related bonus (see next section) of up to £3.60 (mean £3).

**Tasks, stimuli and procedure.** The experiment was run using E-Prime (Psychology Software Tools Inc., Sharpsburg, USA) and a 17" flat (no curvature) CRT monitor placed ~57 cm from the participants' eyes (at this distance  $1^\circ$  of visual angle corresponds to ~1 cm on the monitor). On each trial a black fixation cross (subtending  $0.4^\circ$ ) was presented centrally along with three light blue dots ( $0.3^\circ$  in diameter) at the locations (defined below) where the digits would eventually appear (see Fig. 1). A task cue (one of the letters A, B, C, X, Y and Z, subtending  $0.2^\circ$  horizontally,  $0.3^\circ$  vertically) then replaced the fixation cross for 100 ms, leaving only the three blue dots for the remainder of the cue-stimulus interval (CSI). The cue changed on every trial. The brief display of the cue was intended to encourage advance fixation on the location of the fixation cross and immediate processing of the cue. The stimulus display followed cue onset after one of four CSIs: 120 ms, 620 ms, 1020 ms and 1420 ms. CSI was constant

within a 74-trial block, but varied over blocks; the order of CSIs within the 4-block sequences of which a 16 block session was composed was balanced over participants by a Latin square. The response-stimulus interval was 2250 ms regardless of CSI, except following an error when “ERROR” was displayed for an extra 1000 ms.



*Figure 1.* The time-course of one trial with example displays for Experiment 1. The dots used to identify where the digits would eventually appear were presented in light blue.

The stimulus comprised three different digits (each subtending  $0.4^\circ$  horizontally,  $0.5^\circ$  vertically), chosen from the set 2-9, displayed at three locations arranged in an equilateral triangle,  $5^\circ$  from each other and  $2.7^\circ$  from the centre. In the task-switching condition, the cue specified the classification task to apply: odd/even, low/high or inner/outer, and the location of the digit to apply it to. For each participant each task was

mapped to a single location throughout the experiment (allocation counterbalanced over participants). In the location-switching condition, the cue specified only the location of the relevant digit; the same task was performed throughout the experiment, with eight participants per task.

Mapping of cue to location was the same for all participants ('A' or 'X' referred to the digit at the top, 'B' or 'Y' left, 'C' or 'Z' right). The stimulus was displayed until one of two keys ('c' or 'm' on a standard QWERTY keyboard) was pressed with the left (odd, low, inner) or right (even, high, outer) index finger. Stimuli were generated by first defining the level (e.g., odd, high) of each digit and then randomly selecting a digit from the appropriate set with two constraints: a digit could appear only once in a stimulus and there could be no exact repetition from the previous trial of the whole stimulus (the same three digits in the same locations). Stimuli were also controlled to ensure that the combinations of categories of the three digits (e.g., odd, high, outer) were equiprobable for each task and transition type. The tasks were equiprobable, resulting in a 2:1 switch/repeat ratio. To ensure that analyses contingent on the n-2 trial (triplets ABA vs. CBA, see introduction to Experiment 1) were not confounded with the sequence of tasks, the latter was controlled to ensure that the three tasks were equiprobable for each position in all possible trial triplets.

The CSI was displayed before each block and the mean RT, number of errors and a composite performance score were displayed at the end of each block. Bonus payments were awarded for improvement relative to the average performance on previous blocks with the same CSI. Before the eye-tracking session, task-switching participants practiced each task by itself for 8 trials, and then practiced the cue-task associations in a task-

switching block of 74 trials, in which only one digit was presented centrally on each trial. Location-task mappings were then introduced in another practice block of 74 trials identical to the experimental blocks which followed. For location-switching participants, the practice session had the same number of trials as in the task-switching condition, in this case consisting of one block of 24 trials, in which one digit was displayed centrally, and then two 74-trial blocks equivalent to the experimental blocks that followed.

**Eye-tracking.** An EyeLink 1000 eye-tracker (SR Research, Ottawa, Canada) sampled the gaze position of the right eye and head position (via a sticker placed on the forehead), at a rate of 500 Hz, from the onset of the fixation cross until response; it was calibrated before each 74-trial block. Based on the distribution of fixations obtained, four square regions (side =  $2^\circ$ ) were delineated as containing ‘relevant’ information for the three digits in the stimulus and the cue. On task-repeat trials 95.06% of all fixations occurred within these regions; 94.27% on task-switch trials. In the location-switching condition, these values were 93.95% and 93.97%. Blocks with > 20% of trials containing no fixations in any of the three stimulus regions (suggesting poor calibration) were discarded (mean percentage of blocks discarded for the task-switching condition=0.78%, maximum=6.25%; mean for location switching=0%). The first two trials in each block, trials with RT > 2500 ms (1.61% in the task-switching condition, 0.39% in the location-switching condition) and trials with no fixations on the cue (2.9% in the task-switching condition, 1.54% in the location-switching condition) were omitted from all analyses as were trials following an error. Error trials were omitted from RT and eye-tracking analyses.

Only fixations initiated after cue onset were analyzed. Two measures are presented and were subjected to statistical analysis: (1) total dwell-time on each of the above-mentioned spatial regions of the stimulus within a defined time-window – the summed duration of all fixations on the respective region within the respective time-window; (2) the ‘launch’ time of the first eye-movement away from the cue region. A further measure that was also computed was the fixation count: number of fixations (averaged over all the trials in a given experimental condition) initiated in a particular spatial region during a given time-interval. Because fixation counts reveal a very similar pattern of eye-movements to dwell-time, their analysis is not reported here; however the descriptive statistics for fixation counts are presented in Supplementary Materials.

In ANOVAs, the reported significance values are Huyhn-Feldt-corrected for sphericity violations (but *dfs* are reported uncorrected).

## Results

### **RT and errors.**

**Task- vs. location-switching.** The mean RT and error rate, averaged across all three tasks for both the task-switching and location-switching groups are shown in Figure 2. A switch by CSI by group (task- vs. location-switching) ANOVA on RTs revealed a reliable main effect of switch,  $F(1,46)=107.24$ ,  $p<0.001$ . Although the switch cost was significant in both the task-switching,  $F(1,23)=95.74$ ,  $p<0.001$ , and location-switching,  $F(1,23)=11.63$ ,  $p=0.002$ , groups, it was much larger for the former (106 ms) than the latter (14 ms),  $F(1,46)=62.3$ ;  $p<0.001$  (switch by group interaction). The significant reduction in switch cost with an increasing CSI,  $F(3,138)=4.57$ ,  $p=0.004$ , did not interact with group,  $F<1$ . The switch cost reduced (from the shortest to the longest CSI) from 128

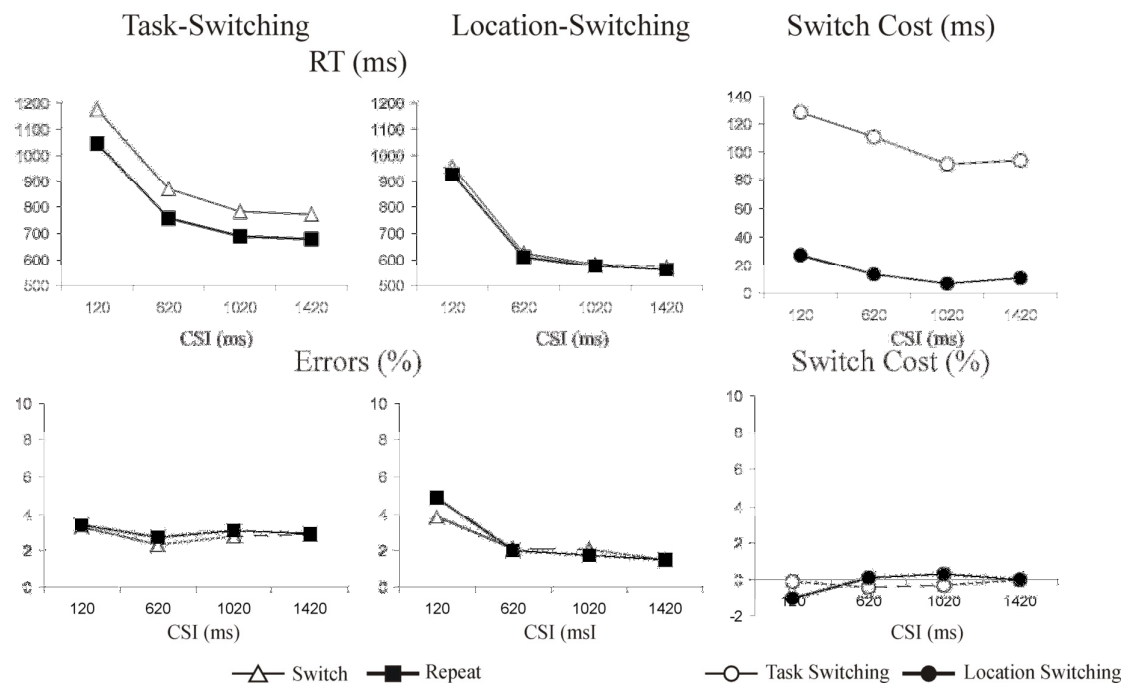
ms to 94 ms for the task-switching group,  $F(3,69)=2.66$ ,  $p=0.055$  (a marginally-significant interaction), and from 27 ms to 10 ms in the location-switching group,  $F(3,69)=2.23$ , n.s. In both groups the switch cost increased slightly (and non-significantly) from CSI=1020 ms to CSI=1420 ms (task switching: from 92 ms to 94 ms; location switching: from 7 ms to 10 ms), suggesting an asymptotic switch cost after ~1 s of preparation. The ANOVAs run separately for the two longest CSIs, to examine this 'residual' switch cost, found it to be statistically significant for the task-switching group: CSI=1020 ms,  $F(1,23)=52.05$ ,  $p<0.001$ ; CSI=1420 ms,  $F(1,23)=48.55$ ,  $p<0.001$ , and only approaching significance for the location-switching group: CSI=1020 ms,  $F(1,23)=2.92$ ,  $p>0.1$ ; CSI=1420 ms,  $F(1,23)=3.0$ ,  $p=0.097$ ; the 95% confidence interval for the switch cost averaged over the two longest CSIs in the location-switching group ( $8.5 \pm 8.7$  ms) included 0, further indicating that it cannot not be reliably distinguished from nil. The ~10-fold difference in the magnitude of the residual switch cost between the task- and location-switching groups (switch by group interaction) was highly significant: CSI=1020 ms,  $F(1,46)=40.85$ ,  $p<0.001$ ; CSI=1420 ms,  $F(1,46)=31.94$ ,  $p<0.001$ .

For the error rates, there were no statistically significant effects involving the switch/repeat factor within or across groups.

**Response congruence.** Because each participant in the location-switching group performed only one task, analyses of within-location and cross-location congruence are possible only for the task-switching group; flanker congruence can be analyzed for both groups. Each kind of congruence has three levels. For example, for within-location congruence the digit can be: congruent (the responses in both irrelevant tasks are the same as in the relevant task), incongruent (the responses in both irrelevant tasks are



different from that in the relevant task) or 'semi-congruent' (the intermediate case: the response in one irrelevant task is the same and in the other irrelevant task is different from the response in the relevant task).



*Figure 2.* Behavioral data from Experiment 1: mean RT, error rate and switch costs (right), for the task-switching (left) and location-switching (middle) groups as a function of cue-stimulus interval (CSI) and transition (switch vs. repeat).

For within-location congruence, an ANOVA with factors congruence, switch, CSI and task found a significant main effect of congruence for RTs,  $F(2,46)=4.99$ ,  $p=0.014$ , and errors,  $F(2,46)=16.11$ ,  $p<0.001$ ; mean RT (errors): congruent=846 ms (1.94%), semi-congruent=842 ms (2.58%), incongruent=862 ms (4.76%). The interaction between congruence and switch did not approach significance for RTs or errors ( $F<1$ ). The RT analysis also revealed a significant main effect of task for both RTs,  $F(2,46)=13.5$ ,  $p<0.001$ , and errors,  $F(2,46)=7.55$ ,  $p=0.004$ , reflecting (for both measures) the best level

of performance in the low/high task (RT=788 ms, errors=2.4%) and the worst in the inner/outer task (RT=903 ms, errors=4.0%; odd/even task RT=859 ms, errors=2.9%)<sup>1</sup>.

The analysis of cross-location congruence found no significant main effect of congruence (mean RT: congruent=846 ms, semi-congruent=847 ms, incongruent=846 ms; errors: congruent=3.10%, semi-congruent=2.81%, incongruent=2.89%) or its interaction with switch. Congruence marginally interacted with CSI for RTs,  $F(6,138)=2.17$ ,  $p=0.052$ , reflecting a marginally reliable congruence effect only for the longest CSI,  $F(2,46)=3.38$ ,  $p=0.051$ . The analysis of flanker congruence (including group as a factor but excluding the task factor) found no significant main effect or interaction involving congruence. For the task-switching group, mean RTs (error rates) were: congruent=844 ms (2.89%), semi-congruent=847 ms (3.07%), incongruent=847 ms (2.65%). For the location-switching group: congruent=675 ms (2.48%), semi-congruent=676 ms (2.36%), incongruent=677 ms (2.60%).

Given the relatively modest effect of within-location congruence, the absence of robust effects of other kinds of congruence, and for the sake of simplicity, these variables were not included in the analyses of eye-movements below.

***N-2 sequence effects.*** An ANOVA on RTs and errors from the task-switching group with factors CSI and n-2 transition (switch: CBA, repeat: ABA) found an n-2 repetition cost for the errors,  $F(1,23)=5.66$ ,  $p=0.026$ , with 0.5% more errors made for ABA than CBA sequences. However, for RTs there was a reliable n-2 repetition benefit,  $F(1,23)=5.91$ ,  $p=0.023$  (ABA responses 14 ms faster than CBA responses), an effect that interacted (diminished) with increasing the CSI,  $F(3,69)=4.35$ ,  $p=0.007$ . Again, given

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<sup>1</sup> The rather opaque interactions involving congruence and task in the RT analysis can be found in the Supplementary Materials.

their equivocal character and small size in the performance data,  $n-2$  sequence effects were not analyzed for the eye-movement data.

**Eye-Tracking.** For the square region surrounding each digit, a mean dwell time was computed for each 20 ms bin following cue-onset – the average number of ms for which that region was fixated in that time bin (minimum=0 ms, maximum=20 ms). (The dwell time divided by 20 is the probability of fixation being in the respective region in that interval - cf. Mayr et al., 2013). Figure 3 shows the mean dwell time in successive bins following cue onset for the task-switching condition (left panels) and the location-switching condition (right panels), for the four CSIs. For repeat trials (those on which the cued task/location was the same as on the previous trial) we distinguish only between fixations on the ‘currently relevant’ and ‘currently irrelevant’ digits. As can be seen, the eyes generally moved some time between 300 and 600 ms following the cue to fixate the relevant digit, with very few inappropriate fixations on the irrelevant digits. For switch trials, we divide fixations on the irrelevant digits into those which landed in the previously relevant and the previously irrelevant region, to detect any tendency to fixate the same region as on the previous trial. In Figure 4 the plots of dwell times on the currently irrelevant digits are rescaled to allow the differences to be seen. Generally speaking, on task-switch trials, appropriate fixation was, on average, both initiated and achieved later than on task-repeat trials and there was some tendency to fixate the previously relevant location on task-switch trials; this tendency was reduced but not eliminated by preparation. In the location-switching condition, there was also a delay in achieving appropriate fixation, but it was smaller than for a task-switch; the tendency to fixate the previously relevant location on location-switch trials was also smaller than on

task-switch trials; both the delay and the tendency to fixate the previously relevant region were eliminated with preparation.

***Dwell time on the relevant region.*** To analyze the apparent delay in attentional selection on switch vs. repeat trials and compare the magnitude of this switch-repeat difference across conditions, a 200-ms time-window was defined over the part of the dwell-time curve that showed maximal rise. For each condition, the time-window started from the time-bin in which the dwell-time (averaged over participants) exceeded 10% of the maximum (10% of 20 ms=2 ms; see Fig. 3 for the time-window boundaries). To estimate the temporal separation between the dwell-time curves for the switch and repeat conditions, we re-sampled the dwell-time curves at a higher temporal resolution – the resolution at which the data were acquired (500 Hz; time-point=2 ms). Then, for every Y-axis value on the repeat curve, we estimated the corresponding value on the switch curve by interpolation<sup>2</sup>, to obtain the difference between the values of the two points on the X (time) axis. Averaging these estimates within the 200-ms time-window defined above provided the mean temporal separation between the switch and repeat curves, which was then submitted to a group by CSI ANOVA. A reliable main effect of group,  $F(1,46)=11.49$ ,  $p=0.001$ <sup>3</sup>, reflected greater separation between the switch and repeat curves in the task-switching group. Although increasing the CSI reduced that separation reliably in both groups (in order of increasing CSIs for the task-switching group: 43 ms,

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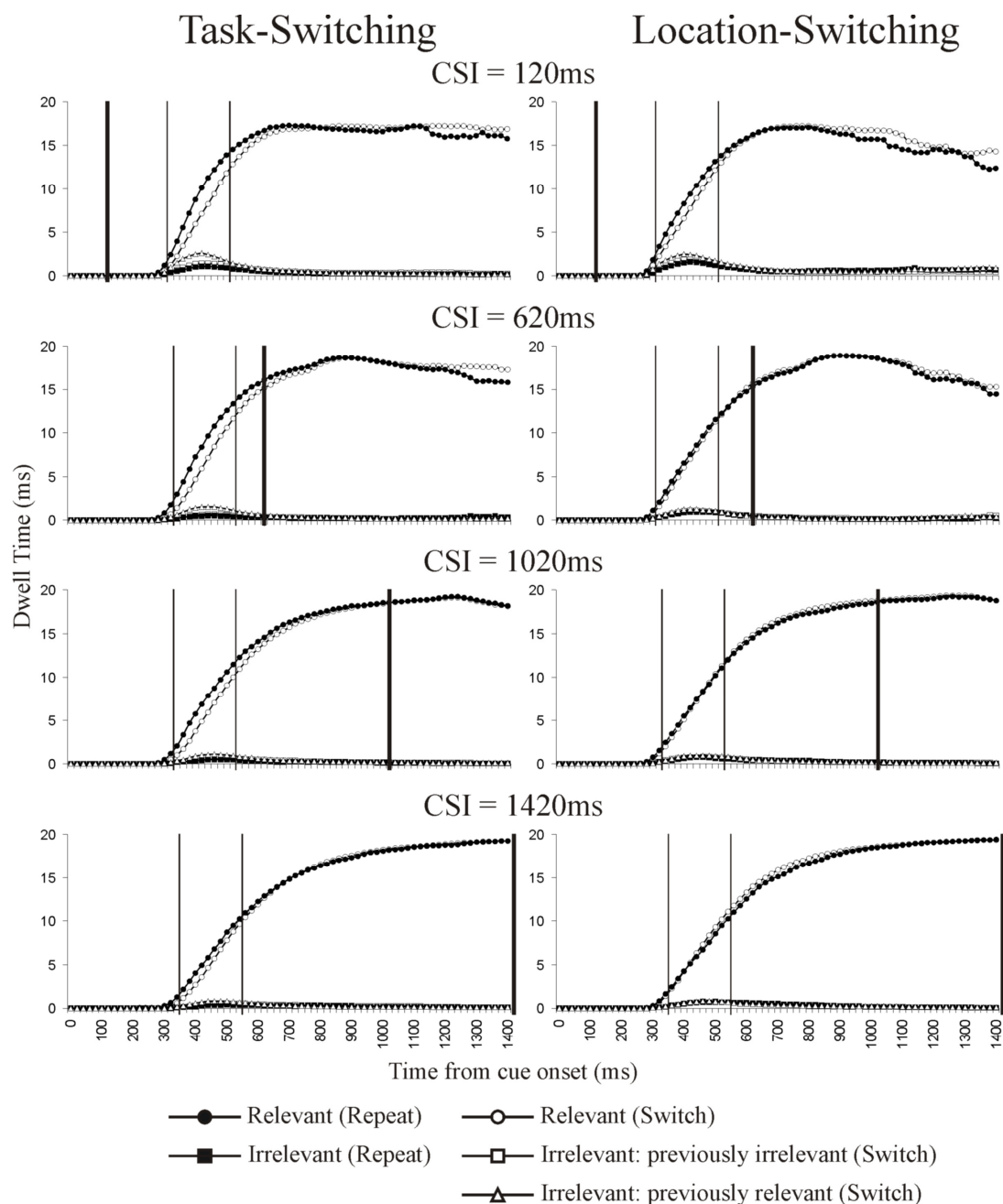
<sup>2</sup> We fitted to the switch curve of each subject a 10-order polynomial (*Polyfit* function in Matlab; Mathworks, Natick, MA, USA). The real (non-complex) polynomial root corresponding to a given Y-axis value on the repeat curve is an estimate of the time at which the switch curve reached this value on the Y axis. This procedure is analogous to a high order spline interpolation.

<sup>3</sup> F-ratios from ANOVAs with task- vs. location-switching conditions as a factor have no subscripts, whereas the F-ratios (and t statistics) from separate ANOVAs for each group have the subscripts ‘task’ or ‘loc’ respectively.

43 ms, 33 ms, 22 ms,  $F(3,69)=4.07$ ,  $p=0.013$ ; location-switching group: 28 ms, 11 ms, 8 ms, -10 ms,  $F(3,69)=14.42$ ,  $p<0.001$ ), only for the task-switching condition did a significant separation remain at the two longest CSIs, as indicated by one-sample t-tests: CSI=1020:  $t_{\text{task}}(23)=4.52$ ,  $p<0.001$ ;  $t_{\text{loc}}(23)=1.37$ , n.s.; CSI=1420:  $t_{\text{task}}(23)=2.75$ ,  $p=0.011$ ;  $t_{\text{loc}}(23)=-1.74$ ,  $p=0.096$ . These results show a greater switch-induced delay in attentional orientation during task switching than during location switching, with a detectable delay at long CSIs only for task switching.

The delay in attending to the relevant region on switch (especially task switch) trials could be due to participants inappropriately fixating an irrelevant region before they fixate the relevant region, and/or to delayed initiation of eye-movements from the cue to the relevant region. The remaining analyses explore both possibilities.

***Dwell-time on the irrelevant regions*** (see Fig. 4). We obtained a measure of the dwell-time on the irrelevant regions by aggregating (for each participant and condition) the dwell-times over the same 200-ms time-window used for the task-relevant region – which effectively is an estimate of the area under the curve within the time-window boundaries.



*Figure 3.* Dwell time (see text for definition) per 20 ms bin in Experiment 1 for 1420 ms following cue onset in the task-switching (left) and location-switching (right) groups 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. Because dwell-time values are several orders of magnitude smaller for the task-irrelevant compared to the task-relevant regions, the former are difficult to discern here – Figure 4 makes them visible by amplifying the scale.

ANOVAs on this measure found that participants attended more to these regions on switch trials than on repeat trials (main effect of switch,  $F(1,46)=33.71$ ,  $p<0.001$ ,  $F_{\text{task}}(1,23)=31.83$ ,  $p<0.001$ ;  $F_{\text{loc}}(1,23)=5.78$ ,  $p=0.025$ ), but more so in the task-switching condition (switch by group interaction,  $F(1,46)=6.76$ ,  $p=0.012$ ).

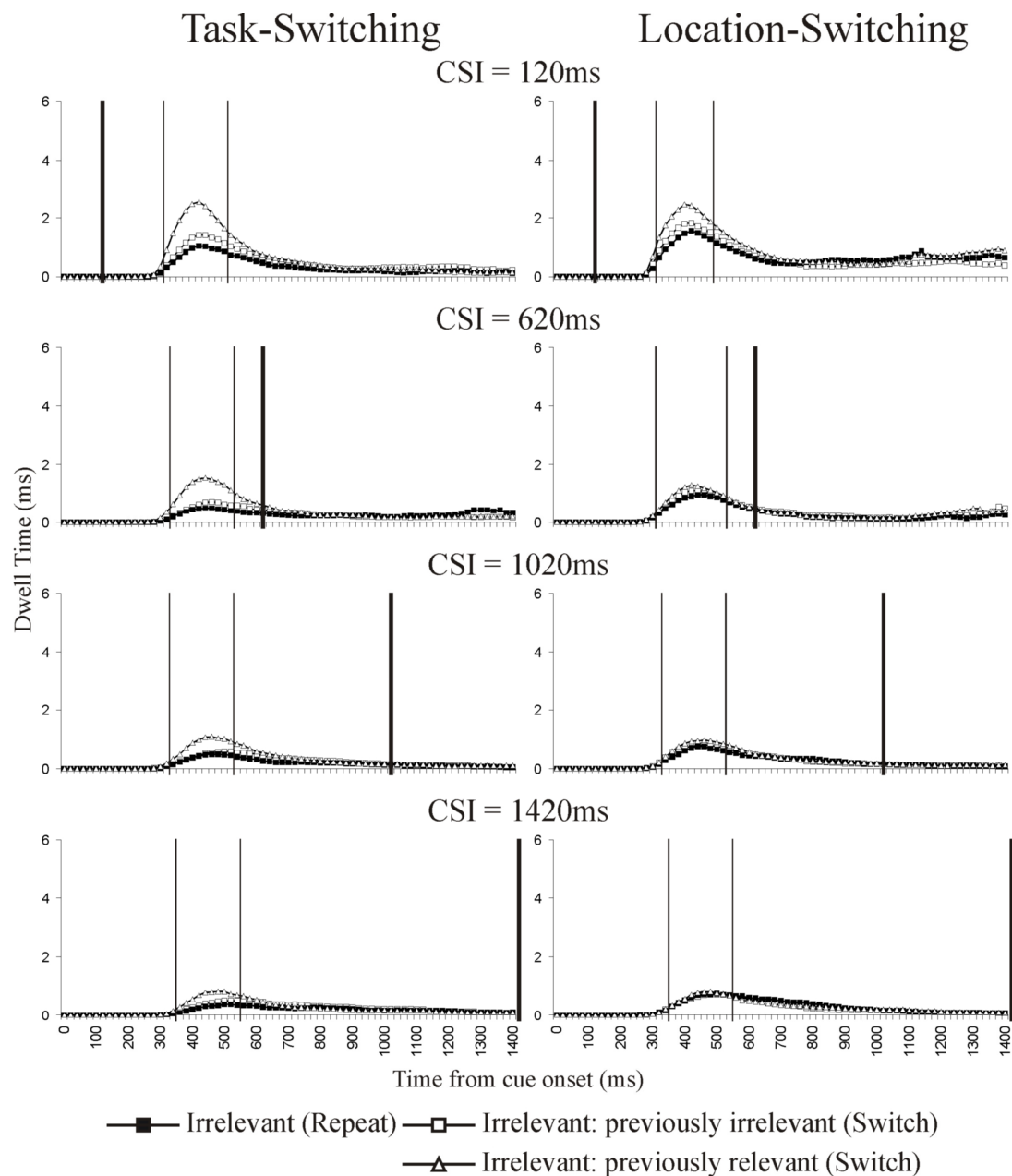


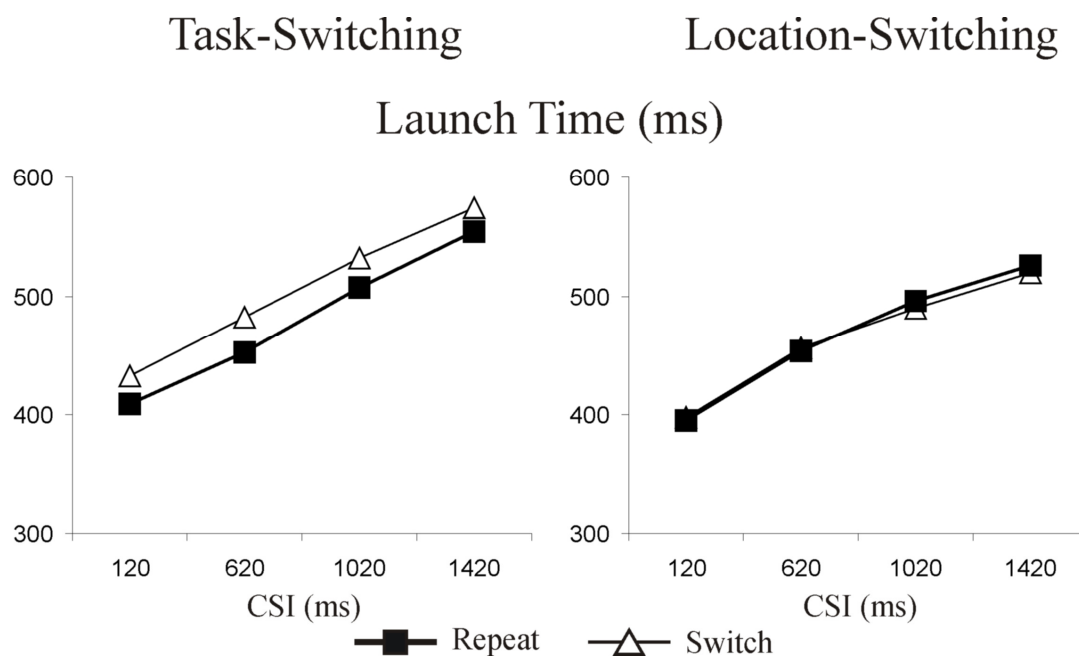
Figure 4. Dwell-time on the task-irrelevant regions in Experiment 1 plotted as in Figure 3 but re-scaled.

This tendency to fixate on the irrelevant regions was reduced with preparation in both groups (switch by CSI interaction,  $F(3,138)=19.63$ ,  $p<0.001$ ,  $F_{\text{task}}(3,69)=9.519$ ,  $p<0.001$ ;  $F_{\text{loc}}(3,69)=11.31$ ,  $p<0.001$ ; switch by CSI by group interaction,  $F(3,138)=0.98$ , n.s.). However, a substantial ‘residual’ difference was present at long CSIs only for the task-switching group (main effect of switch at: CSI=1020,  $F_{\text{task}}(1,23)=11.31$ ,  $p=0.003$ ;  $F_{\text{loc}}(1,23)=2.25$ , n.s.; CSI=1420,  $F_{\text{task}}(1,23)=11.31$ ,  $p=0.003$ ;  $F_{\text{loc}}(1,23)=1.0$ , n.s.).

As noted in the Introduction, using three tasks enables one to distinguish, on switch trials, between the time spent attending to the irrelevant region which was relevant on the previous trial and the time spent fixating the other irrelevant region (which is otherwise equivalent). This contrast serves as one index of carry-over of attentional settings from the preceding trial (attentional inertia) unconfounded from task-independent distraction. A previous-relevance by CSI by group ANOVA (and follow-up ANOVAs) found that participants attended on switch trials more to the previously relevant region than the other irrelevant region in both groups,  $F(1,46)=25.09$ ,  $p<0.001$ ,  $F_{\text{task}}(1,23)=21.38$ ,  $p<0.001$ ,  $F_{\text{loc}}(1,23)=4.92$ ,  $p=0.037$ ), but to a greater extent in the task-switching group (previous relevance by group interaction:  $F(1,46)=5.19$ ,  $p=0.027$ ). This difference reduced with preparation (previous relevance by CSI interaction:  $F(3,138)=11.33$ ,  $p<0.001$ ;  $F_{\text{task}}(3,69)=6.7$ ,  $p=0.004$ ;  $F_{\text{loc}}(3,69)=5.76$ ,  $p=0.002$ ; previous relevance by CSI by group interaction:  $F(3,138)=1.29$ , n.s.), but a non-trivial ‘residual’ difference remained at the two longest CSIs only in the task-switching group (main effect of relevance at CSI=1020,  $F_{\text{task}}(1,23)=11.27$ ,  $p=0.003$ ;  $F_{\text{loc}}(1,23)=0.98$ , n.s.; CSI=1420,  $F_{\text{task}}(1,23)=4.87$ ,  $p=0.038$ ;  $F_{\text{loc}}(1,23)=0.35$ , n.s.).



***Launch times for saccades from the cue to the relevant region.*** The above analyses show that the delay in allocating attention to the task-relevant region elicited by task-switching arises at least in part from inappropriate attention to the previously (but no longer) relevant region. But what happened when the first eye-movement away from the cue was appropriately targeted: was its ‘launch’ also delayed by a task-switch? A group by switch by CSI ANOVA indeed revealed a greater switch-induced delay in the launch of the first correctly targeted saccade in the task-switching group than in the location-switching group, with no discernible effect of switch in the latter case (see Fig. 5): switch by group interaction,  $F(1,46)=13.59$ ,  $p=0.001$ ; by group: main effect of switch,  $F_{\text{task}}(1,23)=17.48$ ,  $p<0.001$ ;  $F_{\text{loc}}(1,23)=0.25$ , n.s. There were no reliable interactions involving the factor CSI.



*Figure 5.* Mean ‘launch time’ of the first saccade to leave the cue and land directly in the currently relevant region for the task-switching (left) and location-switching (right) groups as a function of CSI and transition (Experiment 1).

## Discussion

Performance analyses revealed the familiar switch cost, RISC effect, residual switch cost and small (within-location) response congruence effects in the RTs of the task-switching group. In the location-switching group, there was a much smaller RT cost of switching locations, which was not statistically significant at the two longest CSIs. That there is a location switching cost at all may seem somewhat surprising in the light of the “inhibition of return” literature (though our location-switching condition is very different from a search paradigm for which the idea of optimal foraging might suggest a bias to attend to novel locations, Klein, 2000). But costs of shifting spatial attention of similar (Chiu & Yantis, 2009) or greater (Logan, 2005, short CSIs) magnitude have been documented previously. What is critical, however, is that the effects of shifting attention to a location in the location-switching condition are very much smaller and more easily overcome by preparation than the effect of jointly shifting task and location – as indicated by the vastly larger residual switch cost in the task-switching condition.

The lack of a detectable cross-location congruence effect in the task-switching group or of a flanker effect in either group, or of interactions of these effects with switching, suggests the irrelevant digits were not activating responses via either the current or (in the task-switching group) the previous task-rules. It would appear that (in spite of a small proportion of fixations initially to the wrong location) effective spatial orienting and the acuity drop-off away from the fovea largely prevented processing of digits displayed at irrelevant locations to the level of response activation. The analysis of  $n-2$  sequential effects revealed a reliable  $n-2$  repetition cost for errors and a small but

reliable n-2 repetition benefit for RTs; thus, there was no clear evidence of an overall 'backward inhibition' pattern.

The main purpose of the experiment was to look for delays in attentional orientation and carry-over of the previous trial's attentional parameters associated with task-switching. Analyses of dwell-time (Fig. 3) revealed a clear switch-induced delay in orienting to the currently relevant digit following the cue. This delay was much longer in the task-switching than in the location-switching control condition. Moreover, preparation eliminated the delay in the location-switching condition, while a switch-induced delay remained reliable at the two longest CSIs in the task-switching condition. Switching also led to a tendency to fixate irrelevant regions of the display – mainly the location relevant on the preceding trial (Fig. 4). But this carryover of attentional settings was also much stronger in the task-switching condition, and was present even after ample opportunity for preparation (at the two longest CSIs), indicative of 'residual' attentional inertia. There was no sign of such residual attentional inertia in the location-switching condition – indeed in three of the four CSIs (620 ms, 1020 ms and 1420 ms) there was no preference for the previously relevant region over the other irrelevant region on location switching trials. Importantly, this cannot be explained by an overall reduced tendency to fixate the irrelevant regions on location-switching trials: as Table 1 shows, the overall tendency to fixate an irrelevant region was at least as strong in this condition (see the 'Average' rows in the table) – what was different was the distribution of fixations over the irrelevant regions (see also Fig. 4). In the General Discussion we return to the implications of this pattern, which seems to rule out an account of inertia in terms of

‘default’ fixations on the previously relevant region whenever the attentional settings are unstable or fragile.

Table 1.

*Mean Dwell Time (in ms) on Switch Trials for the Currently Irrelevant Regions in the Time Windows Subjected to Statistical Analysis.*

	CSI			
<b>Task switching</b>	<b>120 ms</b>	<b>620 ms</b>	<b>1020 ms</b>	<b>1420 ms</b>
<b>Previously relevant</b>	19.7	12.6	8.5	6.7
<b>Other</b>	11.1	5.5	4.4	3.9
<b>Average</b>	15.4	9.1	6.5	5.3
<b>Location switching</b>				
<b>Previously relevant</b>	20.2	10.3	8.1	6.7
<b>Other</b>	15.1	8.9	6.9	6.0
<b>Average</b>	17.7	9.6	7.5	6.4

*Note.* The maximum dwell time in the critical time window for each CSI is 200 ms.

The analysis of the latency of the first saccade from the cue to the relevant region (on trials for which the relevant region was correctly targeted on the first saccade away from the cue) also found substantial delays in the task-switching condition, but none in the location-switching condition, demonstrating that the handicap in spatial selection observed on a task-switch trial was not confined to trials on which the irrelevant regions were fixated first (see Fig. 5). The lack of a latency effect for the location-switching condition also implies that (small) delays seen for the shortest CSIs in the dwell-time analyses of that condition were entirely due to occasional fixations on the irrelevant regions.

These results show that there are robust effects of task-switching on orienting attention to the task-relevant location over and above effects of location switching per se, and that the former, unlike the latter, are resistant to elimination through preparation. However, to enable us to use identical cues in the two conditions, the cues had to be

arbitrarily related to both task and location. In principle, this allowed participants in the task-switching condition to treat the cues primarily as location-cues – i.e., to orient first towards the appropriate location and then use the location as the task-cue, rather than treating location as a consequence of the task signaled. This potential partial decoupling of attentional set and (the rest of) task-set, could have led us to underestimate the difference between the effects on attentional orientation of task- and location-switching. In Experiment 2 we therefore changed the task cues to maximize the extent to which attentional settings are likely to be accessed via task-set selection.

### **Experiment 2**

This experiment was identical to the task-switching condition in Experiment 1 except for one important change. We replaced the arbitrary task cues with verbal cues that are semantically transparent with regard to the task (see Method). We expected that such a cue would be less likely to act primarily as a location cue and more likely to encourage access to attentional settings via the task-set. Hence, we anticipated even clearer effects of task-switching on our indices of attentional selection than those observed in Experiment 1.

Having indeed obtained more substantial and robust effects, we took advantage of this to address two additional questions with further analyses. One is whether the effects of task-switching on attentional orienting observed in Experiment 1 actually cause (or at least predict) the performance switch cost. To test this we examined the extent to which the attentional handicap on switch trials predicted the switch cost both over individuals (via correlations) and within individuals (via analyses of fixations based on RT distributions). Second, we asked whether the average task switch-induced delays in

attentional selection we detected are characteristic of most switch trials or whether they arise from a limited subset of trials with very late fixation of the relevant region (cf. De Jong's, 2000, claim that behavioral switch costs arise from a "failure to engage" task-set on a fraction of trials).

## **Method**

24 participants (17 female, mean age, 20.46) received the same payment as in Experiment 1 for their participation.

Depending on the task, the cue was "ODD?" or "EVEN?", "LOW?" or "HIGH?" and "INNER?" or "OUTER" displayed centrally (subtending up to  $0.8^\circ$  horizontally,  $0.3^\circ$  vertically). In all other respects the experiment was identical to the task-switching condition of Experiment 1.

The same square regions as in Experiment 1 were defined for analysis of fixations. On repeat trials 93.93% of all fixations landed within these regions; 93.16% on switch trials. No blocks needed to be discarded due to poor calibration, but the first two trials in each block, trials with  $RT > 2500$  ms (0.95%), trials on which the cue was not fixated (2.2%) and trials following an error were also omitted from all analyses. Error trials were also omitted from all eye-tracking and RT analyses.

## **Results**

### **RT and errors.**

*Effects of task-switching.* The mean RT and errors, averaged over all three tasks can be seen in Figure 6. For RTs, an ANOVA with factors switch, CSI and task found a reliable switch cost (95 ms),  $F(1,23)=81.12$ ,  $p<0.001$ , and switch by CSI interaction,  $F(3,69)=11.34$ ,  $p<0.001$ , reflecting a reduction in switch cost from 124 ms (CSI=120 ms)

to 74 ms (CSI=1420 ms). There was a small increase in switch cost from CSI=1020 ms (71 ms) to CSI=1420 ms (74 ms) but this was not reliable ( $F < 1$ ), suggesting that the effect of preparation reached asymptote after  $\sim 1$  s of preparation. The ‘residual’ switch cost was reliable, as shown by the significant main effect of switch for these two longest CSIs: CSI=1020ms,  $F(1,23)=45.71$ ,  $p < 0.001$ ; CSI=1420ms,  $F(1,23)=47.02$ ,  $p < 0.001$ . The switch cost was also reliable for the errors,  $F(1,23)=6.03$ ,  $p = 0.022$ , but it did not interact reliably with CSI,  $F < 1$ . There was a reliable main effect of task for both RTs,  $F(2,46)=38.97$ ,  $p < 0.001$ , and errors,  $F(2,46)=17.61$ ,  $p < 0.001$ : as in Experiment 1,

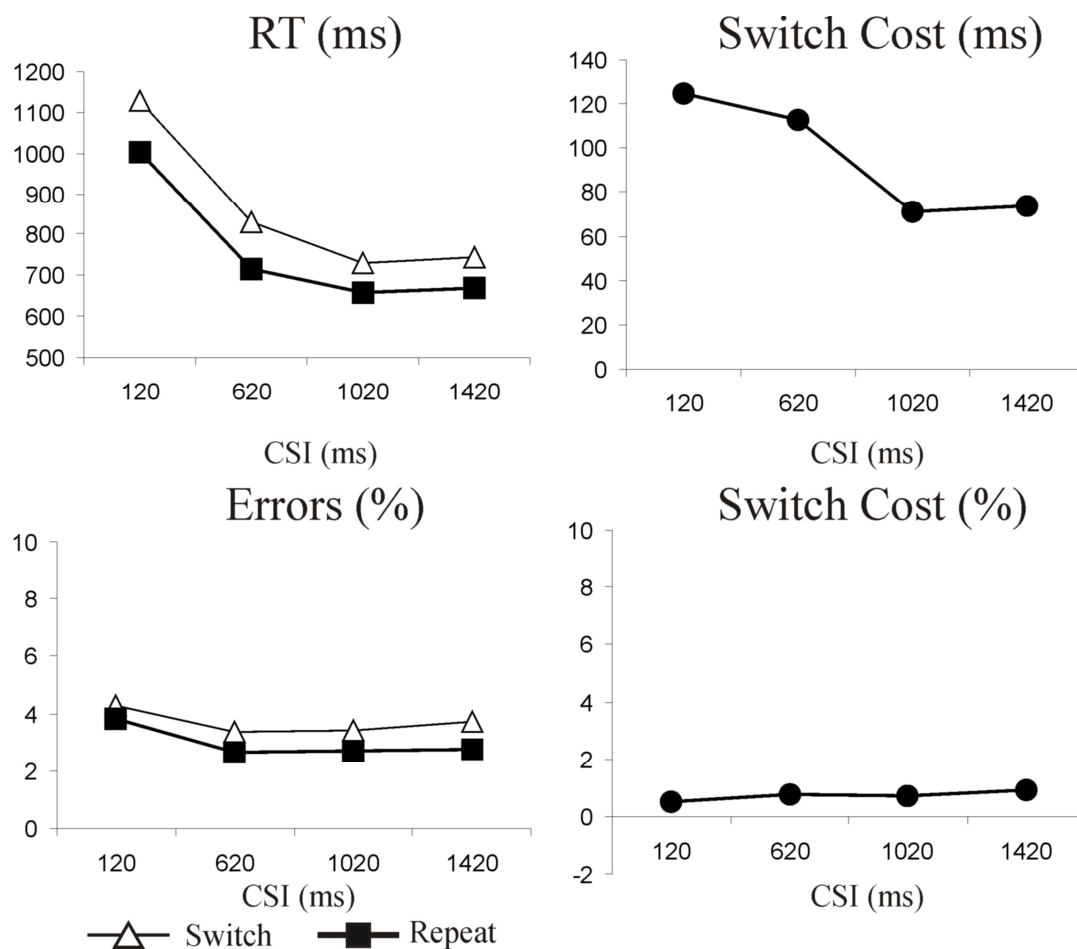


Figure 6. The mean RT, error rate and switch costs for Experiment 2 as a function of CSI and transition.

the low/high task was easiest (RT=756 ms, errors=2.3%) and the inner/outer task the hardest (RT=867 ms, errors=4.32%; odd/even task RT=807 ms, errors=3.39%). There was also a reliable interaction between task and switch for both RTs,  $F(2,46)=7.90$ ,  $p=0.002$ , and errors,  $F(2,46)=8.08$ ,  $p=0.002$ . The odd/even task had the largest switch cost in both measures; the smallest switch cost for RTs was in the low/high task and for errors in the inner/outer task: odd/even, 122 ms (2.3%); inner/outer, 98 ms (-0.1%); low/high, 66 ms (<0.1%).

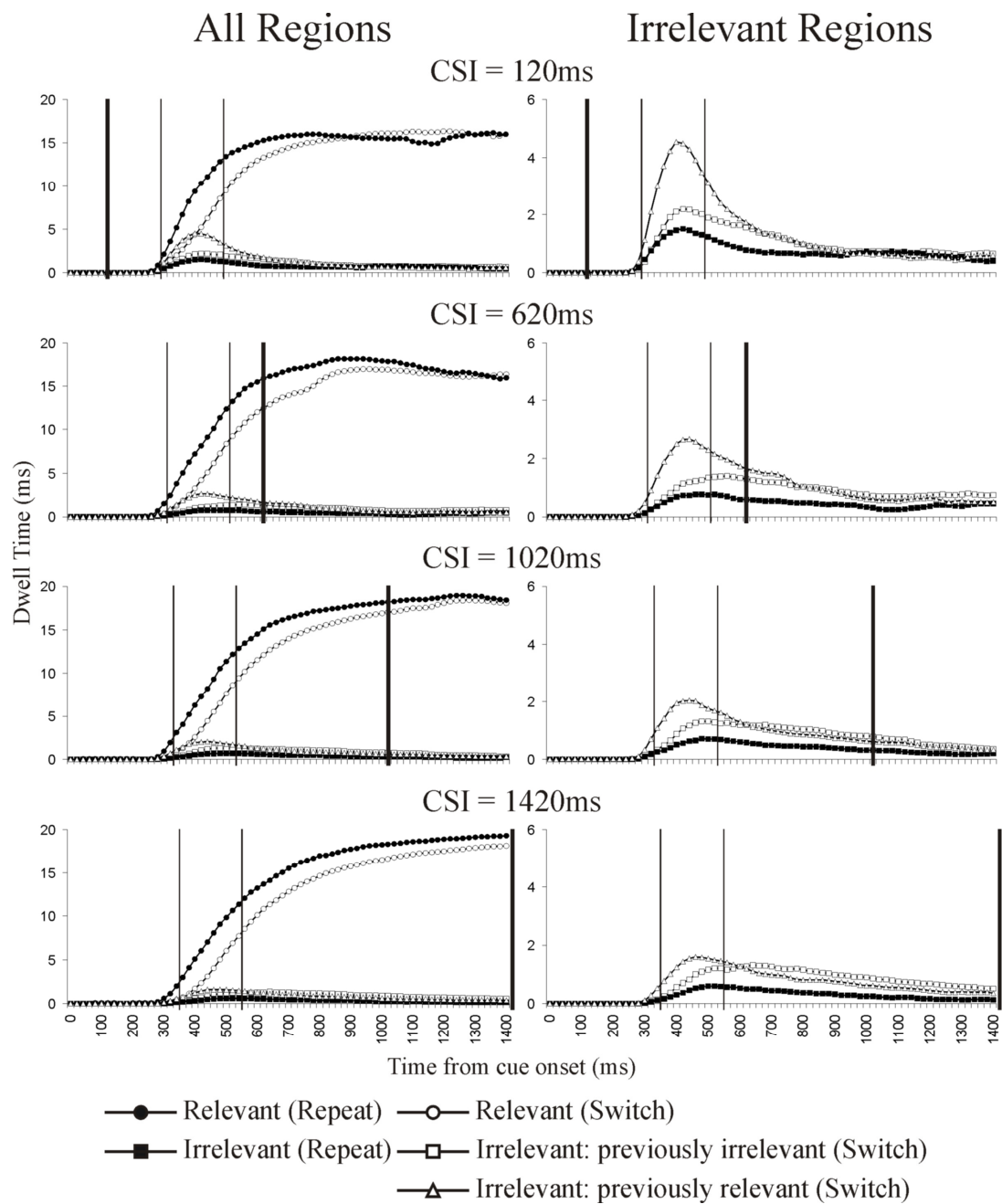
***Response congruence***<sup>4</sup>. The three kinds of congruence were examined as for Experiment 1. Only within-location congruence was associated with a statistically reliable main effect of congruence for both RTs,  $F(2,46)=7.87$ ,  $p=0.003$ , and errors,  $F(2,46)=22.37$ ,  $p<0.001$ . On congruent trials responses were 8 ms faster and error rates 1.1% lower than on semi-congruent trials, on which responses were 17 ms faster and there were 2.2% fewer errors than on incongruent trials; mean RT (errors): congruent=801 ms (2.03%), semi-congruent=809 ms (3.11%), incongruent=826 ms (5.32%). Congruence did not interact reliably with switch or CSI.

There was no reliable main effect of cross-location congruence on RT,  $F(2,46)=0.78$ , or error rate,  $F(2,46)=2.96$ ; mean RTs (errors): congruent=811 ms (3.83%), semi-congruent=809 ms (3.16%), incongruent=810 ms (3.22%), nor was there a reliable main effect of flanker congruence; mean RT (errors): congruent=808 ms (3.63%), semi-congruent=809 ms (3.22%), incongruent=807 ms (3.47%).

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<sup>4</sup> As for Experiment 1, the interactions involving congruence and task can be found in the Supplementary Materials.





*Figure 7.* Dwell-time in Experiment 2, plotted as in Figures 3 and 4: the left panel shows the fixations on both the relevant and irrelevant regions, whereas the right panel shows only the fixations on the irrelevant regions (with the scale adjusted accordingly). Thick vertical lines show the onset of the stimulus and thin vertical lines the time-windows used for statistical analysis.

That only within-location congruence had a robust overall effect suggests that, as in Experiment 1, through effective orienting and/or acuity drop-off away from the fovea, the values of the irrelevant digits had little impact on response activation.

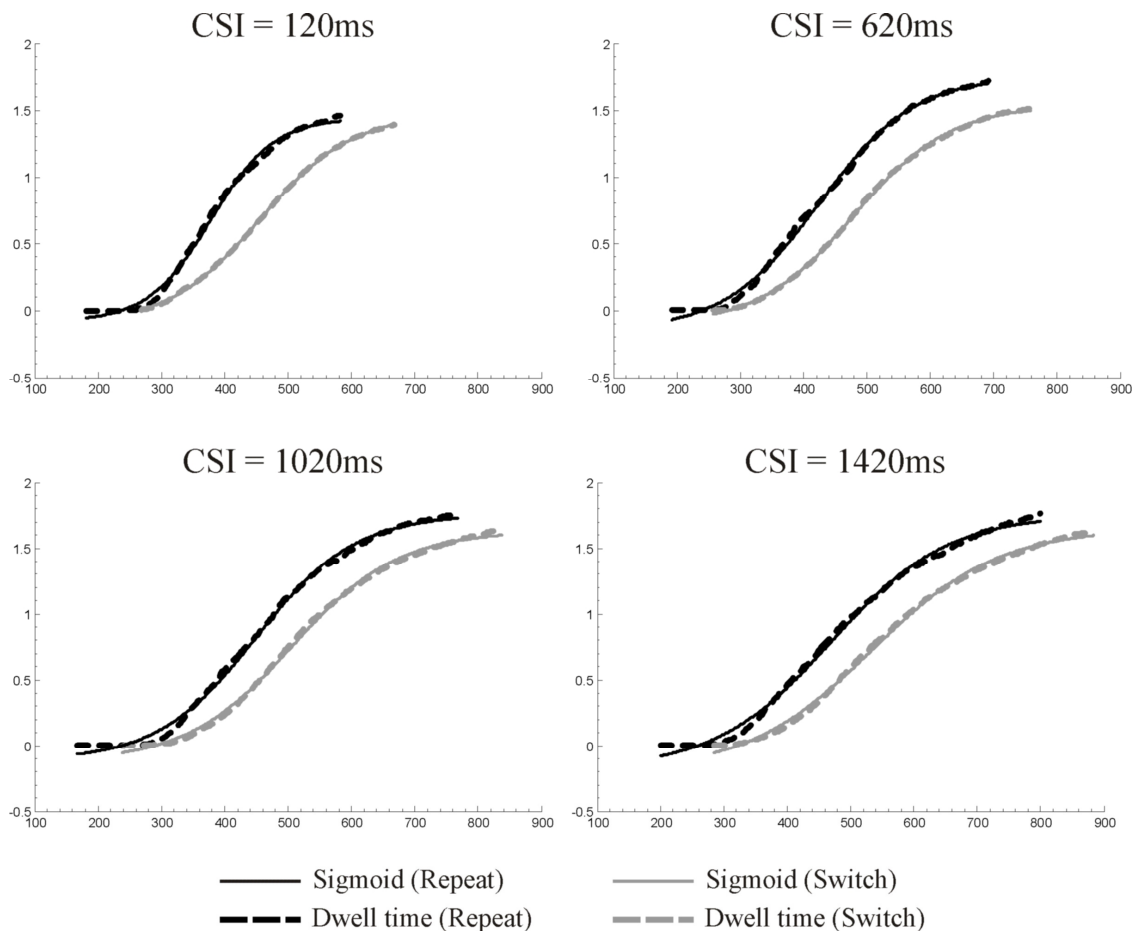
***N-2 sequence effects.*** A further ANOVA was performed on the RT and error rate from switch trials following either ABA or CBA type transitions with the factors CSI and transition from trial n-2 (switch, repeat). The tiny n-2 repeat cost (RT=3 ms, errors=0.04%) was not reliable, nor was there any interaction between n-2 sequence and CSI, all  $F_s < 1$ .

### **Eye-Tracking.**

***Dwell-time on the relevant region.*** Figure 7 shows the mean dwell time in successive 20 ms bins for 1420 ms following cue onset. Estimated in the same way as for Experiment 1, the mean separation between the switch and repeat curves (CSI=120 ms, 89 ms; CSI=620 ms, 89 ms; CSI=1020 ms, 81 ms; CSI=1420 ms, 92 ms) was found to be reliable at each CSI: in order of increasing CSIs  $t(23)=6.26$ ,  $p<0.001$ ;  $t(23)=7.37$ ,  $p<0.001$ ;  $t(23)=7.86$ ,  $p<0.001$ ;  $t(23)=5.88$ ,  $p<0.001$ . A one-way ANOVA with factor CSI found no significant change in the temporal separation with increased time for preparation,  $F<1$ .

***Is the orientation delay characteristic of most switch trials?*** The procedure we used to estimate the delay in appropriate orientation induced by a switch so far simply averages the delays at successive points on the two functions. It does not distinguish between two possibilities: (1) that the whole dwell-time function is shifted rightwards, implying that a task-switch delays orientation on all or most trials; (2) the functions depart from zero at a similar point but a task-switch reduces the rate of increase, implying

that a task-switch delays orientation only on a subset of trials with the slowest deployment of spatial attention (and gaze). Inspection of Figure 7 suggests the former, but to test this formally we carried out a curve fitting procedure as follows.



*Figure 8.* Illustration of the fitting of the sigmoidal function to high-rise portions of the dwell-time curves (averaged over participants) in the four CSIs.

The shape of the portion of a dwell-time curve including a short segment preceding the rise and a similar segment after the rise (see Fig. 8) can be closely approximated by a sigmoidal function which has a parameter specifying the location of the entire curve on the horizontal (x) axis and another parameter that controls slope.

Fitting the sigmoidal enabled us to test for the horizontal (temporal) shift and slope change induced by a task switch (the details on fitting and related statistical tests are presented in Appendix 1). As shown in Table 1, there was a highly significant switch-induced shift at all four CSIs, whereas the slope parameter was significantly reduced by switching only at the shortest CSI. We conclude that the delay in appropriate orientation is characteristic of most rather than a minority of switch trials.

Table 2.

*Estimated Mean Time Shift and Slope Change Induced by a Task Switch and the t-Test Statistic for Each Parameter*

	CSI			
	120 ms	620 ms	1020 ms	1420 ms
<b>Time-shift (ms)</b>	81	60	63	70
<b>t-test</b>	8.44, $p < 0.001$	6.93, $p < 0.001$	6.1, $p < 0.001$	6.01, $p < 0.001$
<b>Slope change (%)</b>	-45.6	-0.6	-6.4	-5.4
<b>t-test</b>	3.20, $p = 0.004$	0.10, $p = 0.920$	1.17, $p = 0.250$	0.60, $p = 0.550$

*Note.* The slope change is given as a % change in the switch condition relative to the slope in the repeat condition.

***Dwell-time in the peri-stimulus interval.*** An important question is whether, by the time the stimulus was presented on long CSI trials, attention was allocated to the relevant region of the stimulus on switch trials to the same extent as on repeat trials or whether there is a ‘residual’ shortfall in dwell-time on the relevant locus at stimulus onset on switch trials relative to repeats. The latter would indicate that even ample preparation does not completely overcome the switch-induced handicap in appropriate allocation of spatial attention. To answer this question, the dwell time for the relevant region summed across the two 20 ms bins bordering (before and after) stimulus onset was submitted to an ANOVA with factors switch and CSI (with only three levels – the eyes never reached the relevant region by stimulus onset for the shortest CSI). Overall, at/around stimulus onset participants spent ~10% (3.8 ms) less time fixating the relevant region on switch trials

relative to repeats (main effect of switch,  $F(1,23)=49.01$ ,  $p<0.001$ ), and although this reduced with CSI (switch by CSI interaction,  $F(2,46)=31.61$ ,  $p<0.001$ ), it remained reliable for the two longest CSIs (CSI=1020: 2.4 ms; CSI=1420 ms: 2.1 ms; main effect of switch at CSI=1020ms,  $F(1,23)=23.12$ ,  $p<0.001$ ; CSI=1420ms,  $F(1,23)=31.42$ ,  $p<0.001$ ). From this we conclude that, even with ample time available to orient attention towards the relevant region, there remains a shortfall in task-relevant attention at stimulus onset.

***Dwell-time on the irrelevant regions.*** An ANOVA on the mean dwell time on the irrelevant regions in the defined 200-ms time-windows (see Table 3) found more time was spent fixating the irrelevant regions on switch than on repeat trials,  $F(1,23)=28.25$ ,  $p<0.001$ . Although this difference reliably reduced with preparation (switch by CSI interaction,  $F(3,69)=8.49$ ,  $p<0.001$ ), it remained reliable for the two longest CSIs (main effect of switch at: CSI=1020ms,  $F(1,23)=17.39$ ,  $p<0.001$ ; CSI=1420ms,  $F(1,23)=19.9$ ,  $p<0.001$ ).

Table 3.

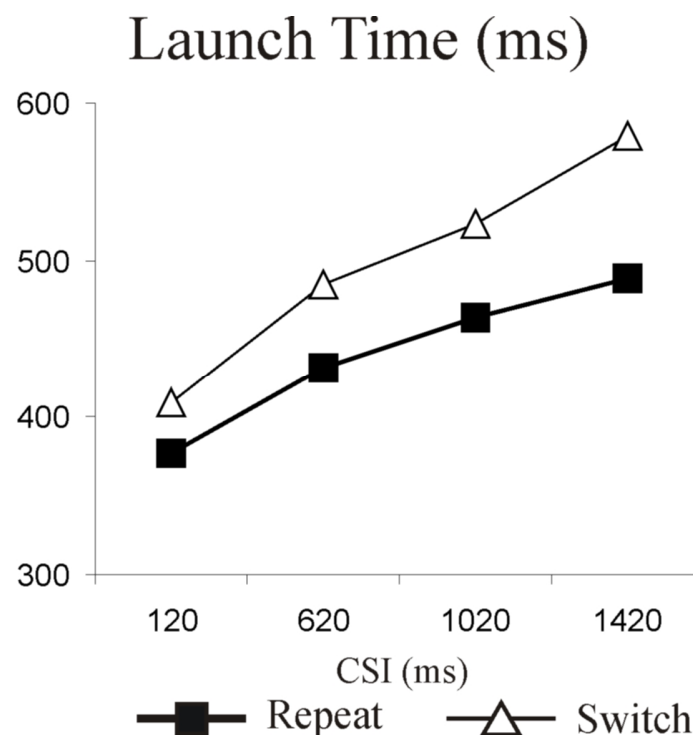
*Mean Dwell Time (in ms) on the Currently Irrelevant Regions in the Time Windows Subjected to Statistical Analysis*

	CSI			
	120 ms	620 ms	1020 ms	1420 ms
<b>Switch</b>	27.48	16.87	14.93	12.22
<b>Repeat</b>	14.26	7.66	6.82	5.52
<b>Difference</b>	13.22	9.21	8.11	6.70
<b>Std Error</b>	2.21	2.03	1.95	1.50

*Note.* The maximum dwell time in the critical time window for each CSI is 200 ms.

Is this effect due to ‘inertial’ orientation of attention to the previously relevant region? Dwell times on the irrelevant regions on switch trials (previously

relevant/irrelevant; see Fig. 7, right panel) were submitted to a previous-relevance by CSI ANOVA (as for Experiment 1). Considerably more time was spent fixating the previously relevant region than the previously irrelevant region,  $F(1,23)=16.08$ ,  $p=0.001$ . This difference was reduced with preparation,  $F(3,69)=12.85$ ,  $p<0.001$ , but remained reliable for the 1020 ms CSI,  $F(1,23)=7.66$ ,  $p=0.011$  and marginally reliable for CSI=1420 ms,  $F(1,23)=3.95$ ,  $p=0.059$ .



*Figure 9.* Mean ‘launch time’ of the first saccade to leave the cue and land directly in the currently relevant region as a function of CSI and transition (Experiment 2).

***Launch times for saccades from the cue to the relevant region.*** As in Experiment 1, we examined potential switch-repeat differences in initiating the eye-movement from the cue to the relevant region for those trials on which the first saccade away from the cue landed in the relevant region (see Fig. 9). A switch by CSI ANOVA on the launch times found a significant main effect of switch,  $F(1,23)=70.73$ ,  $p<0.001$ ,

and switch by CSI interaction,  $F(3,69)=12.0$ ,  $p<0.001$ , reflecting an increasing delay in the launch of the saccade with CSI (in order of increasing CSI: 33 ms, 54 ms, 60 ms, 91 ms). This increase, together with the reduction in inappropriate fixations at long CSIs, suggests that it is late launches that are largely responsible for the delayed arrival of attention at the relevant region after long preparation intervals, whereas on short CSI trials fixation of a previously (but no longer) relevant region is also a significant contributor to the switch-induced delay in arriving in the relevant region.

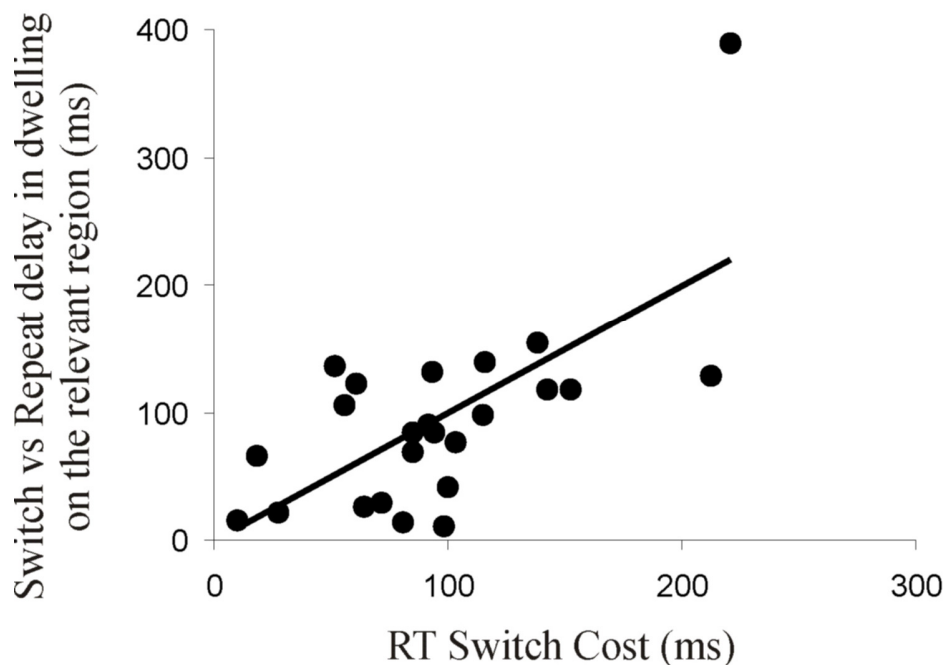


Figure 10. Correlation between the mean RT switch cost and the mean delay in fixating the currently relevant stimulus region within the 200-ms time-window used for analysis, see Figure 7 (Experiment 2).

**Relationship between eye movements and performance.** Are the observed effects of a task-switch on eye-movements predictive of the RT switch cost? Analyses suggest an affirmative answer. First, there is a significant positive correlation over participants between the mean temporal separation between the switch and repeat dwell-time curves

(see above) and the RT switch cost (see Fig. 10),  $r(22)=0.67$ ,  $p<0.001$  (or, with the obvious outlier removed:  $r(21)=0.51$ ,  $p=0.013$ ).

Second, we turned to analyses based on RT distributions, which typically find a substantially smaller switch cost on the trials with the fastest responses than on trials with the slowest responses (e.g., De Jong, 2000; Nieuwenhuis & Monsell, 2002). We examined the switch cost and the relevant region dwell-time, only for the longest CSI, on the trials with the fastest, middle and slowest RTs (i.e., partitioning the RT distribution in each condition<sup>5</sup> into terciles). As expected, the switch cost varied as a function of tercile (tercile by switch interaction,  $F(2,46)=23.02$ ,  $p<0.001$ ), with a switch cost of 134 ms in the slow tercile reducing to 50 ms in the middle tercile and further reducing to 13 ms in the fast tercile. The summed dwell-time for the two 20-ms bins around stimulus onset on the relevant region also showed a similar robust interaction between RT tercile and switch,  $F(2,46)=19.66$ ,  $p<0.001$ , reflecting the largest switch-repeat difference in time spent fixating the relevant region at stimulus onset for the slow RT tercile and the smallest difference in the fast RT tercile, thus paralleling the switch cost effect (see Fig. 11, left panel). This difference remained reliable even for the best-prepared trials: those with the longest preparation time (CSI=1420 ms) and the fastest response times (tercile)  $F(1,23)=6.80$ ,  $p=0.016$ ; mean difference=0.34 ms. Furthermore, a tercile by previous-relevance ANOVA on the dwell-time in the two irrelevant regions for switch trials (again, for the longest CSI; see Fig 11, right panel) found that the strongest bias towards fixating the previously relevant region was on the trials from the slow RT tercile, and the

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<sup>5</sup> Correct RTs were partitioned into terciles separately for each CSI, task and switch/repeat transition type.



weakest bias on the trials from the fast RT tercile (see Fig. 11, right panel); this interaction was also reliable,  $F(2,46)=4.2$ ,  $p=0.021$ .

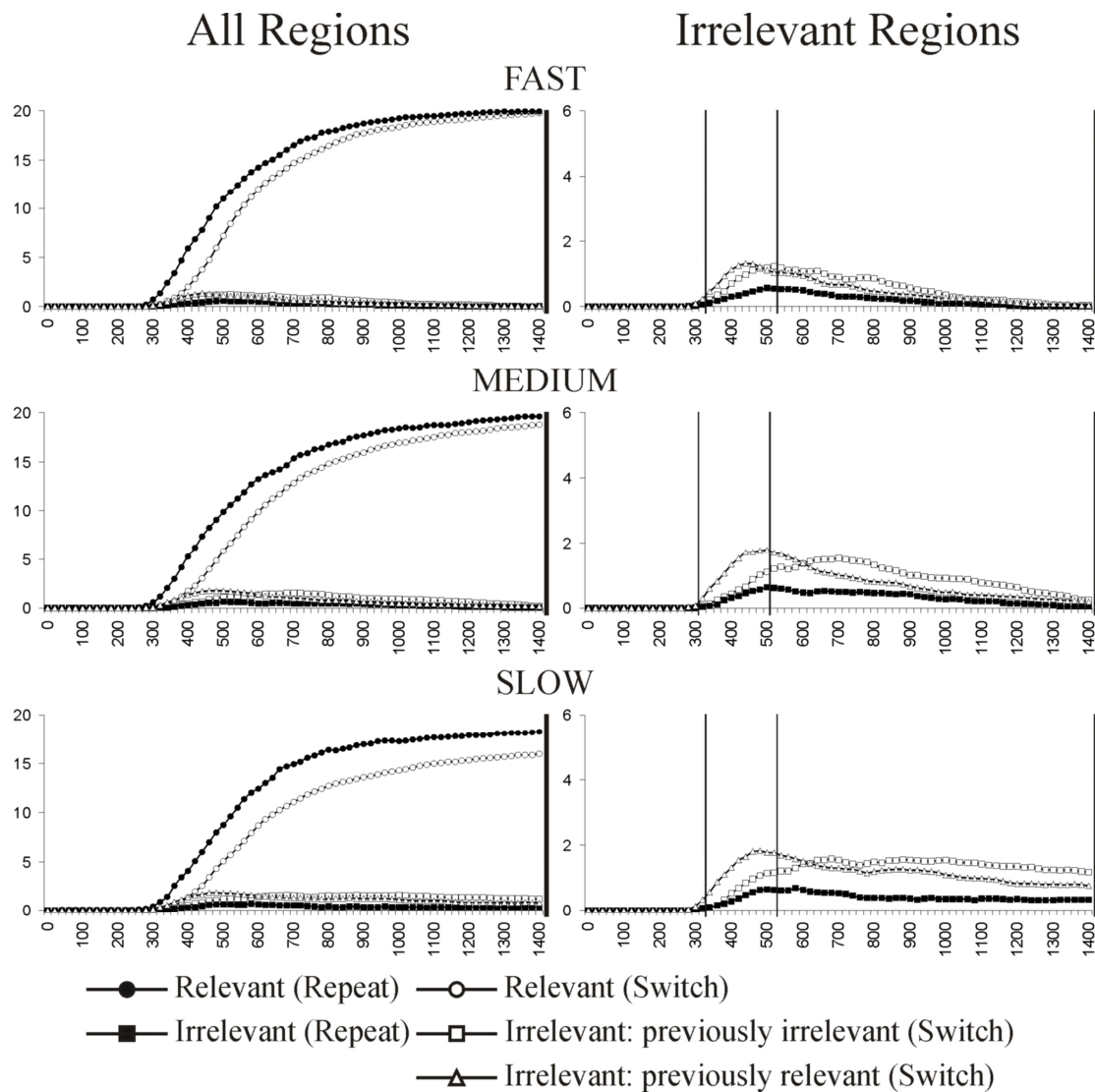


Figure 11. Mean dwell time plotted as in Figure 7 for the terciles with the fastest, slowest and intermediate responses for the CSI of 1420 ms (Experiment 2).

*Comparing dwell-time delay and attentional inertia in Experiments 1 and 2.* As we had hoped, the switch-induced delay in fixating the relevant region we observed in Experiment 2 was numerically considerably larger than the switch-induced delay in the

task-switching condition in Experiment 1. In an ANOVA on the estimated delays with the factors CSI and Experiment, the main effect of experiment was highly significant,  $F(1,46)=16.05$ ,  $p<0.001$ .

The tendency, on switch trials, to fixate the irrelevant region which was relevant on the previous trial was also larger in Experiment 2. Although the previous-relevance by CSI by Experiment ANOVA revealed a marginally reliable interaction between previous relevance and Experiment ( $F(1,46)=3.09$ ,  $p=0.086$ ), the three-way interaction was reliable  $F(3,138)=2.89$ ,  $p=0.048$ . However, follow up ANOVAs on each CSI revealed that the tendency was reliably greater in Experiment 2 only for the shortest CSI (120 ms:  $F(1,46)=5.66$ ,  $p=0.022$ ), with all other  $F$ 's  $<2.5$ .

## Discussion

With the arbitrary cues of Experiment 1, a potential strategy was to interpret the cue initially as a location cue, initiate the shift of attention and then reconfigure the rest of task-set, perhaps cued by the location arrived at. The main aim of the present experiment was to increase the likelihood that spatial attentional settings were, instead, tightly coupled to the task-set. To achieve this we replaced the arbitrary letter cues in the task-switching condition of Experiment 1 with word cues transparently labeling the required categorization.

As in Experiment 1, performance measures revealed a switch cost (including an asymptotic residual cost), a robust (nearly 50%) RISC effect and a (within-location) congruence effect; there was little evidence of the digits at irrelevant locations activating responses via the current or irrelevant task-sets. There was again no clear evidence of  $n-2$  repetition cost ('backward inhibition'). As we hoped, increasing cue transparency helped

reveal robust effects of task-switching on attentional selection, indexed by eye tracking, even more substantial than those observed in Experiment 1. Switching resulted both in a substantial delay in fixating the relevant region (a delay of the same order of magnitude as the residual RT switch cost) and in a strong tendency to fixate the previously (but no longer) relevant region. The analysis that distinguished any horizontal (temporal) shift of the dwell-time curve from a change in its slope, indicated that the effects of switching on spatial attention are not confined to trials with slow orienting but instead reflect delays on most switch trials (as indicated by a shift of the whole curve). Finally, analyses that examined the relationship between the switch-induced handicap in targeting the relevant region and performance showed the delay and inertia in attentional orienting to be highly predictive of the RT switch cost both within and over participants.

### **General Discussion**

This study investigated the dynamics of pre-stimulus reconfiguration of attentional settings, and inertia in attentional parameters, accompanying a task-switch. We recorded eye movements during two task-cuing experiments in which three digit-classification tasks were consistently associated with different locations. The features of our paradigm which make it possible to monitor attentional orientation with eye-tracking – spatially separating the stimulus elements relevant to each task in predictable locations – did not seem to alter the commonly observed patterns of performance in task-cuing experiments. In both of our experiments we observed the familiar switch cost which was reduced considerably (by ~30% in Experiment 1, ~50% in Experiment 2) with opportunity for preparation, but remained substantial (and reliable) at the longest CSIs (1020 ms and

1420 ms) – an asymptotic (residual) cost. There was also evidence that the digit at the task-relevant location activated, to some extent, the response afforded by the alternative tasks, reflected in what we referred to as the ‘within-location’ response congruence effect. The current study aimed to address five key issues outlined in the Introduction. We discuss each of them in turn.

### **Effect of task switching on orientation of spatial attention**

Of the two eye-tracking studies of task-switching described in the Introduction, one used fixations to index the effects of a switch on non-spatial attention (Mayr et al., 2013) and the other aimed to examine the effects of a switch on spatial attention by presenting task-relevant attributes of the stimulus in predictable locations (Longman et al., 2012). However, because Longman et al.’s attributes (face versus letter) could also be selected based on their different features and because eye-movements were only recorded after stimulus onset, one could not be certain that the effects revealed reflected orientation of spatial attention alone. The present design resolved this ambiguity by (1) using stimulus attributes for each task that were perceptually equivalent (digits); (2) examining the attentional dynamics prior to stimulus onset.

### **Online record of attentional dynamics during the preparation interval.**

Although recent studies that used eye-movements as an online index of spatial attention (Longman et al., 2012) or attention to a dimension (Mayr et al., 2013), have found that increasing the preparation interval has substantial effects on the pattern of eye-movements following stimulus onset, these studies did not examine/report pre-stimulus

eye-movements (see Introduction)<sup>6</sup>. To our knowledge, the current investigation is the first attempt to do so. There are at least two motives for examining the preparation interval. First, finding that an increase in the time available for preparation (CSI) results in more effective attentional selection following stimulus onset (cf. Longman et al., 2012; Mayr et al., 2013) does not conclusively demonstrate that attentional parameters are reconfigured in advance of the stimulus: other task-set components might be reconfigured in advance thus enabling attentional resetting to proceed early/rapidly following stimulus onset. Indeed, Meiran et al. (2008) concluded from their simulations that attentional parameters may not be reset during the preparation interval, speculating that such resetting requires the presence of the stimulus and accounting for the RISC effect in terms of pre-stimulus adjustment of S-R parameters instead. Second, because perceptual information needed for response selection may become accessible after stimulus onset but before the relevant stimulus attribute is fixated, there may be temporal overlap between response selection and the fixation-based measure of attentional orienting after onset. In contrast, the pre-stimulus record of eye-movements unambiguously indexes attentional orienting uninfluenced by response selection.

Our results revealed substantial effects of switching tasks on the dynamics of spatial attention during the first ~600 ms following the onset of the task cue. In Experiment 1 the analysis of dwell-time for the task-relevant region found that a task switch led to a delay of ~25-40 ms in orienting to the relevant region, relative to a task repetition (see Fig 3, left panel). In Experiment 2, which replaced the arbitrary letter cues

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<sup>6</sup> Using fixations to track pre-stimulus attention is actually not possible in Mayr et al.'s otherwise ingenious design: it uses post-stimulus shifts in spatial attention to detect the effects of pre-stimulus dimensional selection on target detection; the location of the target is unpredictable.

of Experiment 1 with cues whose task-meaning was more transparent, this delay more than doubled (to ~60-90 ms; see Fig. 7, left panel). This increase suggests that when attentional settings are coupled to (and accessed via) the task-set, the delays in attentional selection (and/or in earlier stages of task-set reconfiguration) can be substantial. Analysis of the 'launch' latency of the first eye-movement from the cue towards the task-relevant region (confined to trials for which this was the first saccade away from the cue) demonstrated that a substantial delay in appropriate orientation induced by a task change was by no means confined to trials on which attention was initially oriented to irrelevant regions; it was also characteristic of those on which the relevant region was the first to be fixated after the cue (see Fig. 5 and Fig. 9). Further analysis of the slopes of the dwell-time curves in Experiment 2 indicated that the delay is not confined to trials with late attentional selection (as indexed by late fixation of the relevant region): it occurred on most trials.

Our results also show that the attentional handicap elicited by a task switch – the delay in fixating the relevant region, as well as the tendency to fixate the previously (but no longer) relevant region – is largely (though not entirely, see below) resolved by 600-800 ms of preparation. Thus, spatial selection parameters can be reconfigured during a task-switch well in advance of the onset of the imperative stimulus (~600-700 ms before stimulus onset in the longest CSI condition). The resetting of spatial attention during a task-switch evidently does not require the presence of the stimulus. Mayr et al.'s (2013) preparation effects suggest that it is not necessary for resetting non-spatial attention either (contrary to Meiran et al., 2008, but consistent with Meiran, 2000).

**Attentional inertia.**

The studies of Longman et al. (2012) and Mayr et al. (2013) found a tendency to misallocate attention to the irrelevant object in the display on task-switch trials – a tendency reduced, but not eliminated, by preparation. This ‘residual’ tendency to attend to the irrelevant object strongly suggests an attentional component of task-set inertia, which we label ‘attentional inertia’. However fixations on the irrelevant object could also be due to general distractibility or difficulty in orienting elicited by a task switch. Our use of three tasks enabled a contrast which showed that, on switch trials, the majority of eye-movements that do not initially land in the relevant region go first to the region that was relevant on the previous trial (see Fig. 4 and Fig. 7), demonstrating a strong persistence of attentional settings from the preceding trial. This persistence is all the more intriguing given the relatively low probability (0.33) of the task and location repeating in the current design

**‘Residual’ attentional handicap during a task switch.**

Crucially, the attentional inertia was not eliminated (and remained statistically significant and appeared asymptotic) at the longest two CSIs (for which the performance switch cost was also asymptotic), even for trials for which preparation was most effective – those with the fastest responses and smallest switch cost. These results reveal the limits of advance reconfiguration of attentional components of task-set and suggest attentional inertia can be an important source of the residual switch cost.

We note that this conclusion is at odds with Lien et al.’s (2010) interpretation of their finding (Experiment 4, see Introduction) that ‘capture’ by the previously relevant

perceptual attribute during a task switch can be completely overcome by preparation (with a task-cue to capture-cue interval comparable to our longest CSIs – 1200 ms). There is at least one major difference between our paradigm and theirs. In our paradigm each task is associated with a spatial location and switching tasks requires shifts of spatial attention. Lien et al. (2010) combined task switching with the contingent capture paradigm, and each of the two tasks was associated with a color, so that switching tasks required attending to a different color. It may be that the dynamics of spatial selection and feature selection (on the color dimension) are different. However Mayr et al.'s (2013) study, discussed above has documented inertia of attention to dimensions of color versus form – though this too is different from attention to a specific value on a dimension.

A more likely possibility is that critical features of Lien et al.'s paradigm encourage a de-coupling of attentional set from other components of the task-set and strong temporal prioritization of the former. In contingent capture experiments, the short duration of the stimulus (50 ms in Lien et al.'s study), requires rapid selection of the object possessing the required feature (in Lien et al. – of the digit in the relevant color), to enable identification of the target digit during the very brief stimulus display. This non-trivial demand for speed of feature (color) selection makes it likely that task selection may be postponed until after stimulus onset, especially if the cue refers transparently to color rather than task (as was intended by Lien et al.'s use of cues that were the initial letters of the color names, e.g., 'R' for 'red'). Late (post-stimulus) task selection may explain both why the authors found no effect of task-switching on attentional capture and why the switch cost was quite large (137 ms) for their generous preparation interval. It is also consistent with our observation of a less robust reduction in RT switch cost with



preparation, and smaller attentional delay effects, in Experiment 1 (which used arbitrary cues potentially interpretable as location cues) than in Experiment 2 (which used cues explicitly labeling the classification task to be performed.).

### **Cost of switching between tasks or locations?**

All this assumes that the delays and inertia we observed are in task-associated spatial attention, not merely in the direction of eye movements to a location, or in task-independent attentional orienting. Unlike our initial investigation that linked tasks to locations (Longman et al., 2012), our present Experiment 1 included a crucial control condition – one in which the same cues signaled the same change (or repetition) of location, whilst a single task was performed throughout. There were effects of a location switch on dwell times and inappropriate fixations without a task switch, but, compared to the effects of a task switch, they were much smaller and, at the longer CSIs, altogether absent. Most notably, the tendency to fixate the previously (but no longer) relevant location more than the other irrelevant location evident at all the CSIs on task switch trials was observed only at the shortest CSI on location switch trials. This suggests that the attentional delays and attentional inertia observed during a task switch in the current experiments, as well as by Longman et al. (2012), cannot be attributed merely to persistence of oculomotor programs, or difficulty in changing the target of spatial attention across trials, irrespective of task-set.

An alternative account to ours that deserves consideration is that spatial orienting in the task switching and location switching conditions may have operated in qualitatively similar ways, but that in the former case the switching between

categorizations constituted an extra cognitive (e.g., Working Memory) ‘load’. As a result (and assuming a degree of processing seriality) deploying spatial attention may not always get high enough ‘priority’ and would sometimes have to ‘wait’, resulting in delays in orienting it. If the wait is long, exceeding some deadline criterion, one may further assume a ‘default mode’ of orienting to the previously attended stimulus region – which should be less likely in the location-switching condition where there is no concurrent ‘load’. It would seem therefore that one need not assume a coupling between task-set and attentional set to account for greater inertia of spatial orienting during task switching. However, one aspect of our results is inconsistent with such an account: the total number of fixations on the irrelevant locations (see Table 1 and Figure 4) was not greater on task switch trials (nor was their latency longer) than on location switch trials, only the distribution over the two irrelevant regions was different (in three of the four CSIs). Thus, orienting to an irrelevant region was just as frequent (and just as late in the preparation interval) on location switch trials – yet there was little sign of ‘default’ orienting to the region fixated on the previous trial (no discernable preference for this region in the long CSIs). Hence we conclude that inertia of the attentional component of the previously relevant task-set is a more plausible interpretation of the carry-over effects we observed in eye-movements on task switch trials.

**A note on ‘inhibition of return’.**

We referred earlier to the substantial literature on ‘inhibition of return’. In the context of the current paradigm, inhibition of return would be reflected in a delay in fixating the relevant region on task (and location) *repetition* trials relative to switch trials,

especially in the location-switching condition of Experiment 1, where there was no task-switching to complicate matters. Clearly our data showed the opposite: delays in orienting were observed in the location-switching condition when a *different* location had to be fixated on successive trials. Of course our situation is very different from the search-like situations used to demonstrate inhibition of return. Moreover, even in a visual search situation there is recent evidence that inhibition of return is observed within rather than across trials (Höffler, Gilchrist, & Körner, 2011), and our switch vs. repeat comparison is quintessentially a contrast of transitions between consecutive trials. We also note that the performance costs of shifting spatial attention were of comparable magnitude to those documented previously (cf. Chiu & Yantis, 2009). They were negligible when there was opportunity for preparation as previously reported by Logan (2005) with a CSI >300 ms, despite some non-trivial differences in paradigm. (Logan's paradigm required attending to two locations simultaneously and, unlike our paradigm, it relied on exogenous cues).

#### **A note on 'backward inhibition'.**

In the current design there was no clear n-2 repetition or 'backward inhibition' effect: considering both RT and errors, performance was not clearly worse on the third trial in an ABA sequence than in a CBA sequence. This is surprising considering that Arbuthnott (2009) found a reliable n-2 repetition cost under similar conditions (constant cue location, distinct target locations). One might be tempted to suggest (in line with Arbuthnott, 2005) that the spatial separation between the tasks and the effective 'filtering out' of the irrelevant attributes (indicated by the near-absence of effects of the irrelevant

digits in the analyses of cross-location and flanker congruence) removes the need for task-set inhibition, though we note we have also not found  $n-2$  effects in other experiments that used co-extensive stimulus attributes (e.g., Van 't Wout, Lavric, & Monsell, submitted, Exp. 2). Other aspects of the present design that have previously been linked with a reduced  $n-2$  repetition cost are the presence of  $n-1$  repetitions (cf. Philipp & Koch, 2006) and the relatively long (albeit not uncommon in conventional task-switching) response-cue interval (Gade & Koch, 2005). The occurrence of robust  $n-2$  effects may require conditions not contained in our design.

### **Summary and conclusions.**

The current study is, to our knowledge, the first systematic investigation of the dynamics of preparatory spatial orienting of attention in task switching. It documents two related effects of a task switch on spatial attention, both of which can be seen in the first ~600 ms of the preparation interval: a delay in attending to the relevant object location and a tendency to misdirect attention to the previously relevant object location. The latter tendency is reduced, but not eliminated, when time is available for preparation. Neither effect can be explained by persistence of oculomotor programs or spatial attention dynamics unrelated to changes in task-set. In conditions which maximize the coupling of attentional set with the rest of task set (i.e., the use of task-transparent cues in Experiment 2) these effects are more substantial and predict the performance switch cost within and over individuals. Given the specific design of our experiments, they can support claims only about spatial attention. But converging evidence from other studies (see

Introduction) suggests that switch-related delays and inertia may be characteristic also of non-spatial attention to dimensions as a component of task set.

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### **Appendix A. Fitting the sigmoidal function to the dwell-time curve for the task-relevant region.**

The standard sigmoidal curve (as implemented in Matlab) has a parameter specifying the location of the entire curve on the horizontal (x) axis and another parameter that specifies the slope (parameters  $a$  and  $c$  respectively in Equation 1 below):

$$(1) \quad f(x, a, c) = \frac{1}{1 + e^{-a(x-c)}}$$

To achieve a satisfactory fit to our dwell-time curves, we added two extra parameters: a ‘lift’ parameter  $m$  – for the position of the entire sigmoidal along the vertical (y) axis and a ‘vertical stretch’ parameter  $n$  (see Equation 2 below) and fitted the sigmoidal to the dwell-time curve using Matlab.

$$(2) \quad f(x, a, c, m, n) = m + \frac{n}{1 + e^{-a(x-c)}}$$

We first selected for each condition a section of the dwell-time curve to fit by: identifying the mid-amplitude  $[(\text{max amplitude} - \text{min amplitude})/2]$ , taking the time point corresponding to that value and setting an equal interval back and forth in time to capture a substantial portion of zero or near-zero amplitude, the segment of steep rise in dwell-time and the portion at/near asymptote (see Fig. 8). We constrained the resulting sections of the dwell-time curve to be of equal width (temporal extent) for the switch and repeat conditions, but their width increased somewhat over the four CSIs: 200 ms, 250 ms, 300 ms, 300 ms, in the order of increasing CSI. The resulting time intervals were (in ms, in the order of increasing CSI) 182-582; 192-692; 168-768; 200-800 for fitting the repeat

dwelling-time curve, and 268-668; 258-758; 238-838; 284-884 for the switch curve. We then computed the difference in the resulting parameters for the horizontal position of the sigmoidal and for its slope to estimate the temporal shift and slope change induced by a switch.

To achieve a good fit, the sigmoidal was fitted to the dwelling-time curve averaged over participants. To assess the statistical significance in the switch-induced shift and slope change, we applied separately for each CSI the “jackknifing” method (Miller, Patterson & Ulrich, 1998) originally developed for the statistical analysis of estimates of brain-potentials obtained from averages over subjects. As well as the average dwelling-time curve, a further 24 dwelling-time curves were computed, each omitting one subject’s data. The sigmoidal (as per Equation 2) was fitted for each of these ‘sub-averages’, the difference between switch and repeat curves in the two relevant parameters (for shift and slope) calculated, and the standard deviation of this difference over the 24 sub-averages computed. From this, an estimate of the variability of shift and slope over participants could be derived using Miller et al.’s formula for computing the standard error; hence the t-statistic could be computed.



**SUPPLEMENTARY MATERIALS:****1. Details of response congruence by task interactions not reported in the paper.****Experiment 1**

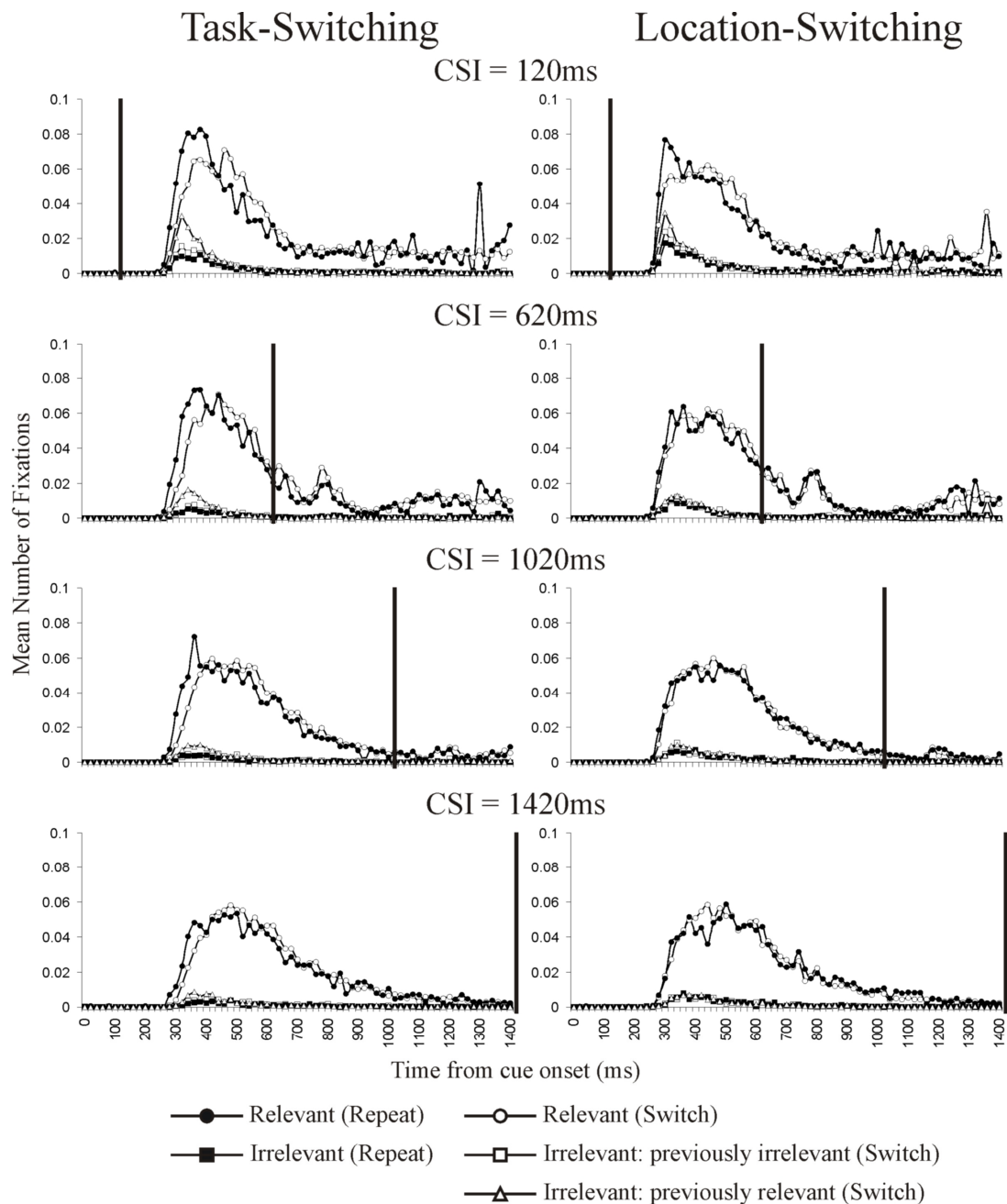
Congruence and task interacted reliably for RTs,  $F(4,92)=19.6$ ,  $p<0.001$ , and errors,  $F(4,92)=8.62$ ,  $p<0.001$ , reflecting a reliable congruence effect in the expected direction in the inner/outer and odd/even tasks and in the opposite direction in the low/high task for RTs, i.e., slowest on congruent trials and fastest on incongruent trials; also for the low/high task most errors were made on congruent trials and fewest were made on semi-congruent trials, but not reliably so. Although the interaction between congruence and switch did not approach significance for RTs or errors ( $F<1$ ), the interaction between congruence, switch and task was reliable for RTs,  $F(4,92)=3.92$ ,  $p=0.009$ , indicating differences in the extent of the congruence effects as described above (the direction of the effects for each task was not modulated by switching). There was one additional complex interaction: congruence by switch by CSI by task (RTs only), but this did not reflect any systematic effect of increasing the CSI. In short, there was some evidence of the relevant digit's irrelevant properties activating responses at all CSIs, with some modulation of the effect by task difficulty. For cross-location congruence, the only reliable interaction was in the error data between congruence, CSI and task,  $F(12,276)=2.07$ ,  $p=0.027$ ; however, the effect of congruence was not reliable in any individual task at any CSI.

**Experiment 2**

Within location congruence did interact with task for both RTs,  $F(4,92)=22.16$ ,  $p<0.001$ , and errors,  $F(4,92)=16.5$ ,  $p<0.001$ . As in Experiment 1, this interaction represents a reliable congruence effect in the expected direction (worsening performance across the three levels of congruence) for the inner/outer and odd/even tasks, which was reliably reversed in the low/high task. For flanker congruence, a three-way interaction with the effects of task and switch was found for RTs,  $F(4,92)=3.17$ ,  $p=0.033$ . However, follow up ANOVAs failed to find any meaningful pattern of congruence effects, or their interaction with switch, in any task.

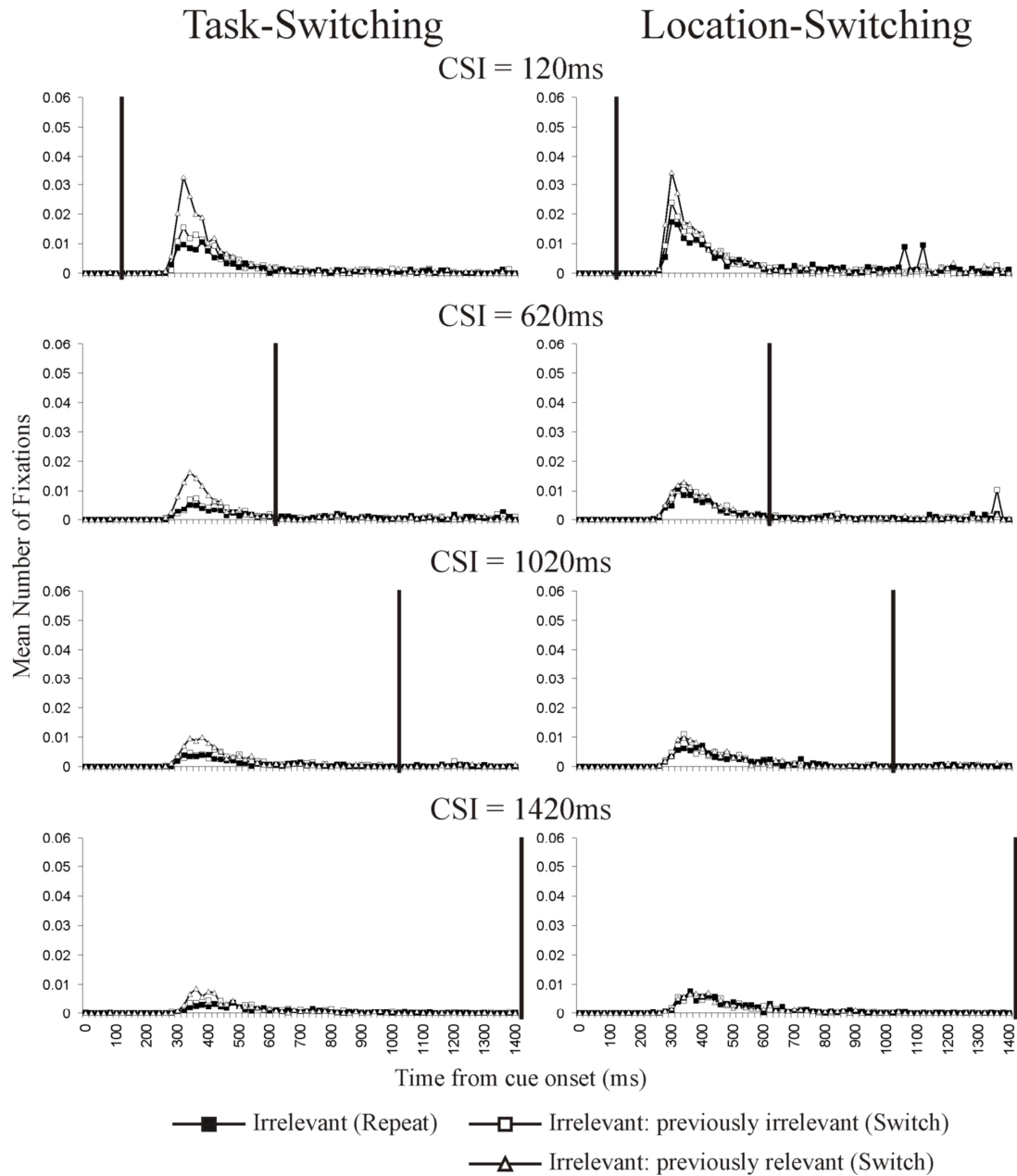
## 2. Plots of fixation counts

The patterns obtained with fixation counts, albeit somewhat noisier, largely replicated those reported in the paper for dwell times.

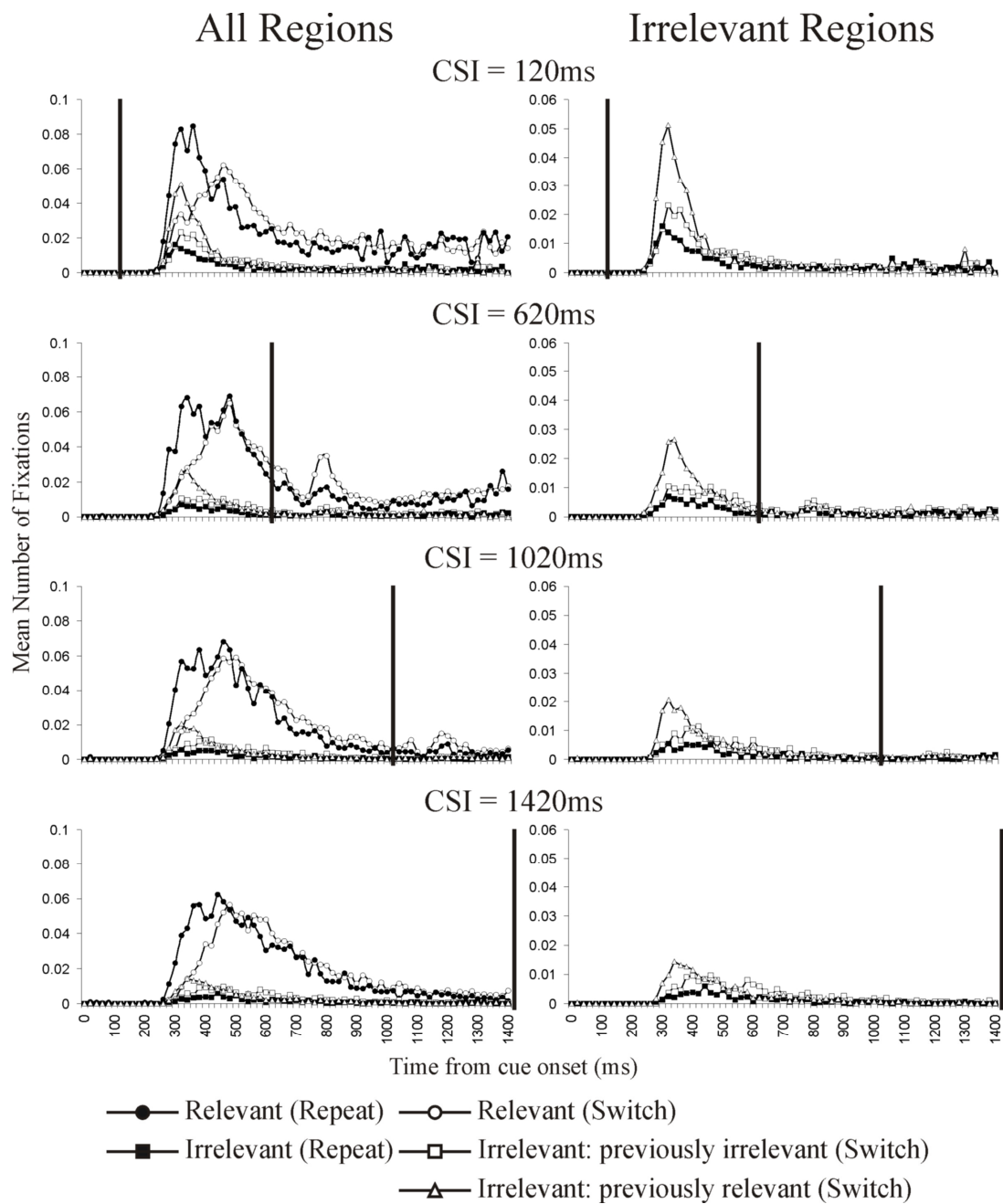


*Figure S1.* Mean number of fixations per 20 ms bin (averaging over trials, then over subjects) in Experiment 1 for 1420 ms following cue onset in the task-switching (left) and location-switching (right) groups as a function of CSI, transition (switch, repeat) and

task-relevance of stimulus region. A fixation was only included in the count for a given 20 ms bin if it started in that bin. Thick vertical lines indicate the stimulus onset time.



*Figure S2.* Mean number of fixations on the task-irrelevant regions in Experiment 1 plotted as in Figure S1, but with an amplified scale.



*Figure S3.* Mean number of fixations in Experiment 2, plotted as in Figures 12 and 13: the left panel shows the fixations on both the relevant and irrelevant regions, whereas the right panel shows only the fixations on the irrelevant regions (with the scale adjusted accordingly). Thick vertical lines show the onset of the stimulus.