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The coupling between spatial attention and other components of task-set: a task switching investigation

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Abstract: 199 words, Text: 10972 words. 40 References, 9 Figures, 2 Tables.

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Abstract

Is spatial attention reconfigured independently of, or in tandem with, other task-set components when the task changes? We tracked the eyes of participants cued to perform one of three digit-classification tasks, each consistently associated with a distinct location. Previously we observed, on task switch trials, a substantial delay in orientation to the task-relevant location and tendency to fixate the location of the previously relevant task – "attentional inertia". In the present experiments the cues specified (and instructions emphasised) the relevant location rather than the current task. In Experiment 1, with explicit spatial cues (arrows or spatial adverbs), the previously documented attentional handicaps all but disappeared, whilst the performance "switch cost" increased. Hence, attention can become decoupled from other aspects of task-set, but at a cost to the efficacy of task-set preparation. Experiment 2 used arbitrary single-letter cues with instructions and a training regime that encouraged participants to interpret the cue as indicating the relevant location rather than task. As in our previous experiments, and unlike in Experiment 1, we now observed clear switch-induced attentional delay and inertia, suggesting that the natural tendency is for spatial attention and task-set to be coupled and that only quasi-exogenous location cues decouple their reconfiguration.

Key words: Task switching, spatial attention, task-set, attentional set

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Even simple activities or tasks require the organisation (or "configuration") of component processes. For example, to make a phone call, one needs to find (perceptually select) the telephone, retrieve the relevant number (from either one's memory or a digital memory) and dial it. Such organization of several processing components into an effective procedure is what is meant by the construct of "task-set". Furthermore, behaviour must not only be goal-oriented, but also flexible: if one needs to send a text message instead of making a call, one needs to "reconfigure" the task-set (e.g., Monsell, 2003) by updating some or all of the component processes. The dynamics of changing task-set have been studied in the laboratory using "task-switching" paradigms (e.g., Allport, Styles, & Hsieh, 1994; Rogers & Monsell, 1995; Meiran, 1996). Many such investigations (for reviews see Kiesel et al., 2010; Monsell, 2003, in press; Vandierendonck, Liefooghe, & Verbruggen, 2010) have been directed at understanding the sources of the performance overhead (longer RT, higher error rate) associated with a task switch – the "switch cost" (Rogers & Monsell, 1995) and the associated modulations of brain activity (e.g., Karayanidis et al., 2010; Lavric, Mizon, & Monsell, 2008).

Among the aspects of task-set control that researchers have examined is the internal organization or "architecture" of the task-set: what its component processes/operations are and how they are reconfigured when the task changes. In most theoretical/computational accounts, task-set is a multi-componential (or multi-parametric) construct. For the classification or identification tasks used in many task-switching experiments, most authors distinguish at least two components: "stimulus-set" — the relevant perceptual or semantic attributes to attend to, and "response-set" — the relevant stimulus-response translation rules/mappings to apply to the value of the attended attribute(s) (e.g., Meiran, 2000; Meiran, Kessler, & Adi-Japha, 2008; Monsell, in press; Logan & Gordon, 2001). Task-sets may contain other parameters which can

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(or might in principle) be adjusted from trial to trial. For example, Philipp and Koch (2011) reported a cost of switching the effectors (hands, feet, voice) used to indicate the same decision from trial to trial and Strayer and Kramer (1994) explored whether participants can be cued to adjust response criteria.

Here we are concerned primarily with the degree of coupling between stimulus-set and response-set components of task-set. At one extreme, these task-set components might be tightly coupled into one "unified" (Meiran, 2010), "flat" (Vandierendonck, Christiaens, & Liefooghe, 2008), "integrated" (Rangelov, Töllner, Müller, & Zehetleitner, 2013) representation. At the other, they might be uncoupled, largely independent, "ad-hoc" (Meiran, 2010), "componential" (Vandierendonck et al., 2008), "agglomerated" (Rangelov et al., 2013). For a coupled architecture, one can further consider the possibility of hierarchical representation, where some components are superordinate and others are subordinate (e.g., Kleinsorge & Heuer, 1999; Kleinsorge, 2004, see below).

To distinguish between these theoretical possibilities researchers have compared the switch cost obtained with trial sequences that require changes in the entire task-set to that obtained with a change in only one component. If the requirement to change multiple components results in a larger switch cost than changing only one, one might conclude that components can be reconfigured relatively independently. If the costs of changing two components were an additive combination of the costs of changing each, that would suggest sequential reconfiguration. Conversely, if the task-set is always reconfigured by resetting all of its components, then switch costs should be constant regardless of which/how many components are required to change (cf., Vandierendonck et al., 2008). Under a hierarchical account (e.g., Kleinsorge & Heuer, 1999; Kleinsorge, 2004), the requirement to change a superordinate component should result in a comparable, or even greater, switch cost than having to change the entire task-set. This

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is because the need to change a superordinate component would trigger the reconfiguration of the entire task-set, including components that did not need reconfiguring – these would have to then be reset back to their original settings. In contrast, changing a subordinate component should result in a smaller switch cost than changing the whole task set, because a subordinate component could be reconfigured on its own.

A number of empirical investigations have tested the theoretical proposals outlined above, one of the task-set components under scrutiny being the setting of the relevant perceptual stimulus attribute (stimulus-set). In perhaps the first such study, Allport, Styles, and Hsieh (1994) presented participants with a string of the same digit repeated (e.g. "5555") and asked them to categorise the parity or the magnitude of either the value of the digit or the number of digits – thus the participant could be asked to switch either the relevant perceptual attribute (identity or numerosity) or the relevant categorization (and the associated S-R rules), or both of them, or neither; these conditions were blocked. Allport et al. found that the cost of switching was the same whatever the number of components that had to change. In contrast, Hübner, Futterer, and Steinhauser (2001), who used the same categorizations, but replaced perceptual switches between digit and numerosity with switches between the local and global levels in Navon digit stimuli (Navon, 1977), found an additive increase in switch cost from changing one task-set component to changing two. However, the measure of switch cost used in both of these studies – the comparison between blocks containing task switches and single-task blocks – is problematic, because it confounds the (trial-wise) switch cost with the "mixing cost": in a mixed-task block performance is considerably worse than in a single-task block, even on task repetition trials (e.g., Los, 1996). Indeed, Hübner et al. (2001) did report a limited analysis of trial-wise switch costs for one of their experiments, and found that the switch cost was not significantly

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different for having to change one versus both task-set components, unlike the pattern

observed in the switch cost computed over blocks.

Studies designed to measure the transient within-block switch cost have not

yielded a clearer consensus. Kleinsorge (2004) used Allport et al.'s (1994) stimuli and

tasks in a task-cuing experiment in which stimulus location cued the relevant dimension

and stimulus colour cued the relevant classification rule. He found that although

switching either the attentional (stimulus-set) or the categorization (response-set)

component resulted in costs, categorization switches incurred a cost larger not only than

the cost of attentional switches, but also larger than the cost of having to change both

the attention and categorization components. (Kleinsorge and Heuer, 1999, had

previously obtained a similar pattern of results when they required participants to switch

between classifying the magnitude versus spatial location of a digit number using

spatially compatible or incompatible S-R rules, but compatibility had somewhat

different meanings for the two classifications: for classifying location it was determined

by the correspondence between the response hand and the number's horizontal position

on the screen, whereas for magnitude a left hand response was 'compatible' with

smaller numbers and 'incompatible' with the larger numbers.) Kleinsorge (2004)

concluded that a change in the hierarchically superordinate task-set components elicits

reconfiguration of hierarchically subordinate components, but not vice-versa. More

recently Vandierendonck et al. (2008) employed the same perceptual attributes and

categorizations, but used a compound textual cue, of which one element informed the

participant of the relevant stimulus-set and the other element informed the participant of

the relevant response-set. They found no greater switch cost when subjects were

required to switch both stimulus-set and response-set than when they were required to

switch one of them; this pattern of results held over several variations of the paradigm

with little modulation (short and long cue-stimulus intervals, tasks with separate vs.

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overlapping responses). Vandierendonck et al. (2008) concluded that the requirement to change either of two task-set components results in the reconfiguration of the whole task-set due to the coupling between components.

In contrast, Kieffaber, Kruschke, Cho, Walker, and Hetrick (2013) found larger switch costs and switch-related brain potential amplitudes when two components had to change than when only one component had to change. They used three tasks, requiring attention to size, colour or shape; two used the same response-set, while the third used a different response-set. For example, in Experiments 2 and 3, participants were required to make same/different judgments of two geometric figures based on either their shape or relative size (the "shape" and "size" tasks), or to identify their colour (the two stimulus elements always had the same colour – red or blue). The cue was the verbal label of the relevant perceptual attribute (e.g., "SIZE"). They reasoned that some task switches involved only a change in the relevant stimulus-set (switches between the "shape" and "size" tasks), whereas others also involved changing the response-set (switches involving the "colour" task). The central finding was that the latter resulted in greater switch costs and larger amplitudes of an ERP associated with preparation for a task-switch than the former.

Although it can be argued that the one- vs. two-component switch conditions in Kieffaber et al.'s (2013) study differed in other respects (e.g., difference in the required perceptual comparison: sampling the value on a perceptual dimension from any spatial element of the stimulus and comparing it to memory vs. discriminating the values for two elements and comparing them to each other), further evidence inconsistent with obligatory resetting of all task-set components when one of them changes comes from a visual search study by Rangelov et al. (2013). Participants switched between the tasks of detecting a singleton target in an array of objects and discriminating the value of a relevant dimension of the singleton; the singleton dimension (colour or orientation) was

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manipulated independently of the task. The key observation was that a task switch did not materially influence the benefit of a dimension repetition (shorter search times when the relevant dimension of the singleton was repeated than when it changed over consecutive trials), which does not sit easily with the notion that switching one task-set component involves obligatory resetting of all its components. In a further study inconsistent with obligatory resetting of all task-set components, Hahn, Andersen, and Kramer (2003) combined switches between two perceptual discriminations (by colour or shape) with two S-R mappings (for each task there were two sets of responses). The three kinds of switch (of stimulus-set, of response-set or both) were either unpredictable (in one experimental session) or blocked – with only one kind of switch per block (in another session). In both the blocked and randomised conditions, the requirement to switch one task-set component resulted in smaller switch costs than switching two; the requirement to switch the stimulus-set resulted in a greater cost than the requirement to switch the response-set, but both resulted in smaller costs than the double-switch condition. This seems inconsistent with either a strong hierarchical account of the kind proposed by Kleinsorge and colleagues (see above), or obligatory reconfiguration of the entire task-set when any change is required (e.g., Vandierendonck et al., 2008).

Based on the totality of these results, it is difficult to draw any firm conclusions about the coupling of task-set components: in some circumstances task-set components seem to be reconfigured together as a whole, presumably suggesting tight coupling, whereas in other cases they seem to be reconfigured independently. Where coupling has been suggested, in some cases it seemed hierarchical and in others not – even in similar paradigms (e.g., Vandierendonck et al., 2008 vs. Kleinsorge, 2004). Furthermore, despite some attempts to ascertain the conditions which promote or discourage the coupling (manipulations of: preparation interval, Kleinsorge, Heuer, & Schmidtke, 2002; Hahn et al., 2003; Vandierendonck et al., 2008; the overlap of the set of responses

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used in the different tasks, Vandierendonck et al., 2008; whether certain types of switches are blocked or not, Hahn et al., 2003), it remains largely unknown what these conditions are. It would seem important to determine such boundary conditions.

One trend that can nevertheless be discerned in the studies just reviewed gives further reason to be disconcerted. The finding that having to change one component can result in an equivalent or larger cost than switching two components seems to be confined to studies in which task-set components are not 'correlated' – i.e. where changing one component is not predictive of whether the other component also must change (e.g., Kleinsorge, 2004; Vandierendonck et al., 2008). Conversely, studies in which task-set components are correlated (e.g., a certain stimulus-set goes with a certain response-set, Kieffaber et al., 2013), tend to find greater switch cost when more task-set components have to change. Yet, an account based on coupling would predict exactly the opposite! If 'obligatory' switches of the whole task-set are due to coupling, then they should be more likely in conditions that promote the coupling/association between task-set components. One must therefore ask whether 'obligatory' reconfiguration of all components results from strategies adopted by participants in conditions with complex cues and a high probability of a switch of some kind (e.g., Vandierendonck et al., 2008) and, consequently, whether comparing costs of single- vs. multiple-component switches in such conditions is a good measure of coupling among components.

In the present study we adopted a different approach. We took a situation where we already have evidence, from on-line measurement of direction of gaze, for strong coupling between reconfiguration of spatial attention and other components of task-set (Longman, Lavric, & Monsell, 2013; Longman, Lavric, Munteanu, & Monsell, 2014). In the current Experiment 1, we modified Longman et al.'s (2014) task-switching conditions by introducing cues and instructions designed to prioritise shifting of the attentional component, and found that this appeared to decouple its reconfiguration

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from the rest of task set. In Experiment 2, we used (arbitrary) symbolic cues with the

same instructions and training, and found that the pattern of data reverted to that

suggesting largely integrated reconfiguration of the whole task-set.

In Longman et al.'s (2014) task-switching conditions, the stimulus consisted of

three digits displayed at the corners of an imaginary equilateral triangle, as shown in

Figure 1[1]. A central cue preceding this stimulus instructed the participant to perform

one of three binary classification tasks (odd/even, low/high, or inner/outer[2]) on one of

the three digits. Each task was consistently associated with a different digit location

throughout the experiment, so the cue actually specified both the location of the relevant

digit and the task to be performed. We monitored eye fixations between cue and

response to index attentional orienting, including any preparatory shift to the relevant

location, and any tendency to fixate the wrong digit. Four cue-stimulus intervals (CSIs)

were used, ranging between 120 and 1420 ms, to capture the typical reduction in the RT

switch cost with increasing opportunity for preparation. To control for any effect on the

ease of orienting to the appropriate digit of merely shifting between locations on

successive trials, a 'location-switching' control condition used the same cues and

stimuli, but each participant performed just one of the three classification tasks

throughout the experiment and the cue indicated only the location of the digit to

classify. In the task-switching condition (but not the location switching control), we

found that fixation of the currently relevant digit was substantially delayed on switch

relative to repeat trials, and that on switch trials the previously (but no longer) relevant

digit location was preferentially fixated over the other irrelevant location, even when the

preparation interval was more than one second. We interpreted the latter effect as

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[1] The displays in Longman et al. (2014) differed from those shown in Figure 1 only in the nature of the
cue.
[2] In the "low/high" classification task, the digits 2, 3, 4 and 5 are "low" and 6, 7, 8 and 9 are "high". In
the "inner/outer" classification task, the digits 4, 5, 6 and 7 are "inner", and 2, 3, 8 and 9 are "outer". Note
that the response categories in these tasks, and the "odd/even" task, are orthogonal.

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diagnostic of "attentional inertia[3]" (persistence over trials in the parameters of the

necessary orientation). The delay in appropriate orientation was also predictive, across

and within individuals, of the success of task-set preparation as reflected in RT switch

costs. Task-switch-induced delays were also recently documented in the allocation of

(non-spatial) attention to the relevant perceptual dimension, using both eye-tracking

(Mayr, Kuhns, & Rieter, 2013) and brain potentials (Elchlepp, Lavric, & Monsell,

2015).

In addition to these eye-tracking results indicative of difficulty of resetting

attentional parameters as a component of the relevant task-set (rather than mere

persistence of a location "habit" or low-level oculomotor priming), the Longman et al.

(2014) study provided evidence relevant to the issue of coupling between attentional

settings and the rest of the task-set. In Experiment 1 of that study we used arbitrary

single-letter cues (e.g., A, B, C), whereas in Experiment 2 the arbitrary cues were

replaced with verbal cues whose meaning was much more transparent with regard to the

required classification (e.g., 'ODD?', 'LOW?', 'INNER?'). Using transparent labels

resulted in a much larger delay in fixating the relevant region and a greater effect of

attentional inertia, whilst also reducing somewhat the performance switch cost. The

smaller delay and inertia effects with arbitrary cues in Experiment 1 suggest that these

task cues may to some extent have acted as location cues, allowing the participants to

prioritise orienting of spatial attention and, hence, weakening its coupling to the other

task-set components.

To test the conjecture that a strong location cue might prioritise attentional

selection and uncouple the resetting of attentional and other components of task-set, in

the first of the present experiments we used the task-switching condition from the

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[3] The term 'attentional inertia" was used by Kirkham, Cruess, & Diamond (2003) to explain young
children's difficulty in switching between sorting cards by colour and sorting by shape. The time-scale of
the persistence of the children's "attentional inertia" seems rather different from the transient one-trial
inertia we detect here in adults; it remains an open question how they are related.

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experiments reported by Longman et al. (2014) but with two important changes. First, we used cues which explicitly indicated the location of the relevant digit (an arrow pointing to the location or a position word label: 'TOP', 'LEFT', or 'RIGHT') and only implicitly the task to be performed on it. Previous research has found both of these types of cue to be highly effective in controlling spatial attention (e.g., Hommel, Pratt, Colzato, & Godijn, 2001). Arrows have been shown to be particularly effective in eliciting what many believe to be automatic orienting to the cued location, even when they are uninformative (e.g., Ristic & Kingstone, 2012), in conflict with task instructions (e.g., Ristic & Kingstone, 2012; Galfano et al., 2012), or even outside one's conscious awareness (Gabay, Avni, & Henik, 2012).

Second, the instructions given to participants and the practice regime before testing also emphasised cue-location associations over cue-task associations. Longman et al. (2014) instructed participants that each cue specified one of three classification tasks, and their initial task-practice blocks used centrally presented digits, so that the association between task and location was introduced relatively late in the practice phase. In contrast, in the present experiment, participants were told that the cues identified which of the three digits in the stimulus array had to be classified; they first practiced one classification task at a time (e.g., odd vs. even) but with three digits presented as in Figure 1 (thus the cue specified only the location) and were told only later that during testing each location would be associated with a different task. Our expectation was that these highly effective symbolic cues for location, together with the modified training regime, would maximise prioritisation of the shift of the attentional "spotlight" to the relevant location, possibly decoupling that operation from the reconfiguration of other aspects of task-set, so that preparatory orienting would no longer be sensitive to whether the task to be performed had to switch or not. A potential corollary of strongly prioritising orientation to the relevant location is that reconfiguring

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other aspects of task-set during the CSI would get lower priority, leading to less effective preparation and larger switch costs than under the conditions examined in Longman et al. (2014).

Experiment 1

Experiment 1 encouraged the decoupling of spatial orientation from other aspects of task-set by using central cues which explicitly direct attention to locations, and by familiarising participants with location switching and cue-location associations before task (classification) switching and cue-task associations. It is also worth noting that the present experiment avoids an important methodological confound that may be a feature of the multi-component task-set switching experiments reviewed earlier – that using only one cue per task can substantially inflate the switch costs due to the contribution of facilitation of cue processing when cues are repeated for task repetitions (e.g., Logan & Bundesen, 2003; Mayr & Kliegl, 2003; Monsell & Mizon, 2006). In the present experiment, as in its predecessor experiments in Longman et al. (2014), the cue type changed on every trial between word and arrow so that there were no cue-repeat trials. A further benefit of using the two types of cue is that we were able to compare performance on trials with word vs. arrow cues. One might predict that arrow cues would 'automatically' orient attention to the relevant location (thereby completely breaking its coupling to the rest of task-set). Word cues which require more interpretation might, to some extent, also activate other task-set parameters (or at least allow time to initiate reconfiguration of other task-set parameters prior to orienting).

Method

Participants. Twenty four students (15 female, mean age=19.29), from the same population as in Longman et al. (2014), participated and were motivated in the

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same way: they received partial course credits and were paid a bonus up to a maximum of £3.60 depending on points awarded for improving performance through the experiment.

Tasks, Stimuli and Procedure. The experiment was run using E-Prime (Psychology Software Tools Inc., Sharpsburg, USA) on a flat 17" CRT monitor placed ~57 cm from the participants' eyes. On each trial a black fixation cross (subtending 0.4°) was presented centrally along with three light blue dots (0.3° in diameter) at the locations where the digits would eventually appear (see Fig. 1). Either an arrow (subtending 0.3° along its shaft, 0.2° laterally) or one of the words 'TOP', 'LEFT' or 'RIGHT' (subtending up to 0.8° horizontally, 0.3° vertically) then replaced the fixation cross for 100 ms, leaving only the three blue dots for the remainder of the CSI. The cue type toggled between word and arrow on every trial. The brief display of the cue was intended to encourage advance fixation of the location where the cue would appear and rapid 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 from block to block; the order of CSIs within each 4-block sequence was Latin-square balanced over participants. There were 16 experimental blocks. To avoid confounding the time available for preparation with possible effects of passive decay of control settings from the previous trial (cf. Meiran, 1996) the response-stimulus interval was 2250 ms regardless of CSI except when the wrong key was pressed, in which case "ERROR" was displayed for an extra 1000 ms.

The stimulus comprised three digits (each subtending 0.4° horizontally, 0.5° vertically) displayed at three locations arranged in an equilateral triangle, 5° from each other and 2.7° from the central location of the cue. The cue specified both the location of the digit to be classified and the classification rule to apply (though see below for the order in which the cue-location and cue-task associations were introduced and

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practiced): odd vs. even; low (≤5) vs. high (≥6); "inner" (4, 5, 6, 7) vs. "outer" (2, 3, 8, 9). Each task was mapped to a single location throughout the experiment (with the mapping rotated over participants). The stimulus was displayed until one of two keys ('c' or 'm' on a standard QWERTY keyboard) was pressed with the left or right index finger. Stimuli were selected from the digits 2-9 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.

The CSI was displayed before each block and the mean RT, number of errors and a composite performance score based on both measures 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, participants practiced cue-location associations from the outset starting with three 8-trial single-task blocks (one block per task). Location-task associations were then introduced in two task-switching blocks of 74 trials each, identical to the experimental blocks which followed, with a CSI of 1020 ms. Throughout the practice session, participants were instructed that the cue identified the location of the digit to be classified and its location defined which classification rule to use.

Eye-tracking. An EyeLink 1000 eye-tracker (SR Research, Ottawa, Canada) recorded movements of the right eye from the onset of the fixation cross until response; it was calibrated before each 74-trial block. Four square regions (side = 2°) were centred on, and delineated as the 'relevant' regions for, the cue and each digit in the stimulus.

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On task-repeat trials 94.24% of all fixations occurred within these regions; 93.99% on task-switch trials. The first two trials in each block, trials with RT>2500 ms (2.1%), trials on which the cue was not fixated (3.4%) and trials following an error were omitted from all analyses. Error trials were omitted from RT and eye-tracking analyses.

Fixations following cue onset were analyzed (as in Longman et al., 2014) to obtain: (1) the total dwell-time on each of the above-mentioned spatial regions of the stimulus within 20 ms time-windows following cue onset (i.e., the summed duration of all fixations on the respective region within the respective time-window); (2) the onset ('launch time') of the first eye-movement away from the cue region.

Results

For each measure we report first the results for the present experiment, then a contrast with Experiment 2 from Longman et al. (2014), in which the cues labelled the task-relevant categories (e.g. "ODD?"). In ANOVAs, the reported significance values are Huyhn-Feldt-corrected for sphericity violations (but *dfs* are reported uncorrected).

RT and errors. Mean RTs and error rates, averaged over the three tasks for the arrow cues and the word cues are presented in Figure 2. A cue type (arrow, word) by switch (switch, repeat) by CSI by task ANOVA on the RTs found a reliable main effect of switch, $F(1,23)=156.27$, MSE=50109.32, $p<0.001$. Although the switch cost was reliable for both types of cue[4], $F_{arrow}(1,23)=134.81$, MSE=34429.03, $p<0.001$; $F_{word}(1,23)=150.59$, MSE=21587.60, $p<0.001$, it was larger with arrow (180 ms) than with word cues (150 ms), as indicated by the switch x cue type interaction, $F(1,23)=10.45$, MSE=5907.31, $p=0.004$. The reduction in switch cost with CSI did not interact with cue type, $F(3,69)<1$, and the switch by CSI interaction was reliable for both types of cue, $F_{arrow}(3,69)=7.53$, MSE=6667.02, $p<0.001$; $F_{word}(3,69)=6.12$,

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[4] F-ratios from ANOVAs with cue type (arrow, word) as a factor have no subscripts, whereas the F-ratios (and t statistics) from separate ANOVAs for each cue type have the subscripts 'arrow' or 'word' respectively.

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MSE=6592.13, p=0.001, with the switch cost reducing from 225 ms at the shortest CSI to 140 ms at the longest CSI for the arrow cues, and from 188 ms to 124 ms for the word cues. ANOVAs run separately for the two longest CSIs to examine the 'residual' switch cost found a reliable main effect of switch for both types of cue: CSI=1020 ms: $F_{arrow}(1,23)=56.90$, MSE=16293.84, p<0.001; $F_{word}(1,23)=61.92$, MSE=8313.74, p<0.001; CSI=1420 ms: $F_{arrow}(1,23)=43.52$, MSE=16241.20, p<0.001; $F_{word}(1,23)=47.87$, MSE=11656.54, p<0.001. There were also reliable interactions between task and switch, F(2,46)=4.24, MSE=14981.27, p=0.022, and cue, task and switch, F(2,46)=3.84, MSE=5520.87, p=0.030. Follow up ANOVAs found a reliable interaction between task and switch for the arrow cues, $F_{arrow}(2,46)=6.28$, MSE=12864.85, p=0.005, with the largest switch cost in the inner/outer task (216 ms) and the smallest switch cost in the low/high task (137 ms, odd/even task: 185 ms); this interaction did not approach significance for the word cues, $F_{word}(2,46)<1$.

There was a main effect of switch in the error analysis, F(1,23)=3.13, MSE=55.41, p=0.033, and although this did not interact with cue type, F(1,23)=2.52, MSE=19.57, n.s., a reliable switch cost was found only for the arrow cues, $F_{arrow}(1,23)=5.55$, MSE=51.42, p=0.027; $F_{word}(1.23)=2.06$, MSE=23.55, n.s. No other interaction involving switch was significant for errors.

Comparison with explicit task-cuing. ANOVAs including experiment as a between subjects factor, and averaging over word and arrow cues for the present data, were conducted to compare the present results obtained with location cues, with those of Experiment 2 in Longman et al. (2014), in which the verbal cues explicitly labelled the task categories.

The RT switch cost was much larger with location cues (167 ms) than with Longman et al.'s (2014) task-label cues (95 ms), F(1,46)=17.81, MSE=20731.03, p<0.001 (see Table 2 for detailed descriptive statistics for each experiment). The

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interaction between switch, CSI and experiment was not reliable, $F(3,138)<1$, indicating

a comparable reduction in switch cost with opportunity for preparation, but the

'residual' switch cost was nearly doubled with location cues (CSI=1020 ms: 141 ms,

CSI=1420 ms: 132 ms) relative to explicit task-cues (CSI=1020 ms: 71 ms, CSI=1420

ms: 74 ms), switch by experiment interaction at: CSI=1020 ms, $F(1,46)=12.81$,

MSE=6872.77, p=0.001; CSI=1420 ms, $F(1,46)=7.67$, MSE=7965.36, p=0.008. There

were no reliable interactions involving the factor experiment in the error data.

Eye-tracking.

Average delay in fixating the relevant region. Figure 3 shows the dwell time on

each of the stimulus regions as a factor of task relevance in successive 20 ms bins for

1420 ms following cue onset. (We also include the equivalent data from Longman et al.,

2014, Experiment 2, for comparison). Compared to the substantial delay in the point at

which attention begins (on average) to shift towards the relevant stimulus on switch

relative to repeat trials in Longman et al. (2014), only a tiny equivalent delay in the

present experiment is visible (if at all) in Figure 3. The delay was estimated as in

Longman et al. (2014)[5] by curve fitting over a 100 ms window covering the early (and

steepest) part of the rise in dwell times on the relevant region. The resulting delay

estimates were submitted to an ANOVA with the factors cue type and CSI. The switch-

related delay in fixating the currently relevant region was smaller with arrow cues (6

ms) than with word cues (15 ms), $F(1,23)=5.07$, MSE=840.74, p=0.034. Neither the

main effect of CSI, $F(1,23)<1$, nor the cue type by CSI interaction was reliable,

$F(3,69)<1$, indicating that the effect of preparation on the delay (with increasing CSI for

the arrow cues: 6 ms, 8 ms, 2 ms, 7 ms; word cues: 23 ms, 16 ms, 13 ms, 9 ms) was not

reliable for either set of cues (main effect of CSI: $F_{arrow}(3,69)<1$; $F_{word}(3,69)=1.59$,

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[5] For each participant a 10-order polynomial was fit to the dwell time curve for switch trials. For every (2 ms) time point on the repeat curve the corresponding time at which the switch condition dwell time reached the same value provided delay estimates, which were averaged over a 100 ms window starting from the first 20 ms bin in which dwell time, averaged over participants, was greater than 2 ms (10% of the maximum). See Fig. 3 for time-window boundaries and Longman et al. (2014) for further details.

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MSE=666.30, n.s.). For each CSI separate t-tests indicated that the estimated delay was reliable for the word cues in all but the longest CSI (in order of increasing CSI: $t_{word}(23)$=3.25, p=0.004; $t_{word}(23)$=2.70, p=0.013; $t_{word}(23)$=2.79, p=0.010; $t_{word}(23)$=1.69, p=0.104) and approached significance for the arrow cues only for the two shortest CSIs (in order of increasing CSI: $t_{arrow}(23)$=1.94, p=0.065; $t_{arrow}(23)$=1.83, p=0.081; $t_{arrow}(23)$<1; $t_{arrow}(23)$<1).

Comparison with explicit task-cuing. The between-experiment contrasts indicate that the switch-related average delay in orientation to the relevant region was an order of magnitude larger with task-transparent cues in Longman et al.'s (2014) Experiment 2 (88 ms) than with location cues (10 ms), $F(1,46)$=42.37, MSE=6792.98, p<0.001. In order of increasing CSI, the estimated delays for the explicit task-cues vs. location cues were: 89 ms vs. 14 ms, 89 ms vs. 12 ms, 81 ms vs. 7 ms, 92 ms vs. 8 ms. Independent samples t-tests run for each CSI found that the estimated delay was larger with task cues than spatial cues at every CSI (in order of increasing CSI: $t(46)$=5.04, p=0.019; $t(46)$=6.23, p<0.001; $t(46)$=6.75, p<0.001; $t(46)$=5.09, p<0.001). The experiment by CSI interaction was not reliable, $F(3,138)$<1.

Delay in launch of appropriately targeted saccades. Does the small average delay in fixating the relevant region on switch trials reflect later launches of fixations to the relevant region, or a higher proportion of fixations going initially to irrelevant regions? We performed an ANOVA on launch times (of the first saccade to leave the cue region) restricted to trials when that first saccade terminated in the relevant digit's region, with the factors cue type, switch, CSI and task (see Figure 4). The overall delay in launch times on switch trials relative to repeats was very small and non-significant (3 ms for each cue type; main effect of switch: $F(1,23)$<1) nor were there any significant interactions involving the factor switch (all Fs<2). This is in marked contrast with the delay of ~60 ms observed for launches of appropriately targeted saccades with task-

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labelling cues in Longman et al. (2014), Experiment 2. Indeed the switch by experiment interaction was highly significant in the between-experiment ANOVA $F(1,46)=62.58$, MSE=4260.89, $p<0.001$, and remained so when tested separately at all CSIs (all Fs>20).

Fixations on task-irrelevant regions. As may be seen in Figure 5, the tendency observed by Longman et al. (2014) to fixate the irrelevant regions on switch trials more than on repeat trials was not visible in the present experiment with location cues. An ANOVA on the dwell time in the irrelevant regions (the analysis window shown in Figure 5 for irrelevant dwell time was 200 ms as in Longman et al., 2014) with factors cue type, switch, CSI and task found no reliable effects or interactions involving the factor switch. ANOVAs performed on these data for each set of cues individually revealed a marginally reliable main effect of switch for the arrow cues, $F_{arrow}(1,23)=3.85$, MSE=0.08, $p=0.062$, with participants making slightly fewer (not more as in Longman et al., 2014) irrelevant fixations on switch trials than repeats. Although the reverse was true for the word cues, this reversal did not approach significance, $F_{word}(1.23)<1$.

'Attentional inertia'. The use of three tasks enabled us to examine the extent to which attention is drawn on switch trials to the location of the previously relevant digit specifically (our measure of 'attentional inertia'), rather than indiscriminately to the locations of either of the irrelevant digits – by distinguishing for the switch trials between the location relevant on the previous trial and the other irrelevant location. The ANOVA performed, for switch trials only, for the dwell time on the irrelevant regions with the factors cue type, CSI, task and previous relevance (previously relevant, previously irrelevant) found that the previously relevant region was preferentially fixated over the other irrelevant region (main effect of previous relevance: $F(1,23)=20.39$, MSE=30.87, $p<0.001$). This effect was reliable for both sets of cues ($F_{arrow}(1,23)=5.72$, MSE=0.62, $p=0.025$; $F_{word}(1,23)=19.35$, MSE=58.33, $p<0.001$) and

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the tendency to fixate the previously relevant region was larger with word cues than with arrow cues (cue type by previous relevance interaction: $F(1,23)=17.92$, $MSE=28.07$, $p<0.001$). Although attentional inertia reduced with preparation for both cue types, $F(3,69)=5.85$, $MSE=19.51$, $p=0.002$, this reduction was more pronounced with word cues probably because there was more of an effect to reduce at short CSIs, $F_{word}(3,69)=4.78$, $MSE=40.27$, $p=0.008$, than with arrow cues, $F_{arrow}(3,69)=4.13$, $MSE=0.98$, $p=0.032$; cue type by previous relevance by CSI interaction, $F(3,69)=3.69$, $MSE=21.85$, $p=0.027$. The ANOVA run separately to examine the 'residual' attentional inertia in the word cues found a reliable main effect of switch at CSI=1020 ms, $F_{word}(1,23)=8.57$, $MSE=20.36$, $p=0.008$, but not at CSI=1420 ms, $F_{word}(1,23)=1.93$, $MSE=15.49$, n.s. For the arrow cues the dwell time in the currently irrelevant regions for switch trials was 0 ms at the two longer CSIs for all participants.

The between-experiments ANOVAs found that location cues significantly reduced the tendency to fixate the irrelevant regions on switch trials over repeats (switch by experiment interaction, $F(1,46)=27.03$, $MSE=222.69$, $p<0.001$). The switch by CSI by experiment interaction was also reliable, $F(3,138)=6.38$, $MSE=22.66$, $p=0.001$, indicating that the interaction between switch and preparation was smaller with spatial cues (presumably because there were so few fixations on the irrelevant regions even at the shortest CSIs), and a reliable switch by experiment interaction was found at each CSI (all Fs>18). In the ANOVA restricted to switch trials, spatial cues were also associated with a reduced bias towards fixating the previously relevant region over the other irrelevant region (previous relevance by experiment interaction: $F(1,46)=12.44$, $MSE=540.59$, $p=0.001$). Although the modulation of the effect of previous relevance by CSI was larger with explicit task-cues (previous relevance by CSI by experiment interaction, $F(3,138)=7.91$, $MSE=56.33$, $p<0.001$), a reliable previous relevance by experiment interaction was found in all CSIs apart from CSI=1420 ms

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where it approached significance [CSI=120 ms: F(1,46)=17.20, MSE=253.73, p<0.001;

CSI=620 ms: F(1,46)=13.70, MSE=162.22, p=0.001; CSI=1020 ms: F(1,46)=6.02,

MSE=145.94, p=0.018; CSI=1420 ms: F(1,46)=3.48, MSE=128.83, p=0.068].

Discussion

In our previous experiments (Longman et al., 2013, 2014) tasks consistently

associated with spatial locations were cued in such a way as to specify the task rather

than the relevant location. We observed substantial delays and "attentional inertia" in

orienting to the task-appropriate location when the task changed, suggesting a strong

coupling of shifts of spatial attention to other aspects of task-set reconfiguration. The

aim of the present Experiment 1 was to investigate whether, when the nature of the cues

and instructions encourage prioritisation of location selection over task selection, the

shift in orientation becomes decoupled from other aspects of task-set control and hence

insensitive to a task switch. The results clearly support this notion. Cuing of location-

linked tasks with arrows pointing to, or words labelling, the locations, resulted in very

much smaller delays in orientation to the relevant location on switch trials, and greatly

reduced "attentional inertia" (the tendency to fixate the previously relevant location on a

switch trial) compared to the substantial effects observed in the Longman et al. (2014)

Experiment 2, whose verbal cues identified the task rather than location. This suggests

that the coupling of spatial attention parameters to other task-set parameters is situation-

dependent.

We also expected that decoupling the spatial attention component of task-set by

prioritizing it would have the consequence that participants would not be so well

prepared for a task switch at a longer CSI; i.e., that preparation would be focused on

acquiring the target region rather than reconfiguring the task set as a whole. And indeed

the use of location cues (and instructions) substantially increased the RT switch cost

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whilst largely eliminating the attentional handicap associated with switching between

tasks.

The differences between arrow and word cues are, although small, also of

interest. Inasmuch as there was evidence of attentional inertia at the longer CSIs with

location cues, it was limited to the word cues, which are arguably less strongly

associated with the precise direction in which attention must be shifted. The switch cost

and its residual component were largest with arrow cues, and they completely

eliminated attentional inertia at the longest CSIs. Intriguingly, with these cues the

switch cost appears to continue to decrease (at least numerically) at the longest CSI

suggesting that it may not yet have reached asymptote, whereas with word cues there

was no further switch cost reduction at the longest CSI. This suggests that arrow cues

are more effective at prioritising attentional selection over the rest of task-set (thus

postponing reconfiguration of other task-set components), whereas word cues – because

they take longer to interpret and/or because the direction they signal is less precise –

partially activate other components of the task-set or at least allow enough time to

initiate their activation prior to orienting.

Experiment 2

Experiment 1 established that, by instructing/training participants to prioritise

attentional selection and using cues which explicitly indicate the relevant location, it is

possible to decouple this component from the remainder of task-set. The results of these

manipulations were to inflate switch costs and greatly reduce or eliminate the observed

effects of a task switch on spatial attention compared to a condition identical except that

task rather than location was explicitly cued and practiced. What about task cues which

are initially associated with neither task nor location? In the Longman et al. (2014)

Experiment 1 we found that such arbitrary cues (letters) were associated with reduced

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but still substantial task-switch-related attentional handicaps compared to cues which explicitly identify the task (Longman et al., 2014, Experiment 2). However, in both those experiments, the instructions and training regime were designed to encourage interpretation of cues as specifying tasks (rather than locations). This led us to ask whether, in circumstances where task and location are consistently associated (as in these designs), and the cue can be interpreted as signalling either, the 'natural' tendency is for reconfiguration of attentional and other components of task-set to be coupled or decoupled. To examine this possibility, in the next experiment we used the task-switching condition and arbitrary letter cues from the Longman et al. (2014) Experiment 1 with one critical difference. Rather than instructing participants that the arbitrary cues identified which classification rule (task-set) to use and that each classification rule should be used at one location throughout the experiment, we instructed participants that the arbitrary cues identified which location was relevant and that a different classification rule should be used at each location throughout the experiment. Furthermore, unlike Longman et al. (2014) Experiment 1, where practicing switching tasks using a single centrally-presented digit preceded the practice with three digits in different locations, the present training regime started (as in the current Experiment 1) with switching locations for a constant categorization task, and only later introduced task-switching.

If the 'natural' tendency is for shifts of spatial attention to remain independent of changes in other components of task-set, then modifying the instruction/training to emphasise a location interpretation of the arbitrary cues should suffice to eliminate or substantially reduce the effects of task-set on attention documented by Longman et al. (2014) in their Experiment 1, and we should get very similar outcomes to those obtained with the explicit location cues of the present Experiment 1. Conversely, if this modification of the instruction/training does not materially alter the effects of a task-

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switch on spatial attention (delay and inertia) observed in Longman et al.'s (2014) Experiment 1, one would have to conclude that the more 'natural' relationship between attentional selection and task-set is to be coupled, and only the use of explicit location cues decouples them. Thus, the present experiment has the potential to clarify which of the two manipulations in Experiment 1 (instructions-training regime or the nature of the cue) had the critical effect of decoupling spatial orienting from the reconfiguration of the rest of the task-set.

Method

A new sample of 24 students (18 female, mean age=19.17) received the same payment as in Experiment 1 for their participation. Participants were instructed that the cue (one of the letters A, B, C, X, Y or Z, subtending 0.2° horizontally, 0.3° vertically) identified which digit to classify (A or X always referred to the digit at the top, B or Y left, C or Z right) and that the digit at each location should be classified with a different rule throughout the experiment. In all other respects the design of the experiment, practice session and instructions given were identical to Experiment 1.

The same square regions as in Experiment 1 were used for analysis. On repeat trials 94.45% of all fixations landed within these regions; 93.96% on switch trials. Two blocks of trials (in different participants) were discarded because >20% of trials contained no fixations in any of the three stimulus regions, suggesting poor calibration. (The same criterion was applied in Experiment 1, but no blocks had to be omitted there). The first two trials in each block, trials with RT>2500 ms (3.2%), trials on which the cue was not fixated (1.4%) and trials following an error were also omitted from all analyses. Error trials were omitted from all RT and eye-tracking analyses.

Results

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RT and errors.

Arbitrary cues with location instructions. The mean RT and error rates, averaged across all three tasks are presented in Figure 6. A switch by CSI by task ANOVA on the RTs found a reliable switch cost of 124 ms, $F(1,23)=70.92$, MSE=31070.00, $p<0.001$ and, although this reduced with opportunity for preparation (from 132 ms at the shortest CSI to 116 ms at the longest), the interaction failed to approach significance, $F(3,69)<1$. A substantial and significant residual switch cost remained at the two longest CSIs (CSI=1020 ms: switch cost=119 ms, $F(1,23)=47.37$, MSE=10762.91, $p<0.001$; CSI=1420 ms: switch cost=116 ms, $F(1,23)=47.27$, MSE=10269.16, $p<0.001$). There were no reliable effects or interactions involving the switch factor in the errors.

Comparison with task-instructions design. A comparison of the current switch costs and preparation effects with those in the task-switching condition with arbitrary cues in Longman et al. (2014), Experiment 1 (see Table 2 for detailed descriptive statistics for that experiment), shows that the switch cost in the latter was smaller for RTs (by 18 ms overall; by 27 ms and 22 ms in the two longest CSIs respectively), but not significantly so (Fs<2). The reduction in switch cost with opportunity for preparation (the RISC effect) for RTs was also slightly greater when participants were led to construe the cue as a task rather than a location cue (from 128 ms at the shortest CSI to 94 ms at the longest). However the three-way interaction between switch, CSI and experiment did not approach significance, $F(3,138)<1$. There were no reliable interactions involving the factor experiment in the errors.

Eye-tracking.

Delay in fixating the relevant region. Figure 7 shows the dwell time on each of the stimulus regions as a function of relevance for 1420 ms following cue onset in successive 20 ms bins. The switch-induced delay in attention to the relevant region was

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estimated in the same way as for Experiment 1 (except due to a shallower curve, the analysis window was 200 ms as in Longman et al., 2014). One sample t-tests performed on the estimated delay at each CSI separately confirmed that the delay was reliable at all CSIs (with increasing CSI: t(23)=5.54, p<0.001; t(23)=4.92, p<0.001; t(23)=3.53, p=0.002; t(23)=3.13, p=0.005). A follow up ANOVA performed to assess the effects of CSI on the delay found that the temporal separation did not change significantly with CSI, F(3,69)<1.

The ANOVA on the estimated switch-induced delay with experiment as a between subjects factor (current experiment vs. Experiment 1 in Longman et al., 2014 – the relevant descriptive statistics for that experiment can be found in Table 2) found that the main effect of experiment did not approach significance, F(1,46)<1, indicating that the 5 ms reduction in the delay with location instructions/training relative to task-related instructions/training was not reliable. There was a significant main effect of CSI when data from both experiments were analyzed together, F(3,138)=3.47, MSE=0.70, p=0.024, indicating that the delay was reduced somewhat with opportunity for preparation, but this effect did not reliably interact with experiment, F(3,138)<1. Follow-up independent samples t-tests demonstrated that the small difference in the estimated delay between experiments was not reliable at any of the CSIs, ts<1.2. With increasing CSI, the estimated delay when participants were instructed that the cues referred to tasks (Longman et al., 2014, Experiment 1) vs. locations (present experiment) were: 43 ms vs. 33 ms, 42 ms vs. 34 ms, 33 ms vs. 27 ms, 22 ms vs. 26 ms.

This average delay in appropriate orientation can be explained at least in part by additional fixations made on the irrelevant regions (see below). To examine whether there was also a delay on the trials with appropriately targeted fixations, an ANOVA was conducted for the 'launch time' of the first saccade to leave the cue, limited to only those trials on which the first saccade to leave the cue landed directly in the relevant

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region (see Figure 8). It found a reliable main effect of switch, $F_{(1,23)}=12.12$,

MSE=4957.87, p=0.002, indicating that attention orientation was reliably delayed (by

20 ms averaged over CSIs) on switch trials relative to repeats. The switch by CSI

interaction did not reach significance, $F_{(3,69)}=2.31$, MSE=1686.20, p=0.084, indicating

modest effects of CSI. The equivalent estimate of a delayed launch in Longman et al.

(2014), Experiment 1, was 25 ms (see Table 2 for the mean launch times for each

condition in that experiment); the between-experiments contrast did not approach

significance, $F_{(1,46)}<1$.

Fixations on task-irrelevant regions. An ANOVA on the dwell time in the

irrelevant regions for the current experiment (see Figure 9) found a reliable main effect

of switch, $F_{(1,23)}=4.72$, MSE=14.43, p=0.04, indicating a greater tendency to fixate the

irrelevant regions on switch trials than on repeat trials. The small numerical reduction in

this tendency with preparation (the switch by CSI interaction) was not reliable,

$F_{(3,69)}<1$.

'Attentional inertia'. A further ANOVA performed on the dwell time in the

irrelevant regions for switch trials with the factors previous relevance, CSI and task

found that the previously relevant region was preferentially fixated over the other

irrelevant region (main effect of previous relevance, $F_{(1,23)}=19.54$, MSE=282.87,

p<0.001). Although there was a tendency for this effect to reduce with preparation, the

previous relevance by CSI interaction was not reliable, F<1, and a reliable main effect

of previous relevance was found in the two longest CSIs (CSI=1020 ms: $F_{(1,23)}=8.53$,

MSE=103.10, p=0.008; CSI=1420 ms: $F_{(1,23)}=9.98$, MSE=110.41, p=0.004).

The analysis over experiments (current experiment vs. Longman et al. 2014,

Experiment 1) found that instructing participants to use the cues to indicate the relevant

location reduced the tendency to fixate the irrelevant regions on switch trials over

repeats (switch by experiment interaction: $F_{(1,46)}=18.35$, MSE=44.20, p<0.001).

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Although this difference was modulated by preparation (switch by CSI by experiment interaction: $F(3,138)=6.39$, MSE=20.57, p=0.002), the effect was in the same direction for all CSIs and reliable in all but CSI=1020 ms (switch by experiment interaction at CSI=120 ms: $F(1,46)=16.47$, MSE=43.36, p<0.001; CSI=620 ms: $F(1,46)=12.71$, MSE=23.17, p=0.001; CSI=1020 ms: $F(1,46)=2.53$, MSE=11.35, n.s.; CSI=1420 ms: $F(1,46)=5.36$, MSE=11.09, p=0.025). However, the comparison of attentional inertia between experiments (see Figure 9 and Table 1) found that the instructional and training manipulation did not reliably influence the extent to which attention was directed on switch trials towards the previously (but no longer) relevant region over the other irrelevant region (relevance by experiment interaction: $F(1,46)<1$).

Comparison with explicit location cues. Experiments 1 and 2 from the present study used the same training regime (aimed at emphasizing location over task), but different types of cue (explicit location cues vs. arbitrary cues that only became related to locations during the experiment). ANOVAs on RTs and error rates with experiment as a between-subjects factor revealed a greater switch cost with location cues (switch by experiment interaction, $F(1,46)=4.80$, MSE=28185.30, p=0.034), especially for the two shorter CSIs (switch by CSI by experiment interaction, $F(3,138)=4.51$, MSE=3534.52, p=0.005), where the switch by experiment interaction was significant (in the order of increasing CSI: $F(1,46)=12.50$, MSE=8820.71, p=0.001; $F(1,46)=6.90$, MSE=8662.60, p=0.012; $F(1,46)=0.82$, MSE=10285.37, n.s.; $F(1,46)=0.407$, MSE=11020.17, n.s.).

Contrasting the two experiments in the current study on our two key fixation measures (task switch-induced delay in orienting to the relevant region and 'attentional inertia') revealed both the delay and attentional inertia to be significantly greater with arbitrary cues than with location cues (main effect of experiment on delay, $F(1,46)=10.28$, MSE=1855.76, p=0.002, and previous relevance by experiment interaction, $F(1,46)=11.84$, MSE=1764.92, p=0.001).

Discussion

The purpose of Experiment 2 was to investigate the extent to which (re)orienting spatial attention becomes decoupled from the reconfiguration of the remainder of task-set when the cues are intrinsically neutral/arbitrary but the instructions emphasise their association with location rather than task. This condition was compared to the otherwise equivalent task-switching condition of Experiment 1 in Longman et al. (2014), in which the instructions and training emphasised the task meaning of the cues. The outcomes of the two experiments were quite similar.

The performance measures showed similar patterns of switch cost and its reduction with preparation, though there was a slightly greater RISC effect in Longman et al.'s (2014) Experiment 1 and a somewhat greater residual switch cost in the present experiment (though neither interaction with experiment was significant). As in the Longman et al. (2014) Experiment 1, we found in the current experiment clear attentional delays and "attentional inertia" at all CSIs; thus a task switch affected the (re)allocation of spatial attention in the current conditions. The only eye-tracking measure that was significantly different between the present experiment and Longman et al.'s (2014) Experiment 1 was the somewhat reduced tendency to fixate an irrelevant region on switch trials relative to repeats in the present experiment. The tendency to fixate, on switch trials, the previously (but no longer) relevant region more than the other irrelevant region – the "attentional inertia" effect – was still numerically and statistically robust and was neither strongly nor reliably reduced by emphasis on the location meaning of an arbitrary cue. The reduced switch-repeat difference in fixating all the irrelevant regions (irrespective of previous relevance) in the present experiment is thus probably indicative of (slightly) reduced distractibility on switch trials rather than reduced attentional inertia. In contrast, a cue that explicitly pointed to or verbally

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indexed location, in the present Experiment 1, all but eliminated attentional inertia as indexed by this measure, suggesting (together with the differences between the two current experiments in RT switch cost and the switch-induced delay in fixating the relevant region) that the type of cue, more so than the nature of the instructions, resulted in decoupling and strong prioritization of reorienting from the rest of the task-set reconfiguration observed in Experiment 1.

Clearly the RT and eye-tracking effects of a task switch in the current experiment are much more like those of Longman et al (2014) Experiment 1, which differed only in the initial instructions and practice, than they are like those of the present Experiment 1, which differed in its use of explicit location cues. We conclude that it is the latter which was primarily responsible for the elimination of attentional delays and larger switch cost observed in Experiment 1 (relative to Longman et al, 2014, Experiment 2). This suggests that, absent of a strong location cue, the natural tendency is for (re)orienting to be coupled with reconfiguration of other components of task set.

General Discussion

The experiments reported here and in our previous articles (Longman et al, 2013, 2014) have explored the extent to which reconfiguration of an attentional parameter of the task-set (the task-relevant location) is coupled to the reconfiguration of other task-set components (the relevant semantic classification and S-R mapping) and the conditions which modulate the strength of this coupling. An innovation of the current study relative to previous studies of task-set architecture and task-set "binding" (e.g., Allport et al., 1994; Hübner et al., 2001; Kleinsorge & Heuer, 1999; Kleinsorge, 2004; Hahn et al., 2003; Vandierendonck et al., 2008) is the use of an on-line measure of the dynamics of resetting the perceptual (stimulus-set) component of the task-set. Our basic reasoning was that, when this component is coupled to the rest of the task-set, its

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reconfiguration should be sensitive to a task switch – indeed, our previous experiments documented such sensitivity in the form of delayed orienting to the relevant attribute and spatial "attentional inertia" (Longman et al., 2013, 2014). Conversely, if the re-orientation of attention during a task switch is readily de-coupled from reconfiguring the rest of the task-set, then, in conditions which encourage such decoupling, there should be little or no effect on the shift of attention to the relevant location of having to change other task-set components. Switching the location and the categorisation task should not result in greater attentional handicaps than switching locations without a task change, which Longman et al. (2014, Experiment 1, location switching condition) found to have only very small effects on both RT and eye-movements.

To explore the boundary conditions for the coupling of spatial attention and other task-set components, the present experiments used the same paradigm as that of Longman et al. (2014), except that the cue either explicitly pointed to or labelled the location of the digit to be classified by the rule appropriate for that location (Experiment 1), or the participant was instructed to interpret arbitrary cues as indicating the location (Experiment 2). Table 2 summarises the effects of switching and preparation for a switch on both RT and eye-tracking indices in both these experiments and those of Longman et al. (2014). The overall pattern seems clear. With cues specifying, and instructions/training emphasising, tasks (Longman et al., 2014, Experiment 2) the appropriate orientation of attention was delayed, and there was marked attentional inertia: a tendency to orient to the location appropriate for the previous task. With cues explicitly indexing, and training and instructions emphasising, location (present Experiment 1), the attentional delay and inertia were very strongly reduced and largely eliminated, but task switch costs were markedly amplified. This experiment established conditions under which spatial attention is rapidly (and effectively) allocated in a way that is independent of (and uninfluenced by) other components of the task-set (the

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required categorisation). But this independence of preparatory orientation comes at a substantial cost to preparing for the required categorisation task, as indicated by the inflated switch cost.

In the other two experiments, with arbitrary cues (Longman et al., 2014, Experiment 1, and the present Experiment 2), the pattern of data was intermediate, but closer to that obtained with task-transparent cues (Longman et al., 2014, Experiment 2): there was a clear effect of a task switch on the effectiveness of spatial orienting, suggesting moderately strong coupling of attentional re-setting to the reconfiguration of other task-set parameters. That the attentional delay and inertia (and indeed the performance switch cost) varied substantially across these three experiments, suggests the degree of coupling also varied – being less robust in the experiments where the neutral (arbitrary) cues could be construed as location cues (whether because of the practice regime, or through their semantic neutrality). This suggests that, in contrast to characterisations in the literature (see Introduction), coupling or 'binding' between components of task-set is not dichotomous, but graded and likely described by a continuum of coupling strengths or perhaps mixtures of strategy over participants, or within participants over trials. That said, some regions of the continuum seem more likely (or 'natural') than others. Under the conditions surveyed in our four experiments, only the explicit arrow cues seemed to completely decouple the reorienting of attention from reconfiguration of other components. With the arbitrary cues, whether they were introduced and trained as location cues (present Experiment 2) or task cues (Longman et al. 2014, Experiment 1) had relatively little effect – a modest reduction in the switch-induced delay in orienting to the relevant stimulus element and in the tendency to fixate the irrelevant regions on switch trials relative to repeat trials, and a ~20-25% increase in switch cost at the longest CSIs. Crucially, the attentional handicaps induced by a task switch remained robust in the current Experiment 2 and were substantially (and reliably)

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greater than in the current Experiment 1, and the switch cost was larger in the current

Experiment 1. This suggests that only cues with a strong habitual association with

direction or location have the power to pull the resetting of attention completely apart

from that of other task-set components.

Other evidence that attention, when strongly prioritised, can be uninfluenced by

the rest of the task-set comes from a study by Lien, Ruthruff, and Johnston (2010). They

incorporated a task switching condition into the contingent capture paradigm (Folk,

Remmington, & Johnston, 1992) in order to test the extent to which switching between

task-sets would influence the vulnerability of the attentional system to capture by

irrelevant stimuli. In their Experiment 4, participants were briefly (50 ms) presented

with four digits, each within a white square. One digit was always green, one was

always red and the other two were presented in white. Participants were required to

classify (for example) either the red digit by parity or the green digit by magnitude, as

specified by a letter cue indicating the relevant colour (e.g., 'R') presented 1350 ms

before the stimulus. As each task was associated with a single colour throughout the

experiment, the cue to the relevant colour also acted as a task cue. Critically, 150 ms

before the stimulus was presented one of the squares surrounding the digits briefly (for

50 ms) changed colour. This 'capture cue' could be presented in the relevant colour or

not and it could be presented in the valid location or not, thereby providing a

comparison between validly and invalidly cued locations as a function of whether the

capture-cue did or did not match the attentional settings for the trial. Lien et al. found no

attentional capture by the previously relevant stimulus attribute when the task (and the

relevant colour) changed.

The contingent capture design used by Lien et al. strongly encourages the

prioritisation of attentional selection in two ways. First, the brevity of the stimulus

display is such that the participant must be ready to attend preferentially to the relevant

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attribute as soon as it is present because failure to do so could result in failure to perceive the digit to be classified. Such prioritisation of attentional selection ensures that the perceptual system is not vulnerable to the capture-cue when presented in the previously relevant colour. However, it may also provide a strong incentive to postpone the selection of the relevant categorisation rule until the relevant digit (colour) is selected, assuming the two kinds of process share resources. The relatively large switch cost (137 ms) recorded at such a long CSI (1350 ms) together with the effectiveness of the capture-cue when presented in the relevant colour suggests that participants had elected to adopt this strategy. Second, Lien et al.'s design also encourages the prioritisation of attentional selection because, like in the current Experiment 1, the cues refer to the to-be-attended attribute (feature), not the classification rule (task). Thus, it seems that the effects of decoupling attention from the rest of task-set are analogous for spatial attention (the present Experiment 1) and attention to features within a perceptual dimension (Lien et al., 2010, Experiment 4). Hence, although the results reported here naturally limit our conclusions to the spatial orienting aspect of the 'stimulus-set' as a component of the task-set (see Introduction), they are likely to generalise to non-spatial aspects of the stimulus-set.

As mentioned in the Discussion of Experiment 1, the arrow cues were particularly potent in eliminating the effects of a task-switch on attentional orienting. Some have proposed arrows represent a type of control of spatial attention distinct from both exogenous and endogenous attentional control (e.g., Ristic & Kingstone, 2012). Hence, might it be that in the present Experiment 1 endogenous spatial attention remained coupled to the task-set (and delayed by a task-switch) despite the lack of a discernable handicap in our fixation-derived measures?[6] There are two indications in our data that this is not the case. The first comes from the effects of a task-switch on

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[6] We thank a reviewer for raising this possibility.

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fixations following location word cues (which require at least some interpretation and therefore must engage endogenous attention) – as already discussed, these effects are only subtly different from the effects on arrow cue trials. Indeed, with regard to the magnitude of the task switch-induced effects on fixation, location word cues are much closer to arrow cues than to task-related word cues, as can be seen in Figures 3-5 and Table 2. Second, if in the current Experiment 1 endogenous attention remained coupled to the rest of task-set as in the Longman et al. (2014) experiments, it is not clear why performance would suffer disproportionally on switch trials, as reflected by the much larger switch cost. On the contrary – if endogenous spatial attention remained coupled to the task-set, effective and effortless exogenous orienting should not handicap the reconfiguring of any task-set components.

The large difference in switch cost between the location cues and task cues conditions is also relevant in the context of another alternative account of our outcomes. Could one explain the presence of a task switch-induced handicap on orienting with task cues and the absence of such a handicap with location cues (especially arrows) as merely reflecting a change in the order of reconfiguring of task-set components, without the need to invoke the degree of coupling among these components? When cues point to locations, their selection is effective and unaffected by a change in the required categorisation. Conversely, when cues transparently refer to the required categorisation, orienting is delayed because the latter has lower priority. What such an account fails to explain is why the strong prioritization of spatial orienting over other task-set components results in such a marked performance decrement on switch relative to repeat trials. Clearly, cues that do not result in automatic (or quasi-automatic) orienting (and preferably refer to the required categorization task), seem to offer some substantial saving in preparation for a change of task, possibly because some stages of task-set selection can run in parallel with (as in Logan & Gordon's, 2001, ECTVA model), or

benefit from, concurrently resetting the attentional parameters. For instance, one can envisage the possibility that when the control of attentional parameters is coupled to the control of other task-set parameters, the activation of the former helps settle the activation of the latter thus resolving (at least to a degree) its competition with parameters belonging to alternative task-sets.

The need for the construct of 'coupling', above and beyond that of the temporal order of readying task-set components, to explain the patterns of fixations presented in Table 2, is also suggested by the attentional inertia observed in all the conditions we have examined except explicit location cues. Preferential fixation of the location associated with the task relevant on the preceding trial over the other irrelevant location (our definition of attentional inertia) is telling, because Longman et al. (2014, Experiment 1) observed no such inertia of location in the condition where location switched without a change of task, except at the shortest CSIs of 120 ms[7]. Thus, spatial attention seems to be 'pulled' towards the location of the previously relevant task, not merely towards the previously relevant location.

To conclude, the coupling between reconfiguration of spatial attentional selection and the anticipatory control of other components of task-set seems to depend on circumstances such as the way the task is cued. It can vary in strength and under extreme circumstances it can be entirely abolished (as when we used quasi-endogenous arrow cues for spatial orientation in the present Experiment 1, or as in the case of feature attention in Lien et al.'s, 2010, contingent capture experiment). But, to judge by the range of conditions we have so far explored, the more natural situation is that the coupling is substantial.

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[7] The only other condition we documented in which attentional inertia was absent was when participants were given ultimate control over the duration of the preparation interval (CSI), by presenting the digits only when the fixation moved away from the location of the cue. The use of such gaze-contingent displays eliminated attentional inertia, but only for the longest CSIs (Longman, Lavric, & Monsell, submitted).

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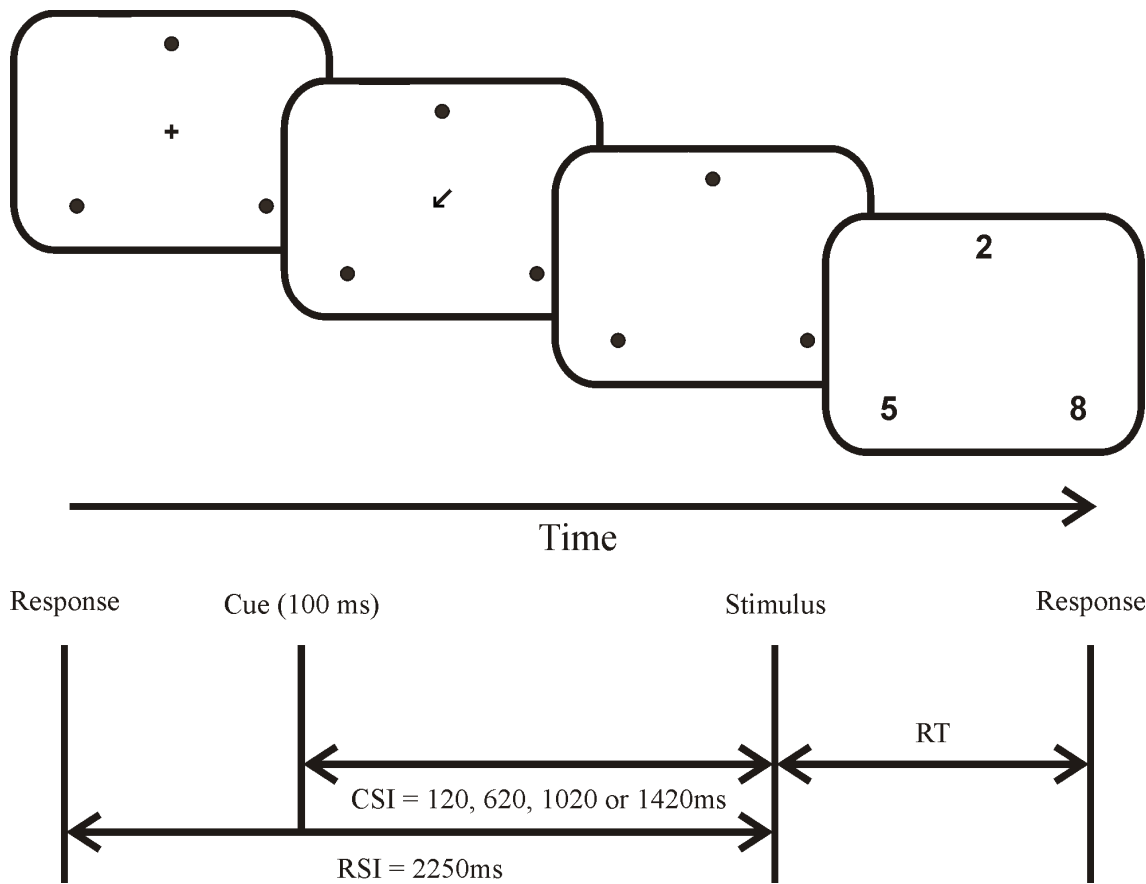
Coupling of task-set parameters

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. Note that each frame shows only the central area of the screen.
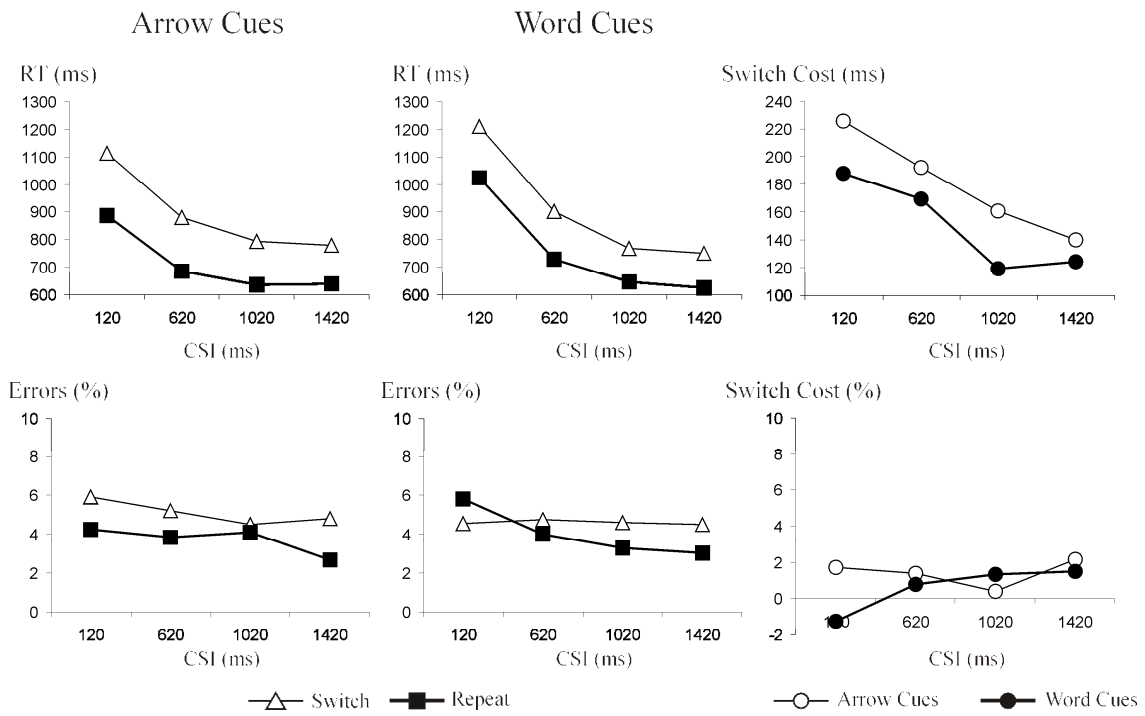
Coupling of task-set parameters

Figure 2. Behavioral data from task switch and repeat trials from Experiment 1 as a function of cue-stimulus interval (CSI). Left panels (arrow cues) and middle panels (word cues): mean RT (ms) above, error rate (%) below. Right panels: switch costs for RT above and error rates below.
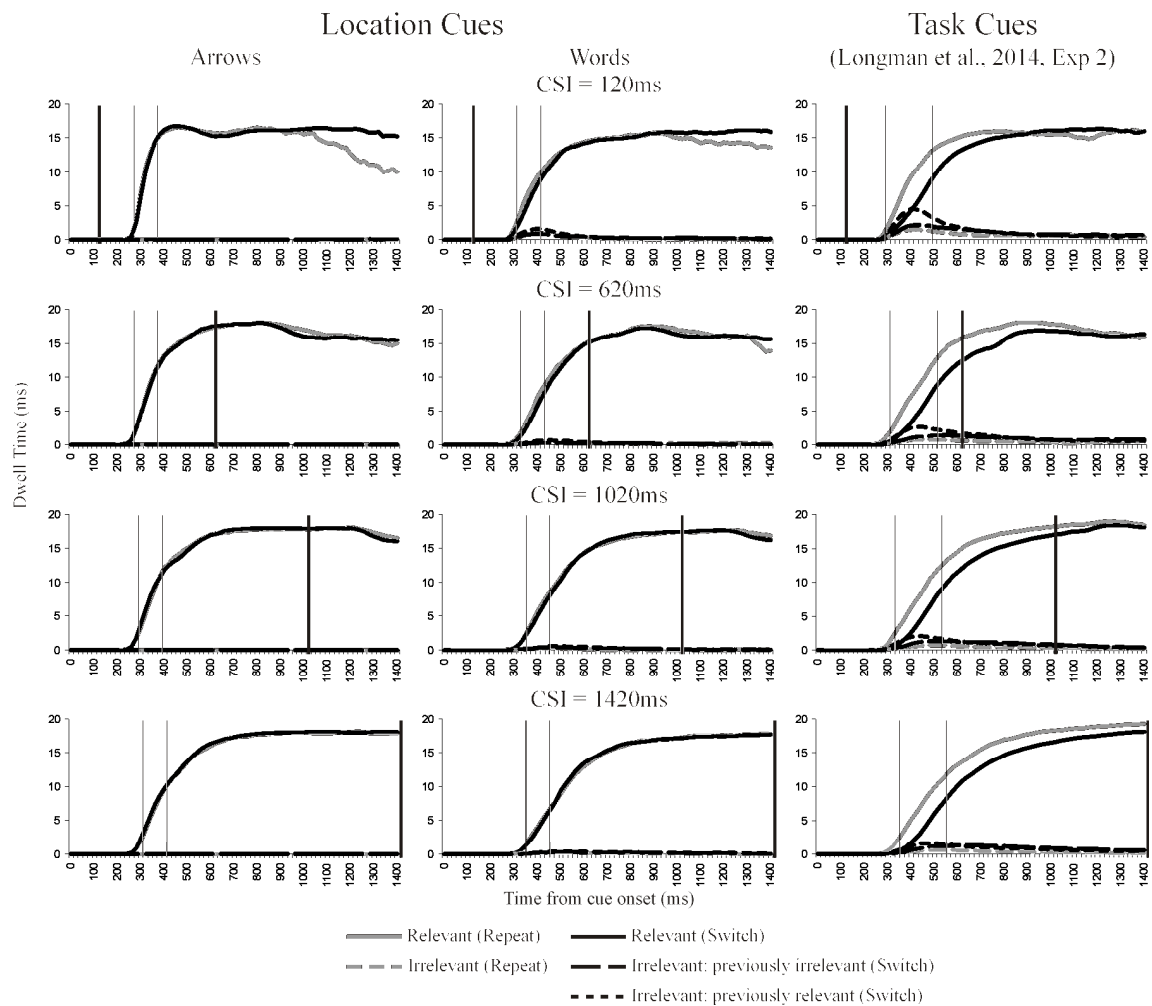
Coupling of task-set parameters

Figure 3. Dwell time per 20 ms bin in Experiment 1 (see text for definition) for 1420 ms following cue onset with arrow cues (left) and word cues (middle) 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 of dwell time in the currently relevant region. The equivalent data from the Longman et al. (2014) Experiment 2 are included (right) for comparison.
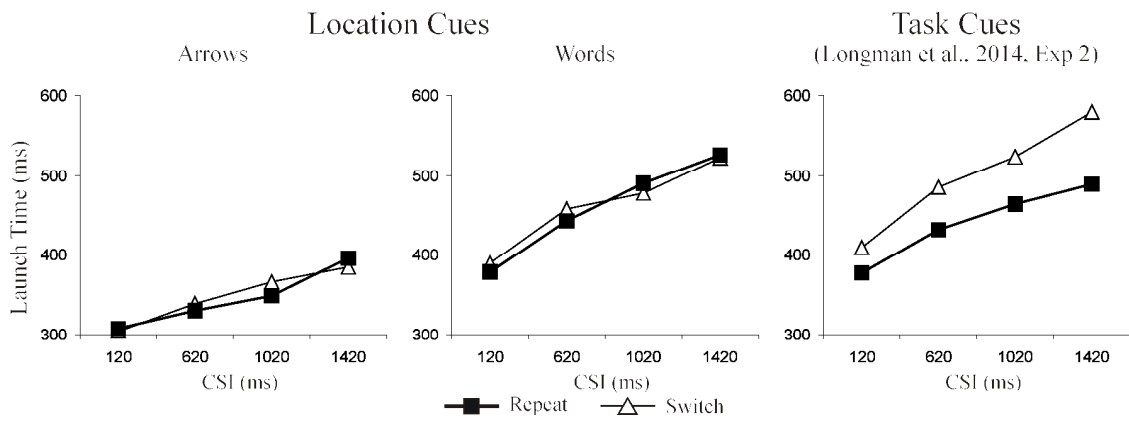
Coupling of task-set parameters

Figure 4. Mean 'launch time' of the first saccade to leave the cue and land directly in the currently relevant region for the arrow cues (left) and word cues (middle) as a function of CSI and transition (Experiment 1). The equivalent data from the Longman et al. (2014) Experiment 2 have been included (right) for comparison.
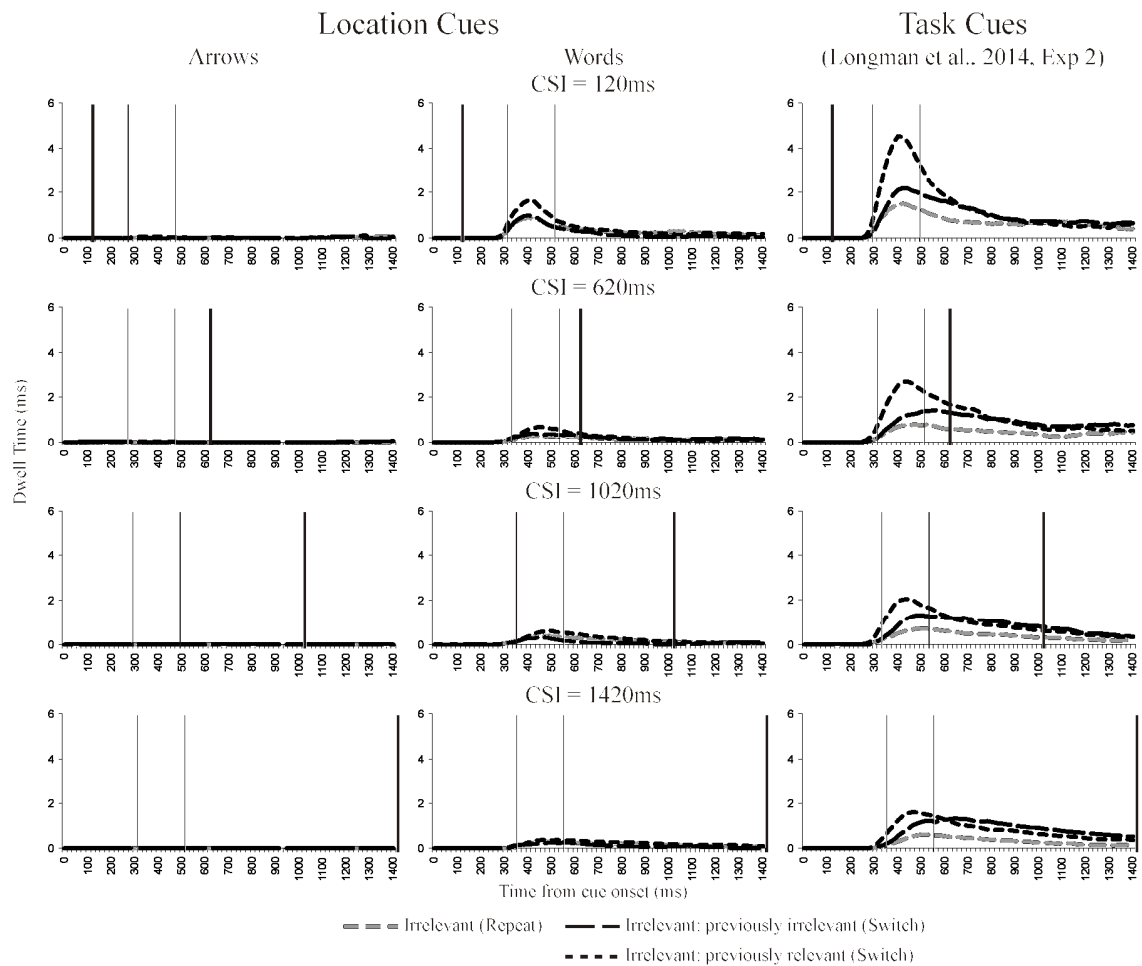
Coupling of task-set parameters

Figure 5. Dwell-time on the task-irrelevant regions in Experiment 1 plotted as in Figure 3, but with a larger scale. The equivalent data from the Longman et al. (2014) Experiment 2 have been included (right) for comparison.
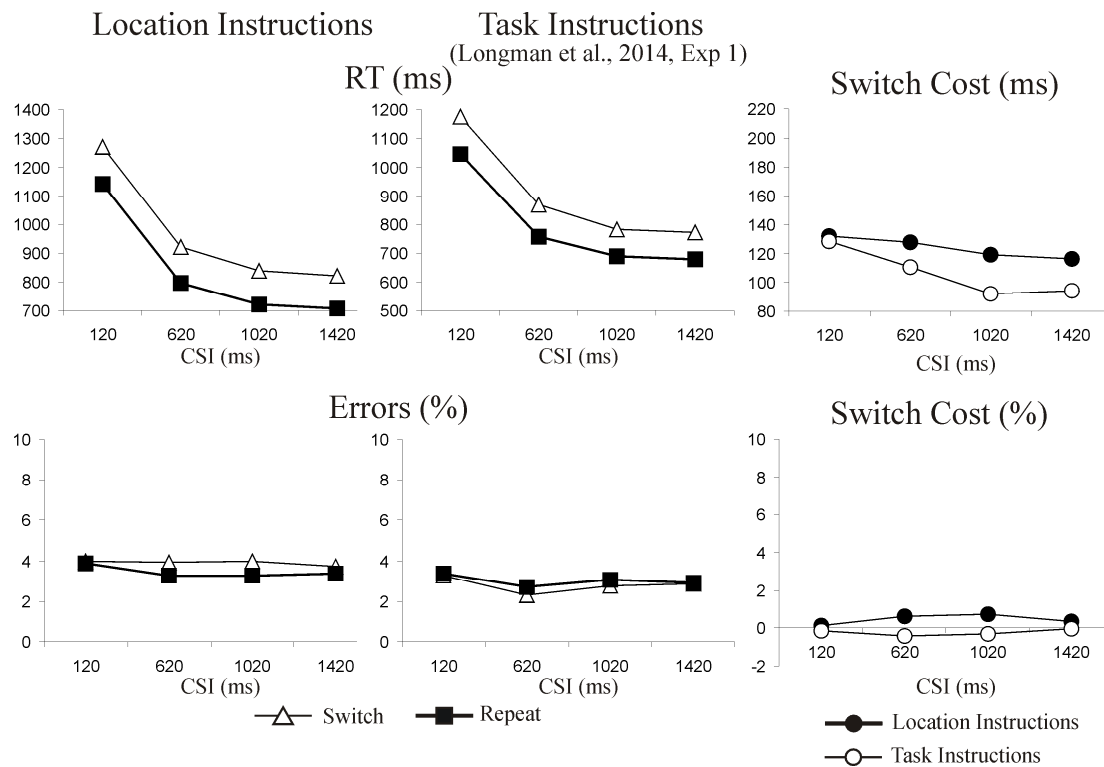
Coupling of task-set parameters

Location Instructions

Task Instructions
(Longman et al., 2014, Exp 1)

Figure 6. The mean RT, error rate and switch costs for Experiment 2 as a function of CSI and transition (left). The same measures from the Longman et al. (2014) Experiment 1, which used instructions and training that emphasised tasks over locations are included (middle) for comparison. Right panels: switch costs for RT above and error rates below.
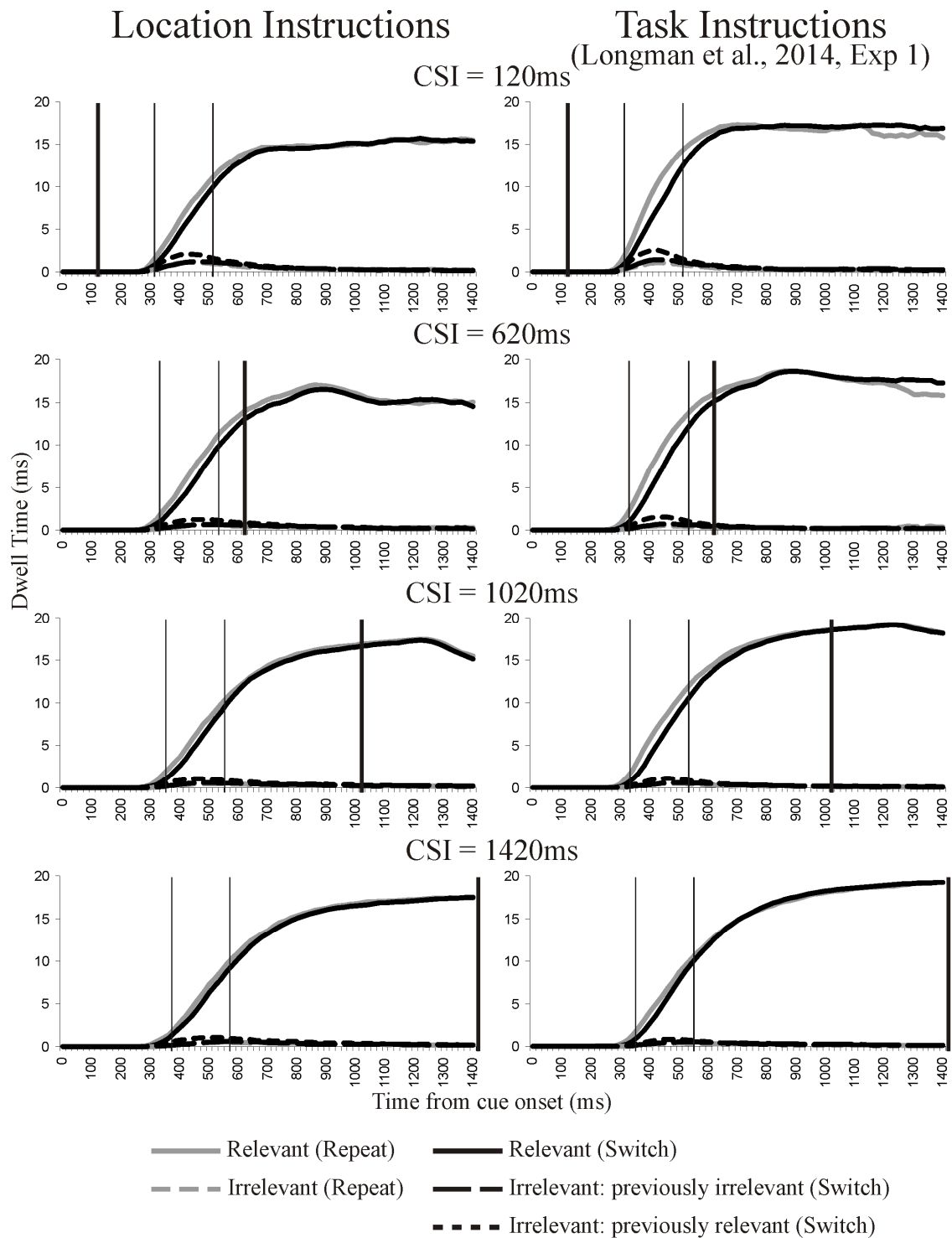
Figure 7. Dwell-time in Experiment 2, plotted as in Figure 3 and 5. The equivalent data from the Longman et al. (2014) Experiment 1 have been included (right) for comparison. Thick vertical lines show the onset of the stimulus and thin vertical lines the time-windows used for statistical analysis.
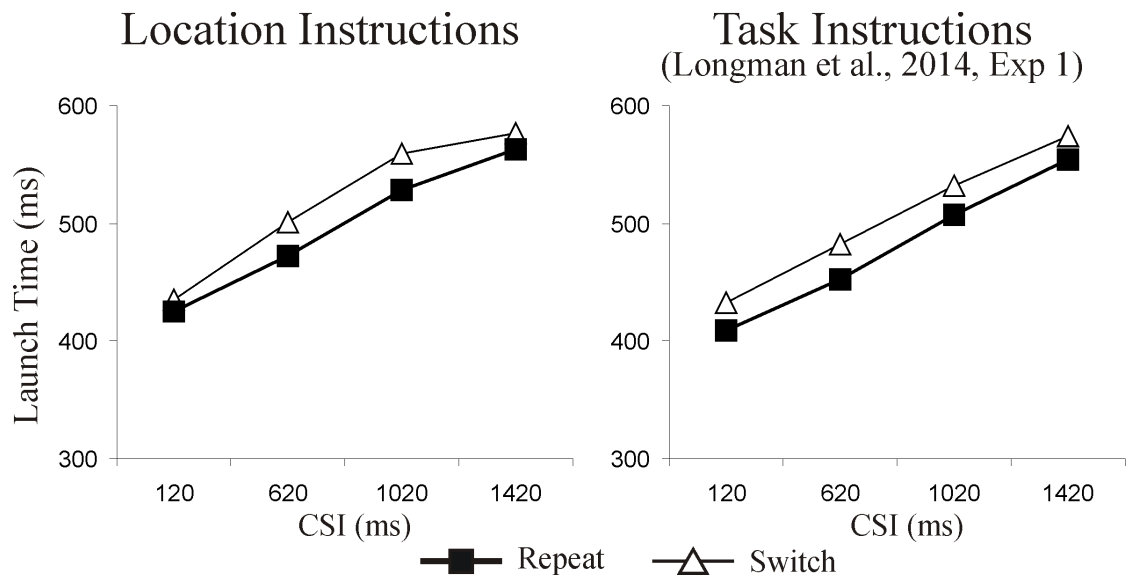
Figure 8. Mean 'launch time' of the first saccade to leave the cue and land directly in the currently relevant region as a function of CSI and transition (Experiment 2). The equivalent data from the Longman et al. (2014) Experiment 1 have been included (right) for comparison.
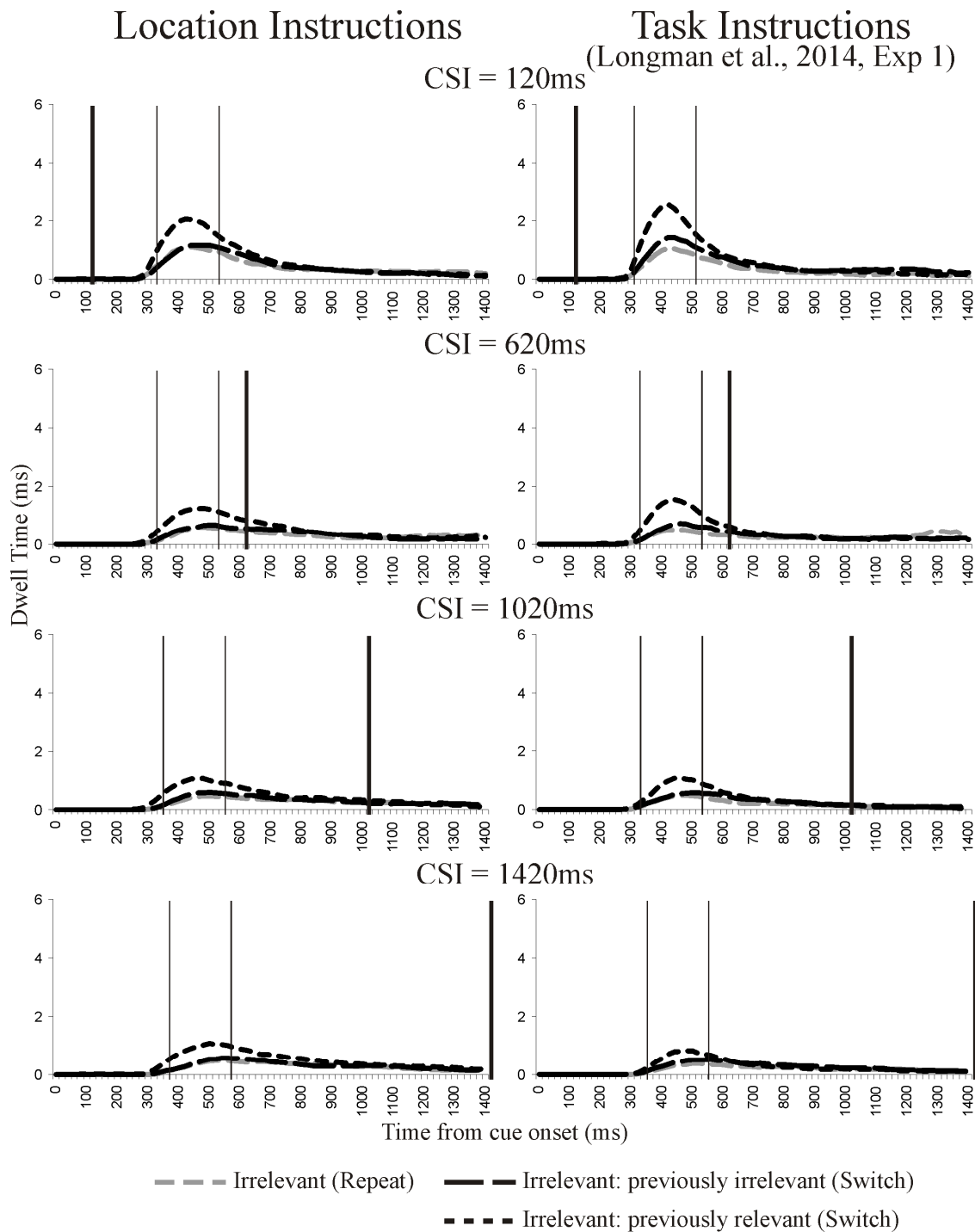
Figure 9. Dwell-time on the task-irrelevant regions in Experiment 2 plotted as in Figure 5. The equivalent data from the Longman et al. (2014) Experiment 1 have been included (right) for comparison.

Coupling of task-set parameters

Table 1.

Mean Difference (Standard Error in Parentheses) in Average Dwell Time (Previously Relevant Minus Previously Irrelevant, ms.) in the Currently Irrelevant Regions on Switch Trials, as a Function of Instructions and CSI.

	CSI (ms)							
	120		**620**		**1020**		**1420**	
Location Instructions (Present Exp. 2)	8.44	(1.79)	5.86	(1.32)	4.94	(1.69)	5.53	(1.75)
Task Instructions (Longman et al., 2014, Exp. 1)	8.61	(1.87)	7.04	(1.55)	4.17	(1.24)	2.84	(1.29)

Coupling of task-set parameters

Table 2.
Mean RT Switch Cost, Estimated Switch Induced Delay in Dwell Time on the Relevant Digit, Switch Induced Delay in Launch Time of the First Correctly Targeted Saccade to Leave the Cue and Attentional Inertia (Previously Relevant Minus Previously Irrelevant Dwell Time on the Currently Irrelevant Regions on Switch trials) for the Present Experiments 1 and 2 and for Longman et al. (2014), Experiments 1 and 2.

	CSI (ms)							
	120		**620**		**1020**		**1420**	
RT Switch cost (ms)								
Present								
Experiment 1 (Explicit location cues and instructions)	210	(14.8)	185	(13.7)	141	(16.5)	132	(18.1)
Experiment 2 (Arbitrary cues and location instructions)	132	(16.4)	128	(17.1)	119	(17.3)	116	(16.9)
Longman et al. (2014)								
Experiment 1 (Arbitrary cues and task instructions)	128	(14.3)	111	(15.7)	92	(12.7)	94	(13.5)
Experiment 2 (Explicit task cues and instructions)	124	(16.1)	113	(12.6)	71	(10.5)	74	(10.7)
Estimated delay in orientation (ms)								
Present								
Experiment 1 (Explicit location cues and instructions)	14	(4.2)	12	(2.8)	7	(3.6)	8	(5.3)
Experiment 2 (Arbitrary cues and location instructions)	33	(6.0)	34	(7.0)	27	(7.7)	26	(8.4)
Longman et al. (2014)								
Experiment 1 (Arbitrary cues and task instructions)	43	(6.2)	42	(8.0)	33	(7.3)	22	(8.2)
Experiment 2 (Explicit task cues and instructions)	89	(14.2)	89	(12.0)	81	(10.4)	92	(15.6)
Launch time delay for appropriate fixations (ms)								
Present								
Experiment 1 (Explicit location cues and instructions)	2	(2.5)	8	(4.9)	-2	(5.6)	-13	(10.9)
Experiment 2 (Arbitrary cues and location instructions)	10	(7.4)	28	(6.7)	30	(9.3)	13	(9.6)
Longman et al. (2014)								
Experiment 1 (Arbitrary cues and task instructions)	24	(5.4)	30	(7.8)	25	(9.1)	20	(12.2)
Experiment 2 (Explicit task cues and instructions)	33	(4.9)	54	(8.3)	60	(9.9)	91	(12.5)
Attentional inertia (ms)								
Present								
Experiment 1 (Explicit location cues and instructions)	3.1	(0.8)	1.2	(0.5)	1.1	(0.4)	0.5	(0.3)
Experiment 2 (Arbitrary cues and location instructions)	8.4	(1.8)	5.9	(1.3)	4.9	(1.7)	5.5	(1.8)
Longman et al. (2014)								
Experiment 1 (Arbitrary cues and task instructions)	8.6	(1.8)	7.0	(1.6)	4.2	(1.2)	2.8	(1.3)
Experiment 2 (Explicit task cues and instructions)	18.4	(3.7)	12.1	(3.0)	7.8	(2.8)	5.3	(2.7)