

Spatial attention in task switching

Submitted by Cai Stephen Longman, to the University of Exeter as a thesis for the
degree of Doctor of Philosophy in Psychology

May 2014.

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Acknowledgements

First and foremost I would like to thank my supervisors Aureliu and Stephen. Without their support, guidance, consistently high expectations and faith in my ability this thesis would at best have turned out very different, at worst it might never have been completed. Their meticulous attention to detail and encyclopaedic knowledge give me faith in the quality of the work presented within these pages. I only hope that their professionalism and passion for the subject continue to inspire me to work to the same high standard as my career progresses.

On a more personal note, I would like to dedicate this thesis to two people who are no longer with us but without whom it is likely that I would never have started the process to which this thesis marks the completion.

Mary Landrum was diagnosed with terminal cancer and was told that she had 12-18 months to live... a full eight years before she passed away. I saw her fight this disease every step along the way and although some of her most treasured parting advice was to 'not work so hard', her determination to enjoy her remaining time to the fullest is a constant reminder to me that this life is not a rehearsal.

Bridget Longman was down-to-earth, straight-talking, creative, talented, a real calming influence and devastatingly intelligent. She was also the most interesting and inspirational person I ever met. Without her financial support I would not have been able to attend university in my teens or return to university in my thirties.

Last, but by no means least, it goes without saying that I could never have made it through this process or dedicated so much time to my work without the love and support of Sara.

Abstract

This thesis is a systematic investigation of preparatory reorienting of task-relevant spatial attention. Task switching experiments typically report a performance overhead when the current task is different to that performed on the previous trial relative to when the task repeats. This ‘switch cost’ tends to reduce as participants are given more time to prepare (consistent with an active reconfiguration process) but a ‘residual’ switch cost usually remains even at very long preparation intervals (often interpreted as evidence of carryover of response selection parameters from the previous trial which are immune to preparation). Although attentional selection of perceptual attributes is often considered to be part of task-set and is included in some models of task-set control, little research has investigated the dynamics of this component in detail.

Over a series of seven experiments in which tasks were consistently mapped to screen locations, eye-tracking was used to systematically investigate task-relevant spatial selection of perceptual attributes during the preparation interval and early after stimulus onset. Experiment 1 revealed a switch-induced delay in appropriate attention orientation and a measure of ‘attentional inertia’ which could not be explained by task-independent re-orienting to locations or low-level oculomotor phenomena but were markers of task-relevant spatial selection. Experiment 2 provided a sensitive measure of both of these attentional handicaps and demonstrated that they both contribute to the switch cost (including its residual component). Although attentional inertia reduced with preparation, both handicaps were present at the longest preparation intervals. The constancy of the delay in attending to the relevant attribute reflects the effort to re-allocate attention, rather than peculiarities of spatial orienting when the cue and stimulus are presented near-simultaneously on trials with short cue-stimulus intervals. The presence of attentional inertia in blocks with long preparation intervals suggested

some component of inertia immune to preparation (though see Experiments 5 and 6 below).

Experiments 3 and 4 investigated the extent to which attentional selection can be decoupled from other task-set components. Cues which explicitly provided location information reduced (or eliminated) the attentional effects found in Experiment 2 indicating that attentional selection can be decoupled from other task-set components. However, Experiment 3 found that the ‘natural’ state is for attentional selection to be coupled at least to a degree (and accessed via) task-set.

Experiment 5 combined eye-tracking with ERPs to investigate the relative order of attentional selection and reconfiguration of other task-set components. A well-documented ERP marker of task-set preparation always followed onset of the first fixation on the currently relevant stimulus element indicating that (at least some) task-set components are reconfigured in a serial order with spatial selection preceding other components (e.g., loading of S-R rules or other parameters into working memory).

Experiments 6 and 7 investigated the nature of attentional inertia. In Experiment 6 participants were given ultimate control over the duration of the preparation interval which eliminated attentional inertia (at least as indexed by preferential fixation of the previously relevant element on switch trials). In Experiment 7 the stimulus comprised three items which were from perceptually distinct classes (digits, letters, objects) to investigate whether the presence of task-specific features would elicit extra attentional inertia and whether early spatial selection was effective enough to block the processing of task-irrelevant features once the stimulus was presented. Although there was some evidence that the previously relevant stimulus element ‘captured’ attention, this tendency was modest in the fixations and absent in performance measures (response congruence effects).

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Declaration

The research reported in this thesis was carried out at the University of Exeter between October 2009 and May 2014, and was supervised by Dr. Aureliu Lavric and Prof. Stephen Monsell.

This thesis has not been submitted in whole or in part for any other degree, diploma or qualification at any university. Chapters 2 and 3 have been prepared as journal articles. Chapter 2 was authored by Cai S. Longman, Aureliu Lavric, Cristian Munteanu and Stephen Monsell and has been accepted for publication in *Journal of Experimental Psychology: Human Perception and Performance*. I conducted the experiments, wrote them up and produced all the figures and tables. Cristian Munteanu helped write some code which we used in the analysis of the eye movement data; Aureliu Lavric and Stephen Monsell edited the manuscript, suggested extra analyses and commented on interpretations. Chapter 3 will be submitted under the authorship of Cai S. Longman, Aureliu Lavric and Stephen Monsell. I conducted the experiments and analyses, wrote them up and produced all the figures and tables. Aureliu Lavric and Stephen Monsell edited the manuscript, suggested extra analyses and commented on interpretations.

Cai S. Longman

Exeter, May 2014.

1

General Introduction

“Every one knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization, concentration, of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others, and is a condition which has a real opposite in the confused, dazed, scatterbrained state which in French is called *distraction*.”

(James, 1890, pp 403-404)

Cognitive control and the task switching paradigm

When engaged in an activity even as mundane as writing an email or answering the telephone, it is necessary to configure and organise several cognitive systems toward the desired goal. This is at least in part due to the fact that many real-life stimuli allow us to interact with them in multiple ways. For example, modern smart phones can be used to communicate in several ways and we can also use them to engage in a number of other activities including playing games, browsing the internet, listening to music, taking photographs and finding directions to the nearest restaurant. Each of these activities requires the configuration of several component processes which may include: attending to the appropriate input modality, location in space and specific stimulus attributes to ensure all appropriate information is collected (e.g., ‘listen to speech at the earpiece’); individual task-goals or stimulus-response (S-R) rules which are important for effective achievement of the goal through specific processes and actions (e.g., ‘understand and respond at appropriate times in the conversation’); and assignment/readying of effectors appropriate to pursuit of the goal (e.g., ‘respond by

speaking into the mouthpiece’). The effective organisation of these (and possibly other) processes has been referred to as ‘task-set’ – a set of component processes which work together towards achievement of a specific processing goal when the appropriate information is available.

Task-set control has been extensively studied over the past two decades using variations on the ‘task switching’ paradigm. In a typical task switching experiment participants are asked to learn two (or sometimes more) simple tasks, usually requiring computer key press responses, and switch between them intermittently throughout the experiment. The stimuli which are to be processed under these task rules have in the majority of experiments been bi-/multivalent (affording responses in two or more tasks) so the same stimulus set is used in all conditions. There are several ways to specify the relevant task on each trial (see below). The most critical comparison for investigation of cognitive control is the difference in performance between trials where the task is the same as on the previous trial (task-repeat) and those on which it changes (task-switch).

The modern task-switching paradigm was inspired by earlier research into switching between cognitive operations using list presentation. Almost a century ago Jersild (1927) reported that, with certain stimuli, participants took longer to complete lists of simple arithmetic calculations when asked to alternate between two operators (+, -) than when they were required to use only one (referred to as the ‘shifting cost’). After ~70 years of relative quiet (e.g., Spector & Biederman, 1976; Sudevan & Taylor, 1987), the last two decades have seen a massive resurgence of interest in task switching in part due to the publication of two reports within a year of each other during the 1990s. Although there are other important reports based on Jersild’s original method from around the same time (discussed below) these two in particular documented overlapping empirical phenomena, but came to strikingly different conclusions regarding their

interpretation (for reviews see Kiesel et al., 2010; Monsell, 2003; Vandierendonck, Liefvooghe & Verbruggen, 2010).

Allport, Styles and Hsieh (1994) used a paradigm very similar to Jersild's 'timed blocks' design (at least in five out of seven experiments, the remaining two are described in more detail below) in that the critical comparison was between the times taken to work through entire lists of stimuli. Allport et al.'s tasks used Stroop-like stimuli (e.g., colour words presented in inks of different colours) and participants were asked to perform blocks of either a single task or alternating tasks. In their Experiment 5, participants were required to switch between tasks in lists of two trials each thereby allowing Allport et al. to manipulate the order of the tasks. Using this manipulation, they were able to demonstrate that switching to the more dominant task (e.g., word reading) was more demanding than switching to the less dominant (e.g., colour naming). They concluded that the greater degree of inhibition put in place to overcome the urge to respond according to the dominant task on non-dominant task trials must itself be overcome when returning to the dominant task on the subsequent trial. They concluded that Jersild's shifting cost could largely be explained by passive interference from the previous task-set ('task-set inertia'; TSI) rather than an active endogenous process.

Meanwhile, Rogers & Monsell (1995) had come up with an elegant design which also required predictable switching between tasks but which addressed many of the disadvantages of the timed blocks design. The block-by-block comparison utilised by Jersild (1927) and Allport et al. (1994) makes it impossible to distinguish between the 'switch cost' (participants respond more slowly and sometimes less accurately on switch trials relative to repeats) and the 'mixing cost' (the performance deficit associated with being ready to perform two tasks instead of one – typically assessed by comparing task repetitions in a block containing switches with performance in single-

task blocks) where additional load on working memory (and possibly other factors) could also impact on performance. Rogers and Monsell (1995) addressed this issue by introducing the ‘alternating runs’ design in which participants are required to switch predictably between tasks on every n^{th} trial (e.g., in an AABBA sequence, when n is 2) thereby allowing a direct comparison between performance on switch and repeat trials within a block. Rogers and Monsell reported a substantial switch cost and, by manipulating the response-stimulus interval (RSI), they were also able to demonstrate that the switch cost reduced as participants were given more time to prepare (I will refer to this as the ‘reduction in switch cost’ or ‘RISC’ effect). Taken together, these findings led Rogers and Monsell to conclude that an active (endogenous) reconfiguration process (‘task-set reconfiguration’; TSR) is required when the task switches and if this process cannot be completed before stimulus onset it must be completed afterwards thereby contributing more to the switch cost at shorter preparation intervals.

The alternating runs paradigm is not without limitations. For example the time available for passive dissipation of the task-set state established on the previous trial is identical to the time available for active preparation for a change of task on the present trial. Thus it is impossible to distinguish between the contributions made by these two processes to the switch cost. It may also be that, given the predictable task order, participants might initiate preparation prior to the inter-trial interval (though if this was so then one would expect to see poorer performance on the trial immediately preceding a switch in alternating runs experiments, and this does not seem to happen). Meiran (1996) addressed these limitations in his ‘task cueing’ design (based on Sudevan & Taylor, 1987), in which the sequence of tasks is unpredictable and a cue specifies which task to perform on the current trial (thereby also ensuring that participants cannot prepare for the upcoming trial until the cue is encoded). By independently manipulating the cue-stimulus interval (CSI) and the RSI, Meiran was able to dissociate passive

decay and active reconfiguration and went on to demonstrate that they have independent effects which may index TSR and decay of TSI respectively (e.g., Meiran, Chorev & Sapir, 2000).

However, the task cueing design has also been subject to criticism. Logan and Bundesen (2003) noted that, with one cue per task, a task change is perfectly confounded with a cue change. By introducing two cues and therefore three transition types (cue and task change, cue changes but task repeats, cue and task repeat) into the task-cueing design Logan and Bundesen claimed that the ‘task-switch cost’ could largely be explained by changing the cue rather than switching between task-sets. They went on to conclude that the switch cost and RISC effect do not necessarily measure an endogenous act of control, but can be explained by cue encoding processes which benefit from cue repetition (priming) and the appropriate response is selected by combining the properties of the cue and stimulus together. Logan has since expanded on this account (e.g., Schneider & Logan, 2005, 2007) stating that, even with two cues per task, the cues can become associated with each other (because they indicate the same task) and can therefore prime the associated S-R rule in much the same way as with only one cue per task. However, Mayr and Kliegl (2003) also used two cues per task, but their results suggested that both task- and cue-changes make a contribution to the switch cost. Finally, in a recent study Forrest, McLaren and Monsell (in press) induced two groups of participants to use either a task-rule strategy (i.e., TSR) or a ‘cue + stimulus → response’ strategy (CSR; as posited by Logan and colleagues). Although it was possible to induce participants to use a CSR strategy (at least with small stimulus sets), they found that there was a natural inclination towards using a TSR strategy and that there were significant performance differences between the two groups. The CSR group had smaller switch costs, no discernible RISC effect and they also displayed greater effects of response congruence (discussed in more detail below) than the TSR

group. These results indicate that if participants in all task switching experiments were using a CSR strategy (as proposed by Logan and colleagues) then the pattern of results typically reported in these experiments would be very different.

To address the controversy surrounding the task-cueing design, Monsell and Mizon (2006) attempted a systematic investigation of several parameters of the paradigm. One of them was the probability of a task-switch – they found that when the likelihood of a switch is high, participants tend to modify their behaviour accordingly and start to initiate the reconfiguration process early (before the cue). Thus, on repeat trials a second reconfiguration process might be necessary following cue onset which contributes to response times (RTs) and reduces the detected switch cost, whereas on switch trials the early initiation of TSR may compromise the detection of the RISC effect. They concluded that a lower switch probability is optimal for obtaining a robust measure of endogenous control. With regard to the relative contribution of cue- and task-changes to the switch cost, their results were consistent with Mayr and Kliegl's (2003) conclusion that both kinds of change make a substantial contribution to the switch cost when one cue is used per task – contrary to Logan and Bundesen's (2003) claim. Monsell and Mizon (2006) also manipulated the transparency of the task-cue and concluded that cues which require a lot of interpretation can add to the variability of cue processing time, thus potentially complicating the estimation of the switch cost.

Monsell and Mizon concluded their paper by describing a “recipe for measuring task-set reconfiguration” (p. 512) which includes: 1) using at least two cues per task to unconfound task changes and cue changes; 2) keeping RSI constant to unconfound TSI and TSR; 3) using a low probability of a task-switch to avoid early TSR and, on repeat trials, unnecessary TSR; 4) using task-transparent cues to ensure that cue interpretation per se has a minimal impact on performance; and 5) motivating participants to use the cues to initiate preparation. All of the experiments reported in this thesis try, wherever

possible, to follow this ‘recipe’ (though there are some exceptions which deviate from the recipe in order to study specific aspects of task-set control which could not otherwise be investigated conclusively).

There are two further task-switching designs which should also be mentioned for completeness: some researchers (e.g., Gopher, Armony & Greenspan, 2000) ask participants to continue performing a particular task until they are cued to switch (what Monsell, 2003, refers to as ‘intermittent cueing’), whilst others (e.g., Arrington & Logan, 2004) ask participants to switch between the tasks ‘at will’ but try to maintain a pre-defined switch:repeat ratio – ‘voluntary switching’.

A switch cost (task-switch minus task-repeat RT) is consistently reported whichever of the paradigms outlined above is used, as is a RISC effect; and a ‘residual switch cost’ – even at very long preparation intervals there remains a substantial switch cost (but for some rare exceptions see Astle, Jackson & Swainson, 2008a, and Verbruggen, Liefoghe, Vandierendonck & Demanet, 2007). It has been recorded even with very long preparation intervals (e.g., Kimberg, Aguirre & D’Esposito, 2000, found a switch cost with 8 seconds of preparation time) but experiments systematically varying the preparation interval usually find that the switch cost reaches asymptote when participants are given around 600-1500 ms to prepare. The reduction of the switch cost with preparation has led most researchers to agree that these measures index a reconfiguration process (although the contribution made by passive dissipation is still unclear and precisely what gets reconfigured is still a matter of much debate). Interpretation of the residual switch cost remains more controversial (as discussed below). Having introduced the essence of the TSR and TSI accounts of what makes switching difficult, I will now give a fuller description of the evidence in support of these (not incompatible) interpretations of the switch cost and its residual component.

Interpreting the switch cost

Before I describe some of the key interpretations of the switch cost and its residual component in more detail, it is necessary to give a brief idea of precisely what components make up a task-set and how they interact.

Task-set components. There are several components of task-set which might require reconfiguration or which might suffer from interference when the task changes. For example Arrington, Altman and Carr (2003) note three classes of components which can broadly be thought of as three stages of processing: perceptual encoding of the stimulus, the use of rules to transform the encoded stimuli into appropriate responses and, finally, response operations. Response operations (selection, programming, execution) should occur deep into the response interval and seem a likely source of the residual switch cost (discussed below), while perceptual (and attentional) processes occur closer in time to stimulus presentation (this component is discussed in much more depth below). The focus of this thesis will be on the contribution of the resetting of early perceptual (attentional) processing to task-set reconfiguration and preparation, and the literature review in this chapter will focus especially on this component.

As an example of research attributing switch costs to reconfiguration of later components one might mention Mayr and Kliegl's (2000) proposal that the switch cost arises from the time taken to load the currently relevant S-R rules into procedural working memory. Another line of research into the contribution of later processes to the switch cost includes investigation of the response selection component. For example Schuch and Koch (2003) combined task switching with a go/no-go paradigm and concluded that execution of the response on the previous trial is necessary for recording switch costs. However, Verbruggen, Liefoghe and Vandierendonck (2006) asked participants to select a response before they were informed whether to execute it or not

and found that the switch cost was not influenced by whether the response was executed or not, concluding that it is response selection that is essential to explain the switch cost. Nonetheless, Philipp, Jolicoeur, Falkenstein and Koch (2007) found larger switch costs when the response was executed indicating that both of these processes make a contribution.

Another significant line of research investigates the organisation of these components within a task-set. For example Arrington et al. (2003) propose a ‘multi-dimensional task space’ in which the three classes of component represent the dimensions and specific attributes of each class form the values along the dimensions. By manipulating the proximity of components within this task space (e.g., participants were required to switch between classifying the height, width, colour or brightness of a rectangle) they were able to demonstrate that switching between components which share common attributes (e.g., height and width judgements require classification of the form as opposed to the surface properties of the rectangle) is easier than switching between components which are further apart in task space (e.g., switching between height and colour classifications). Although their evidence is consistent with the notion that TSR is easier when switching closely related components, they also admit that the pattern of results might indicate the level of interference between components due to TSI rather than the ease of reconfiguring between them.

Arrington et al. (2003) manipulated one class of component at a time (perceptual or response selection), but other work has questioned whether task-set can be reconfigured one component at a time or if all components must be reconfigured together. Vandierendonck, Christiaens and Liefoghe (2008) used rather complex cues to indicate (for example) whether the participant should classify the number or value of digits presented in compound stimuli and also whether they should perform an odd/even or low/high classification. By doing so they were able to instruct participants to switch

attentional parameters, S-R rules or both. They found that the switch cost was equal whether the participants were required to reconfigure either parameter individually or both together and concluded that TSR requires the resetting of all components within a task-set. However, Kieffaber, Kruschke, Cho, Walker and Hetrick (2013) used a particularly elegant design with simpler cues indicating which of three tasks to perform given a pair of coloured shapes, for example: shape (same, different), size (same, different) or colour (red, blue). Switching from the shape to the size task therefore required only one component to be reset (attention) but switching from the colour task to the size task required both attentional selection and response selection to be reconfigured. They found poorer performance and greater amplitude of a switch-induced EEG deflection associated with task-set preparation (posterior positivity, see following section) in the latter case indicating that (when interpretation of the cue does not interfere with performance) reconfiguring two task-set components is more difficult than reconfiguring only one. Although these studies have gone some way towards examining the architecture of task-set, they assume that, rather than ask whether, task-set can be reconfigured through an endogenous act of control and if so, which components are accessible to such a process.

Task-set reconfiguration. As mentioned above, Rogers & Monsell (1995) proposed the TSR interpretation of the switch cost based on their finding that it was attenuated when the time available for preparation (RSI) was constant within a block (but not when the preparation interval varied from trial-to-trial indicating that the RISC effect was not simply a result of passive decay of TSI). Converging evidence for an endogenous preparatory process (TSR) and its contribution to the switch cost comes from electrophysiological (ERP) studies of task switching which have consistently reported a protracted positive polarity deflection on switch trials relative to repeats in posterior electrodes (often on the left of the scalp) in the late portion of the preparation

interval (see Karayanidis et al., 2010, for a review). Karayanidis, Coltheart, Michie and Murphy (2003) used the alternating runs paradigm and found not only the positivity late in the preparation interval, but also a negative deflection after and time-locked to stimulus onset. Nicholson, Karayanidis, Bumak, Poboka and Michie (2006) replicated these findings but also manipulated cue transition (switching vs. repetition) in order to investigate whether the effects reflected cue- or task-switches. Switching cues did not influence performance (RTs and the switch cost), whereas switching tasks did.

Furthermore, switching the cue elicited an ERP deflection distinct from the pre-stimulus task-switch-related positivity, with a much earlier onset, a different time-course and a distinct topography, consistent with the interpretation that task-switch costs cannot be reduced to cue encoding effects. Although these studies provide evidence of extra pre-stimulus brain activity at a time when TSR is presumed to happen on a switch trial, and post-stimulus negativity associated with a task switch (possibly reflecting TSI) they did not directly link these components to performance.

Lavric, Mizon and Monsell (2008) used the task-cuing design and also found the switch-induced positivity late in the CSI accompanied by a concurrent frontal negativity. Previous research (e.g. De Jong, 2000; Nieuwenhuis & Monsell, 2002) had demonstrated that responses at the faster end of the RT distribution tend to display a smaller switch cost than those at the slower end, which has been taken as a measure of preparedness: those trials with faster RTs (and smaller switch costs) index better preparation than those with longer RTs (and larger switch costs). If the switch-induced ERP positivity found in the preparation interval does indeed measure task-set reconfiguration, then there should be some modulation of the effect by RTs. Lavric et al. (2008) divided each participant's ERP data for the switch and repeat conditions into sets corresponding to terciles (thirds) of the RT distributions for those conditions and found that the tercile with the fastest RTs had a much larger switch-related positive

deflection before the stimulus, as well as smaller RT switch costs, than the slowest tercile. This links the magnitude of the ERP positivity to the RT switch cost within participants. Over participants, Lavric et al. were also able to correlate the RT RISC effect with the magnitude of the ERP principal component which captured the posterior positivity and the anterior negativity, further adding support for this ERP component as an index of effective anticipatory TSR.

In a related study Elchlepp, Lavric, Mizon and Monsell (2012) compared the data from Lavric et al. (2008), in which the stimuli were bivalent, to a condition in which the stimuli were univalent (affording responses in only one task) and found that bivalent stimuli were associated with a greater switch cost and RISC effect. The posterior positivity late in the CSI was also smaller with univalent stimuli suggesting that preparation was most effective when cue interpretation was necessary for task identification. Nonetheless, verbal (but not picture) cues were associated with evidence of effective preparation (RISC effect) and the posterior positivity late in the CSI in both experiments but picture cues were associated with these indices of preparation only with bivalent stimuli suggesting that linguistic cues are more conducive to eliciting TSR even with univalent stimuli either because TSR processes rely on internal linguistic self-instruction (for a fuller discussion on this point see Van t'Wout, Lavric & Monsell, 2013) or because linguistic cues are processed more automatically. Elchlepp et al. also found that the switch-induced negative deflection was reduced (but not eliminated) with univalent stimuli. Because the univalent stimuli afforded responses in only one task, but contained the perceptual dimension of the other task (e.g., the stimuli in the shape task were all presented in black colour – this did not afford responses in the colour task, because black was not mapped to a response there; however black is a colour and therefore enables attentional selection of the colour dimension) Elchlepp et al.

concluded that the most likely source of the negativity is interference in earlier component processes such as attentional selection and/or the activation of task goals.

The evidence presented thus far indicates that the posterior positivity late in the CSI and the anterior negativity early in the response interval are not only very robust ERP effects in task switching, but that the former is associated with active preparation and the latter with interference from (possibly an attentional component of) the other task-set. However, Astle, Jackson and Swainson (2008b) were able to eliminate both of these effects by consistently associating each task with a spatial location. Participants were presented with coloured letters and were required to indicate whether the letter was a vowel or consonant or whether it was presented in upper or lower case. They were informed which task was relevant at the start of each block and subsequent trials were preceded by a symbol indicating whether they should continue using the same task (=) or switch to the alternative task (<>). In one group of participants the colour of the stimulus also unambiguously cued the task (e.g., when the task was to indicate the case of the letter it was always presented in pink) while in the other this was achieved by the location of the stimulus (e.g., when the task was to indicate the case of the letter it was always presented to the left of fixation). Thus there were two distinct cues informing the participant which task to perform – the ‘switch or stay’ cue (which was essentially redundant) and the colour or location of the stimulus itself (which could potentially be used exclusively). The switch cost and its reduction with opportunity for preparation were comparable in both groups, but the posterior positivity and the anterior negativity were only present when the colour of the letter indicated which task to perform. Because the tasks were identical in both groups and the only difference was the additional information available from the colour/location of the stimulus, Astle et al. concluded that neither of the ERP components reflects generic anticipatory control processes. One possibility, at least regarding the absence of the switch-related positivity

in the preparation interval on spatially-cued trials, is that participants used the preparation interval only to shift spatial attention but postponed TSR until after the stimulus (a possibility which is further discussed in Chapters 3 and 4). This does not, however, explain why there was little evidence of the positivity protruding into the post-stimulus interval (as is typically found by others when the preparation interval is short or ineffectively used, e.g., Karayanidis et al., 2003; Lavric et al., 2008). So although there is neural evidence for an endogenous act of control late in the preparation interval which has been associated with behavioural indices of preparing to switch between tasks, the results of Astle et al. raise a question about the conditions under which it indexes endogenous TSR.

Task-set interference. As discussed, in their pioneering study Allport et al. (1994) concluded that the asymmetrical switch cost found with Stroop-like stimuli (switching to the dominant task was associated with a larger switch cost than switching to the non-dominant task and this effect was largely unaffected by increasing the opportunity for preparation) represents the time taken to overcome persistent ‘proactive interference’ from the previously relevant task-set – TSI. Although TSI has been proposed to represent both persistence of activation (discussed below) and inhibition from the preceding trial there is a rich line of research specifically investigating the carryover of task-set inhibition.

Mayr and Keele (2000) proposed that the inhibition of a task-set pushes its activation level below baseline and it takes time for this to recover. It follows then that a task-set which was inhibited recently should be more difficult to access than one which was inhibited less recently. By using three tasks, they were able to measure this difference by comparing performance on the third trial in an ABA (n-2 repetition) sequence to that in a CBA (n-2 switch) sequence (where A, B and C represent three tasks). At least in situations where there are no n-1 task repetitions, it seems that there is

a cost associated with repetition of the task which was relevant on trial $n-2$ – commonly referred to as ‘ $n-2$ repetition cost’ or ‘backward inhibition’. Although the effect has since been confirmed in multiple studies (see Koch, Gade, Schuch & Philipp, 2010, for a review), $n-2$ repetition costs are typically not found in task switching experiments which include $n-1$ repetitions (e.g., Phillip & Koch, 2006) and seem to be modulated by several other factors (e.g., number of cues per task, spatial distribution of cues/stimuli, duration of the response-to-cue interval). This raises the issue of whether inhibition is a feature of task switching in general or is only present under certain circumstances. If the latter is the case, inhibition is unlikely to contribute to the phenomena always reported in conventional task switching experiments.

The persistence of task-set inhibition is not the only way that TSI could occur. Indeed Yeung and Monsell (2003a) developed a simple modelling framework (see below) to account for Allport et al.’s paradoxical asymmetry of switch costs: it assumed carryover of task-set activation, not inhibition. Yeung has also probed for evidence of TSI with neuroimaging. In a functional magnetic resonance imaging (fMRI) study Yeung, Nystrom, Aronson and Cohen (2006) presented participants with a composite stimulus made of a word superimposed on a face. The task was to either identify the gender of the face or the number of syllables in the word, with runs of 4 trials between possible task-switch points. Because each of these tasks is associated with specific brain regions, Yeung et al. were able to compare brain activity in each region with performance and found that the switch cost positively correlated with activity in the region associated with the irrelevant task, rather than the relevant task thus providing neural evidence suggesting that the switch cost is caused largely by carryover of task-set activation.

Inertia, in the sense of persistence of activation or inhibition from trial to trial of task-set parameters is not the only way in which interference might be generated by

prior performance of the competing task. Allport and Wylie (2000) manipulated the order in which stimuli were presented and demonstrated that the carryover of responses made to the same stimuli earlier in the experiment (negative priming) interferes with current task goals even over multi-trial lags. Waszak, Hommel and Allport (2003, 2005) further investigated the effect of stimulus-task associations on the switch cost. They presented participants with bivalent stimuli in two phases. In the first ('baseline') phase participants were required to respond to only one of the tasks afforded by the stimulus. In the second ('alternating') phase participants were required to respond to both tasks afforded by the stimulus in runs of three trials each. Critically, some of the stimuli presented in the alternating phase were novel and some had been processed under competing task rules in the baseline phase. Waszak et al. (2003) predicted that the interference, and hence the switch cost, would depend on the prior history of the stimulus. This supposition was confirmed: a larger switch cost was obtained for a stimulus previously encountered in the other task and the effect was found to be present over 100 trials after the previous presentation of the stimulus. However, in order to make a direct comparison to earlier investigations (e.g., Allport & Wylie, 2000; Wylie & Allport, 2000) the analyses were limited to those trials on which the participant switched to the dominant task. Waszak et al. (2005) addressed this issue by extending the analyses to include both switch and repeat trials for both the dominant and non-dominant tasks and observed that long-term interference was particular to switch trials for the dominant task, but was found on both switch and repeat trials in the non-dominant task thereby indicating that interference influences performance only when task competition is high. Thus, it appears necessary to invoke TSI to explain why long-term associative reactivation affects performance on switch trials only in the dominant task and on both switch and repeat trials in the non-dominant task. On dominant task repeat trials associative reactivation of recently used S-R rules struggles to overcome

the highly practiced S-R rules associated with the stimulus. Waszak et al. (2005) also investigated the relative contribution of ‘negative priming’ (the difficulty in responding to a stimulus which had previously been a distractor – associative reactivation of task-set inhibition) and ‘competitor priming’ (the difficulty in suppressing a distractor which had previously been the relevant element of the stimulus – associative reactivation of task-set activation). Whilst negative priming was detected (and had a modest effect) only when the stimulus set was small (i.e., when stimuli were repeated frequently throughout the experiment), competitor priming was substantial regardless of stimulus set size.

The possibility that S-R rules might be ‘re-activated’ by the stimulus was further examined by Wylie, Javitt and Foxe (2006) using fMRI. Participants were presented with identical stimuli at three stages: in the first stage (single task block) each stimulus was associated with a single task; in the next stage the same stimuli were associated with a second task (dual task block); in the final stage, the procedure was identical to the first stage (single task block) but now each stimulus had been associated with a second task-set. Performance and brain activity from stages 1 and 3 were compared. Performance was found to be significantly worse in the final stage, where the stimuli had been associated with a competing task-set, than in the first, where they had not. Brain activity in areas associated with the novel tasks introduced in stage 2 remained active in stage 3. Like Yeung et al. (2006), Wylie and colleagues concluded that a large part of the switch cost can be explained by carryover of activity in brain regions associated with competing task-sets, though the time-scales of the carryover effects documented in the two studies were very different (over trials in Yeung et al., and over stages in Wylie et al.). It would seem therefore, that interference is a likely contributor to both the switch cost and its residual component (whether in the form of TSI or

associative reactivation of previously relevant S-R rules) with inertia of task-set activation being the more dominant force.

Interaction between TSR and TSI. The evidence in support of both TSR and carryover accounts (TSI and/or associative reactivation) makes it difficult to select one interpretation of the switch cost over the other and the dominant view is that they probably both make a contribution (e.g., Monsell, 2003). Most proponents of a carryover/competition account would likely agree that some form of reconfiguration is required when the task switches, to ensure that the appropriate task wins the competition. Most proponents of TSR would likely agree that a primary purpose of reconfiguration is to overcome (at least part of) carryover of previous task-set(s). However, the exact relation between these two sources of the switch cost remains unclear.

Meiran, Chorev and Sapir (2000) independently manipulated the CSI and response-to-cue interval in a task-cuing design and demonstrated that both influence the switch cost. They concluded that the switch cost “has at least three components reflecting (1) the passive dissipation of the previous task-set, (2) the preparation of the new task-set, and (3) a residual component” (p. 211).

By manipulating the practice schedule through an experimental session Yeung and Monsell (2003b) were able to demonstrate that, like the asymmetric switch costs found with Stroop stimuli (e.g., Allport et al., 1994) it is more difficult to switch to the more recently practiced task. Critically, Yeung and Monsell were able to show that increasing preparation time reduces this supposed effect of TSI which was previously assumed to be largely reduced by passive dissipation (e.g., Meiran et al., 2000) thus raising doubts over the claim that TSI is unaffected by endogenous control.

In another study from the same year Yeung and Monsell (2003a) were able to reverse the asymmetrical switch cost by reducing the interference from the competing

task-set. They achieved this by presenting the two attributes of the stimulus asynchronously or by using different response sets for each task (e.g., vocal and manual). They went on to discuss their findings with reference to a simple modelling framework which assumes that task-set activation is a summation of task strength, priming (carryover) and ‘just enough’ control to respond correctly on most trials. Because cognitive control is an effortful process participants tend to use the minimum required in order to achieve a reasonable degree of accuracy in the face of interference from priming of the previous task (inertia of task-set activation). Yeung and Monsell’s (2003a) model explains both the asymmetry of switch costs and the reversal of the asymmetry when interference is reduced (such as in their experiments) indicating the extent to which TSR is commonly used to overcome TSI.

Interpreting the residual switch cost. Because pre-stimulus TSR processes can reduce the switch cost but not eliminate it, some other mechanism must explain its residual component. Essentially there are three classes of theory used to explain residual switch costs: (1) because interference from competing task-sets (either in the form of TSI or associative reactivation) cannot be fully overcome by TSR; (2) some component of TSR cannot be completed until after the stimulus; and (3) a probabilistic ‘failure to engage’ effective preparation on some trials.

TSI and associative reactivation of responses have been identified as likely sources of the residual switch cost because until relatively recently (e.g., Yeung & Monsell, 2003a) they were both considered to be largely unaffected by preparation. Although associative reactivation of S-R rules has been recorded over 100 trials after the previous presentation of the stimulus, the effect of TSI has been found to reduce as a function of the time available for passive decay (RSI; e.g., Meiran et al., 2000). Critically, even at very long preparation intervals, TSR is not able to abolish either effect.

Task-relevant response selection (or execution) processes seem a likely candidate for late components requiring reconfiguration and have been proposed as contributors to the residual switch cost by some (e.g., Meiran, 2000, Rubinstein, Meyer & Evans, 2001; Schuch & Koch, 2003). Rogers and Monsell (1995) proposed it to be a likely source of the residual switch cost because of the interaction between switching and response congruence effects. Bivalent stimuli (which afford responses in both tasks) can be congruent (same response in both tasks) or incongruent (different responses in the two tasks). For example digits might be classified as odd/even or lower/higher than 5 by using left/right key presses respectively. Thus, because the digit 3 can be classified as ‘odd’ and ‘low’, both requiring a left-hand response, it would be a congruent stimulus, whereas the digit 9 can be classified as ‘odd’ (left-hand response) and ‘high’ (right-hand response) – an incongruent stimulus. Incongruent stimuli nearly universally elicit longer RTs but Rogers and Monsell (1995) found that this ‘congruence effect’ was greater on switch than repeat trials and was largely unaffected by the time available for preparation (for a fuller discussion on this point, see Monsell & Mizon, 2006). More recently Monsell, Sumner and Waters (2003) demonstrated that although the switch cost is largely limited to the first trial of a run the congruence effect persists throughout a run of (at least) 4 trials. This intriguing result indicates that interference in the response selection component of task-set might be difficult to overcome through preparation alone, or even when the new task has been performed several times on consecutive trials. Rogers and Monsell (and Rubinstein et al., 2001) suggested that retrieval of S-R rules might be cued (exogenously) by the presence of a task-relevant stimulus and that this is the source of the residual switch cost.

Following their claim that execution of a response is necessary for recording switch costs, Schuch and Koch (2003) concluded that suppression of irrelevant S-R rules can only occur once the conflict has been detected – during response selection.

They therefore concluded that the control process required to suppress interference in this component was the source of the residual switch cost. Similarly, Meiran's (2000) model of executive control in task switching (discussed at length below) assumed that the residual switch cost could be explained by the need to overcome perseveration in a response selection module (R-Set) once the stimulus is present.

The failure-to-engage (FTE) hypothesis was proposed by De Jong (2000). Based on application to RT distributions of a mixture model, De Jong concluded that the mean residual switch cost (and indeed the RISC effect) comes about as a result of some trials on which preparation is effective and complete and some on which it was not (the probability of achieving preparation increases with the duration of the preparation interval). As noted earlier, the switch cost is much smaller on those trials with fast RTs than those on which responding is slow, suggesting greater variability over trials in the success of task-set preparation on switch trials. This model goes further and proposes a discrete binary function for preparedness with a higher probability of effective preparation when RTs are fast (given enough preparation time). Nieuwenhuis and Monsell (2002) tested the FTE theory using data from one previous and one new experiment which manipulated incentives to prepare. Although their modelling of cumulative RT distributions provided some evidence in support of FTE, they also found that strong incentives to prepare only marginally improved the probability of successful preparation (as estimated by fitting the mixture model) and concluded that there was an intrinsic limit to the level of preparation attainable prior to stimulus onset.

Task-relevant control of selective visual attention.

Having reviewed some of the key themes in the task switching literature the following section will focus specifically on the attentional component of task-set. I will start with a brief review of some of the relevant theories of selective visual attention and

a discussion on which early processing stages are accessible to top-down control including some of the experimental research on shifting attentional set in task switching and some of the key modelling frameworks of task-set control which include an attentional component.

Orienting visual attention. We are under a constant bombardment of information through our senses. It is impossible to process all of the information to the same degree so some mechanism is necessary to select relevant information for further processing while ignoring what is irrelevant. Visual attention is the mechanism which filters visual information for further processing. There are several levels at which visual attention can select information for further processing such as from a specific location in space, perceptual dimension (e.g., form, colour), feature within a dimension (e.g., square, red) or a particular object in the visual field.

Treisman (1969) describes a model of perception which supposes that sensory information is processed by individual ‘analyzers’ specific to a perceptual feature, dimension or object and each analyzer has a limited processing capacity. Although much of Treisman’s review is concerned with tests of auditory attention, analyzer theory can be equally applied to visual attention. For example Allport (1971) presented participants with three coloured shapes, each containing a black digit and asked them to report the identity of the shapes, the colours, the digits or combinations of these on each trial. Allport demonstrated that identifying either shapes or digits is as easy as identifying a combination of shapes and colours (which are discriminated under different perceptual dimensions) but identifying a combination of shapes and digits (both of which require discrimination by form) can be much more difficult. This conclusion is consistent with Treisman’s notion that attention is dependent on various analyzer modules (e.g., form, colour) which have a limited processing capacity because

processing multiple objects with a single analyzer is more difficult than processing each object with a different analyzer.

Duncan (1984) proposed that visual information is primarily selected on the basis of the whole object (i.e., Gestalt groupings) rather than specific dimensions within the object or its spatial location/area. In a series of experiments participants were briefly presented with stimuli made up of a rectangle with a line struck through its middle and were required to identify two features of the line or the rectangle or one feature from each. Responses to the second to-be-reported feature were more accurate when the features were from the same object despite the feature pairs within and across objects being equidistant. In a second experiment participants were always required to report features from two objects, but the dimensions of the features could be the same or different. Responses were equally accurate in both conditions so Duncan concluded that selection of visual information was determined, at least in part, by the number of objects to be attended rather than their spatial distribution or the dimensions to be reported. It should be noted however that Treisman (1969) suggested that analyzers at lower levels (such as those concerned with straight or curved lines) might be combined to produce analyzers at higher levels of perceptual processing (such as the objects used in Duncan's experiments).

In a related series of experiments based on Duncan's (1984) design Müller and O'Grady (2000) were able to demonstrate that although directing attention to one object is easier than directing it to two, contrary to analyzer theory which proposes that each analyzer has a limited processing capacity, processing one dimension from two objects is easier than switching the dimension between objects. Although this finding is consistent with the notion that attention can be directed towards a single dimension within a multiple-item stimulus set, the proposed process which allows attentional selection of dimensions differs greatly from that proposed in analyzer theory (where

each analyzer processes information at a preattentive stage but has a limited capacity to do so), but is very much in line with current research on the control of attention in visual search paradigms discussed below (e.g., Dimensional Weighting Account, Found & Müller, 1996, assumes that focused attention has a limited processing capacity, but switching between dimensions, even at preattentive stages, is effortful). Of course visual attention is neither exclusively object- nor dimension-based (as indicated by Treisman's notion of combined analyzers) and each of these theories require that attention should be able to select relevant information from a particular location in space.

Location-based theories of visual attention describe selection of information with the metaphor of a 'spotlight' (e.g., Posner, Snyder & Davidson, 1980) or 'zoom lens' (e.g., Eriksen & Eriksen, 1974). They propose that attention filters information by selecting a specific location in space on which to focus. Evidence in support of location-based selection of visual information is extensive with the most common evidence coming from 'spatial cuing' paradigms (e.g., Posner, 1980) which demonstrate that RTs to a stimulus are faster when the item is presented in a validly cued location than when the location-cue is invalid. Later developments of this kind of theory have examined, for example, movement of the spotlight (e.g., Posner, Snyder & Davidson, 1980), the size (e.g., LaBerge, 1983) or shape (e.g., Müller & Hübner, 2002) of the spotlight, and whether it can be directed towards more than one distinct region simultaneously (e.g., Müller, Malinowski, Gruber & Hillyard, 2003).

Another important idea which has been extensively researched is that attention can be attracted quickly and effortlessly through an exogenous event (such as a sudden onset in the visual field) or more slowly and deliberately through endogenous control (Posner, 1980, suggests that exogenously driven shifts of attention result in a ~50 ms advantage in eye movement latencies relative to shifts which are controlled

endogenously). In an early study by Jonides (1981) participants were presented with an arrow cue either at a central or peripheral location indicating where a target was likely to appear amongst a set of distractors. Jonides concluded that although both cue types were able to induce shifts of attention, peripheral (exogenous) cues required less cognitive resources, were more difficult to ignore, were effective even when not anticipated and were more effective in directing attention (as evidenced by their ability to capture attention and influence performance whether they were valid or not) than central (endogenous) cues.

The extent to which early processing stages and exogenous capture of attention are accessible to top-down control is of particular relevance to this thesis. A large body of research has been produced investigating the early stages of perceptual processing and the extent to which they are top-down modifiable in visual search paradigms. Another relevant line of research has investigated whether the supposed ‘involuntary’ shifts of attention measured in paradigms which use exogenous cues to capture attention are also top-down modifiable. Before discussing the extent to which attentional capture by exogenous cues is contingent on top-down control mechanisms I will first describe some of the relevant research investigating voluntary shifts of attention in visual search experiments.

Shifts of attention in visual search. In the visual search paradigm participants are typically shown an array of items and must look for the odd-one-out target (‘singleton’) – either to decide whether a target is present or not, or to report some property of the target. There are three basic paradigms commonly used: in ‘feature search’ participants are required to make a present/absent judgement for a singleton differing from the distractors on a single dimension (e.g., find the red object amongst green objects); in ‘conjunction search’ participants are required to find the singleton differing from the distractors on multiple dimensions (e.g., find the red cross amongst

green crosses and red circles); in ‘compound search’ participants are required to find the singleton and then respond to a property of it, such as another object superimposed on it (e.g., find the red object then identify whether the arrow on it is pointing up or down).

Search times tend to increase as a function of the number of distractors unless the target is particularly salient or ‘pops out’ due to its contrast with the other items in the display (e.g., in feature search paradigms). Treisman and Gelade (1980) proposed Feature Integration Theory (FIT) to explain this robust effect. FIT assumes that feature searches are so efficient because the stimuli are processed at a preattentive stage (as suggested by analyzer theory) which analyzes all items in the display in parallel for their values in a number of separate elementary feature domains or cortical maps: orientation, colour, motion, etc. Within any one of these representational domains, any item highly contrasting to others on that single dimension ‘pops out’, automatically attracting the focus of spatial attention, and thereby producing flat search times whatever the size of the display. However, in conjunction search the output from multiple analyzer systems must be integrated (via focused attention) to detect a feature conjunction, and focal attention can examine only one display object at a time. Thus search times increase as a function of the number of items in the display, with a 2:1 slope ratio for “absent” and “present” decisions, as would be expected for a self-terminating serial search.

The clear formulation of FIT attracted further research which revealed its limitations. For example, the simple contrast between “serial search” and flat “popout” functions turned out not to be a dichotomy; intermediate patterns could easily be found; moreover, relatively steep functions could be observed for some apparently single feature targets, and shallow function for some apparently conjunctive targets, depending on the similarity relations between targets and distractors, and among the distractors (see Desimone & Duncan, 1995; Duncan & Humphreys, 1989) which led to alternative accounts being proposed.

A full account of these developments is not germane to the present thesis. However, one critical issue is which levels of processing are subject to top-down control. The FIT model, like Broadbent's (1958) filter model, assumed a preattentive stage (prior to focal attention) not subject to top-down control. More recent approaches, such as Desimone and Duncan's (1995) "biased competition" account, assume that top-down biasing can be applied to select processing at any level – location, simple features, complex conjunctions, and objects. For example, there is clear electrophysiological (e.g., Magnun & Hillyard, 1991) and fMRI (e.g., Kastner, De Weerd, Desimone & Ungerleider, 1998) evidence that endogenous cuing of location modulates activation very early in the visual pathway.

In the case of visual search, Wolfe's (1994) Guided Search model extended FIT to allow top-down prioritisation of one 'feature map' (e.g., red objects) over another. These are then integrated to form an overall 'activation map' which guides focused attention to the items in the display which are most likely to be the target. Much of the current debate in the visual search literature surrounds an extension of Guided Search proposed by Müller and colleagues (e.g., Found & Müller, 1996; Müller, Heller & Ziegler, 1995) which assumes that the appropriate 'saliency map' can be weighted by top-down control if the target dimension is known in advance. If the target dimension is not known in advance then the most recently used weightings carry over to (and, if they are not appropriate, prolong) the new search – the Dimensional Weighting Account (DWA).

A key finding of Found and Müller (1996) which is of particular relevance for this thesis is that feature search times are longer when the dimension under which the target is classified is different to the relevant dimension on the previous trial relative to when the dimension remains the same (this 'dimensional switch cost' is usually referred to as a 'dimension repetition benefit' or DRB in the visual search literature), but search

times are largely unaffected by switching the specific feature to be searched within a dimension (e.g., red vs. blue colour). Much like in the task switching literature, there is some controversy over whether DRBs are driven by endogenous control processes, (exogenous) passive priming or both. In their Experiment 2, Müller, Reimann and Krümenacher (2003) presented participants either with an uninformative ‘neutral’ cue or an informative ‘valid’ cue that specified the target dimension on the subsequent trial. The DRB was smaller in the valid-cuing condition (~15 ms) than when the cue was neutral (~25 ms) suggesting that, when available, valid cues were used to control the weighting of preattentive saliency maps. When the cue was neutral, top down control could not modulate the weightings. However, even when the cues were valid and there was ample time to reconfigure attentional settings (the longest CSI used was 2200 ms), there remained a ‘residual’ cost of switching dimensions which Müller et al. (2003) attributed to passive carryover of attentional setting from the previous trial.

Maljkovic and Nakayama (1994) also found intertrial facilitation when the target dimension was repeated from the previous trial, but they interpreted it as a purely passive priming effect (‘priming of popout’). In their Experiment 4, they even asked participants to vocalise the target dimension during the intertrial interval when the dimension switched in a predictable sequence. Although this did speed search times overall, it did not reduce the DRB and even extended it in one participant.

A similar position is also held by Theeuwes and colleagues (e.g., Mortier, Theeuwes and Starreveld, 2005; Theeuwes, Reimann & Mortier, 2006) who claim that the preattentive stage of visual search is inaccessible to top-down control, but suggest that perhaps later stages are. Mortier et al. (2005) used a similar paradigm to Müller et al. (2003) but eliminated the search aspect of the design in some blocks. The task was to identify whether a singleton (a coloured circle, a large grey circle, or a grey triangle amongst an array of grey circles) was present or absent. In non-search blocks there was

only one item presented and the task was to identify whether the item was the target or not. They found a comparable DRB when the dimension of the single item was repeated from the previous trial indicating that top-down weighting of the preattentive saliency map to locate the target is not necessary to explain the effect. They concluded that perhaps the preattentive stage is immune to top-down control and the DRB has its locus at later stages of processing. In a related report, Theeuwes et al. (2006) asked participants to search for a singleton among an array of items similar to those used by Mortier et al. (2005). The target dimension was cued (verbally) beforehand with 83% validity but the cue validity effect (faster search times on validly cued trials) did not interact with DRBs in feature search (Experiment 1) suggesting that the latter effect could be explained by bottom-up priming alone. By asking participants to respond to the angle of a tilted line superimposed on the singleton in Experiments 2 and 3, Theeuwes et al. were able to eliminate the cuing effect found in Experiment 1. If DRBs can be explained entirely by top-down control of preattentive stages of processing then the cuing effect should have been of a similar magnitude whatever the response selection criteria. In order to confirm the hypothesis that DRBs can be explained by bottom-up priming (rather than top-down control) at preattentive stages of processing, Theeuwes et al. (2006, Experiments 4 and 5) used the actual singleton (one of the two possible target objects) as the cue in a compound search design, similar to that used in their Experiments 3 and 4, and manipulated the cue validity between experiments. When cue validity was 17% (i.e., participants could use top-down control to predict the defining feature of the target – it was not the same as the item used for the cue) the validity effect was just as strong and in the same direction as when cue validity was 83% (where the target was cued exogenously). This striking result suggests that preattentive stages of processing might not be accessible to top-down control, but are susceptible to carryover of recent perceptual priming. Theeuwes et al. (2006) therefore

concluded that perhaps DRBs can be explained by bottom-up priming at early (preattentive) stages or top-down modulation of later stages of processing including response selection.

A more recent study from the Müller group (Töllner, Grammann, Müller, Kiss & Eimer, 2008) came to different conclusions. The target was either a red circle or a blue square amongst seven distractors (blue circles). A grating (three black bars) aligned either horizontally or vertically was superimposed over each shape. Participants were asked to identify the orientation of the grating on the target singleton. Thus, the dimension of the target (attentional selection) and/or the orientation of the grating (response selection) could switch/repeat from the previous trial. By recording brain potentials Töllner et al. were able to investigate the extent to which common ERP effects assumed to represent attentional selection of a target among distractors (N2pc; Eimer, 1996) and response selection (LRP; Eimer, 1998) are modulated by between-trial changes in the target dimension and/or the required response. N2pc peak latency and amplitudes were found to be modulated by dimension changes (but not changes of the target feature or response) while the LRP amplitude was found to be modulated by changes in response (but not the target dimension). Töllner et al. indicated that this pattern of results is consistent with the assumptions of DWA and is inconsistent with accounts of DRBs which assume they derive exclusively from later (response selection) stages of processing. However, they admit that their results cannot conclusively determine whether the delay in N2pc peak latencies are a result of DRBs or ‘dimension switch costs’ and cannot make any claims about whether early preattentive stages are accessible to top-down control.

The current position held by the Müller group is that the DWA can be extended to include multiple levels of processing, each of which is accessible to top-down control – the Multiple Weighting Systems hypothesis (MWS; Rangelov, Müller & Zehetleitner,

2011a, 2011b, 2012; Zehetleitner, Rangelov & Müller, 2012). MWS supposes that different paradigms place different demands on at least three systems (stimulus selection, perceptual or semantic analysis and response selection) each of which can be weighted by top-down control independently of the others. Rangelov et al. (2012) argue that by removing the visual search element from their experimental paradigm, Mortier et al. (2005) eliminated DRBs in the stimulus selection system, but were still able to measure them in later systems. Because the stimulus must be perceptually analysed in order to generate a correct response, dimension repetition is still able to improve performance. Critically, Rangelov et al. (2012) go on to describe how MWS can also be applied to task switching. As with visual search paradigms, intertrial effects arise in task switching when it is necessary to update a given system between trials. Rangelov et al. note that most task switching paradigms require participants to select specific stimulus elements, update the S-R rules (analysis of the stimulus) or both. Thus, the switch cost can be explained as a necessary reweighting (top-down control) of these systems between trials: when the task switches so do the rules for stimulus selection, analysis or both so these systems must be controlled in order to accommodate the changing demands of the task. This proposal (which currently has no computational implementation) is very similar to theories proposed a decade or so earlier in the task switching literature (e.g., Arrington et al., 2003), some implemented in computational models (e.g., Meiran, 2000). One could say that Rangelov et al. (2012) represents the beginning of visual search researchers' recognition of the relevance of the task switching literature in much the same way that task switching researchers should recognise the relevance of the visual search literature. Clearly there is an agreement between these areas of research that top-down control can modulate processing in at least three stages: stimulus encoding, response selection and response execution. However, direct investigations studying the precise dynamics of top-down control in

each of these stages, whether there are similarities in the way top-down control influences processing at each stage and how top-down control at each stage interacts with processing at other stages remains scarce.

Attentional set in task switching. An example of experimental research which speaks to this issue from the task switching perspective comes from Rushworth, Passingham and Nobre (2005) who compared ERPs recorded when participants were required to switch between what they call “intentional sets” (same attentional settings, different S-R rules) or “attentional sets” – (same S-R rules, different attentional settings), using an intermittent instruction paradigm (i.e., occasional cue displays between runs of trials). Participants were presented with two coloured shapes either side of fixation. One was always a rectangle, the other a triangle, one was always red and the other was always green. Participants were required to respond with a left/right key press according to the symbol superimposed on one of the objects, using the same S-R rule throughout the experiment (i.e., a compound search design with only two stimulus elements). For some runs of trials the relevant object was specified by shape (e.g., respond to the symbol on the triangle) and for others by colour (e.g., respond to the symbol on the red object). Because there was a symbol on each object, attention to the appropriate object was essential. The intermittent cues informed the participant to either ‘stay’ using the same dimension or ‘switch’ to the alternative dimension. Hence the attentional set varied but the intentional set (S-R rule) remained constant. ERPs were compared to data from an earlier investigation (Rushworth, Passingham & Nobre, 2002) in which participants classified a shape as triangle or square throughout, but from time to time the S-R assignment reversed or stayed the same, as conveyed by similar “stay” and “switch” cues. Hence in the earlier experiment the attentional set remained constant and the intentional set varied.

Although Rushworth et al. observed, among the cue-locked ERP effects of switching, the above-mentioned switch-related posterior positivity, their analysis was focused on an earlier, more anterior, positivity induced by both kinds of switch. Source estimation revealed differences in the cortical generators of this positivity when participants switched attentional vs. intentional set – a lateral frontal source for the former and a medial frontal source for the latter. However, direct statistical comparisons of the ERPs found little difference between the two conditions, which precluded firm conclusions about preparation for the two kinds of switch. A further issue is that because the two studies had only one CSI (2000 ms) there is no behavioural measure of preparation for either attentional or intentional set switching. Analysis of stimulus-locked ERPs found that implementation of attentional and intentional sets also shared some processes. More striking though was the finding that both were associated with switch-related differences in the ERP several trials after a switch cue. This was taken as evidence that passive carryover of task-set affects attentional selection as well as response selection. As noted earlier, Monsell, Sumner and Waters (2003) found evidence of response conflict several trials after a switch, but there is less evidence that the effects of previous attentional set persists in the same way.

Involuntary capture of attention by salient stimuli. Having discussed the conditions under which the early stages of selection of perceptual attributes are accessible to endogenous control and when they suffer from carryover of previously relevant attentional settings, I will now describe some of the research conducted on the extent to which exogenously triggered shifts of attention are top-down modifiable.

Yantis and Jonides (1984) showed that visual search times were faster when the target item's onset was abrupt in relation to the more gradual onset of the distractors. They also demonstrated that if a distractor's onset was abrupt the search time for the target was initially delayed and search then proceeded in a typical serial manner

resulting in longer search times for larger arrays of items. They concluded that attention had been (involuntarily) captured by the abrupt onset item (whether it was the target or not). Jonides and Yantis (1988) went on to claim that an abrupt onset is particular in its ability to capture attention which is not shared by other forms of saliency such as luminance or colour singletons. However, in a related series of experiments Yantis and Jonides (1990) used both central (endogenous) cues and abrupt onsets (exogenous cues) and found that when the central cue was informative (either appearing before the stimulus array or being highly predictive of the location of the target) the effect of endogenous control was enough to overcome the capture of attention by the abrupt onset. They concluded that although abrupt onsets do typically capture attention, there are conditions under which this is not the case – e.g., when attention has been voluntarily directed to a different location in accordance with current task goals. This leaves at least a potential avenue for top-down modulation of attentional capture by salient stimuli.

Folk, Remington and Johnston (1992) proposed a much stronger view which they refer to as the Contingent Involuntary Orienting Hypothesis – involuntary attention capture is always accessible to top-down control and is contingent on a match between properties of the cue and the target. In their experiments five boxes, arranged in a cross formation, were visible throughout as placeholders for the stimuli. The task was to identify the target ('=' or 'X') via a key press. Of particular relevance to this thesis are the results from their Experiment 3 in which the target was either the only symbol presented in one of the four peripheral boxes (sudden onset singleton) or a symbol was presented in each of the four peripheral boxes but only one of them was presented in red whilst the others were presented in white (colour singleton). In both conditions the stimulus was only visible for 50 ms. Critically, 150 ms prior to the stimulus being presented, one of the locations was 'cued' by either four white dots briefly (50 ms)

appearing around one of the boxes (sudden onset cue) or by four white dots briefly appearing around all of the boxes except for one where the four dots were presented in red (colour cue). This uninformative cue could indicate any of the four peripheral boxes equiprobably so cue validity was 25%. The participant was required to identify the target symbol via a key press. Folk et al. found that RTs were faster when the cue validly identified the target location only when the cue and target shared perceptual properties (e.g., when the cue and target were both sudden onsets). They concluded that attention is only captured by exogenous cues if they share the perceptual properties which are of importance for the current task goals – i.e., even involuntary shifts of attention are dependent on top-down control settings.

Task switching and attentional capture. Lien, Ruthruff and Johnston (2010, Experiment 4) wanted to investigate the extent to which attentional settings would be carried over from the previous trial if participants were required to switch settings between trials. To do this they incorporated a task switching condition into the contingent capture paradigm used by Folk et al. (1992). Participants were briefly (50 ms) presented with four digits (one was red, another was green and the remaining two were white). Each digit was presented at the centre of a white square (the four white squares were themselves presented at the corners of an invisible square). The task (cued on every trial by the initial letter of the relevant colour presented within a fifth white square in a central position) was to classify the relevant digit, identified by its colour, under a parity or magnitude judgement. Each classification rule was consistently associated with a single colour throughout the experiment (e.g., classify the red digit under the parity rule). Similar to Folk et al.'s design, one of the white squares surrounding the digits would briefly (50 ms) change colour 150 ms prior to the stimulus. This 'capture-cue' was uninformative and its colour and/or location could either match, or not, that of the target digit. Attention was captured by the cue, as indexed by faster

RTs to targets presented at the same location, only if it matched the attentional settings for the trial (Folk et al.'s 'contingent capture' effect). Despite reporting large switch costs, Lien et al. found that, on switch trials, the capture cue was not effective when it matched the colour that was relevant on the previous trial. Contrary to Rushworth et al. (2005), they concluded that, with ample preparation time (their CSI was 1350 ms), there is no carryover of attentional settings from the previous trial and attention orientation does not contribute to the (residual) switch cost.

The discrepancy between the findings of Lien et al. (2010) on one hand and Rushworth et al. (2005) on the other leaves open the question of whether attention reconfiguration is part of the task-set and the extent to which carryover of attentional settings contribute to the switch cost. Two recent studies have systematically investigated whether attentional selection contributes to the switch cost by recording eye movements during task switching (Longman, Lavric & Monsell, 2013; Mayr, Kuhns & Rieter, 2013); these will be described in more detail in the section on eye-tracking in task switching below.

Experimental investigations of attention control in task switching. The experimental research presented so far which attempts to examine attention control in task switching (e.g., Lien et al., 2010; Rushworth et al. 2005) differs from typical task switching experiments in one critical way. Most task switching experiments require the participant to switch between S-R rules while in most visual search paradigms the latter remain constant. Nonetheless, attentional selection has long been considered part of the task-set. For example, Meiran (1996) observed that "shifting attention between perceptual attributes is probably part of the reconfiguration process" (p. 1424), Monsell (1996) listed "perceptual orienting" as part of task-set, several models of task-set control acknowledge that attentional selection might also require reconfiguration when switching between tasks (discussed below) and the tasks used in task-switching

experiments often require participants to shift attention between perceptual or semantic dimensions. Nevertheless, it seems fair to say that the need to shift attention has been somewhat neglected in favour of the need to change the task rules in theoretical accounts of switch costs.

In a recent example of research which investigates early stages of processing in task switching, Elchlepp, Lavric and Monsell (in press) used established ERP markers to determine whether early (perceptual) or later (response) processes contribute to the residual switch cost. Participants were presented with letter strings which had some letters coloured blue and some coloured red. The tasks involved classifying the stimulus either lexically (classify the object as living/non-living or classify the string as a word/non-word) or perceptually (indicating whether the colours of the letters were arranged symmetrically or asymmetrically). By analysing the switch-induced delay in the latency of ERP markers commonly associated with the frequency of the word in the semantic (living/non-living) task and lexicality of letter strings in the lexical decision task, Elchlepp et al. were able to demonstrate that a prepared (the CSI was ample) task switch substantially delayed these markers which occur prior to response selection. One possible explanation is the persistence of attentional settings from the previous trial (to colour pattern over orthography). Another (related) explanation is competition between the lexical processing pathway and the form judgement pathway (cf. Yeung et al., 2006) and inertia in activation of whichever was used more recently (i.e., the delay is post-perceptual).

An earlier report which merits mention is Allport et al.'s (1994) Experiments 6 and 7, which investigated the extent to which switch costs could be measured in a 'rapid sequential visual presentation' paradigm. Participants were presented with sequences of stimuli (e.g., object words) in quick succession and were required to report a subset of them (e.g., those which are smaller in size than a football) on completion of the list.

Rapid processing of the items was essential to achieve levels of accuracy above chance, but responses could be made at the participants' leisure. The dependent variable is accuracy rather than RT; the rapid presentation of items ensures response accuracy does not reach ceiling so that meaningful comparisons can be made between conditions.

Allport et al. asked participants to switch the target criterion (e.g., between 'animal' and 'not animal') during some sequences, cued by shifting the location at which the stimuli were presented on screen, and demonstrated that there was a cost in accuracy related to switching categories during a sequence. In a follow-up experiment (Experiment 7) some sequences had to be recalled under the same categorization rule throughout, but the location at which items were presented shifted during the sequence. Under these conditions, Allport et al. were able to demonstrate that shifting attention between categories ("semantic space") and shifting attention between locations (physical space) were both associated with poorer performance. However, the cost of shifting between categories (and locations) could not be explained by simple shifts of spatial attention alone (which were also associated with a performance cost, albeit much smaller and with faster recovery). This indicates that shifting spatial attention comes at a cost, even when it is not bound to other components of task-set. However, they did not use their paradigm to investigate the effects of task switching on spatial attention per se.

Models of attention control in task switching. Before I conclude this literature review of the research which is of particular relevance to this thesis by describing the two recent investigations of attention control in task switching using eye-tracking, I will consider how models of task-switching have (or have not) accommodated the idea of attention as a component of task-set.

Gilbert and Shallice (2002) proposed an influential model of task switching which is based on an earlier model by Cohen, Dunbar and McClelland (1990) designed to predict performance in a Stroop task. Cohen et al.'s model was designed to predict

performance in single-task blocks but incorporated modules specific to both word reading and colour naming tasks. They also included ‘Task Demand’ units which applied relevant weightings (top-down control) to intermediate units thereby modulating the strength with which the input units activate the response units (i.e., S-R mappings) to ensure a correct response is given whichever task is currently relevant.

Gilbert and Shallice (2002) made some relatively minor changes to the Cohen et al. model so that it could predict performance in task switching rather than single task blocks. The basic structure remained the same but they allowed some parameters to be carried over from the previous trial. An important difference is the inclusion of two (rather than one) response units – one for each task. Top-down control is incorporated in the cumulative activation of one of the task units according to which is appropriate on a given trial. Activation of the task units is then used to weight the response unit for the relevant task thereby ensuring a correct response is given. The model does not distinguish between attentional selection and response selection – both are done via weighting of the relevant response unit. Additionally, specific stimuli can activate task-sets with which they have previously been associated (associative reactivation). Gilbert and Shallice were able to model several of the common empirical effects reported in task switching experiments (e.g., the switch cost, its reduction with time to prepare, response congruence effects, the asymmetric switch costs reported by Allport et al., 1994, and stimulus specific response priming – however, the latter effect was limited to priming of responses from the previous trial because the model assumed carryover of S-R rules from the previous trial only). However, the model was not able to replicate other effects (e.g., residual switch cost, long-term priming). Gilbert and Shallice’s model performs identical processes whether the task repeats or switches which led them to conclude that many of the commonly reported effects in task switching experiments can be explained in the absence of an additional TSR process on switch trials. However, it

could be argued that, because their model achieves top-down control through weighting the task demand units and the weights only change on switch trials there is an endogenous reconfiguration process incorporated into the model, but it does not directly contribute to RT as an inserted stage. Critically, Gilbert and Shallice attribute the effects associated with carryover of task-set to extended response selection processes because these are the units which are weighted according to the activation of the task demand units.

Meiran and colleagues (Meiran, 2000; Meiran, Kessler & Adi-Japha, 2008) propose a modelling framework which explicitly divides task-set into two distinct components: the first (S-Set) processes representations of physical stimulus attributes to obtain the category of the stimulus (e.g., high/low or odd/even); the second ('R-Set') maps the stimulus category to a response (e.g., odd→left or high→left). Task-set control is exercised by re-weighting the potential categories in the S-Set (e.g., activating high/low relative to odd/even) and the potential mappings in the R-Set (e.g., high→left and low→right activated relative to odd→left and even→right, essentially changing the meaning of the responses). But these two re-weightings occur at different times. The original model (Meiran, 2000) assumed that top-down resetting of the S-Set bias is sufficient on switch trials. Reweighting the response selection (R-Set) bias happens only later, as a consequence of generating one response. Hence perseveration of the R-Set parameter from the previous trial is the source of the residual switch cost. Thus, the switch cost is a result of both active reconfiguration of the S-Set bias (when this is not completed in advance of the stimulus) and passive carryover of the R-Set parameter which can also be modulated by executive control, but not in advance of the stimulus. The model also explains the RISC effect (if there is no time to bias S-Set before stimulus onset, then it must be done after) and the effect of response congruency (R-Set weightings do not completely suppress the irrelevant response meanings, and they are

more active on switch trials because the R-Set weighting has not yet been changed). Meiran describes the model as fitting “reasonably well” with these common task switching effects, but admits that the fit may be unaffected by which set is actively reconfigured and which is prone to perseveration or their relative order.

More recently, Meiran, Kessler & Adi-Japha (2008) tested several instantiations of another model based on a similar architecture – CARIS (control of action representation and input selection). They report that the best fit to experimental data is with a hybrid model which assumes that biasing of action representations can be performed in advance of the stimulus if preparation time permits (i.e., selection of the appropriate S-R rule can be actively prepared in advance of the stimulus) while input selection cannot (i.e., attentional selection of relevant stimulus attributes cannot be reconfigured in advance of the stimulus and suffers from interference due to carryover from the preceding trial). Essentially, the other assumptions made by Meiran’s (2000) earlier model remain (control of task-set involves distinct S-Set and R-Set component processes which are reconfigured separately) but now S-R mappings (or response meanings) are reconfigured before the stimulus if preparation time is available and attention to a dimension is not. The reason for this reversal of the order in which component processes are reconfigured can be found in two intervening reports by Meiran. Meiran and Marciano (2002) presented participants with composite stimuli which could differ on four dimensions (shape, fill, size and the orientation of a line struck through the shape). The task was to make a same/different judgement with a shift between three possible components: perceptual (shape vs. fill), task-rules (same vs. different) or responses (yes-no vs. no-yes response mappings). They did not find a RISC effect when participants switched between perceptual processes (suggesting that they cannot be reconfigured in advance of the stimulus), but did find that preparation reduced the switch cost when the relevant dimension stayed the same but the task-rules or

response categories changed (suggesting that these processes can be reconfigured in advance of the stimulus). Meiran, Hommel, Bibi and Lev (2002) used the same stimulus set, but only presented one item at a time and participants were required to classify the stimulus according to the cued task (dimension). They found a RISC effect when the relevant dimension (and therefore the meaning of the responses) changed. Thus, although (at least part of) the other components can benefit from advance preparation, when attentional demands are high (such as in Meiran and Marciano's same/different task), attentional selection of perceptual attributes cannot.

Like Gilbert and Shallice (2002), Logan and Gordon's (2001) computational model of task-set control (executive control theory of visual attention; ECTVA) incorporates top-down control modules into an existing model of attention control (Bundesen's, 1990, theory of visual attention, TVA). Like Meiran, Logan and Gordon also assume that shifting between task-sets involves updating two distinct components (e.g., a perceptual module, whose processing is determined by top-down adjustment of attentional parameters in a way described by TVA, and a random-walk exemplar-based decision module that applies particular mappings of a stimulus category to a response). But rather than being controlled in a serial order at distinct times (as in CARIS), task-set parameters are transmitted to both modules from a WM module simultaneously, to bias the likelihood that one stimulus attribute will be selected over another, the likelihood that one response will be selected over another and the extent to which the speed of reaching an appropriate decision is prioritised over its accuracy. The model was really developed to account for the PRP dual-task effect, but Logan and Gordon speculate that task-switching costs could also be explained in part by the time taken to transmit these parameters from WM to the perceptual and decision modules. Their assumption of parallel unlimited transmission predicts that switch costs should be greater the more parameters need to be changed (cf. the Kieffaber et al., 2013, finding above), but no

assumption is made that some parameters can or cannot be changed in advance of the stimulus.

More recent models of task-set control (excluding Meiran et al., 2008) either fail to address the control of attentional selection of stimulus attributes (e.g., Altmann & Gray, 2008) or carry over the assumptions of one of the models already described. For example Brown, Reynolds and Braver's (2007) model of executive control in task switching adds a stimulus incongruity (conflict) detector module and a change detection module (which monitors for response repetitions) to a model with a similar architecture to Cohen et al.'s. The main purpose of the conflict detector is to enhance activation of the currently relevant task-set when an incongruent stimulus is observed. Thus, attention is directed towards the currently relevant stimulus attribute and RTs (and the switch cost) can be modulated via the hidden 'plan' module which codes S-R rules in much the same way as the hidden units in Cohen et al.'s model. Another by-product of this enhanced activation of task-set is that, on the subsequent trial, performance is speeded if the task repeats or slowed if the task switches. Brown et al. attribute this to carryover of task-set weightings due to attention being directed towards the relevant stimulus attribute via the incongruity detector module. This notion is echoed by Goshke's (2000) 'selection-orienting dilemma' which broadly states that attention should be flexible enough to be directed towards immediately important information necessary to control current behaviour while allowing irrelevant information to be processed sufficiently to override behaviour if it is deemed necessary (e.g., the smell of gas should not be ignored while attending to the immediate goal of writing a thesis). Although the weighting of attentional parameters is not 'wired' into Brown et al.'s model explicitly, there is an implicit assumption made that attention control is bound to task-set.

In summary, some theoretical models do implement top-down control of attentional selection of perceptual information, whilst others assume it without explicit

implementation, but there remains some controversy over how/when it plays a part. Gilbert and Shallice (2002) assume that re-weighting the response units according to current task demands is equivalent to influencing attentional selection without any equivalent re-weighting of the input units. Meiran and colleagues (2000, 2008) assume that reconfiguring attentional selection and response selection parameters are distinct processes, but have changed their mind about which of these can be done in advance of the stimulus. Logan and Gordon (2001) assume that the parameters of perceptual processing and response selection modules are reset in parallel. Müller and colleagues' (1995, 1996) dimension weighting account also allows the application of top-down control at early (perceptual) stages of processing and their more recent multiple weighting systems hypothesis (e.g., Rangelov et al., 2012) extends this to assume that all stages of processing are accessible to top-down control. This idea has been expressed neurobiologically by Desimone and Duncan (1995) and arguably dates back to Treisman (1969) who suggested that attentional selection happens at multiple levels of processing (though she assumed a pre-attentive processing stage which was inaccessible to top-down control).

Using eye-tracking to study attention control in task switching.

The main aim of the experiments documented in this thesis was to use eye-tracking to study the dynamics of attention in task-switching. I will conclude this introductory chapter by describing the (only) two prior studies that have used eye-tracking for this purpose¹ and provide the immediate context for the experimental chapters that follow. The project for my Masters thesis (Longman, Lavric & Monsell, 2013) was the first to use eye-tracking as a measure of spatial attention per se when switching between tasks associated with different locations. There is also a study by

¹ There is also a line of research that has examined switching between pro- and anti-saccade tasks (Hunt & Klein, 2002; Hodgson, Golding, Molyva, Rosenthal & Kennard, 2004) but this is using saccades as a response modality rather than to track attention.

Mayr, Kuhns and Rieter (2013) who used eye-tracking to monitor the consequences of a switch between perceptual dimensions in what is essentially a visual search task.

Before I discuss these two studies, I will briefly review some of the terminology used, some basic principles of, and some more complex issues associated with, the use of eye-tracking as a measure of attention. In addition to describing the cognitive processes which may influence the measures gained from eye-tracking, a pertinent question is: how accurately do eye-movements reflect visual attention?

Eye-tracking as a measure of attention. Researchers have been measuring eye movements for over a century, but modern eye-tracking devices offer spatial and temporal acuities that provide detailed information on *where* participants are looking in a display and *when* they look there (see Liversedge & Findlay, 2000; Rayner, 1998, and Rayner, 2009, for reviews).

Eye movements are typically categorised as either ‘saccades’ or ‘pursuit’. Saccades are fast eye movements between locations while pursuit movements are much slower and are used when following the trajectory of a moving object. The eyes move so quickly during a saccade (a 5° movement typical of scene perception usually lasts ~50 ms) that we are effectively blind until we fixate an object or location. Fixations typically last around 250 ms but their duration does vary considerably with more complex tasks. The term ‘fixation’ is somewhat of a misnomer since the eyes never actually stop moving. During a fixation the eyes are prone to ‘drift’ and also make tiny movements (‘microsaccades’ or ‘nystagma’) which are thought to maintain activity in retinal cells which are sensitive to change rather than absolute luminance values. The retina is typically, if slightly arbitrarily, divided into three regions: the fovea (a dense cluster of cells at the centre of the retina with very high acuity and a diameter of roughly 1° of visual angle), the parafovea (an area surrounding the fovea with a diameter of roughly 5° of visual angle with moderate acuity) and the periphery (with a much less

dense clustering of cells which makes detail difficult to see, but detects motion and other changes enabling the fovea to be brought to bear). The purpose of most eye movements (see below for exceptions) is to ensure that the fovea is positioned in order to get the most detailed image of the region of highest interest or importance in the field of vision (sometimes called ‘foveation’).

Eye-tracking research uses various measures depending on the specific cognitive processes under investigation but tend to focus on measuring the location and the timing of fixations and saccades. The number of fixations within a pre-defined region and the proximity of fixation to a particular point or object (usually measured in degrees of visual angle) are typical measures of the extent to which a particular object or location has been targeted. ‘Dwell time’ is the total time spent fixating a particular item or region in a specified interval (excluding corrective saccades or irrelevant fixations) and can be used as a measure of the time spent processing information from that region relative to another. Some researchers use a total viewing time (the time from the start of the first fixation to the end of the last fixation within a particular region) rather than individual fixation dwell times because corrective saccades are often used to adjust the gaze position within a region. Saccade latencies (or ‘launch times’) are often used as a measure of the time required to initiate a saccade to a particular region, including saccade programming time. Although the time it takes to program a saccade is fairly consistent, some programs may be discarded before the saccade is initiated which requires a second saccade to be programmed. Saccade latencies are also influenced by the time spent fixating a particular object (complex information may take more time to process which delays initiation of the next saccade). Fixation latencies (or ‘landing time’ of the first fixation within a region) are used by some researchers as a form of ocular RT where a response is made by fixating a particular region, but this measure can also indicate the time at which a particular object is first viewed. Finally, saccade

trajectories are sometimes used to estimate the initial direction of eye movements or to investigate interference (or reprogramming) during a saccade (i.e., warping of a saccade path away from or towards a competing target).

Most of the time our gaze and our attention are directed at the same location, but it is possible to direct the eyes to one location ('overt attention') while attending to events in another ('covert attention'). For example it may be wise to avoid eye contact with an aggressive person while attending to their movements. There is a wealth of research on the coupling of overt and covert attention. This issue is beyond the scope of this thesis because the experiments described herein are such that the participants' eye movements were unconstrained and dissociation between overt and covert attention is unlikely, but I summarise briefly what is known about the relation between attention and fixation.

At one extreme, Rizzolatti, Riggio, Dascola and Umiltà (1987) proposed the Premotor Theory of Attention (PTA) which stipulates that attention is oriented towards a location only when a saccade program is ready to be executed (i.e., shifts of attention depend on oculomotor programming). This view is echoed by Deubel and Schneider (1984) who demonstrated that the object of a saccade is processed at the cost of the object of covert attention. They unambiguously cued the target of a saccade, but sometimes the discrimination item was presented at a different location. Discrimination was only above chance when the target of the saccade matched the location of the discrimination item. Although PTA offers some fairly strict ideas about the relationship between overt and covert attention, the idea that they are obligatorily linked is not an uncommon view. For example, Hoffman (1998) agrees with this view but reverses the control relationship suggesting that spatial attention directs eye movements and precedes them by 100-250 ms. This seems to be the presiding view in current research

with Liversedge and Findlay (2000) referring to the commonly used ‘rubber band’ analogy – covert attention moves first and ‘pulls’ the eyes after it.

An alternative view is that covert attention and eye movements are independent. Although advocates of this extreme view are rare, Corbetta (1998) demonstrated that, while spatial attention and eye movements share many cortical regions, there are also regions which are specific to each. This more modest view also has its supporters. For example Belopolski and Theeuwes (2009, 2012) propose an updated version of PTA which distinguishes between shifting and maintenance of attention. By asking participants to independently direct attention to one location while planning a saccade to another they were able to demonstrate that shifts of attention are obligatorily linked with programming of eye movements, but the programs can be suppressed in a very short time. This is consistent with the intuition that, although it is possible to direct covert attention without a saccade ensuing, maintaining that division for an extended period is difficult.

Although this debate is far from over, there does seem to be ample evidence that covert attention *usually* precedes eye movements within a very short timeframe unless eye movements are explicitly suppressed. This makes eye-tracking a suitable tool for measuring the dynamics of an attentional component of task-set (if the different tasks are associated with different locations) and how this component is affected by task switching. Because eye movements can be recorded throughout a trial it also provides a window into attentional orienting during the preparation interval and early in the latent interval between stimulus and response.

It is worth noting that although attention to objects, dimensions, features of a dimension and even other sensory modalities (e.g., sounds, tactile information) are also often associated with directing attention to a particular location in space, eye movement measures are particularly suited to the investigation of overt visual-spatial attention and

can be limited with regard to insights into situations where the items of interest are spatially coextensive (e.g., coloured shapes) or not easily distinguished by their spatial location alone (e.g., various classifications of a single digit). For this reason the experiments described in this thesis attempted to limit attentional processes to spatial attention alone. The only exception is Experiment 7 (Chapter 6) where I specifically wanted to quantify the relationship between spatial attention and attention to features.

Eye-tracking in task switching. Two recent studies have used eye-tracking to investigate the attentional component of task-set. Although there are some striking similarities between their conclusions, they both leave several questions unanswered and a certain ambiguity concerning interpretation of their results.

Mayr, Kuhns and Rieter (2013) presented participants with three vertical blue bars at the vertices of an imaginary equilateral triangle (the triangle could adopt one of four rotations on a given trial so each item could appear in twelve possible locations). On each trial, one bar had a different shade of blue to the others (the colour singleton) and one had a gap near the top or the bottom (the gap singleton). The tasks were to either classify the shade of the colour singleton (as light or dark blue) or the position of the gap on the gap singleton (as high or low). Hence switching tasks here requires a shift in the dimension (colour, form) on which the singleton is defined. Each stimulus was preceded by a central cue (two per task) stating which task to perform at a CSI of either 300 ms or 1000 ms. Fixations were analysed for a 700 ms window following stimulus onset as a measure of attentional selection of the task-relevant (or irrelevant) bar. Consistent with a reconfiguration model of task switching, Mayr et al. found that fixation of the task-relevant stimulus attribute was delayed on switch trials relative to repeats (by ~100ms) at the short CSI but this delay was not evident at the long CSI. However, fixating the irrelevant stimulus attribute (e.g., the colour singleton on gap-task trials) was more likely on switch trials than repeats at both the short and long CSIs

(albeit to a lesser extent on long CSI trials) suggesting some carryover of attentional settings from the previous trial which seems immune to preparation.

Mayr et al. also manipulated the probability of a task switch between participants (25%, 50% or 75%) and found that the attentional effects were much smaller when the probability of a switch was high. This finding is consistent with Monsell and Mizon's (2006) proposal that a high switch probability encourages participants to reconfigure before the cue is present in anticipation of a switch. With a short CSI this can result in an additional reconfiguration process being necessary during the response period on repeat trials. When the CSI is long, the cue is presented with ample time for this second reconfiguration to take place before stimulus onset.

Mayr et al. thus used eye-tracking as a measure of spatial attention to index delays and inertia in shifts of attention between non-spatial dimensions (colour and form). In contrast, Longman, Lavric and Monsell (2013) used eye-tracking as a measure of spatial attention per se in task-switching by linking stimulus attributes relevant to the two tasks to different and predictable locations. We presented participants with a photograph of one of four faces with one of four letters superimposed on the forehead. The tasks were to identify either the face or the letter by pressing one of four keys. An auditory cue presented either 200 ms or 800 ms before the stimulus informed the participant which task to perform. Eye movements were recorded from stimulus onset until response. Like Mayr et al., Longman et al. also found that selection of the task-relevant stimulus attribute was delayed on switch trials relative to repeats and that switching was associated with a tendency to misallocate attention to the previously relevant region (which we termed 'attentional inertia'²). Both of these effects were reduced, but not eliminated at the longer CSI. Additional analyses demonstrated

² This term might seem to imply a difficulty in moving attention from its current location. However, fixation on each trial started from a central location. So what we mean by this term is inertia in attentional parameters: a tendency to go from the starting location to the same task-relevant location as before.

that these effects were associated with the switch cost between (via correlation) and within (via RT distributional analysis) participants.

Both of these studies indicate that eye-tracking offers a direct window to investigate the dynamics of attention control in task switching at a high temporal resolution. They also provide some clear evidence that an attentional component of task-set seems to be a non-trivial contributor to the switch cost through both reconfiguration and carryover of attentional parameters relevant to the task.

Nonetheless, many questions remain unanswered and there are several limitations to the specific designs of these exploratory investigations which are discussed at length in the introduction to the first empirical chapter of this thesis (Chapter 2).

Overview of the thesis

Attentional set is a somewhat neglected component of task-set despite being included in several models of cognitive control. Direct experimental investigations of an attentional component of task-set are relatively scarce and have come to conflicting conclusions. Although it is possible to investigate attentional processes via behavioural indices (e.g., in the visual search paradigm) it would be illuminating to acquire an online measure of attentional selection during the preparation period and early stimulus selection stages. This can be done with a high temporal resolution in at least two ways: by recording brain potentials or eye movements. Although it is possible to investigate attentional selection via brain potentials (e.g., the N2pc component) recording eye movements would seem to offer a more direct and unambiguous measure of at least the spatial component of stimulus selection at an equal temporal resolution and with better spatial resolution (the N2pc component can indicate which hemifield is being attended but eye-tracking can easily indicate the target of attentional selection within 1° of visual angle). Two recent studies have used eye-tracking to investigate the dynamics of this

component in task switching and have reported that attentional selection of task-relevant stimulus attributes is delayed on switch trials relative to repeats (suggesting a non-trivial attentional component of task-set reconfiguration) and suffers a tendency to be misallocated to the previously relevant stimulus element (suggesting carryover of attentional settings). This thesis reports seven experiments that further systematically investigate the relationship between task-switching and spatial attention when tasks are associated with different display locations.

The starting point is the Longman et al. (2013) study reviewed above, which consistently associated two tasks to two locations within the stimulus array and used eye-tracking to monitor attentional dynamics during task switch and repeat trials. Chapters 2 and 3 are presented in the form of journal articles (one accepted, one to be submitted shortly) reporting four experiments in which shortcomings of that initial study are overcome and different ways of cueing the task and the location are compared. Three locations, equidistant from fixation, are now used, with a digit displayed in each location and each associated with a different binary classification task. Using three locations allows one, on switch trials, to distinguish a tendency to orient to the location appropriate for the previous task from a tendency to orient to any wrong location. In these experiments, unlike that of Longman et al. (2013), fixations are also monitored between cue and stimulus to assess preparatory orienting, and the CSI is varied over a greater range and number of values to capture the asymptote of the RISC function. In addition, Experiment 1 adds a key control condition to address the question of whether the attentional delays and inertia observed are associated with task switching or merely reflect the need to orient in different directions on successive trials; in this physically identical control condition just one task was performed throughout the experiment on the digit at the cued location. Experiments 2-4 and the task-switching condition of Experiment 1 differ in how the task is cued, specifically in the explicit or implicit

emphasis on orienting to a location versus preparing for a task; differences between them suggest that the location (or orientation) specification is coupled with other components of task set unless location is explicitly cued.

In Experiment 5, reported in Chapter 4, eye-tracking was combined with ERPs in order to investigate the relative timing of attentional selection and the task-set components indexed by the switch-related “late positivity” observed in ERPs during a long CSI.

The experiments in Chapters 5 and 6 further investigate the nature of attentional inertia. Experiment 6 (Chapter 5) asks whether it is possible to eliminate attentional inertia if participants are given ultimate control over the duration of the preparation interval. Experiment 7 (Chapter 6) brings a further change to the paradigm of Experiments 1-4 by displaying at each location items belonging to different perceptual categories (a digit, a letter, an object) and requiring decisions about features specific to those categories (parity, consonant/vowel, living/man-made). This then adds to the need to shift between locations and change the classification task the need to attend to different features; does this increase or decrease the attentional inertia previously observed?

Chapter 7 summarises the current findings and their theoretical implications and offers some directions for how to take this research further.

2

Attentional inertia and delayed orienting of spatial attention in task switching

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 behavioural 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 reaction time 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.

Introduction

Purposeful behaviour 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, 2008a, 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). 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, Muylaert, 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., colour 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 levels, and the perceptual selection parameter and S-R biasing parameter influence processing concurrently, as part of the same processing stage. 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 colour or shape of two coloured shapes and identify the symbols superimposed on it (e.g., respond via a key press 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 would 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 & 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 of 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 colours, 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

colour and location did or did not match the colour 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 colour.

Although switch costs were substantial, Lien et al. found no evidence of capture by the *previously* relevant colour 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 colour of the colour 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 (colour, form). A recent investigation in our laboratory (Longman, Lavric & Monsell, 2013) 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, in press) of prepared switching between processing the perceptual and lexical properties of a word stimulus (judging the symmetry of colours 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. (2013) 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., 2013) 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 may include any of the following: 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 by Longman et al. (2013) 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. (2013), 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. 2.1). 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 2.1, 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° of visual angle corresponds to ~1 cm on the monitor). 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 (defined below) where the digits would eventually appear (see Fig. 2.1). A task cue (one of the letters A, B, C, X, Y and Z, subtending 0.2° horizontally, 0.3° 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.

The stimulus comprised three different digits (each subtending 0.4° horizontally, 0.5° vertically), chosen from the set 2-9, displayed at three locations arranged in an equilateral triangle, 5° from each other and 2.7° 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.

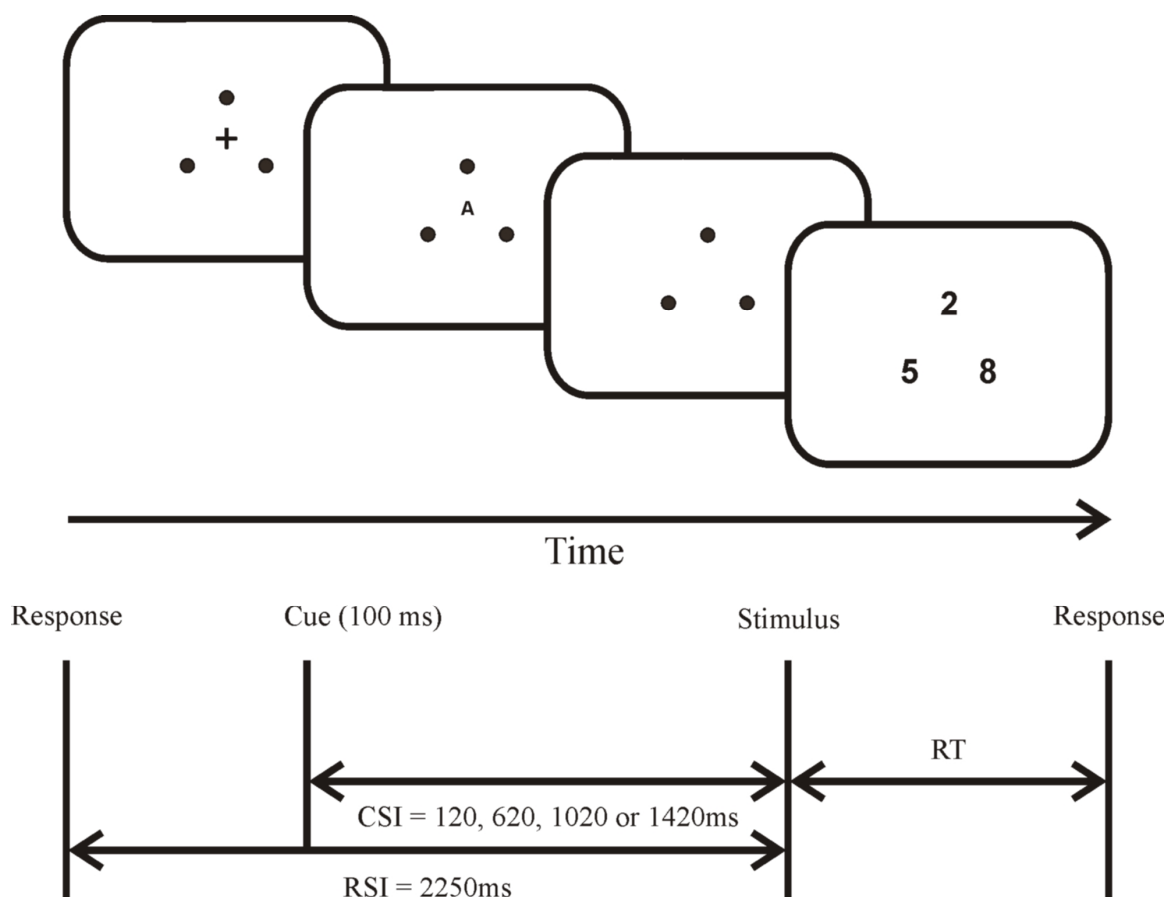


Figure 2.1. The time-course of one trial with example displays for Experiment 1. The dots used to identify where the digits would eventually appear were presented in light blue rather than black.

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°) 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 (Appendix 2).

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 2.2. 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 ± 8.7 ms) included 0, further indicating that it cannot 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).

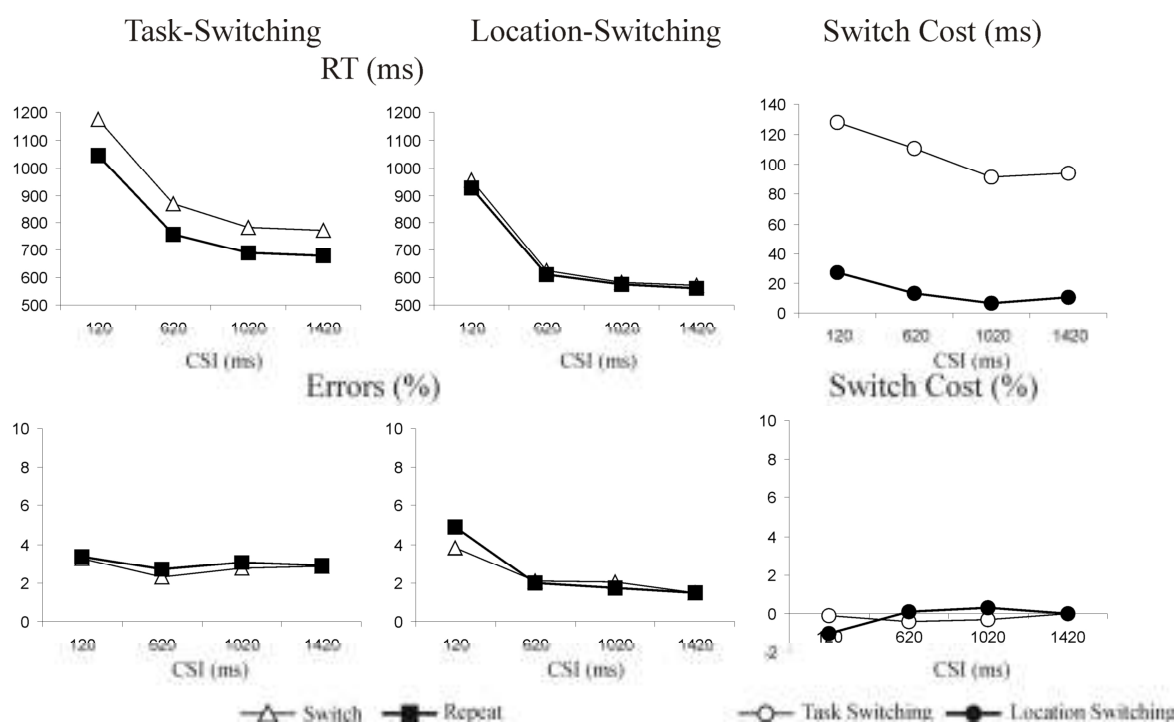


Figure 2.2. Behavioural data from Experiment 1: mean RT, error rate and switch costs (right), for the task-switching (left) and location-switching (middle) groups as a function of cue-stimulus interval (CSI) and transition (switch vs. repeat).

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%, for the odd/even task, RT=859 ms, errors=2.9%)¹.

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,

¹ The rather opaque interactions involving congruence and task in the RT analysis can be found in the Supplementary Materials (Appendix 2).

$F(1,23)=5.91$, $p=0.023$ (ABA responses 14 ms faster than CBA responses), an effect that interacted with increasing CSI, $F(3,69)=4.35$, $p=0.007$. Again, given 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 2.3 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 2.4 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. 2.3 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 interpolation², 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, $F(1,46)=11.49$, $p=0.001$ ³, 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, 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

² 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.

³ 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.

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. 2.4). 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. 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, $F(1,46)=6.76$, $p=0.012$).

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.).

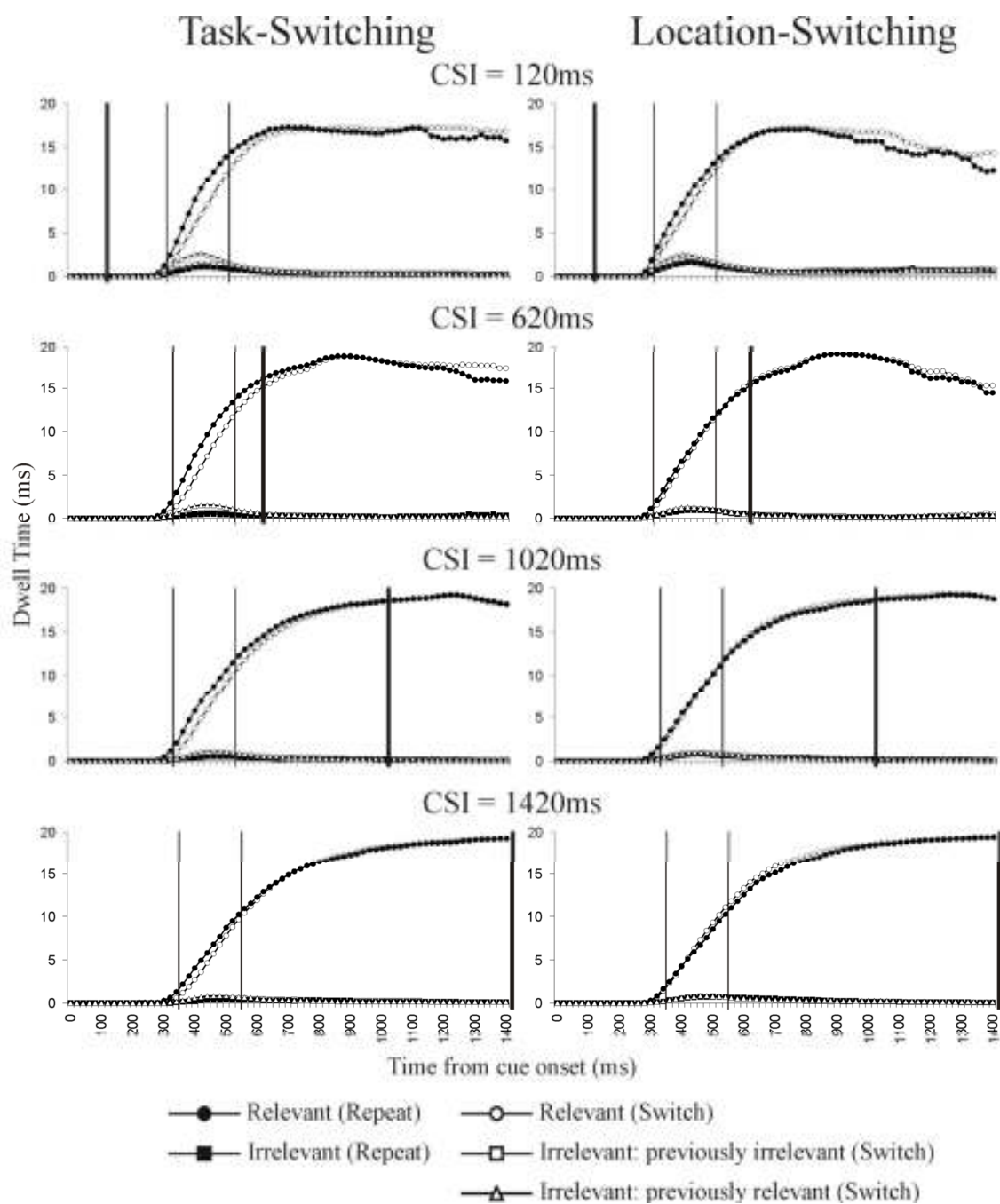


Figure 2.3. Dwell time (see text for definition) per 20 ms bin in Experiment 1 for 1420 ms following cue onset in the task-switching (left) and location-switching (right) groups as a function of CSI, transition (switch, repeat) and task-relevance of stimulus region. Thick vertical lines indicate the 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 2.4 makes them visible by amplifying the scale.

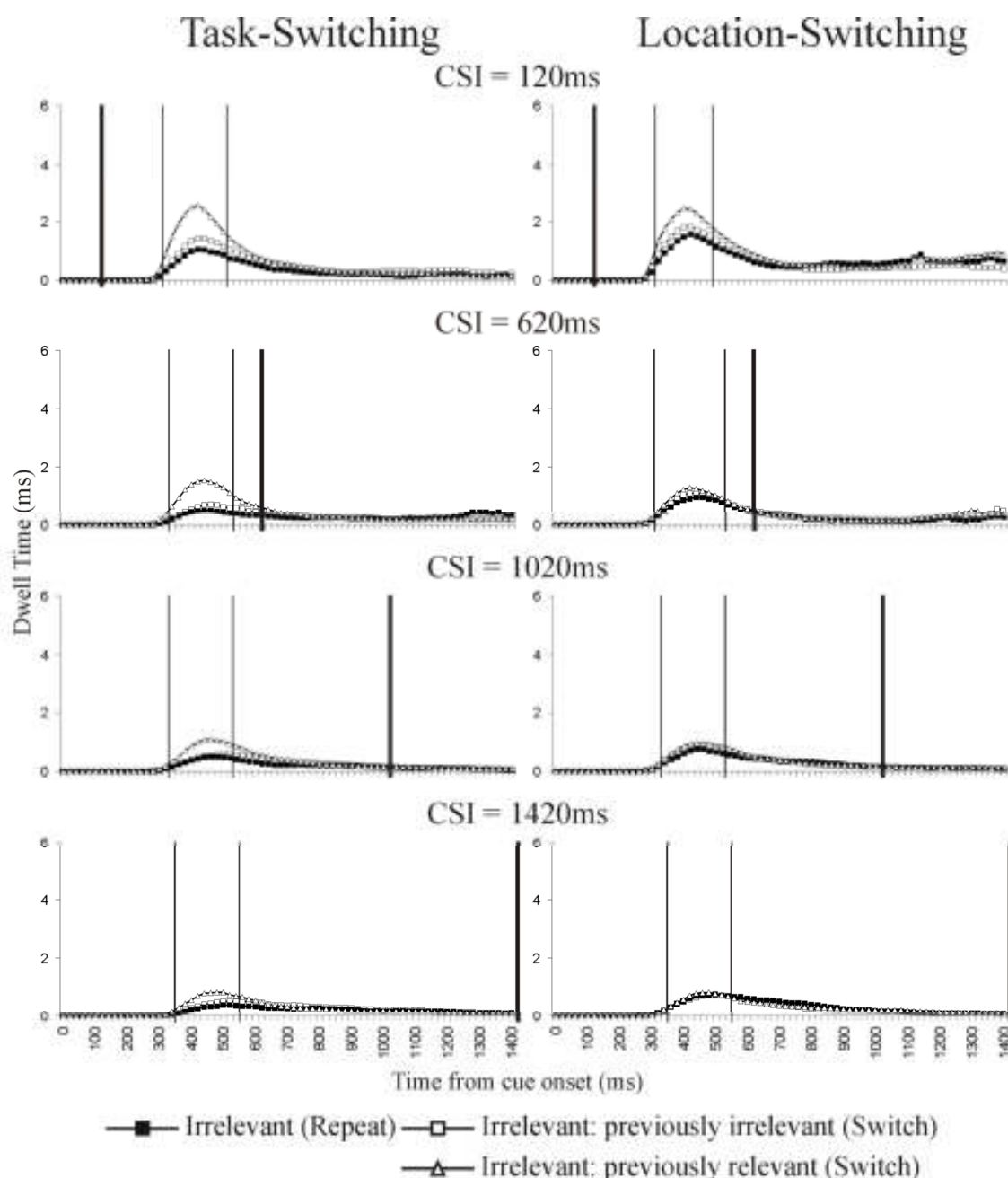


Figure 2.4. Dwell-time on the task-irrelevant regions in Experiment 1 plotted as in Figure 2.3 but re-scaled.

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 with 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.).

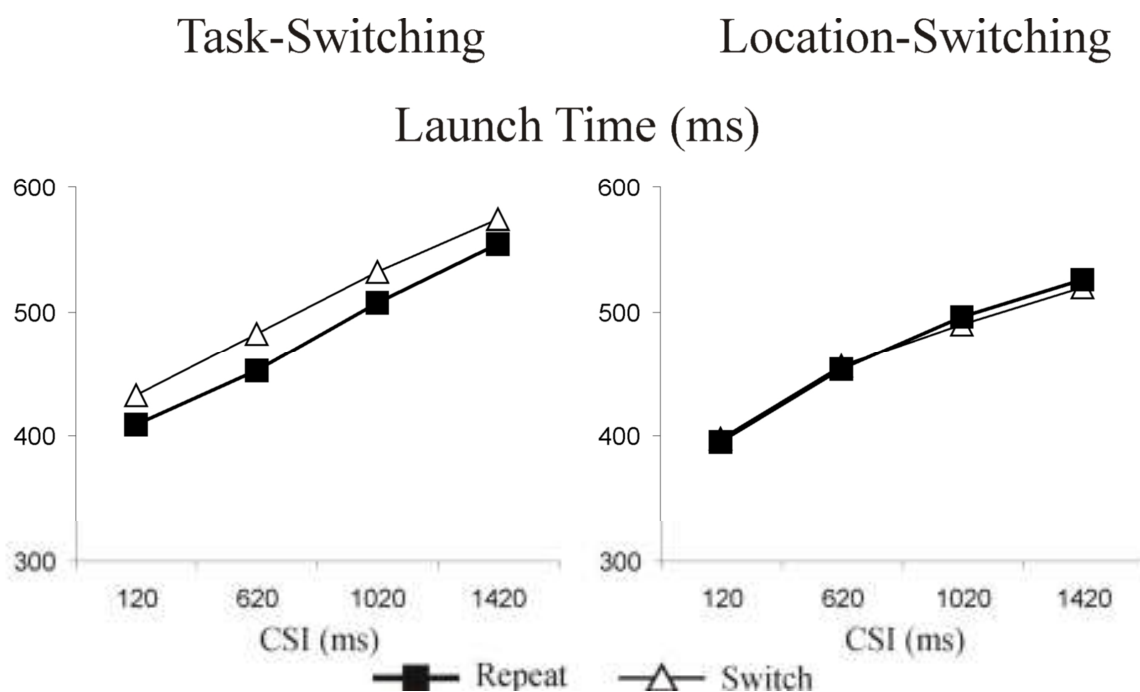


Figure 2.5. Mean ‘launch time’ of the first saccade to leave the cue and land directly in the currently relevant region for the task-switching (left) and location-switching (right) groups as a function of CSI and transition (Experiment 1).

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. 2.5): 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.

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. 2.3) 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. 2.4). 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 strong (and statistically reliable, see Results above) 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 2.1 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. 2.4). 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 2.1.

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

	CSI (ms)			
	120	620	1020	1420
Task switching:				
Previously relevant	19.7	12.6	8.5	6.7
Other	11.1	5.5	4.4	3.9
Average	15.4	9.1	6.5	5.3
Location switching:				
Previously relevant	20.2	10.3	8.1	6.7
Other	15.1	8.9	6.9	6.0
Average	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. 2.5). 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 signalled. 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 behavioural 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° horizontally, 0.3° 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 2.6. 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 ~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, 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 congruence⁴. 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

⁴ As for Experiment 1, the interactions involving congruence and task can be found in the Supplementary Materials (Appendix 2).

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%).

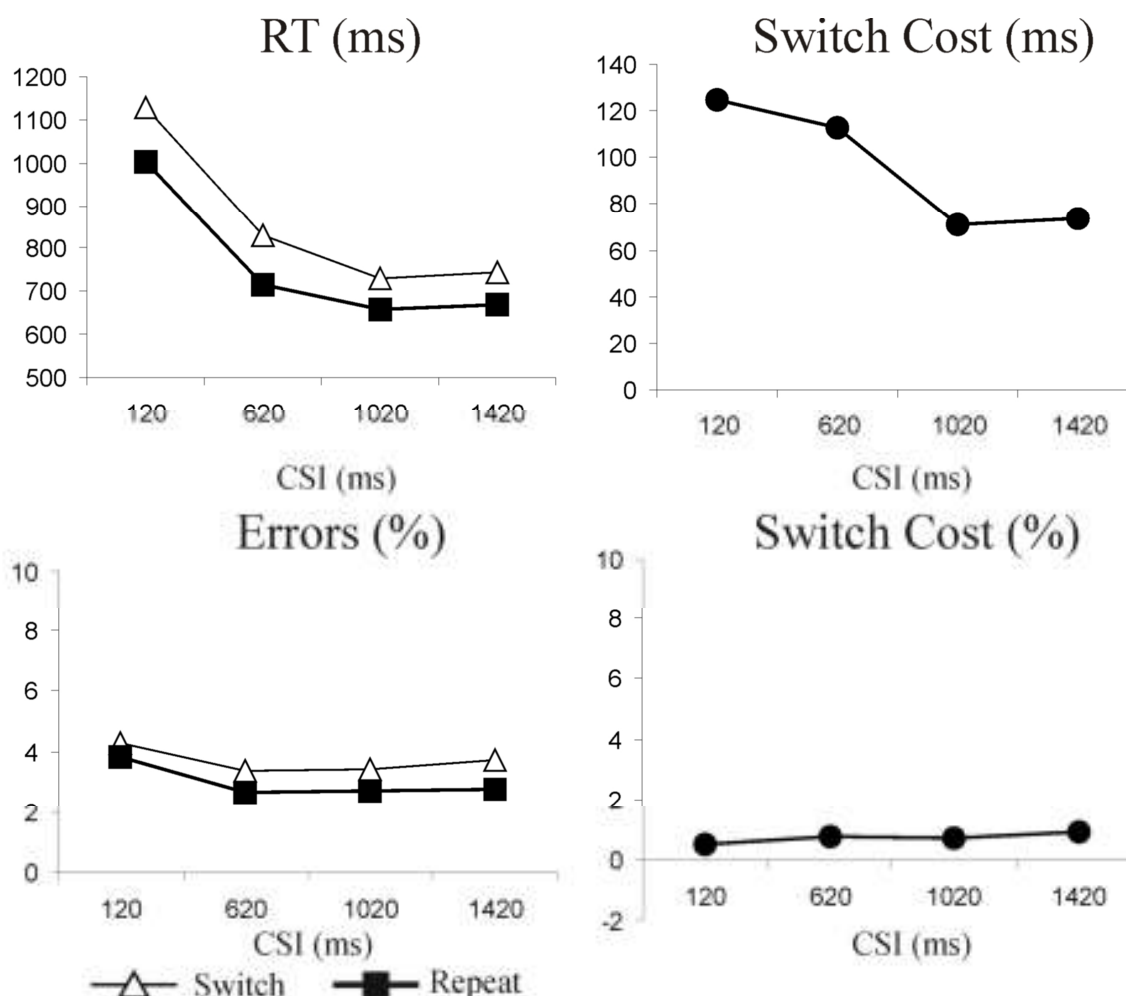


Figure 2.6. The mean RT, error rate and switch costs for Experiment 2 as a function of CSI and transition.

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 $F_s < 1$.

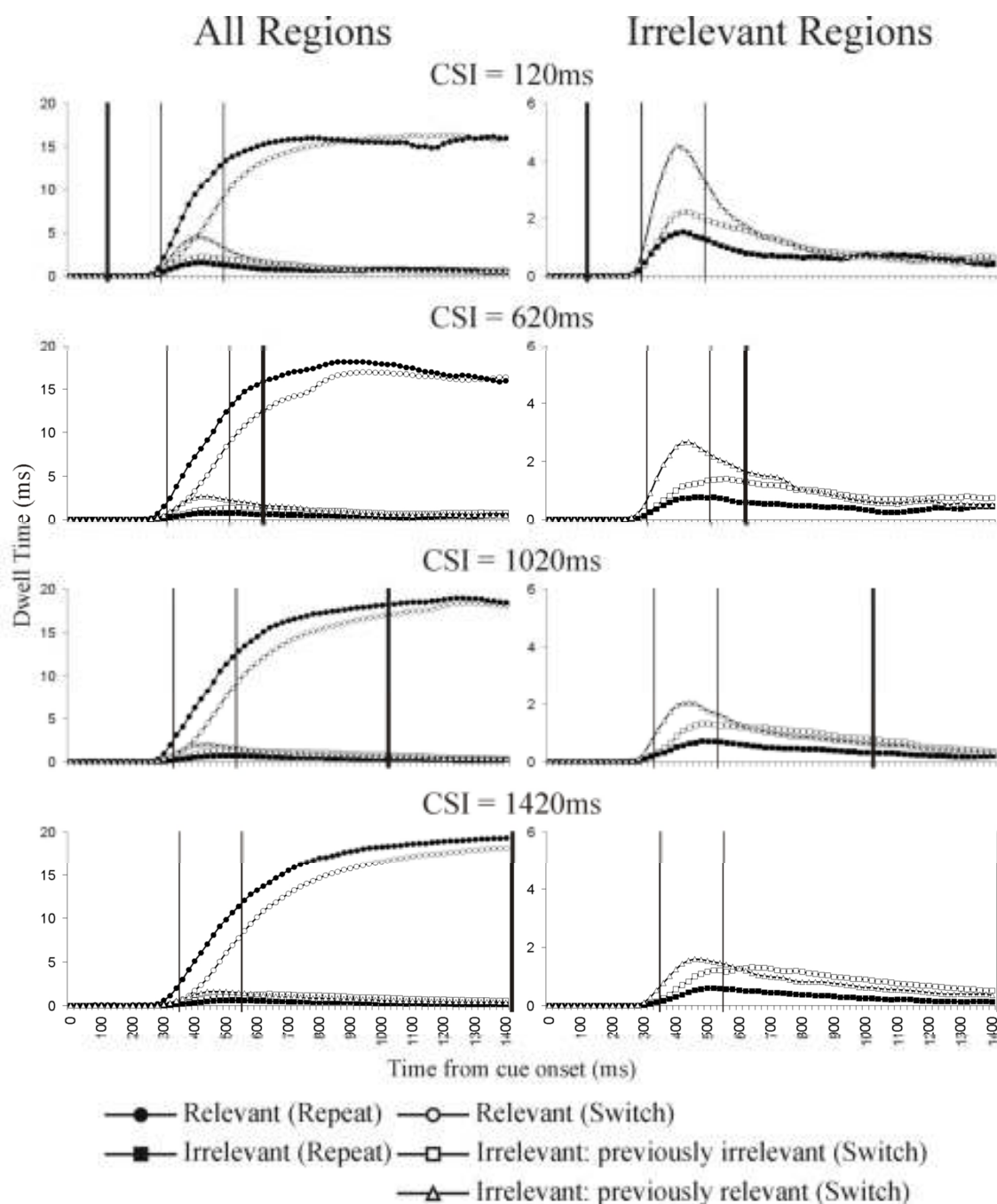


Figure 2.7. Dwell-time in Experiment 2, plotted as in Figures 2.3 and 2.4: the left panel shows the fixations on both the relevant and irrelevant regions, whereas the right panel shows only the fixations on the irrelevant regions (with the scale adjusted accordingly). Thick vertical lines show the onset of the stimulus and thin vertical lines the time-windows used for statistical analysis.

Eye-Tracking.

Dwell-time on the relevant region. Figure 2.7 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, $F<1$.

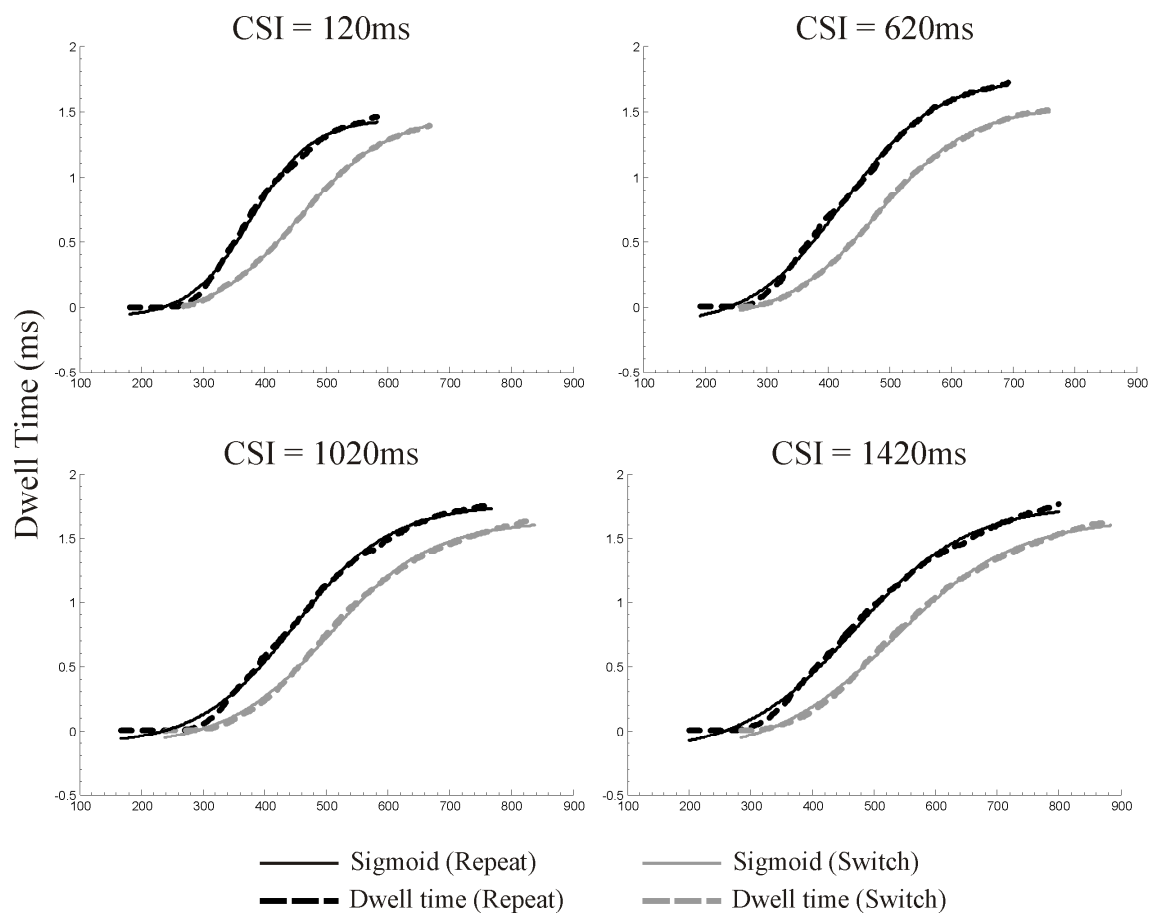


Figure 2.8. Illustration of the fitting of the sigmoidal function to high-rise portions of the dwell-time curves (averaged over participants) in the four CSIs.

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 2.7 suggests the former, but to test this formally we carried out a curve fitting procedure as follows.

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. 2.8) 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 2.2, 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 2.2.

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

	CSI (ms)			
	120	620	1020	1420
Time-shift (ms)	81	60	63	70
t-test	8.44, p<0.001	6.93, p<0.001	6.1, p<0.001	6.01, p<0.001
Slope change (%)	-45.6	-0.6	-6.4	-5.4
t-test	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 2.3) 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 2.3.

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

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

Note. The maximum dwell time in the critical time window for each CSI was 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. 2.7, 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, $F(1,23)=3.95$, $p=0.059$.

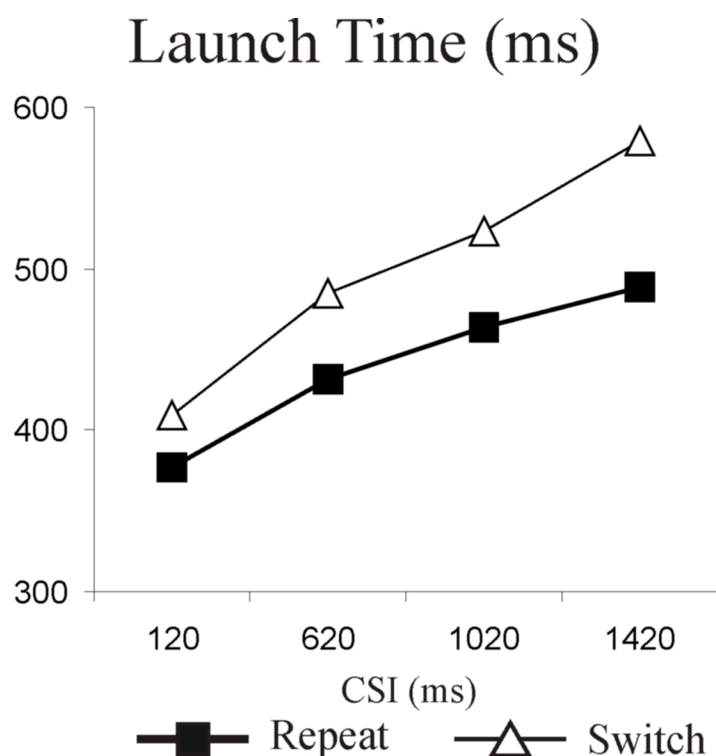


Figure 2.9. Mean ‘launch time’ of the first saccade to leave the cue and land directly in the currently relevant region as a function of CSI and transition (Experiment 2).

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. 2.9). 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 the previously (but no longer) relevant region is also a significant contributor to the switch-induced delay in arriving in the relevant region.

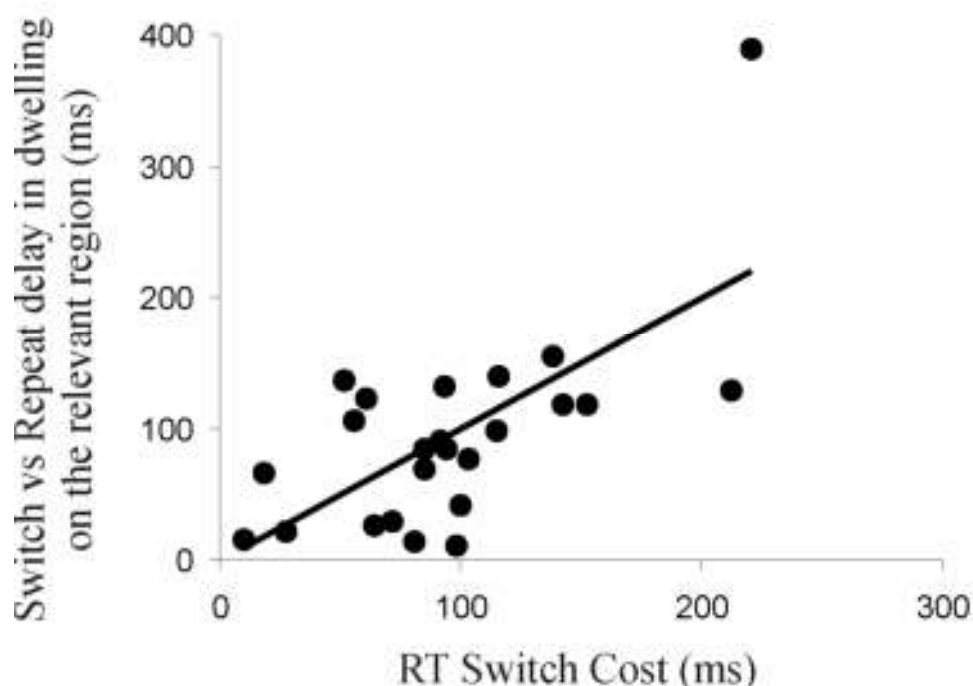


Figure 2.10. Correlation between the mean RT switch cost and the mean delay in fixating the currently relevant stimulus region within the 200-ms time-window used for analysis, see Figure 2.7 (Experiment 2).

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. 2.10), $r(22)=0.67$, $p<0.001$ (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 condition⁵ 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 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. 2.11, 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. 2.11, right panel) found that the strongest bias towards fixating the previously relevant region was on the trials from the slow RT tercile, and the weakest bias on the trials from the fast RT tercile (see Fig. 2.11, right panel); this interaction was also reliable, $F(2,46)=4.2$, $p=0.021$.

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

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, $F(1,46)=16.05$, $p<0.001$.

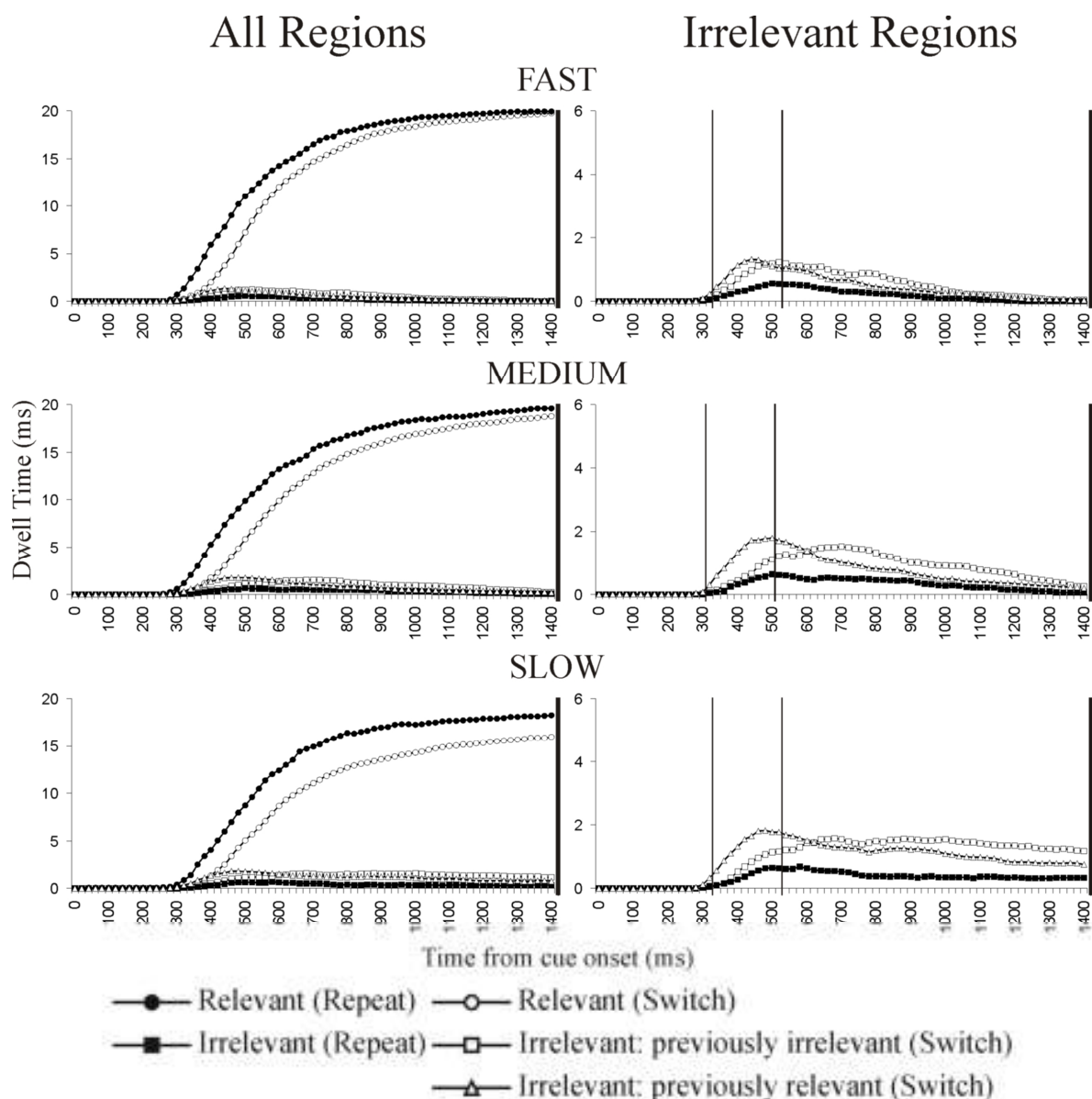


Figure 2.11. Mean dwell time plotted as in Figure 2.7 for the terciles with the fastest, slowest and intermediate responses for the CSI of 1420 ms (Experiment 2).

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 labelling 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, as 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., 2013). 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., 2013) 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)⁶. 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., 2013; 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

⁶ 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.

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. 2.3, left panel). In Experiment 2, which replaced the arbitrary letter cues of Experiment 1 with cues whose task-meaning was more transparent, this delay more than doubled (to ~60-90 ms; see Fig. 2.7, 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. 2.5 and Fig. 2.9). 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. (2013) 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. 2.4 and Fig. 2.7), 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 colour, so that switching tasks required attending to a different colour. It may be that the dynamics of spatial selection and feature selection (on the colour dimension) are different. However Mayr et al.’s (2013) study, discussed above has documented inertia of attention to dimensions of colour 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 (e.g., of the digit in the relevant colour), to enable identification of the target digit during the very brief stimulus display. This non-trivial

demand for speed of feature (colour) selection makes it likely that task selection may be postponed until after stimulus onset, especially if the cue refers transparently to colour rather than task (as was intended by Lien et al.'s use of cues that were the initial letters of the colour 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 labelling 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., 2013), our present Experiment 1 included a crucial control condition – one in which the same cues signalled the same change (or repetition) of location, but 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. (2013), 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 2.1 and Figure 2.4) 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 clear 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, Experiment 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.

Appendix 1 Chapter 2: 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. 2.8). 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 dwell-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 dwell-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 dwell-time curve, a further 24 dwell-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.

Appendix 2 Chapter 2: 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.

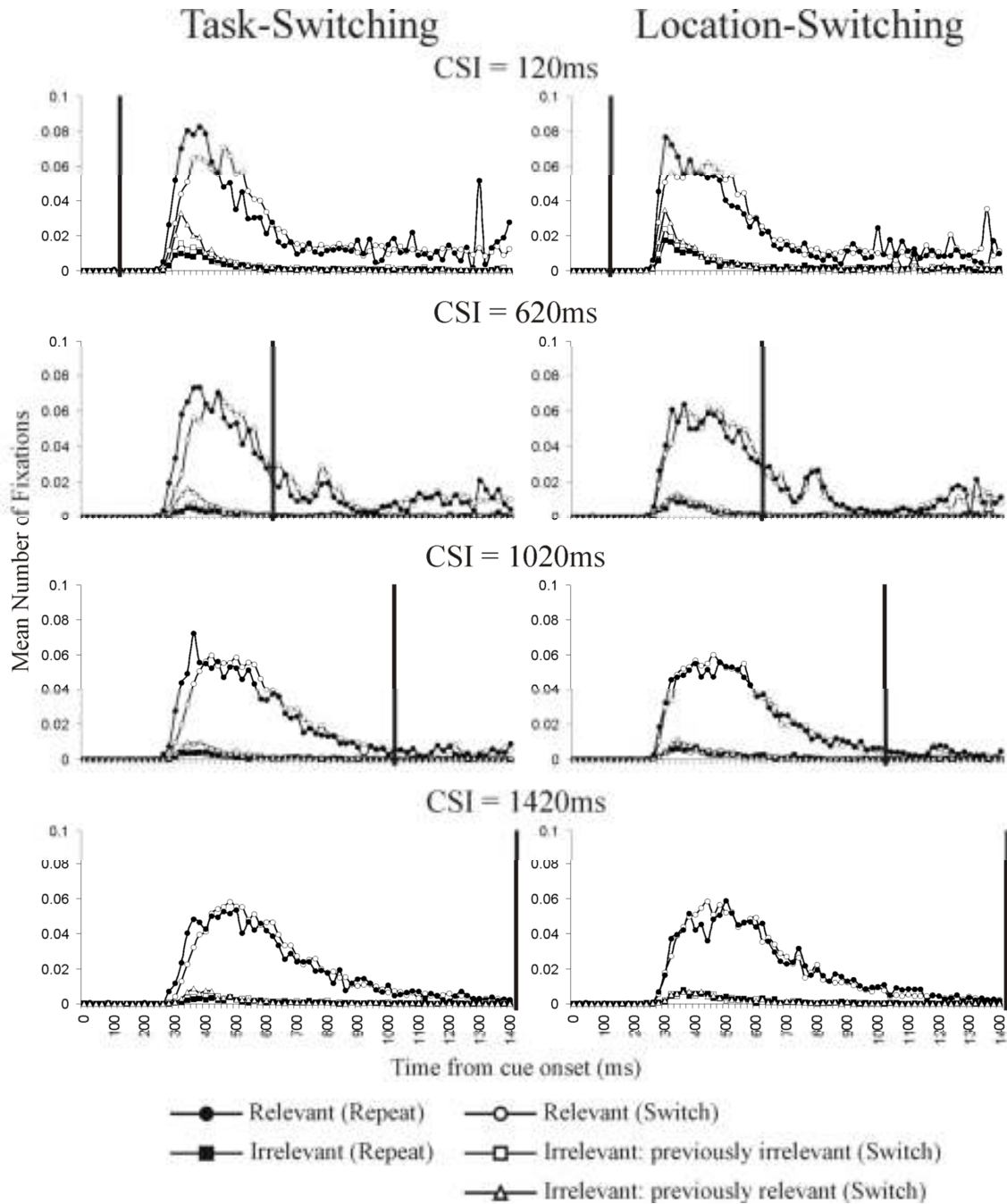


Figure S2.1. Mean number of fixations per 20 ms bin (averaging over trials, then over subjects) in Experiment 1 for 1420 ms following cue onset in the task-switching (left) and location-switching (right) groups as a function of CSI, transition (switch, repeat) and task-relevance of stimulus region. A 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.

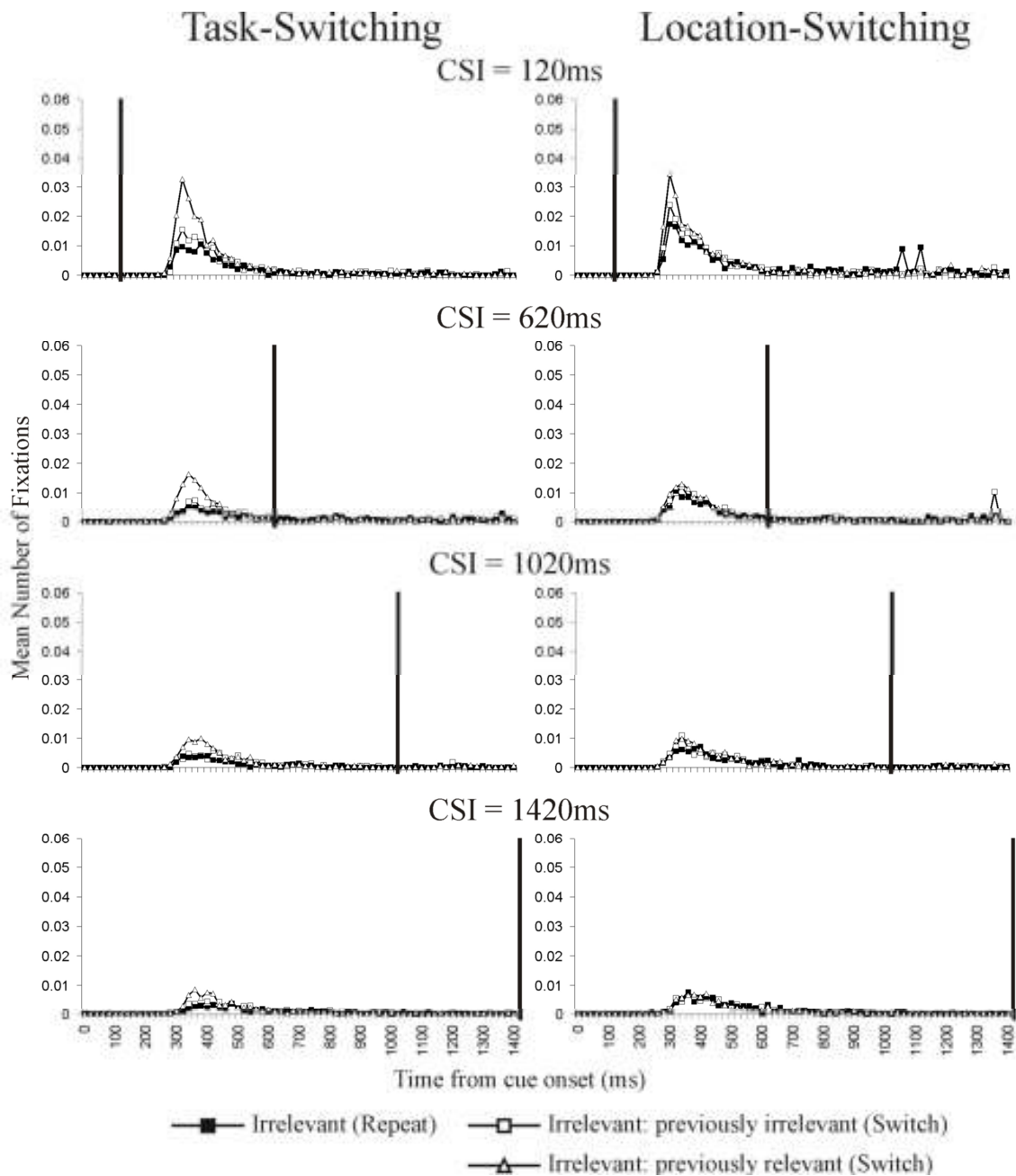


Figure S2.2. Mean number of fixations on the task-irrelevant regions in Experiment 1 plotted as in Figure S1, but with an amplified scale.

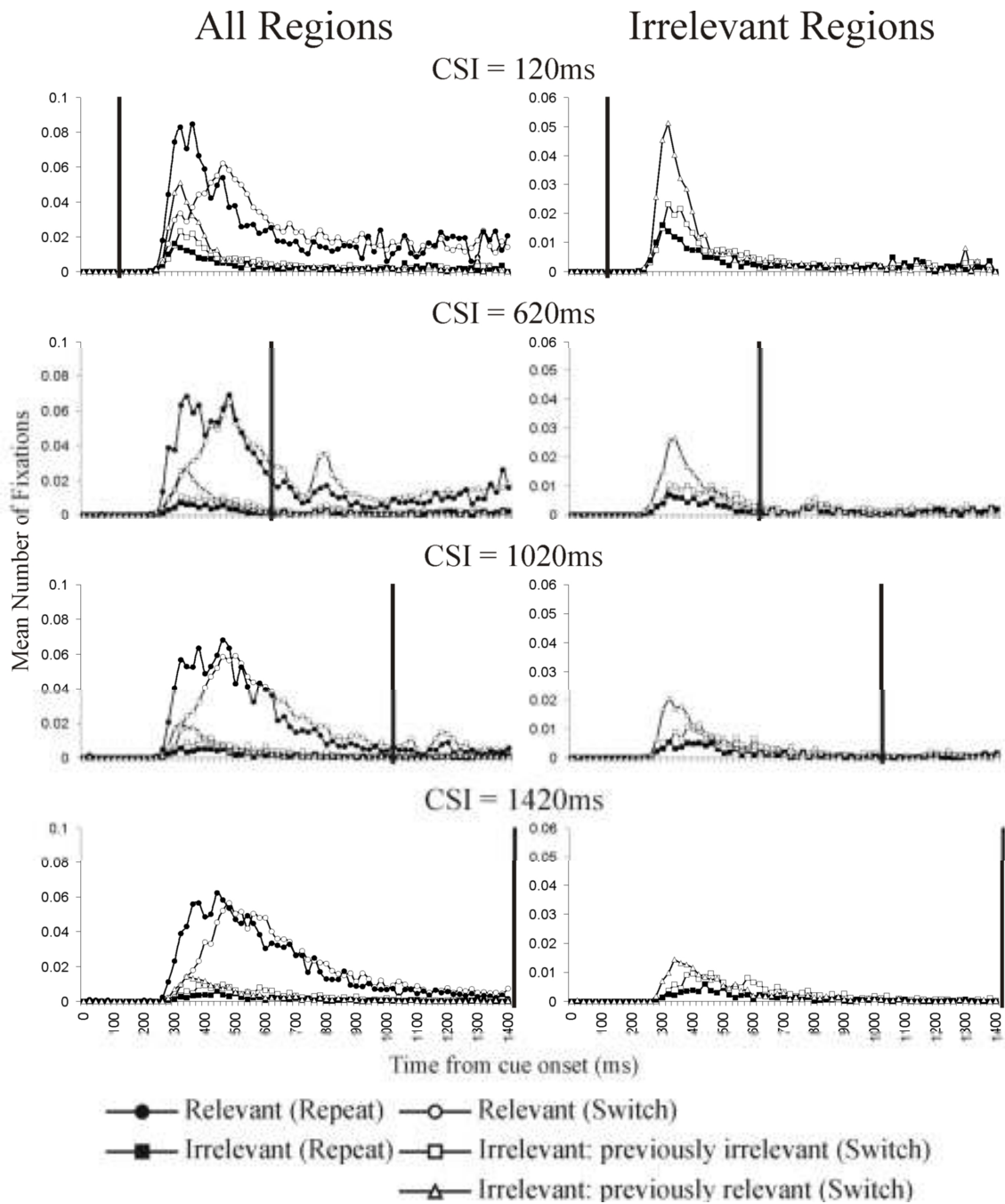


Figure S2.3. Mean number of fixations in Experiment 2, plotted as in Figures S1 and S2: the left panel shows the fixations on both the relevant and irrelevant regions, whereas the right panel shows only the fixations on the irrelevant regions (with the scale adjusted accordingly). Thick vertical lines show the onset of the stimulus.

3

Attentional set can be decoupled from task-set, but usually isn't.

Abstract

To what extent does inertia in attentional parameters contribute to the cost of switching between tasks? Using tasks associated with different spatial locations and eye-tracking, Longman, Lavric, Munteanu and Monsell (in press) found substantial delays in preparatory shifts of attention to the location required for the task and a tendency to orient to the previously relevant location; these attentional effects correlated with behavioural switch costs. They used either arbitrary task cues or cues that verbally labelled the classification task to be performed. The present experiments employed the same paradigm except the cues emphasized the relevant location rather than the task. In Experiment 3, with arrow or spatial adverb cues explicitly signalling the relevant location, the previously reported delay in orienting to the relevant stimulus element and 'attentional inertia' were both greatly reduced or eliminated, yet the behavioural cost of a task switch increased. Hence, with cues that prioritize orienting to the appropriate location, attentional and other aspects of task-set can become decoupled, but at a cost to the efficacy of task-set preparation. Experiment 4 used arbitrary cues but merely instructed participants that the cue indicated the location of the digit to be classified rather than the task. This more subtle association of the cue to location rather than task did not materially change the attentional delay and inertia observed by Longman et al. (in press, Experiment 1), suggesting that the more 'natural' tendency is for attentional set and task-set to be coupled.

Introduction

Changing tasks often requires, among other things, the re-setting of attentional parameters according to the specific needs of the new task: we may need to attend to a different location, dimension, feature or modality. Where attention has been recognised as a component of task-set, there is uncertainty over how (and the extent to which) the re-setting of such parameters contributes to the 'task switch cost' (e.g., Logan & Gordon, 2001; Meiran, 2000; Meiran, Kessler & Adi-Japha, 2008). Although several studies have investigated a shift of attention without a change in task-set (e.g., Chiu & Yantis, 2009; Found & Müller, 1996; Koch, Lawo, Fels & Vorländer, 2011; Rushworth, Passingham & Nobre, 2005) we focus here on the situation where a change of task requires a shift of attention and where a measure of attention is available to assess the extent to which attentional parameters display the same delays in orienting and carryover of settings from the previous trial commonly observed with other task-set components. The dynamics of attentional selection in such a situation have been the subject of several recent investigations. Of the four extensively reviewed here, three conclude that attentional selection is a significant contributor to the switch cost whilst the third concludes that it is not.

We start with the latter case. Lien, Ruthruff & Johnston (2010) incorporated a task switching condition into the contingent capture paradigm (Folk, Remington & 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 and concluded that carry-over of the attention set from the previous trial did not contribute to the relatively large task switch cost (137 ms) observed in their experiment, at least given sufficient time to (re)set attentional parameters (the 1200 ms between the task cue and the capture-cue).

A different conclusion was reached by Mayr, Kuhns and Rieter (2013), who investigated the dynamics of selection of perceptual dimensions using a 'task-cueing' paradigm (Meiran, 1996, Sudevan & Taylor, 1987). The stimulus contained three small blue vertical bars arranged in a triangle. One bar always differed from the others in its hue (the colour singleton) while another was always broken with a gap either above or below the midline (the gap singleton). A central cue (e.g. "color", or "gap") presented a variable interval before the stimulus indicated whether the participant should identify the shade of the colour singleton (light/dark) or the location of the gap (top/bottom) in the gap singleton. Eye movements recorded from stimulus onset showed that fixation of the currently relevant item was delayed on switch trials relative to repeats and there were numerous fixations on the previously relevant item during switch trials. Preparation reduced the extent of these effects, but neither was eliminated at the long cue-stimulus interval (CSI) of 1000 ms.

In two studies, we examined the dynamics of spatial attention when participants switched between tasks associated with different locations. Longman, Lavric & Monsell (2013) presented participants with a composite stimulus made of a photograph of a face with a letter superimposed onto its forehead and cued them to identify either the face or the letter. Eye movements recorded from stimulus onset demonstrated that switching between tasks was associated with fewer fixations on the currently relevant part of the stimulus and more fixations on the previously relevant part (e.g., on the letter during face task trials). These effects were also reduced with preparation but remained reliable at the longer CSI (800 ms).

In a more recent study (Longman, Lavric, Munteanu & Monsell, in press) henceforth referred to as LLMM, the stimulus consisted of three digits displayed at the corners of an imaginary equilateral triangle. In a task-switching condition a central cue preceding this stimulus instructed the participant to perform one of three binary classification tasks (odd/even, low/high, or inner/outer¹). Each task was consistently associated with one of the three digit locations, so that the cue specified both the location of the relevant digit and the task to be performed. Four cue-stimulus intervals (CSIs) were used to assess the impact of preparation on the cost of a task switch, and we monitored eye fixations between cue and response to index attentional orienting, including any preparatory shift to the relevant location and tendency to fixate the wrong digit. 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 so that the cue indicated only the location of the digit to classify.

¹ In the "inner/outer" classification task, the digits 2, 3, 8 and 9 are "outer", and 4, 5, 6 and 7 are "inner". Note that the response assignments in this, the odd/even and the low/high tasks are orthogonal.

In the task-switching condition, 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. We interpreted the latter effect as diagnostic of “attentional inertia” (i.e., persistence over trials in the parameters of the necessary orientation shift from the centre). Although the attentional inertia effect was reduced in conditions with longer preparation intervals, it was still significant at the longest CSIs (1020 ms, 1420 ms). 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. In the control condition with shifts in location but not task, a small delay in fixation and an “attentional inertia” effect were also found, but they were very much smaller, and eliminated at longer preparation intervals.

We concluded that the attentional effects found in our task-switching condition were due not merely to the persistence of a location “habit” or priming of low-level oculomotor processes but largely reflected the difficulty of resetting attentional parameters as a component of the relevant task-set. Hence, at least under these conditions, the resetting of attentional parameters was a significant contributor to task-switch costs.

Of course there were important differences among the paradigms used in the studies reviewed above. Our eye-tracking experiments (Longman et al., 2013, and LLMM) were expressly designed to track the dynamics of *spatial* attention. Mayr et al. (2013) instead used fixations to index shifts of attention between stimulus *dimensions* (colour, shape). Lien et al.’s (2010) paradigm measured the ease of shifting attention to *feature values* within the dimension of colour (i.e., a shift between red and green targets). One possibility is that that shifting attention between features of the same dimension is simply easier and makes a less detectable contribution to task-switch costs

than shifting attention between dimensions or spatial locations, but this seems unlikely as feature repetition has detectable effects in visual search experiments (e.g., Found & Müller, 1996). We suggest that the explanation for the different conclusions reached in the above studies is more likely to lie in the extent to which conditions encouraged attention to be coupled with, and accessed via, task-set.

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 preferentially attend to the relevant 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) coupled 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 the cues refer to the to-be-attended feature, not the classification rule (task). Under such conditions attentional selection might become decoupled from (and prioritised above) other task-set components (e.g., relevant categorisation, S-R rules) thereby maximising the resources available to re-set attentional selection parameters alone rather than doing so as part of a task-set – a conjecture consistent with the lack of attentional capture by previously relevant stimulus attributes.

The LLMM study provides some evidence that the nature of the task cue may determine the degree of coupling between attention and 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 transparent with regard to the classification task required (e.g., ‘ODD?’, ‘LOW?’, ‘INNER?’). This manipulation 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 effects in Experiment 1, with arbitrary cues suggest that the arbitrary task cues may have acted as location cues to some extent, thus prioritising orienting spatial attention and weakening the coupling between task-set and attentional set.

To test this speculation, in Experiment 3 of the present study we repeated exactly the task-switching condition used in both experiments of LLMM, but used a cue (an arrow or position label) that explicitly indicated the location of the relevant digit and only implicitly the task to be performed on it. We predicted that such a “pointing” cue would encourage participants to prioritise getting the attentional “spotlight” to the relevant location, decoupling that operation from reconfiguring other aspects of task-set, so that preparatory orienting would no longer be sensitive to whether the task to be performed was changing. A potential corollary of prioritising orientation to the relevant location is that other aspects of task-set would be less well prepared, leading to larger switch costs than under the conditions of LLMM.

Experiment 3

Experiment 3 encouraged the decoupling of spatial orientation from other aspects of task-set by using cues which explicitly direct attention to locations (arrows pointing to the locations and the words ‘TOP’, ‘LEFT’ and ‘RIGHT’). The instructions given to participants and the practice regime before testing also emphasised cue-location associations over cue-task associations whereas the LLMM study instructed participants that each cue specified one of three classification tasks and the initial task-

practice blocks used centrally presented digits, so that the association between task and location was introduced relatively late. In the present experiment, participants were told that the cues identified which of the three digits had to be classified; they first practiced one classification task at a time (e.g., odd vs. even) with three digits presented as in Figure 3.1 (thus the cue specified only the location) and were told only later that during testing each location would be associated with a different task.

Method

Participants. 24 students (15 female, mean age=19.29), from the same population as took part in LLMM, participated and were motivated in the same way: they received partial course credits and were paid up to a maximum of £3.60 for earning bonus 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 (zero curvature) 17" CRT monitor placed ~57 cm from the participants' eyes (at this distance 1° of visual angle corresponds to ~1 cm on the monitor). 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. 3.1). Either an arrow (subtending 0.2° horizontally, 0.3° vertically) 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 changed on every trial, thus unconfounding task switching and cue switching (cf. Logan & Bundesen, 2003; Monsell & Mizon, 2006). 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. In order 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: odd vs. even; low (2, 3, 4, 5) vs. high (6, 7, 8, 9); “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 generated 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 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.

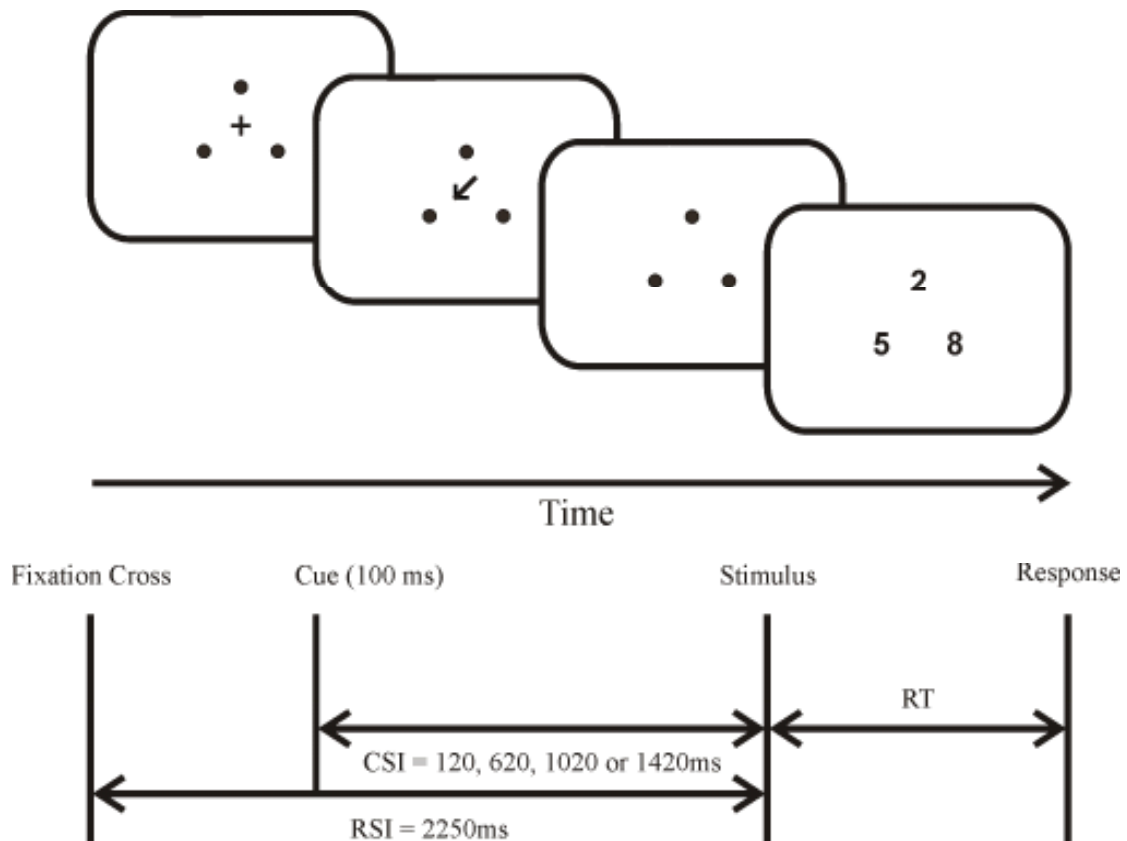


Figure 3.1. The time-course of one trial with example displays for Experiment 3. The dots used to identify where the digits would eventually appear were presented in light blue.

Before the eye-tracking session, participants practiced cue-location associations from the outset starting with three 8-trial 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 containing 'relevant' information for, the cue and each digit in the stimulus. On task-repeat trials, 94.24% of all fixations occurred within these regions; on task-switch trials, 93.99. No blocks needed to be discarded due to poor calibration. 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 analysed (as in LLMM) to obtain: (1) total dwell-time on each of the above-mentioned spatial regions of the stimulus within the critical 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. As in LLMM, fixation counts per time window were also analysed, but add nothing to the dwell time analysis, and are not reported here.

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

Results

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 3.2. A cue (arrow, word) by switch (switch, repeat) by CSI by task ANOVA on the RTs found a reliable main effect of switch, $F(1,23)=156.27$, $p<0.001$. Although the switch cost was reliable for both types of cue² ($F_{\text{arrow}}(1,23)=134.81$, $p<0.001$; $F_{\text{word}}(1,23)=150.59$, $p<0.001$) it was larger with arrow (180 ms) than with word cues (150 ms), $F(1,23)=10.45$, $p=0.004$. The reduction in switch cost with CSI did not interact with cue, $F(3,69)<1$, and the switch by CSI interaction was reliable for both sets of cues ($F_{\text{arrow}}(3,69)=7.53$, $p<0.001$; $F_{\text{word}}(3,69)=6.12$, $p=0.001$) 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

² 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.

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 sets of cues (CSI=1020 ms: $F_{\text{arrow}}(1,23)=56.90, p<0.001$; $F_{\text{word}}(1,23)=61.92, p<0.001$; CSI=1420 ms: $F_{\text{arrow}}(1,23)=43.52, p<0.001$; $F_{\text{word}}(1,23)=47.87, p<0.001$). There were also reliable interactions between task and switch, $F(2,46)=4.24, p=0.022$, and cue, task and switch, $F(2,46)=3.84, p=0.030$. Follow up ANOVAs found a reliable interaction between task and switch for the arrow cues, $F_{\text{arrow}}(2,46)=6.28, p=0.005$, 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, $F_{\text{word}}(2,46)<1$.

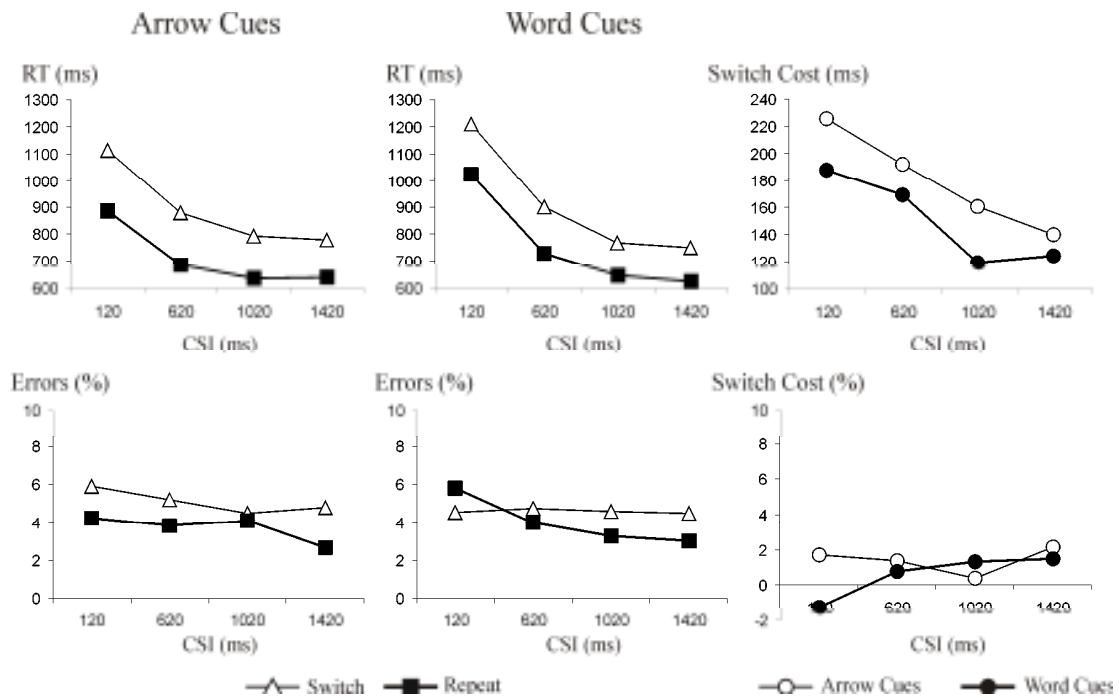


Figure 3.2. Behavioral data from task switch and repeat trials from Experiment 3 as a function of cue-stimulus interval (CSI). Left panels (arrow cues) and middle panels (word cues): mean RT (ms) above, error rate (%) below. Right panels: switch costs for RT above and error rates below.

There was a main effect of switch in the error analysis, $F(1,23)=3.13, p=0.033$, and although this did not interact with cue, $F(1,23)=2.52, n.s.$, a reliable switch cost was

found only for the arrow cues, $F_{\text{arrow}}(1,23)=5.55$, $p=0.027$; $F_{\text{word}}(1,23)=2.06$, 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 LLMM Experiment 2, in which the verbal cues explicitly labelled the task categories. The RT switch cost was much larger with location cues (167 ms) than with the task-label cues of LLMM (95 ms), $F(1,46)=17.81$, $p<0.001$. The interaction between switch, CSI and experiment was not reliable, $F(3,138)<1$, indicating a comparable reduction in switch cost with preparation time, 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: $F(1,46)=12.81$, $p=0.001$; CSI=1420 ms: $F(1,46)=7.67$, $p=0.008$. There were no reliable interactions involving the factor experiment in the error data.

Eye-tracking.

Average delay in fixating the relevant region. Figure 3.3 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 have also included the equivalent data from LLMM 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 the LLMM experiment, no equivalent delay in the present experiment is visible in the figure. The delay was estimated as in LLMM³ by curve fitting and estimating the average delay for a 100 ms window covering the early part of the rise in

³ For each participant a 10-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. 3.3 for time-window boundaries and LLMM for details.

dwell times on the relevant region. The resulting delay estimates were submitted to an ANOVA with the factors cue and CSI which revealed that the small switch-related delay in fixating the currently relevant region was smaller with arrow cues (6 ms) than with word cues (15 ms), $F(1,23)=5.07$, $p=0.034$. Neither the main effect of CSI, $F(1,23)<1$, nor the cue by CSI interaction was reliable, $F(3,69)<1$, indicating that the duration of the preparation interval did not affect 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) were not reliable for either set of cues (main effect of CSI: $F_{\text{arrow}}(3,69)<1$; $F_{\text{word}}(3,69)=1.59$, n.s.). T-tests performed for each CSI separately indicated that the estimated delay was reliable for the word cues in all but the longest CSI (in order of increasing CSI: $t_{\text{word}}(23)=3.25$, $p=0.004$; $t_{\text{word}}(23)=2.70$, $p=0.013$; $t_{\text{word}}(23)=2.79$, $p=0.010$; $t_{\text{word}}(23)=1.69$, $p=0.104$) and only approached significance for the arrow cues in the short CSIs (in order of increasing CSI: $t_{\text{arrow}}(23)=1.94$, $p=0.065$; $t_{\text{arrow}}(23)=1.83$, $p=0.081$; $t_{\text{arrow}}(23)<1$; $t_{\text{arrow}}(23)<1$).

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 LLMM Experiment 2 (88 ms) than with location cues (10 ms), $F(1,46)=42.37$, $p<0.001$. Neither the main effect of CSI, $F(3,138)<1$, nor the experiment by CSI interaction were reliable, $F(3,138)<1$. 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: $t(46)=5.88$, $p=0.019$; $t(46)=17.07$, $p<0.001$; $t(46)=34.31$, $p<0.001$; $t(46)=20.91$, $p<0.001$). 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.

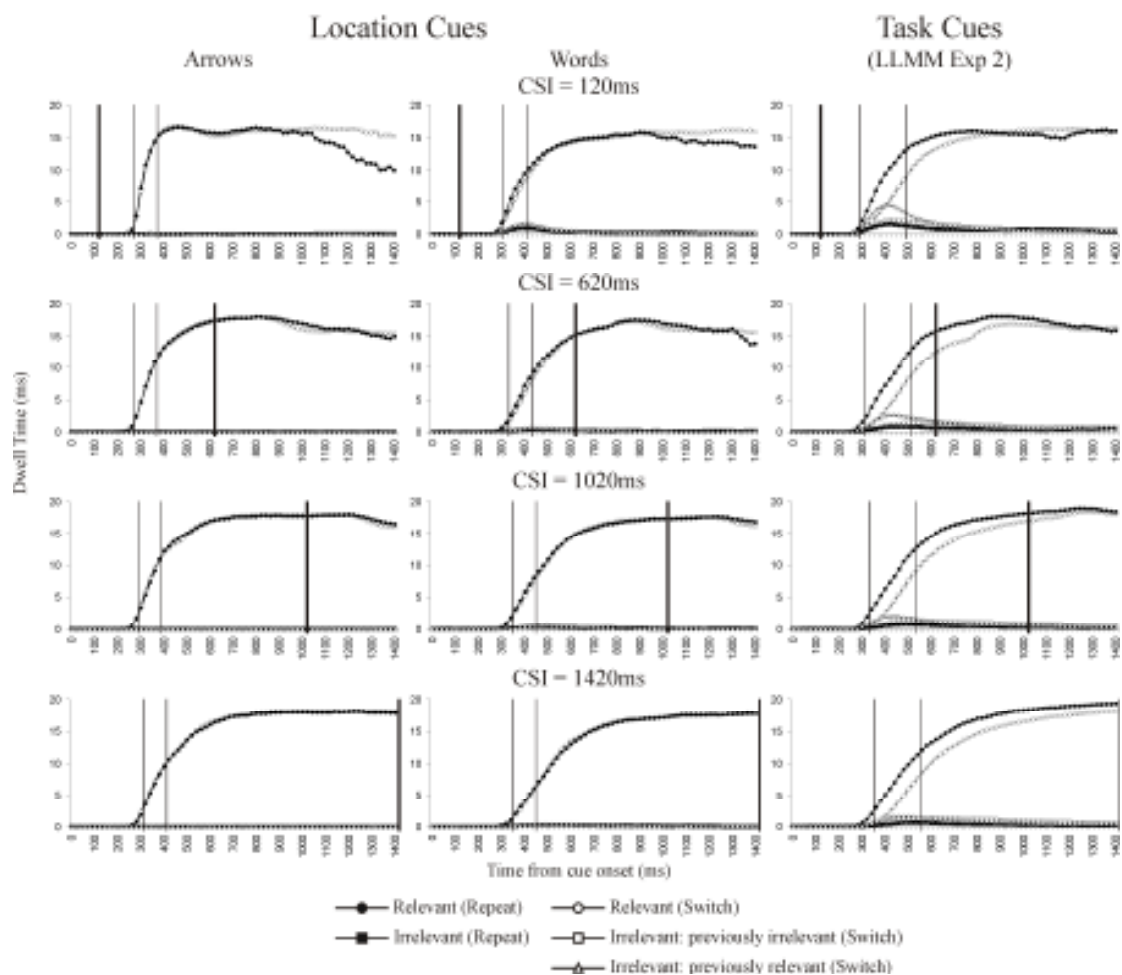


Figure 3.3. Dwell time per 20 ms bin in Experiment 3 (see text for definition) for 1420 ms following cue onset with arrow cues (left) and word cues (middle) as a function of CSI, transition (switch, repeat) and task-relevance of stimulus region. Thick vertical lines indicate the stimulus onset time, thin vertical lines show the time-windows used for statistical analysis of dwell time in the currently relevant region. The equivalent data from LLMM Experiment 2 have been included (right) for comparison.

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, switch, CSI and task (see Figure 3.4). The overall delay in launch times on switch trials relative to repeats was very small (3 ms for each cue) but not reliable, main effect of switch: $F(1,23) < 1$, nor were there any significant interactions involving the factor switch (all $F_s < 2$). This is in marked contrast with the delay of ~60

ms observed for launches of appropriately targeted saccades with task-labelling cues, and indeed the interaction is highly reliable in the between-experiment ANOVA $F(1,46)=62.58, p<0.001$, further confirming that the delay in appropriate orientation was much larger for explicit task cuing than spatial cuing. This switch by experiment interaction was reliable when tested separately at all CSIs (all F 's >20).

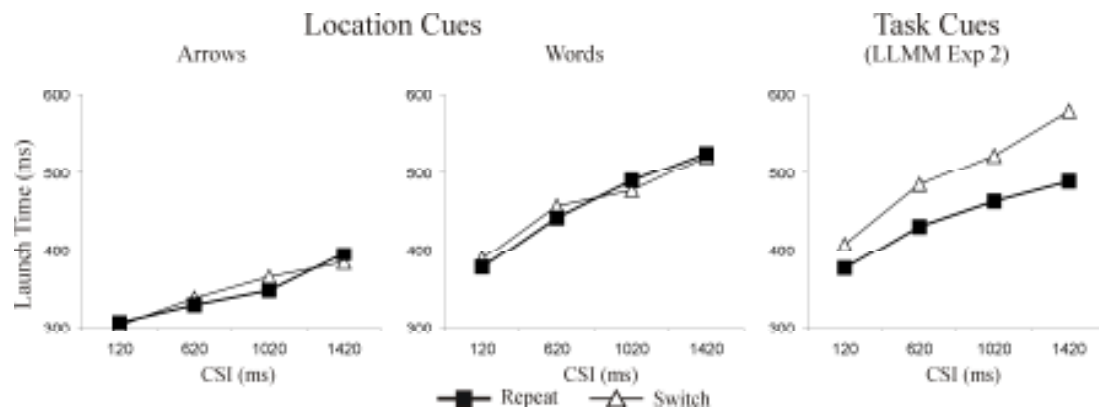


Figure 3.4. Mean 'launch time' of the first saccade to leave the cue and land directly in the currently relevant region for the arrow cues (left) and word cues (middle) as a function of CSI and transition (Experiment 3). The equivalent data from LLMM Experiment 2 have been included (right) for comparison.

'Attentional inertia'. The tendency observed in LLMM to fixate the irrelevant regions on switch trials more than on repeat trials was not detectable in the present experiment with location cues. An ANOVA on the dwell time in the irrelevant regions (note that the analysis window for irrelevant dwell time is 200 ms as in LLMM, see Figure 3.5) with factors cue, 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 confirmed these results, but there was a marginally reliable main effect of switch for the arrow cues, $F_{\text{arrow}}(1,23)=3.85, p=0.062$, with participants making slightly fewer irrelevant fixations on switch trials than repeats. Although the reverse was true for the word cues, this reversal was not reliable, $F_{\text{word}}(1,23)<1$.

The ANOVA performed for the dwell time on the irrelevant regions, for switch trials only, with the factors cue, CSI, task and relevance (previously relevant, previously irrelevant) found that the previously relevant region was preferentially fixated over the other irrelevant region (main effect of relevance: $F(1,23)=20.39$, $p<0.001$). This effect was reliable for both sets of cues ($F_{\text{arrow}}(1,23)=5.72$, $p=0.025$; $F_{\text{word}}(1,23)=19.35$, $p<0.001$) and the tendency to fixate the previously relevant region was larger with word cues than with arrow cues (cue by switch interaction: $F(1,23)=17.92$, $p<0.001$). Although attentional inertia reduced in conditions with longer preparation intervals for both cue types, $F(3,69)=5.85$, $p=0.002$, this reduction effect was more pronounced with word cues than with arrows ($F_{\text{arrow}}(3,69)=4.13$, $p=0.032$; $F_{\text{word}}(3,69)=4.78$, $p=0.008$; cue by relevance by CSI interaction: $F(3,69)=3.69$, $p=0.027$). 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, $F_{\text{word}}(1,23)=8.57$, $p=0.003$, but not at CSI=1420 ms, $F_{\text{word}}(1,23)=1.93$, n.s. For the arrow cues the dwell time in the currently irrelevant regions for switch trials was 0 ms at the 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: $F(1,46)=27.03$, $p<0.001$). The switch by CSI by experiment interaction was also reliable, $F(3,138)=6.38$, $p=0.001$, indicating that the interaction between switch and preparation interval was smaller with spatial cues (presumably because there were so few fixations on the irrelevant regions even at shorter CSIs), and a reliable switch by experiment interaction was found at each CSI (all $F's>18$). 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 (relevance by experiment interaction: $F(1,46)=12.44$, $p=0.001$). Although the modulation of the effect of previous relevance by CSI was larger with

explicit task-cues, $F(3,138)=7.91$, $p<0.001$ (relevance by CSI by experiment interaction), a reliable relevance by experiment interaction was found in all CSIs apart from CSI=1420 ms where it approached significance (CSI=120 ms: $F(1,46)=17.20$, $p<0.001$; CSI=620 ms: $F(1,46)=13.70$, $p=0.001$; CSI=1020 ms: $F(1,46)=6.02$, $p=0.018$; CSI=1420 ms: $F(1,46)=3.48$, $p=0.068$).

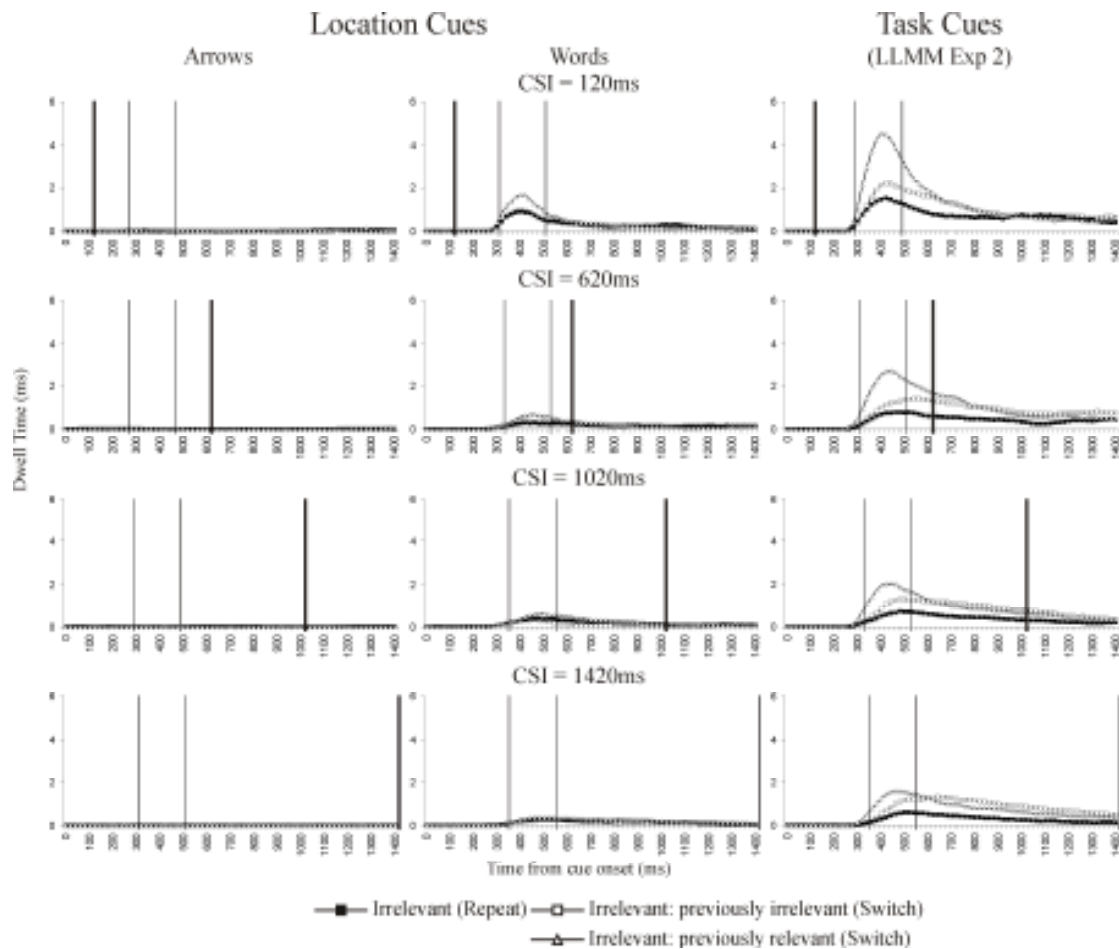


Figure 3.5. Dwell-time on the task-irrelevant regions in Experiment 3 plotted as in Figure 3.3, but with a larger scale. The equivalent data from LLMM Experiment 2 have been included (right) for comparison.

Discussion

In our previous experiments (Longman et al, 2013 and LLMM) tasks consistently associated with spatial locations were cued in such a way as to emphasize 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 spatial attention with other aspects of task-set reconfiguration. The aim of Experiment 3 was to investigate whether, when the nature of the cues and instructions encourage participants to prioritise 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 of the present experiments clearly support this notion. Cuing location-linked tasks with arrows pointing to, or words labelling, the locations, we found only very small delays in orientation to the relevant location on switch trials, and little evidence for “attentional inertia” (the tendency to fixate the previously relevant location on a switch trial) compared to the large effects observed in the LLMM 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. And this in turn may explain why Lien et al. (2010) found little evidence of attentional selection contributing to the effects of a task switch.

We were also interested in the idea that decoupling the spatial attention component of task-set by prioritising it would have the consequence that participants would not be so well prepared for a task switch at a longer CSI; their preparatory effort 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 as well as eliminating the attentional handicap associated with switching between tasks. Inasmuch as there was evidence of attentional inertia at the longer CSIs with location cues, it was largely limited to the word cues which possibly require greater interpretation than arrows when determining the location to which they refer.

Experiment 4

Experiment 3 established that, by cuing location explicitly, it is possible to decouple attentional set from task-set thereby inflating the switch cost and greatly reducing or eliminating the observed effects of a task switch on attention compared to a condition identical except that task rather than location was explicitly cued.

What about task cues which are initially associated with neither task nor location? In the LLMM study we found (Experiment 1) that such arbitrary cues (letters) were associated with somewhat reduced but still substantial task-switch-related attentional handicaps compared to cues which explicitly identify the task-set (Experiment 2). However, in both of those experiments the instructions and training regime were designed to encourage interpretation of cues as specifying tasks (rather than locations), see above. 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' (or default) tendency for attentional set and task-set is to be coupled or decoupled. To examine this possibility, in the next experiment we employed the task-switching condition from LLMM Experiment 1 with one critical difference. Rather than instructing participants that the arbitrary cues identify 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 same arbitrary cues identified which location is relevant and that a different classification rule should be used at each location throughout the experiment.

If the 'natural' tendency is for spatial attention to remain independent 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 with by LLMM Experiment 1, and we should see the same outcome as with the explicit location cues of the present Experiment 3. Conversely, if

this modification of the instruction/training does not largely eliminate the effects of a task-switch on spatial attention (delay and inertia) observed in LLMM Experiment 1, one would have to conclude that the more 'natural' relationship between attentional set and task-set is to be coupled at least to a degree.

Method

24 different students (18 female, mean age=19.17) received the same payment as in Experiment 3 for their participation. Participants were instructed that the cue (the letter 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 in each location should be classified with a different classification rule throughout the experiment. In all other respects the design of the experiment, practice session and instructions given were identical to Experiment 3.

The same square regions as in Experiment 3 were used for analysis. On repeat trials 94.45% of all fixations landed within these regions; 93.96% on switch trials. As in Experiment 3, blocks with >20% of trials containing no fixations in any of the three stimulus regions were omitted due to poor calibration. Two blocks in total (one block each from two participants) were discarded as a result of this precaution. 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 eye-tracking and RT analyses.

Results

RT and errors.

Arbitrary cues with location instructions. The mean RT and error rates, averaged across all three tasks are presented in Figure 3.6. A switch by CSI by task

ANOVA on the RTs found a reliable switch cost of 124 ms, $F(1,23)=70.92$, $p<0.001$ 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, $F(1,23)=47.37$, $p<0.001$; CSI=1420 ms: switch cost=116 ms, $F(1,23)=47.27$, $p<0.001$). There were no reliable effects or interactions involving the factor switch in the errors.

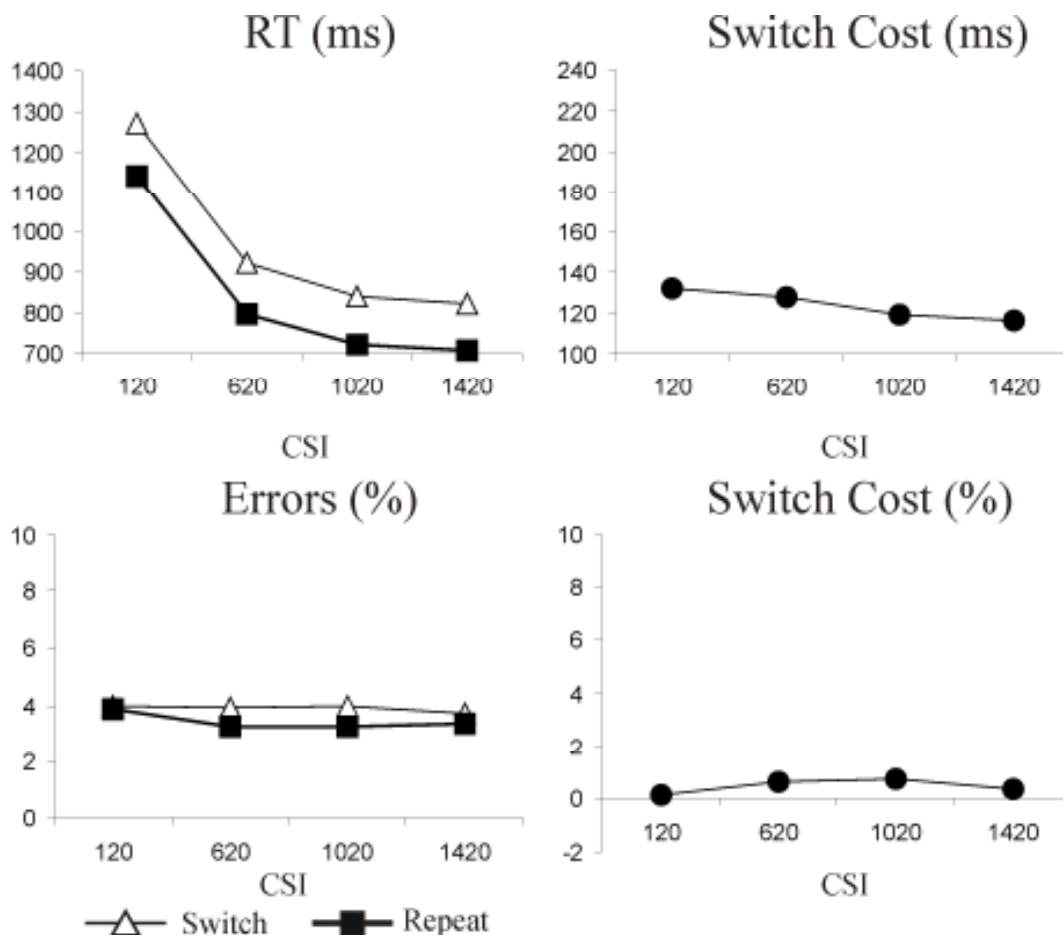


Figure 3.6. The mean RT, error rate and switch costs for Experiment 4 as a function of CSI and transition.

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 LLMM Experiment 1 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 ($F_s < 2$). The RISC effect for RTs was also slightly greater when participants were led to construe the cue as a task (rather than 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 failed to 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 3.7 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 estimated in the same way as for Experiment 3 (except due to a less steep rise of the curve, the analysis window was 200 ms as in LLMM). 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 whether the delay was reduced in conditions with longer preparation intervals found that the temporal separation was comparable in all CSIs, $F(3,69) < 1$.

The ANOVA on the estimated switch-induced delay with experiment as a between subjects factor (current experiment vs. the LLMM experiment with arbitrary cues) 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 analysed together, $F(3,138)=3.47$, $p=0.024$, indicating that the delay was reduced at longer preparation intervals; this effect did not 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, $F_s < 1$. With increasing CSI, the estimated delay

when participants were instructed that the cues referred to tasks vs. locations were: 43 ms vs. 33 ms, 42 ms vs. 34 ms, 33 ms vs. 27 ms, 22 ms vs. 26 ms.

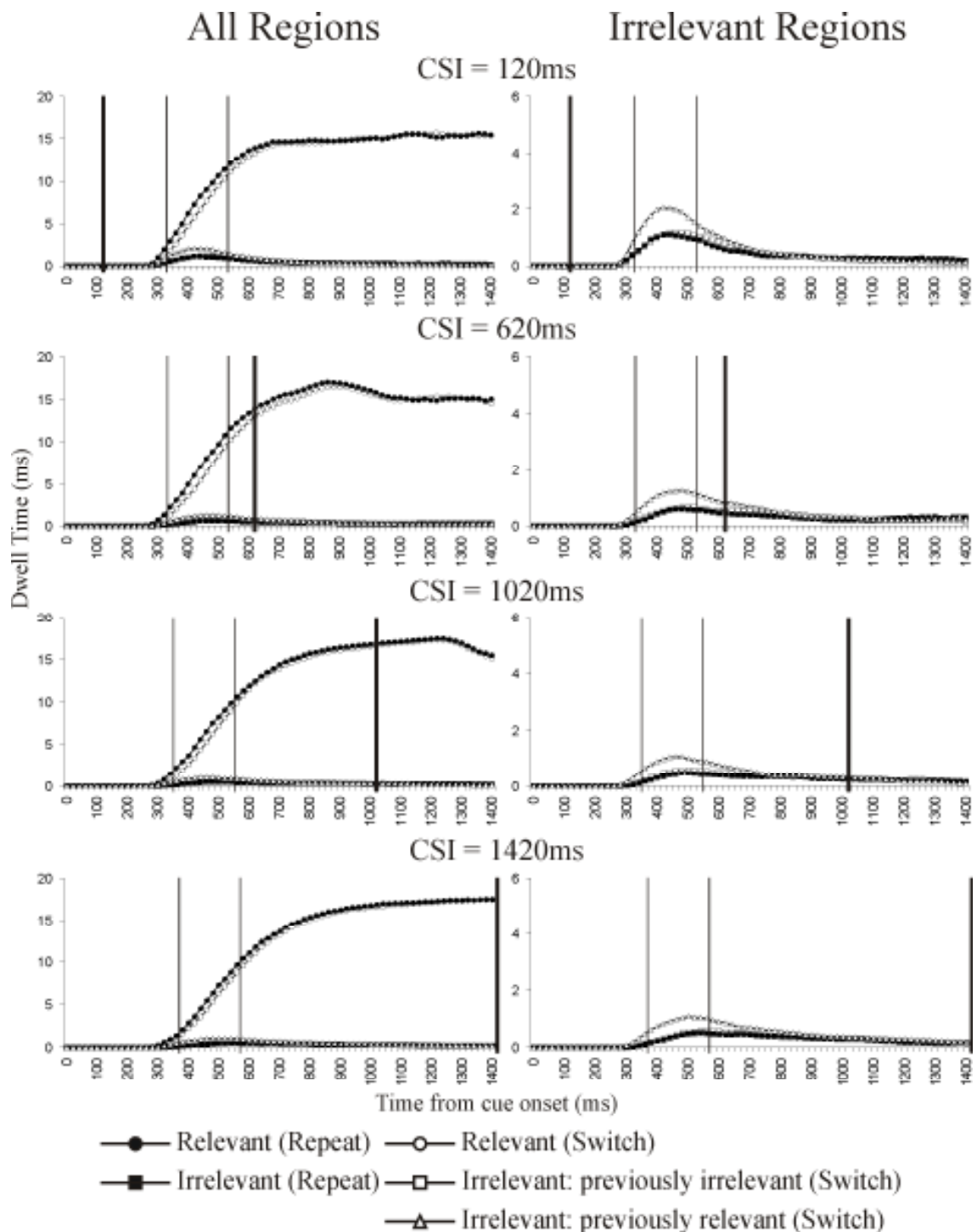


Figure 3.7. Dwell-time in Experiment 4, plotted as in Figures 3.3 and 3.5: the left panel shows the fixations on both the relevant and irrelevant regions, whereas the right panel shows only the fixations on the irrelevant regions (with the scale adjusted accordingly). Thick vertical lines show the onset of the stimulus and thin vertical lines the time-windows used for statistical analysis.

This average delay in appropriate attention 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 from the present experiment on which the first saccade to leave the cue landed directly in the relevant region (Fig. 3.8). It found a reliable main effect of switch, $F(1,23)=12.12$, $p=0.002$, 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, $F(3,69)=2.31$, $p=0.084$, indicating modest effects of CSI (see Fig. 3.8). The equivalent estimate of a delayed launch in LLMM Experiment 1 was 25 ms; the between-experiments contrast did not approach significance, $F(1,46)<1$.

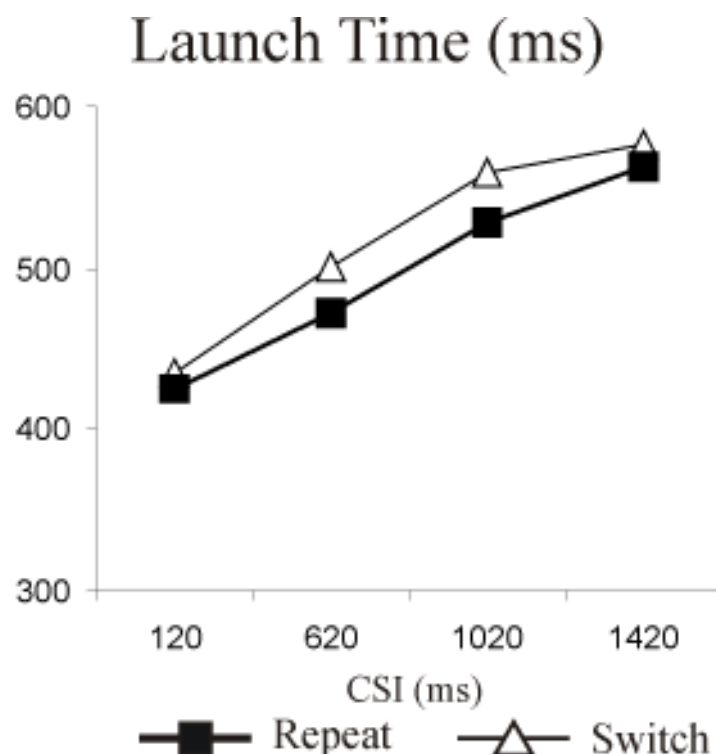


Figure 3.8. Mean 'launch time' of the first saccade to leave the cue and land directly in the currently relevant region as a function of CSI and transition (Experiment 4).

'Attentional inertia'. An ANOVA on the dwell time in the irrelevant regions for the current experiment (see Figure 3.7) found a reliable main effect of switch, $F(1,23)=4.72$, $p=0.04$, indicating a greater tendency to fixate the irrelevant regions on switch trials than on repeat trials. The small numerical reduction in this tendency at longer preparation intervals (the switch by CSI interaction) was not reliable, $F(3,69)<1$.

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, $F(1,23)=19.54$, $p<0.001$). Although there was a tendency for this effect to reduce at longer preparation intervals, the previous relevance by CSI interaction was not reliable, $F(3,69)<1$, and a reliable main effect of previous relevance was found in the two longest CSIs (CSI=1020 ms: $F(1,23)=8.53$, $p=0.008$; CSI=1420 ms: $F(1,23)=9.98$, $p=0.004$).

Table 3.1.

Mean (Standard Error in Parentheses) of the Difference 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. 4)	8.44	(1.79)	5.86	(1.32)	4.94	(1.69)	5.53	(1.75)
Task Instructions (LLMM Exp. 1)	8.61	(1.87)	7.04	(1.55)	4.17	(1.24)	2.84	(1.29)

The analysis over experiments (current experiment vs. LLMM Experiment 1) found that instructing participants to use the cues as location cues reduced the tendency to fixate the irrelevant regions on switch trials over repeats (switch by experiment interaction: $F(1,46)=18.35$, $p<0.001$). Although this difference was modulated by the duration of the preparation interval (switch by CSI by experiment interaction: $F(3,138)=6.39$, $p=0.002$), 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: $F(1,46)=16.47$, $p<0.001$; CSI=620 ms: $F(1,46)=12.71$, $p=0.001$; CSI=1020 ms: $F(1,46)=2.53$, n.s.; CSI=1420 ms: $F(1,46)=5.36$, $p=0.025$). However, the comparison of attentional inertia between experiments (see Table 3.1) 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: $F(1,46)<1$).

Discussion

The purpose of Experiment 4 was to investigate the extent to which attentional set is decoupled from task-set when the cues are intrinsically neutral/arbitrary but the instructions emphasize their association with location rather than task, in contrast to the otherwise identical Experiment 1 of LLMM, in which the instructions and training emphasized their task-meaning. The outcome of the two experiments was quite similar.

The performance measures showed similar patterns of switch cost and its reduction with preparation, though there was a slightly (but not significantly) greater residual switch cost in the present Experiment 4. None of the eye-tracking measures of spatial attention reliably differed between experiments, except the somewhat reduced tendency to fixate irrelevant regions on switch trials 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 neither strongly nor reliably reduced by emphasis on the location meaning of an arbitrary cue, in contrast to the effect of explicit pointing or verbal indexing of location in the present Experiment 3, which all but eliminated attentional inertia as indexed by this measure. 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 rather than reduced attentional inertia.

Table 3.2.

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 3 and 4 and for LLMM Experiments 1 (Task Switching Condition) and 2.

	CSI (ms)			
	120	620	1020	1420
RT Switch cost (ms)				
Present				
Experiment 3	210 (14.8)	185 (13.7)	141 (16.5)	132 (18.1)
Experiment 4	132 (16.4)	128 (17.1)	119 (17.3)	116 (16.9)
LLMM				
Experiment 1	128 (14.3)	111 (15.7)	92 (12.7)	94 (13.5)
Experiment 2	124 (16.1)	113 (12.6)	71 (10.5)	74 (10.7)
Estimated delay (ms)				
Present				
Experiment 3	14 (4.2)	12 (2.8)	7 (3.6)	8 (5.3)
Experiment 4	33 (6.0)	34 (7.0)	27 (7.7)	26 (8.4)
LLMM				
Experiment 1	43 (6.2)	42 (8.0)	33 (7.3)	22 (8.2)
Experiment 2	89 (14.2)	89 (12.0)	81 (10.4)	92 (15.6)
Launch time delay (ms)				
Present				
Experiment 3	2 (2.5)	8 (4.9)	-2 (5.6)	-13 (10.9)
Experiment 4	10 (7.4)	28 (6.7)	30 (9.3)	13 (9.6)
LLMM				
Experiment 1	24 (5.4)	30 (7.8)	25 (9.1)	20 (12.2)
Experiment 2	33 (4.9)	54 (8.3)	60 (9.9)	91 (12.5)
Attentional inertia (ms)				
Present				
Experiment 3	3.1 (0.8)	1.2 (0.5)	1.1 (0.4)	0.5 (0.3)
Experiment 4	8.4 (1.8)	5.9 (1.3)	4.9 (1.7)	5.5 (1.8)
LLMM				
Experiment 1	8.6 (1.8)	7.0 (1.6)	4.2 (1.2)	2.8 (1.3)
Experiment 2	18.4 (3.7)	12.1 (3.0)	7.8 (2.8)	5.3 (2.7)

General Discussion

Our experiments explore the conditions under which attentional selection contributes to the cost of switching tasks. Recent studies that recorded eye-movements

(as an index of attention) during task-switching found switch-related delays and inertia in the deployment of spatial attention (Longman et al., 2013; LLMM) and attention to a dimension (Mayr et al., 2013). In contrast, Lien et al.'s (2010) combined use of task switching and the contingent capture paradigm (Folk et al., 1992) revealed no attentional capture by the previously relevant stimulus feature (colour value) during a task-switch. However, Lien et al.'s (2010) cues may have encouraged attentional selection to be prioritised over the selection of other aspects of task-set. And there were indications in the LLMM study that the binding of attention to (other aspects of) task set might be greater with a cue that explicitly identified the task than with an arbitrary cue that could be construed as either a location or a task cue, though the latter interpretation was encouraged by training and instruction.

The present experiments were identical to those of LLMM, except that the cues either explicitly “pointed to” the location of the digit to be classified by the rule appropriate for that location (Experiment 3), or the participant was instructed to interpret arbitrary cues as indicating the location (Experiment 4). Table 3.2 summarises the effects of switching and preparation for a switch on both RT and eye-tracking indices in both these experiments and those of LLMM. It is immediately apparent that using explicit location cues greatly reduced or altogether eliminated the attentional effects associated with switching between tasks, whilst at the same time substantially increasing (nearly doubling) the RT switch cost. The combined pattern of fixation and performance results strongly suggest that in some conditions, spatial attention can be rapidly (and effectively) allocated in a way that is independent of (and uninfluenced by) the current task-set, but at a considerable cost to readying of the full task-set. In the other three experiments, substantial delays in orienting attention were observed, and a substantial “attention inertia” effect – the tendency on task-switch trials to fixate the location appropriate for the task performed on the previous trial, suggesting that the

default mode is to couple attentional set with other task-set parameters. These effects, and by inference the coupling, were maximal in LLMM Experiment 2, in which the cues verbally and explicitly signalled the task, and the attentional effects clearly predicted RT switch costs.

An obvious question concerns the source(s) of the substantial extra switch cost we observed with explicit location cues (relative to task-related cues in LLMM): if both task-set and attentional set need to be reconfigured, why does the strong prioritisation of the latter over the former result in such a marked performance decrement on switch relative to repeat trials? Clearly, the binding of attentional parameters into task-set seems to offer some substantial saving in processing, possibly because some stages of task-set selection can run in parallel with (or benefit from) concurrently resetting the attentional parameters. For instance, one can envisage the possibility that when attentional parameters are accessed via task-set, this helps settle the activation of the rest of the task-set resolving (at least to a degree) its competition with the alternative task-sets.

Although in LLMM we make the observation that the delay in orienting and attentional inertia contribute to the residual switch cost, in the current Experiment 3 both of these attentional effects are greatly reduced (or eliminated) but the residual switch cost is inflated relative to when the cues explicitly name the relevant task. In the current study, the switch cost and its residual component were largest with arrow cues which completely eliminated attentional inertia at the longest CSIs. Intriguingly, with these cues the switch cost appears to continue to reduce (at least numerically) between the longest CSIs suggesting that it had not yet reached asymptote, whereas with the word cues the residual switch cost did not further reduce. This suggests that whilst the arrow cues are very effective at unbinding attentional selection from the rest of task-set (postponing reconfiguration of other task-set components), the word cues (which take a

little longer to interpret) might, to some degree, also activate the task to be performed.

Whilst the results from LLMM indicate that attentional handicaps typically contribute to the residual switch cost, clearly there are cases where their contribution is limited and its source lies elsewhere (perhaps in components found at later processing stages such as response selection/execution).

The two experiments using cues without any intrinsic meaning (LLMM Experiment 1 and the present Experiment 4) both produced results indicative of coupling between attentional and other parameters of task set, albeit not as strong as with cues explicitly naming the classification to be performed. It did not make much difference whether the instructions encouraged participants to construe the arbitrary cue as indicating the location of the digit to be classified more than the task, or the task to be performed more than the location. We interpret this as indicating that the coupling of location and other task-set parameters in task-set reconfiguration is the natural default, and only more extreme emphasis on orienting to a location breaks that coupling.

To conclude, the extent to which switching between tasks associated with different locations influences attention seems to be strongly dependent on the coupling between task-set and attentional set. It also seems that, although under extreme circumstances this coupling can be almost entirely abolished (as in the case of spatial attention in the present Experiment 3 and in the case of feature attention in the contingent capture paradigm, Lien et al., 2010), the more typical situation is that of rather robust coupling, even in conditions that do not explicitly promote it. Furthermore, although such coupling between attentional set and task-set might result in transient difficulties in allocating attention, it also results in very clear performance benefits during a task switch.

4

Examining the seriality of anticipatory task-set reconfiguration with combined ERPs and eye-tracking

Introduction

In the research reported thus far in this thesis, the dynamics of (re)orienting spatial attention in task-switching has been documented using eye-movements which were recorded well before performance measures (RT and errors) could be acquired – during the preparation (cue-stimulus) interval. Eye-tracking can therefore be seen as a quasi-online¹ measure of (a component of) task-set reconfiguration. The aim of the experiment reported in the current chapter is to relate this measure to another online measure of TSR – the late posterior switch-induced ERP positivity (e.g., Lavric et al., 2008), also referred to as ‘parietal positivity’ (Karayanidis et al., 2003; 2010), which is typically observed from about 400-500 ms following the onset of a task cue when the sequence of tasks is unpredictable, and earlier in predictable task sequences (see General Introduction). The posterior positivity is not the only ERP feature that differentiates between switches and repeats during the preparation interval (see Karayanidis et al., 2010, and Lavric et al., 2008, for discussions of switch-related ERP effects observed during the preparation interval), but it is by far the most consistently reported correlate of preparation for a task-switch. (Recently, it has also been found during preparation for switching languages in a picture naming task, Clapp, Elchlepp, East, Lavric & Monsell, in preparation.) It is the switch-induced potential that shows the clearest relation to performance: its magnitude is positively correlated over participants with the reduction in RT switch cost (Elchlepp et al., 2012), and negatively correlated with the residual switch cost (Kieffaber & Hetrick, 2005); it is large on those trials that have fast responses and small switch costs, and is virtually absent during the CSI (and

¹ Quasi – because there is a lag between attention being oriented and the onset of the associated eye-movement, e.g. Rayner (1998).

delayed until post-stimulus) on those trials with slow responses and large switch costs (Lavric et al., 2008; Karayanidis et al., 2011; Clapp et al., in preparation); when cue processing is optional (e.g., when stimuli afford responses in only one task), the positivity is more consistently observed for task cues that are maximally effective in eliciting preparation (verbal cues), than for cues that are less effective (picture cues; Elchlepp et al., 2012). Inasmuch as ERP features/components can be ‘signatures’ of psychological processes, the positivity may be an electrophysiological signature of advance TSR (Lavric et al., 2008).

As already discussed in the introduction to Chapter 2, in computational models of task-set there are two perspectives on the dynamics of (re)configuring its constituent components. One perspective, represented by the ECTVA model by Logan and Gordon (2001) is that different parameters that make the task-set are configured (transmitted from working memory to perceptual and response execution systems) in parallel. According to another class of model (Meiran et al., 2000; 2008), the reweighting of perceptual and response parameters is done serially, in distinct processing stages (though the order of these stages has changed from the early to the more recent models of this class, see Chapter 2).

In the current experiment (which used a paradigm essentially equivalent to that of Experiment 2, Chapter 2) the time-courses of spatial orienting and of the switch-induced positivity were compared by means of concurrent eye-tracking and electroencephalography. Unlike fixations on attributes of the stimulus, the positivity is unlikely to reflect attentional (perceptual) processes per se – it has been found both when task switching involved a change in perceptual attributes (e.g., Lavric et al., 2008; Rushworth et al., 2002), and when it did not (e.g., switching between semantic categorizations of digits, e.g., Nicholson et al., 2006). Thus, the switch-related patterns of fixations and the switch-induced positivity are indices likely to reflect separable TSR

processes. If the processes they reflect occur in parallel, then one would expect, assuming a lag of ~120-200 ms between attention being allocated to a location and an eye-movement being initiated towards it (cf. Rayner, 1998), the first eye-movement away from the task cue to follow the onset of the positivity by a comparable interval. Serial processing would be more compatible with a pattern of results in which the onset of the positivity either precedes the eye-movements by a substantially longer lag, or follows these – but the former, though theoretically possible, is highly unlikely: given the onset of fixations in Experiment 2 (Chapter 2), the positivity would have to start before 200 ms following the cue onset, whereas its typical onset is at 400-500 ms following cue onset. The more plausible outcome predicted by a serial account of TSR is that the onset of the positivity would either follow the eye-movement or precede it by at least 100 ms.

Method

Participants

Twelve undergraduate students (8 female, mean age = 21.5) received course credits plus a ≤£2 performance-related bonus (see next section).

Tasks, Stimuli and Procedure

The stimuli were presented using E-Prime (Psychology Software Tools Inc., Sharpsburg, USA) on a standard 17” CRT monitor. Each trial (see Fig. 4.1) started with a blank screen which was followed by the presentation of a central fixation cross (subtending 0.4°) and three light blue dots (0.3° in diameter) at the locations where the three digits would eventually appear. After 300 ms, the fixation cross was replaced with a 0.8° x 0.3° word cue (‘ODD?’, ‘EVEN?’, ‘LOW?’, ‘HIGH?’, ‘INNER?’ or ‘OUTER?’) displayed for the entire CSI, which specified one of three classification

tasks (odd vs. even; low [<6] vs. high [>5], inner [4, 5, 6, 7] vs. outer [2, 3, 8, 9]), each mapped to a single location throughout the experiment for all participants: odd/even task = top digit, low/high = bottom left digit, inner/outer = bottom right digit. The cue, which changed on every trial to unconfound task switches from cue switches (Logan & Bundesen, 2003; Monsell & Mizon, 2006), was followed by the stimulus at one of two cue-stimulus intervals (CSIs): 100 ms or 1000 ms. To unconfound the effects of endogenous preparation from those of passive decay of task-set inertia (Meiran, 1996), the response-stimulus interval was 2100 ms regardless of CSI, except following an error when “ERROR” was presented for a further 1000 ms. The CSI was constant throughout a 74-trial block but changed over blocks, to provide an estimate of the reduction in the behavioural switch cost with preparation. Given the present focus on events during the preparation interval, 9 out of the 12 blocks had a long CSI. Short CSI blocks were interspersed among long CSI blocks at regular intervals (one in every four blocks); the four possible resulting sequences (where the first short CSI block was the 1st, 2nd, 3rd or 4th in every four blocks) were equally represented over participants.

The stimulus, comprising three digits ($0.4^\circ \times 0.5^\circ$) presented at the corners of an invisible equilateral triangle (positioned at 5° from each other and 2.7° from the centre), was presented until one of two keys (‘c’ or ‘m’ on a standard ‘QWERTY’ keyboard) was pressed with either the left or right index finger, respectively. Stimuli were generated by first selecting the category (e.g., odd, inner) for each digit, then randomly selecting a digit from the appropriate set with two constraints: a digit could not be repeated in a stimulus and there could be no exact repetition of the entire stimulus from the previous trial (all three digits in the same locations). The combinations of the three categories (e.g., even, low, outer) were equiprobable for each task and transition type. The tasks were equiprobable (resulting in a 2:1 switch:repeat ratio) to discourage early preparation.

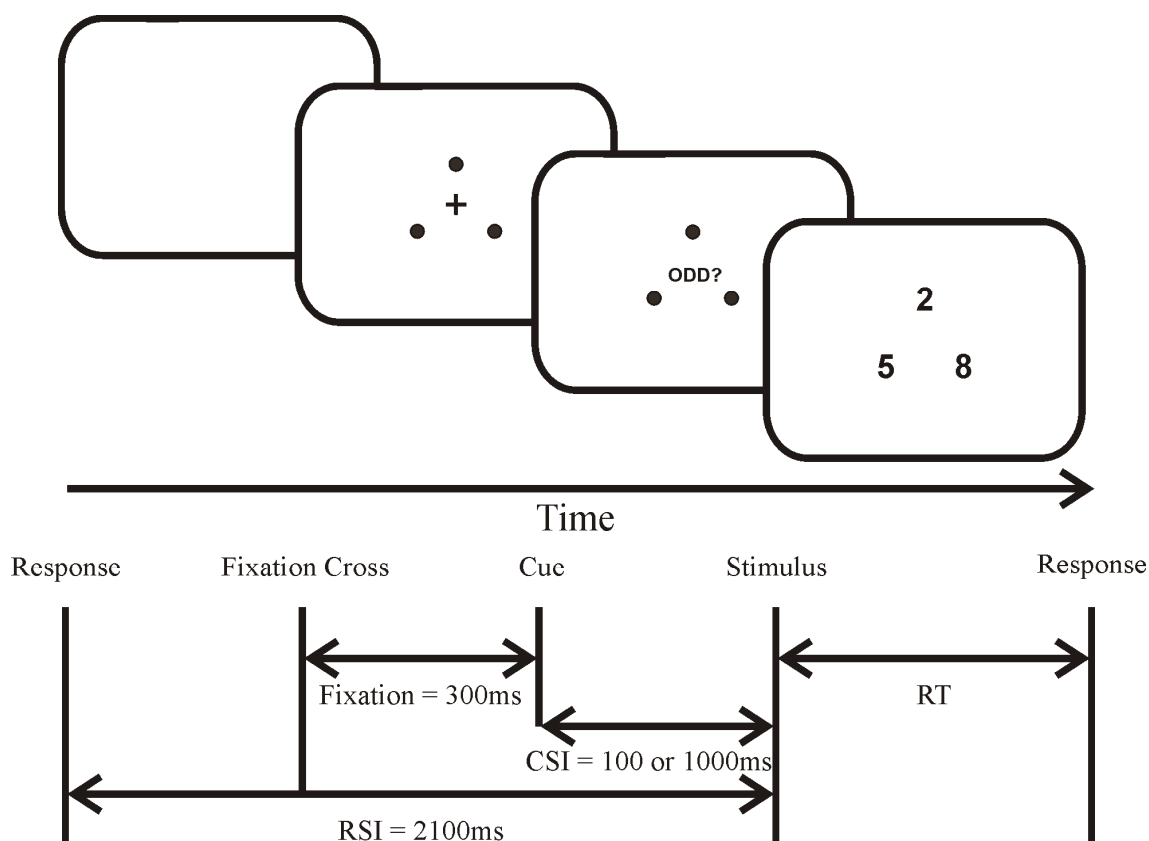


Figure 4.1. The time course of one trial with example displays. The dots where the digits would eventually appear were presented in light blue.

The CSI was displayed before each block. The mean correct RT, number of errors, a composite score for the block, the target score for the block (mean score from previous blocks with the same CSI) and the bonus points (used to calculate bonus payments) were displayed at the end of each block.

The experiment started with a practice run comprising: three 8-trial blocks each requiring one of the three classifications of single digits presented centrally; a task-switching block (74 trials) with single digits presented centrally; and (following the introduction of the task-location mappings) two task-switching blocks equivalent to the test blocks described above.

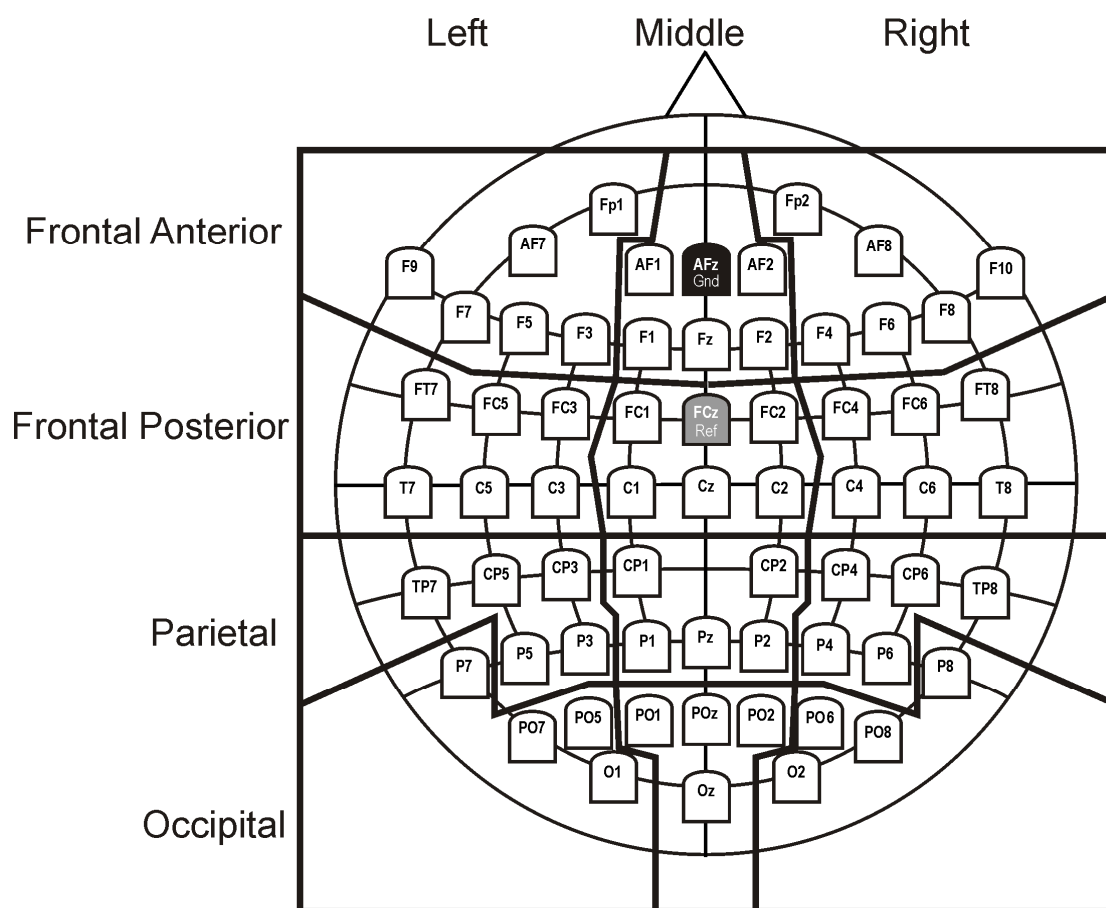


Figure 4.2. Distribution of electrodes and regions used for statistical analysis.

Eye-tracking and EEG/ERP

An EyeLink 1000 eye-tracker (SR Research, Ottawa, Canada) recorded the movements of the right eye (sampling rate, 500 Hz) with calibration between blocks. The EEG was sampled continuously at 500 Hz (bandpass 0.016-100 Hz, reference Cz, ground AFz) using 64 Ag/AgCl active electrodes in a 10-10 configuration (ActiCap and BrainAmp, Brain Products, Munich, Germany). All impedances were kept below 10k Ω . Following offline filtering with a 20 Hz low-pass filter (24dB/oct) and re-referencing to the averaged earlobes, Independent Component Analysis (ICA, Bell & Sejnowski, 1995) was used to correct for ocular artifacts². The EEG was segmented into 1000 ms

² Eye movements are typically discouraged during the interval of interest in ERP studies in order to avoid ocular artifacts. This was not possible in the current experiment because eye movements were also of interest during the same interval. Using the ICA to correct for ocular artifacts meant that, although some trials were omitted from further analysis due to other (residual) artifacts, none were omitted due to ocular artifacts.

epochs time-locked to cue onset plus a 100 ms pre-cue baseline epoch. Following baseline correction, the segments were inspected for residual (muscle, head movement, skin and other) artifacts, and those free of artifact averaged for every participant/condition. For statistical analysis, electrodes were averaged for 4 anterior-to-posterior regions, each containing 3 levels of laterality (left, middle, right; see Fig. 4.2), this averaging along two spatial dimensions were reflected in the Region and Laterality factors in ANOVAs.

Results

The first two trials in each block, trials following an error, with $RT > 2500$ ms, or with no fixations on the cue for 1000 ms following cue onset were discarded from all analyses. Error trials were omitted from RT, eye-tracking and ERP analyses. Significance levels were adjusted using the Huynh-Feldt correction for violations of sphericity (for transparency, *dfs* are reported unadjusted).

RT and Errors

A switch by CSI by task ANOVA found the 107 ms RT switch cost to be significant, $F(1,11)=41.41$, $p < 0.001$ (see Fig. 4.3). It reduced reliably from 135 ms at the short CSI to 80 ms at the long CSI, (switch by CSI interaction, $F(1,11)=8.97$, $p=0.012$), but remained significant at the long CSI, $F(1,11)=25.23$, $p < 0.001$. No effects involving switch were significant for the error rates ($F_s < 1$). There were no reliable effects or interactions involving the factor task for either RTs or errors.

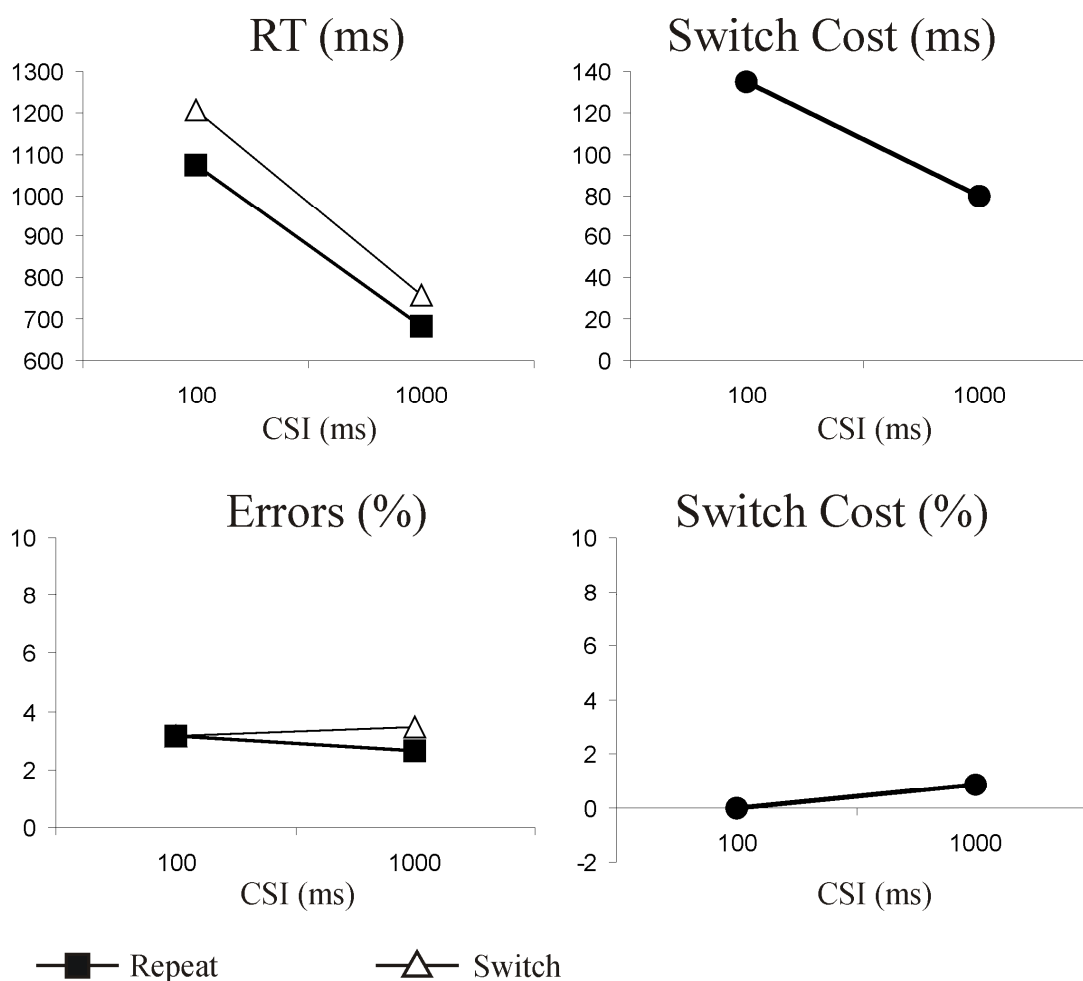


Figure 4.3. Mean RT, error rates and switch costs as a function of cue-stimulus interval (CSI) and transition (switch, repeat).

Eye-tracking

Fixations in four square regions (side = 2°) centred on the three digits and the cue were analysed; 92.8% (repeat trials) and 92.43% (switch trials) of fixations landed in these regions³. Figure 4.4 (left panel) shows the mean time spent fixating the regions for the three digits over the course of the trial in 20 ms time-bins ('dwell-time'⁴). The effects of a task-switch were tested statistically in a 200 ms window selected to reflect the maximal rise in dwell-time: for each CSI the window started from the bin where dwell-time for the currently-relevant region on repeat trials (averaged over participants)

³ Blocks with >20% of trials containing no fixations in any of these regions (indicating poor calibration) were discarded (one block in one participant).

⁴ This measure is analogous to the probability of fixating a given region, which can be obtained by simply dividing each dwell-time value by 20.

exceeded 2 ms (10% of the maximum). For the task-relevant region, a task switch appears, as before, to delay/prolong the rise of the curve. To examine the apparent switch-induced delay we estimated (as in the previous experiments) the time separation between the switch and repeat dwell-time curves for every time-point (2 ms) and averaged the estimates for the 200 ms analysis window. One-sample t-tests showed the switch-induced delay to be significant for each CSI: CSI=100 ms, $t(11)=3.71$, $p=0.003$; CSI=1000 ms, $t(11)=3.32$, $p=0.007$. An ANOVA with the factor CSI was run in order to assess the effect of preparation interval on the estimated delay but found that the reduction (from 107 ms at the shorter CSI to 77 ms at the longer) did not approach significance, $F(1,11)<1$.

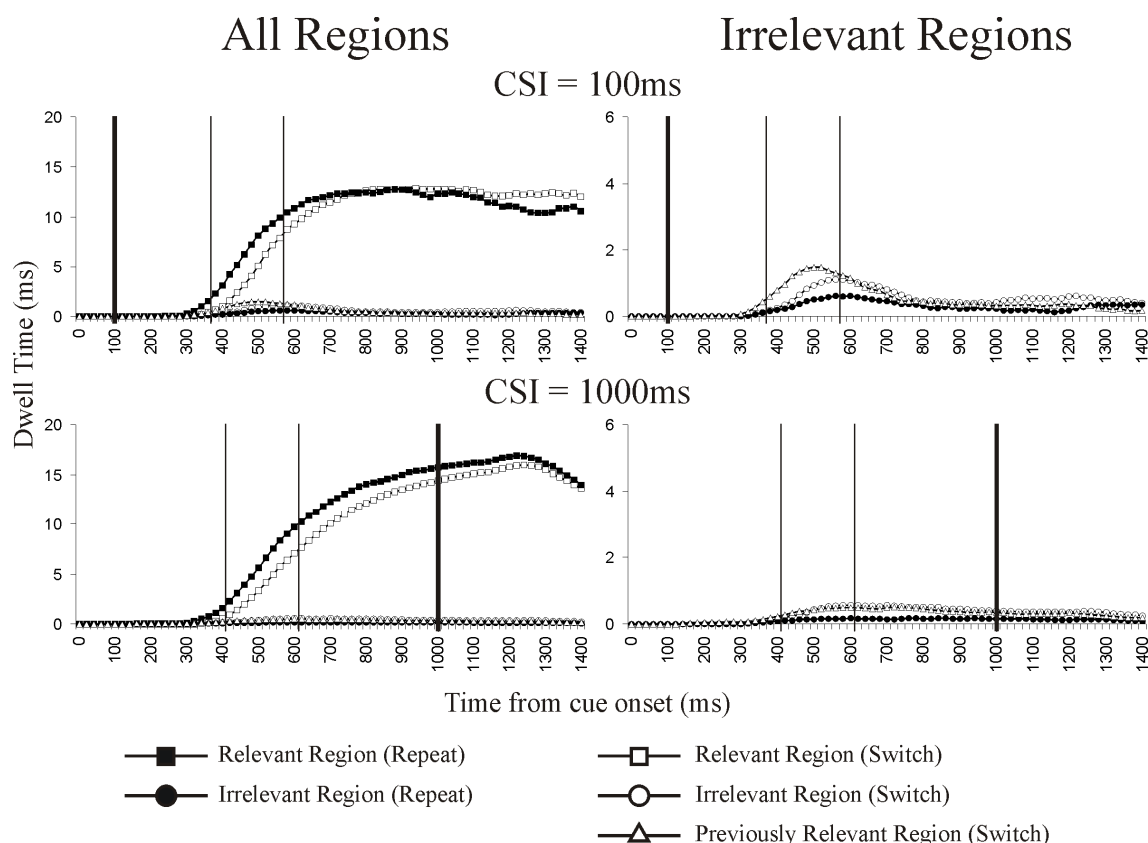


Figure 4.4. Dwell time per 20 ms bin for 1420 ms following cue onset as a function of CSI, transition (switch, repeat) and task-relevance of stimulus region. Thick vertical lines indicate the stimulus onset time, thin vertical lines show the time-windows used for statistical analysis.

The delay in fixating the relevant region on switch trials may be at least in part due to gaze being drawn toward the irrelevant digits during a task-switch. This was consistent with the significant main effect of switch in the switch by CSI by task ANOVA performed on the dwell time on the irrelevant regions, $F(1,11)=12.38$, $p=0.005$ (see Fig. 4.4, right panel). There were also reliable interactions between task and switch⁵, $F(2,22)=10.98$, $p=0.001$, and CSI, task and switch, $F(2,22)=5.53$, $p=0.011$, reflecting larger differences found in the low/high task. To examine attentional inertia we compared, for switch trials, the previously (but no longer) relevant region with the other irrelevant region. A previous relevance (previously relevant, previously irrelevant) by CSI by task ANOVA found a reliable interaction between previous relevance and CSI, $F(1,11)=18.13$, $p=0.001$; follow-up analyses revealed a strong preference for the previously relevant region (the previously relevant minus previously irrelevant difference in dwell time was 5.6 ms; standard error = 2.3) when CSI = 100 ms, $F(1,11)=6.28$, $p=0.029$, but a non-significant reversal of the effect (-0.2 ms difference in dwell time; standard error = 1.4) when CSI = 1000 ms, $F<1$ (see Fig. 4.4, right panel).

To examine whether the switch-induced delay in fixating the relevant digit arose only/mainly on (the minority of) trials containing fixations on the task-irrelevant digits we analysed the mean 'landing time' of the first fixation on the relevant digit only for trials on which the first eye movement away from the cue resulted in a fixation on the relevant region. This analysis reveals a switch-induced delay of 55 ms in appropriate orienting, confirmed by the significant main effect of switch in the switch by CSI by task ANOVA performed on these data, $F(1,11)=14.40$, $p=0.003$. This delay increased numerically (but non-significantly, $F(1,11)=2.64$, n.s.) with CSI (from 39 ms to 71 ms), suggesting faster, but more error-prone (see irrelevant dwell-time analysis above), fixations on short CSI switch trials. Mean landing time of the first fixation to land in the

⁵ Only ANOVA effects involving the switch factor are presented.

relevant region limited to those trials where the first eye movement away from the cue terminated in the relevant region were (in order of increasing CSI): switch = 594 ms, repeat = 554 ms; switch = 711 ms, repeat = 640 ms.

Thus far then, the eye movement data largely replicate the pattern of preparatory orientation of attention we have seen before with task-identifying cues; the exception is the lack of a significant “attentional inertia” effect in fixations to irrelevant regions at the long CSI.

ERPs

I present first an analysis of the ERP data alone (without relating them to fixations). An inspection of the topographies (see Fig 4.5B) reveals the familiar and substantial posterior positivity induced by a task-switch starting about 400 ms before the end of the 1000 ms CSI. A switch by region by laterality ANOVA run on ERP amplitudes averaged for the 600-800 ms window found a reliable main effect of switch, $F(1,11)=16.77$, $p=0.002$. Reliable interactions between switch and region, $F(3,33)=6.09$, $p=0.019$, and switch and laterality, $F(2,22)=10.18$, $p=0.001$, indicated the expected localisation of the positivity in posterior electrodes towards the left of the scalp (in many previous studies, particularly those that used word cues, the positivity was somewhat left-lateralised, e.g., Elchlepp et al., 2012; Lavric et al., 2008). Interestingly, in addition to the posterior positivity, there is an earlier switch-induced negative-polarity deflection maximal over the centro-parietal scalp, confirmed in the analysis of the 300-500 time-window by the significant main effect of switch, $F(1,11)=8.96$, $p=0.012$.

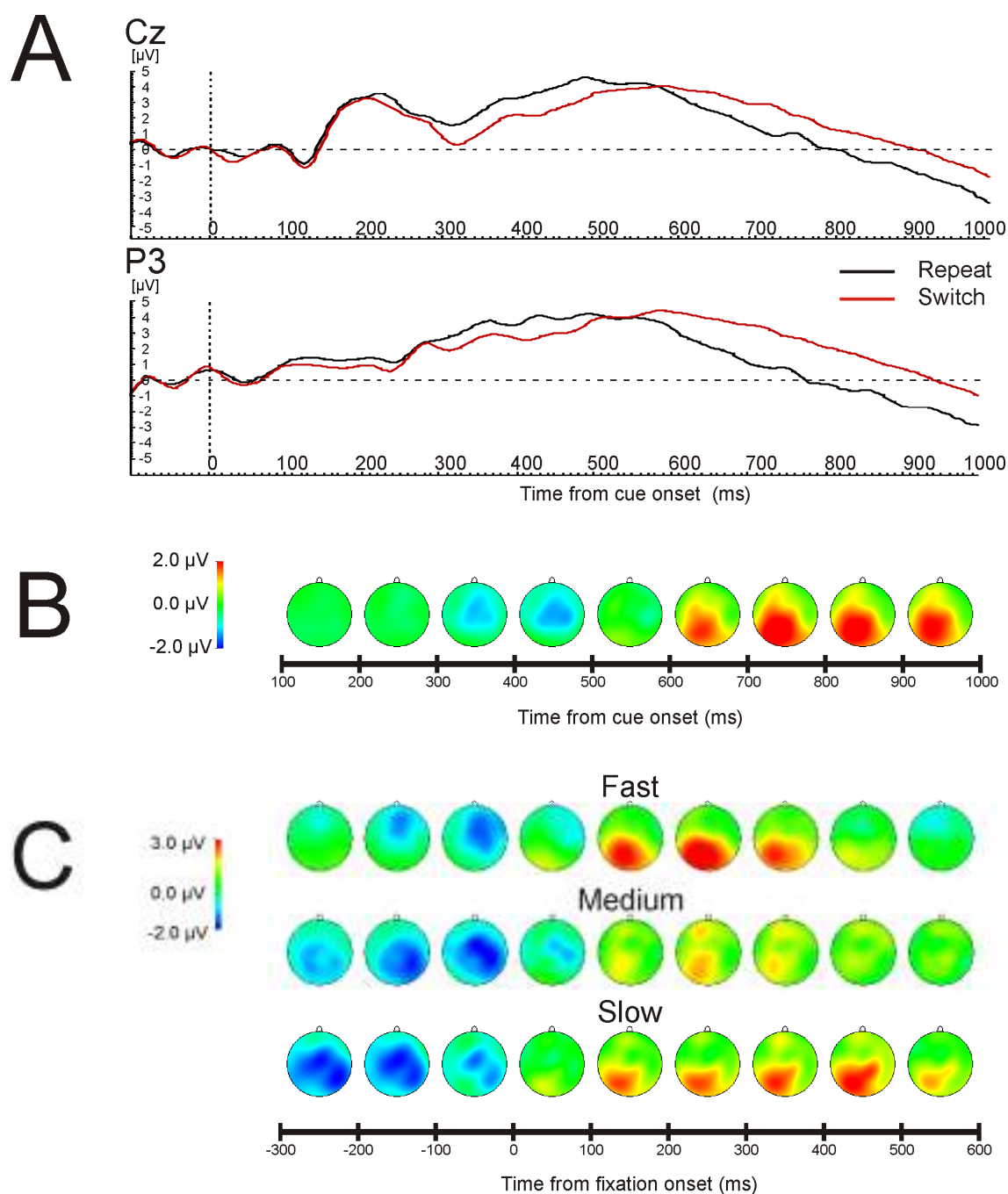


Figure 4.5. (A) Mean switch and repeat waveforms from two example electrodes showing the extent of the early negativity (Cz) and late positivity (P3). (B) Cue-locked switch minus repeat ERP topographies. (C) Fixation-locked switch minus repeat ERP topographies for the fast, medium and slow fixation 'landing times' (see text for description).

The primary aim of the current investigation was to relate the time-course of (re)orienting spatial attention during a task-switch to previously-documented brain potentials induced by preparation for a switch (posterior positivity). Our approach was two-fold.

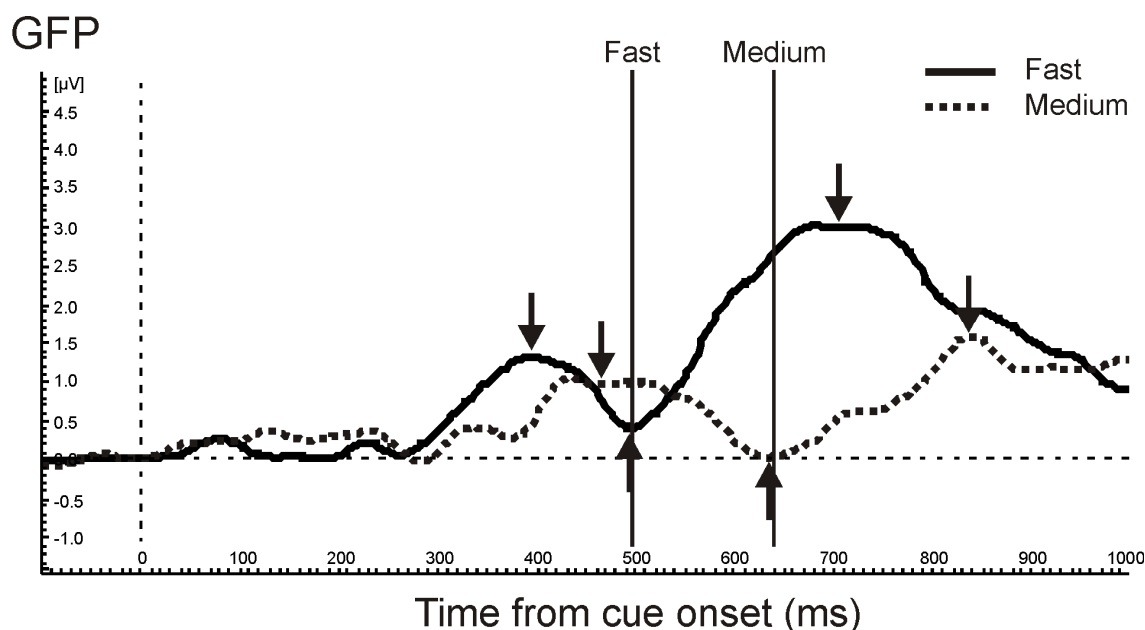


Figure 4.6. Switch minus repeat difference waves (computed as Global Field Power, GFP, see main text) for the trials with fast and intermediate fixation landing times (see text for description). Arrows show the peaks (early negativity and late positivity) and the intervening minimum which were submitted to statistical analysis. Vertical lines show the mean landing time of the first relevant fixation for the fast and medium terciles.

First, we examined the latency of the two relevant maxima (peaks) of the switch-repeat difference wave (posterior positivity and central negativity), and the latency of the intervening minimum, as a function of which part of the distribution of fixation landing times in the relevant region the ERPs were computed for – the terciles of trials with the fastest, slowest and intermediate landing times (see Fig. 4.6). To avoid an arbitrary selection of the electrode(s) for the difference wave, we used a measure that pools over the amplitude of all scalp electrodes: the Global Field Power, computed as root-mean-square – the square root of the mean of the squared switch-repeat difference over all scalp electrodes (see Hamburger & Van der Burgt, 1991, for the superiority of GFP for latency analyses). Note that because switch-repeat differences are squared before averaging them over electrodes, both the switch positivity (the second maximum in the difference wave) and the switch negativity (the first maximum in the difference

wave) are both positive-polarity peaks in the plot. To assess statistically potential delays in the latency of peaks in the difference wave, we needed to identify not only the mean but also the variance over subjects of the position of these peaks. Because single subjects' waveforms/difference waves are typically too noisy to unambiguously locate features seen in the grand average, we used the same method as that employed in Chapter 2 (Exp. 2) for fitting the sigmoidal function to dwell-time curves – “jackknifing” (Miller et al., 1998). Because it was difficult to identify a peak for the positivity for the tercile with the slowest fixations (probably due to inter-trial variability of the positivity relative to cue onset), the analysis was confined to the fastest and intermediate terciles. All three peaks were delayed in the intermediate tercile relative to the fast tercile (see Fig. 4.6), two of them reliably: negativity maximum, 72 ms, $t(11)=1.73$, $p=0.112$; positivity maximum, 133 ms, $t(11)=4.66$, $p<0.001$; intervening minimum, 140 ms, $t(11)=4.23$, $p=0.001$. This analysis suggests a relation between the onset of fixation on the task-relevant region and (1) the maximum of the central negativity, and (2) the onset and maximum of the posterior positivity. Importantly, as one can see in Figure 4.6, the negativity precedes the average onset latency of the first fixation on the relevant region, whereas the positivity follows it.

Second, we re-segmented the EEG into 900 ms-epochs time-locked to the landing time of the first fixation on the currently relevant region: 300 ms pre- until 600 ms post-fixation onset. If, as the above latency analysis suggests, the posterior positivity always follows the (re)orienting of attention, one would expect the positivity to be confined to the post-landing part of the interval. As Figure 4.5C illustrates, this was indeed the case: for each tercile, the positivity emerged only after the onset of the first fixation on the relevant attribute of the stimulus. The converse was true for the central negativity: it always emerged and returned to baseline prior to fixation landing in the relevant attribute. This pattern of observations was confirmed statistically by t-tests run

on ERP amplitudes⁶ for the scalp regions in which the negativity and positivity were maximal: the former was only significant pre-landing and the latter post-landing (see Table 4.1). Both the switch negativity and the switch positivity are (at least numerically) more protracted in the slowest tercile relative to the fast and intermediate terciles (see Fig. 4.5, C), most probably because of the greater variability in their time-course in the slowest tercile.

Table 4.1: Mean ERP Amplitude Difference (Switch-Repeat) and Switch vs. Repeat T-test Statistics as a Function of Speed of Fixating the Relevant Region for the Parts of the Scalp Where the ERP Effects Were Maximal: Middle Central Region (Negativity) and the Average of the Left and Middle Parietal and Occipital Regions (Positivity).

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

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

⁶ T-tests were not corrected for multiple comparisons to ensure sensitivity to switch-repeat differences.

Discussion

The current experiment employed essentially the same paradigm as Experiment 2 (Chapter 2); the only change is that, to maximise the number of trials in the long CSI condition for ERP analysis, there were only two CSIs instead of four and the distribution of trials (blocks) with the two CSIs was unequal (75% were in the long CSI condition), whereas in Experiment 2 there were equal numbers of trials in each CSI condition. The performance was strongly reminiscent of that in Experiment 2, as were the fixations on the task-relevant region: the relatively large switch cost when CSI = 100 ms was reduced by ~40% by increasing the CSI to 1000 ms; switching delayed fixation on the task-relevant attribute by 70-100 ms – this delay cannot be explained by occasional fixations on irrelevant regions on switch trials, because it was of a comparable size when the first eye movement away from the task cue was appropriately targeted. There was, however, one outcome that was not consistent with the results from Experiment 2 – in the present experiment there is no sign of attentional inertia in the long CSI condition, as indexed by preferentially fixating on switch trials the previously (but no longer) relevant attribute over the currently irrelevant attribute that was previously irrelevant. I will return to this important result after the ERP findings are discussed.

The primary goal of the experiment was to relate the time-course of the switch-related preparation positivity in the ERP to fixation latencies on switch trials. For this to be possible, there needs to be a positivity at the long CSI; the analysis of ERPs time-locked to the cue onset revealed a robust positivity with the expected time-course and scalp distribution: a protracted switch-repeat difference emerging in the late part of the CSI, maximal over the parietal-occipital scalp and somewhat left-lateralised. The presence of a robust switch-induced posterior positivity appears at odds with its absence in one condition of the previous report by Astle et al. (2008b), in which, as in the

present experiment, the tasks were consistently associated with locations (each of two letter classification tasks was associated with one side of the screen, see General Introduction). However, an important design difference may explain the discrepant findings. In Astle et al.'s study the stimulus consisted of only one element, presented on the left or the right side of the screen – thus the stimulus unambiguously specified the task. As a consequence, the processing of the task cue was not essential for task selection but might be used to reorient covert spatial attention which was not possible when the colour of the stimulus indicated the task (indeed such an interpretation is acknowledged by the authors). This may have introduced greater variability (over trials and/or subjects) in the timing of the processes indexed by the positivity. In the current design the processing of the cue is obligatory – together with the presence of competing stimulus elements this strongly encourages early TSR. The recording of fixations as a proxy for spatial orienting enabled in the current study a clear temporal disambiguation of (re)orienting from other TSR processes (reflected by the posterior positivity).

Nonetheless, if we assume that Astle et al. were indeed able to eliminate the posterior positivity (which has been recorded in multiple experiments using various paradigms; see Karayanidis et al., 2010, for an extensive review of such studies) then we are forced to question whether it represents an obligatory (reconfiguration) process on switch trials. Such a discussion is beyond the scope of this thesis, but clearly any interpretation of this effect would necessarily need to account for all of the conditions in which it has been recorded and those in which it has not (Astle et al., 2008b, is the only example of this component being eliminated of which I am aware).

As explained in the Introduction, a theoretical account that assumes (re)configuring of components of task-set in parallel (e.g., ECTVA) is only consistent with the gaze 'landing' in the relevant region ~200 ms or so after the onset of the positivity. A sequential (positivity then fixation, or fixation then positivity) pattern of

results would be consistent with a serial TSR account (e.g., Meiran, 2000; Meiran et al. 2008). The present results revealed a clear sequential relationship between the positivity and fixation on the relevant region. ERP analyses based on distributions of fixation latencies (cue-locked and fixation-locked) found the onset of the positivity always after the mean landing time of the fixation on the task-relevant stimulus attribute, strongly supporting a serial reconfiguring (or resetting) of task-set components. Nonetheless, it is possible that the posterior positivity might index cognitive processes occurring prior to fixation (i.e., temporally overlapping with the earlier, more central, negativity).

However, given the temporal relationship between the switch-related ERP positivity and fixation on the relevant attribute, it seems highly unlikely that the former should be the ‘neural precursor’ of the latter hence it is unlikely to be the neural correlate of reorienting spatial attention during a switch. Instead, the current analysis revealed another switch-repeat difference in the ERP – a switch-related negativity over the central frontal and parietal scalp. Like the timing of the positivity, its timing also seemed tightly coupled to the latency of fixation, but, unlike the positivity which always followed the fixation, the negativity always preceded it – which also supports a serial model of TSR. The negativity is thus a plausible electrophysiological correlate of reorienting attention during a task-switch in the current design, in which tasks are associated with locations and early (during the preparation interval) eye-movements to these locations are encouraged. Given the scalp distribution of the negativity, its anatomical substrates are likely to be in the superior parietal lobule and the frontal eye-fields (and/or supplementary eye-fields), both regions involved in spatial orienting and programming of eye-movements. It therefore seems likely that this component reflects early reorienting of task-relevant attention or ‘unpacking’ of task-set components which can be reconfigured soon after cue interpretation. In the current experiment attentional orienting is necessarily spatial in nature, but it remains to be seen whether the negativity

is also found in experiments where early reorienting can be achieved non-spatially or where other task-set components can be selectively reconfigured prior to stimulus onset.

I now return to the absence in the fixation data of a discernable indication of attentional inertia at the longest CSI. Another instance of no residual attentional inertia can be found in Experiment 6 (Chapter 5) – but there the CSI was self-generated, whereas in the previous experiment on which the current experiment was modelled (Experiment 2, Chapter 2), attentional inertia was present, and statistically reliable, even when CSI was 420 ms longer than the long CSI here. The crucial difference seems to be CSI variability over the course of the experiment. In the current experiment, there were long (3 blocks-long) stretches of the same (long CSI), separated by only one short CSI block. In Experiment 2 the CSIs of 120 ms, 620 ms, 1020 ms and 1420 ms alternated continuously. Thus, it is possible that the increased proportion of long CSI trials, together with a simpler distribution of CSIs in the current experiment may have shifted the criterion along the speed-accuracy continuum for launching an eye-movement further from the speed end (and closer to the accuracy end) in the current experiment relative to Experiment 2. This interpretation is essentially the same as the account for the absence of residual attentional inertia when CSI is self-generated (see Chapter 5, for more discussion of this idea).

Finally, the present results may have implications concerning the functional interpretation of the switch-induced preparation positivity. In their review, Karayanidis et al. (2010) have proposed that the positivity may reflect processes that are common to various components of task-set, based on finding the positivity both in paradigms that required only changes of the stimulus features to be attended to, without changes in the S-R mappings (Rushworth et al., 2002; see also Kieffaber et al., 2013) and in paradigms requiring only changes of the S-R mappings without changes of stimulus attributes (Rushworth et al., 2005). However, our data show that the positivity is unlikely to be

causally linked to the reorienting of spatial attention in task-switching, raising doubts about the non-specificity of the positivity. The present data also show that the positivity is unlikely to reflect the early activation of the relevant task-set, often conceptualised as ‘task-set goal’ (e.g. Goschke, 2000) – presumably the activation of the relevant goal has to precede the reorienting of spatial attention, at least when task-set and spatial attention are well-coupled, as we assume they are here (see Chapter 3). Although this still does not provide a specific interpretation of the positivity, it narrows it down somewhat, suggesting that it is likely to reflect loading into working memory of relevant task categories, or S-R mappings, or relevant non-spatial features of the stimulus. However, if we assume that Astle et al. (2008b) were indeed able to eliminate this component by presenting stimuli at distinct spatial locations then perhaps there are other means by which these processes can be achieved that do not require the processes indexed by the posterior positivity.

5

Is there attentional inertia when the preparation interval is self-generated?

Introduction

In Chapter 2 I introduced the paradigm used to investigate the time-course of orienting spatial attention during the preparation interval. The cues were presented at four CSIs (120 ms, 620 ms, 1020 ms and 1420 ms; the CSI varied over blocks of trials but remained the same within a block) to determine whether the attentional inertia reported in our earlier study (Longman et al. 2013) was indeed ‘residual’ (asymptotic). In a control (location switching) condition, the participants switched locations while performing the same task throughout the experiment. In all CSIs task switching (but not location switching) induced a delay in fixating the task-relevant region of the stimulus and a tendency on switch trials to orient preferentially towards the irrelevant element of the stimulus that was previously relevant, as compared to the other irrelevant stimulus element. This ‘attentional inertia’ was reduced in conditions with longer preparation intervals but a substantial bias towards fixating the previously (but no longer) relevant region was still reliable at the two longest CSIs suggesting that it had reached an asymptotic minimum. Although a CSI of 1420 ms is relatively generous (in most task-switching experiments asymptotic preparation is achieved within 1 s or less), it is possible that the presence of a time limit may have encouraged rapid deployment of spatial attention (i.e., before attentional parameters have been fully reconfigured), such that other TSR processes can also occur during the preparation interval. Thus, a bias towards speed over accuracy in spatial orienting might explain why a component of attentional inertia is seemingly immune to preparation (the same reasoning is invoked for explaining the absence of attentional inertia at the longest CSI in Experiment 5, Chapter 4). In Experiment 2 (Chapter 2) the tendency to fixate the previously (but no

longer) relevant region over the other irrelevant region on switch trials was eliminated (by fixating the currently relevant region) on average by ~700 ms after cue onset – several hundred milliseconds before stimulus onset in the long CSI blocks. This effort to orient rapidly may at least in part explain the vulnerability to the carryover of the most recent attentional settings on long CSI trials. A pertinent question is therefore whether one would observe any such inertia without a deadline on preparation.

Arrington, Logan & Schneider (2007) used a ‘dual response’ paradigm to investigate the extent to which pre- and post-stimulus processes contribute to the switch cost, in which participants were required to press a key when they were ready for the stimulus to be presented. Their design is of interest for the current experiment because it used a methodology which one can adapt to differentiate early (e.g., attentional selection) and late (post-attentional) pre-stimulus TSR stages. If attentional inertia can be eliminated by such a manipulation then it would appear that the previously reported asymptotic component of attentional inertia might be strategic – participants may find an acceptable balance between the speed of attentional selection and its accuracy, so as to enable them to complete (or at least initiate) other stages of TSR before stimulus onset. If the criterion is shifted towards accuracy (by removing time constraints) the bias towards fixating the previously relevant region (relative to the other irrelevant region) on switch trials may be reduced or altogether eliminated.

The current experiment was designed to test this conjecture directly. By employing certain features of eye-tracking it is possible to grant the participant control over the timing of the preparation interval, without having to ask them to engage in any extra behaviours (such as making an extra key press, cf. Arrington et al., 2007). The cues and stimuli were identical to those used in Experiment 2 (Chapter 2) but the participant was able to initiate stimulus onset by shifting their gaze from the cue to any of the three critical stimulus regions. By recording eye movements from cue onset it

was therefore possible to establish whether attentional inertia can be eliminated by putting the CSI under the participant's control.

Method

Participants

Eighteen participants (10 female, mean age = 21.54), were either paid £10 (£5/hr) or awarded partial course credits plus a performance-related bonus of up to £4.50 for their participation.

Tasks, stimuli and procedure

The experiment was run using Experiment Builder (SR Research, Ottawa, Canada) on a flat-screen (zero curvature) 17" CRT monitor placed ~57 cm from the participants' eyes (at this distance 1° of visual angle corresponds to ~1 cm on the monitor). Each trial started with a blank screen followed by a centrally presented black fixation cross (subtending 0.4°) presented at one of three response-fixation intervals (RFIs; 700 ms, 1200 ms, 1700 ms; randomised over trials, but equiprobable for each task, transition type and level of each element within the stimulus). The three RFIs were used in order to permit analyses — as explained later — that unconfound the time available for preparation from that available for passive decay of task-set (cf. Meiran, 1996). After the fixation cross had been visible for 400 ms (minimum) and then fixated for a further 100 ms it was replaced with a task-cue ("ODD?", "EVEN?", "LOW?", "HIGH?", "INNER?", "OUTER?" subtending up to 0.8° horizontally, 0.3° vertically) accompanied by three light blue dots (0.3° in diameter) at the locations where the digits would eventually appear (see Fig. 5.1). Trials on which the interval between the onset of the fixation cross and the onset of the cue exceeded 1000 ms (assumed to reflect problems with the eye-tracking system) were omitted from all analyses (1.07%). The

cue changed on every trial, thereby unconfounding task switching and cue switching (cf. Logan & Bundesen, 2003; Monsell & Mizon, 2006). Participants were instructed that the cue would remain visible as long as it was fixated and that the stimulus would appear as soon as they moved their eyes towards one of the stimulus elements. This was implemented by presenting the stimulus as soon as the gaze crossed the boundary of one of the invisible square (side = 2°) regions centred on each of the three stimulus elements. Participants were instructed that "...the cue will stay on screen as long as you are looking at it and as soon as you move your eyes the stimulus will appear so you can take as long as you need to prepare...". They were therefore able to self-impose the time available for preparation. The stimulus remained on screen until a response was made by pressing one of the keys ('c' or 'm') on a standard QWERTY keyboard. If an incorrect response was made "ERROR" was displayed for 1000 ms before the start of the next trial.

The stimulus comprised three digits (each subtending 0.4° horizontally, 0.5° vertically) displayed at the points of an invisible equilateral triangle, 5° from each other and 2.7° from the central location of the cue. The cue specified the classification task to apply: odd vs. even; low (≤ 5) vs. high (≥ 6); "inner" (4, 5, 6, 7) vs. "outer" (2, 3, 8, 9); with each task mapped to a single location throughout the experiment (counterbalanced over participants). Stimuli were generated 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 transition type, task and RFI.

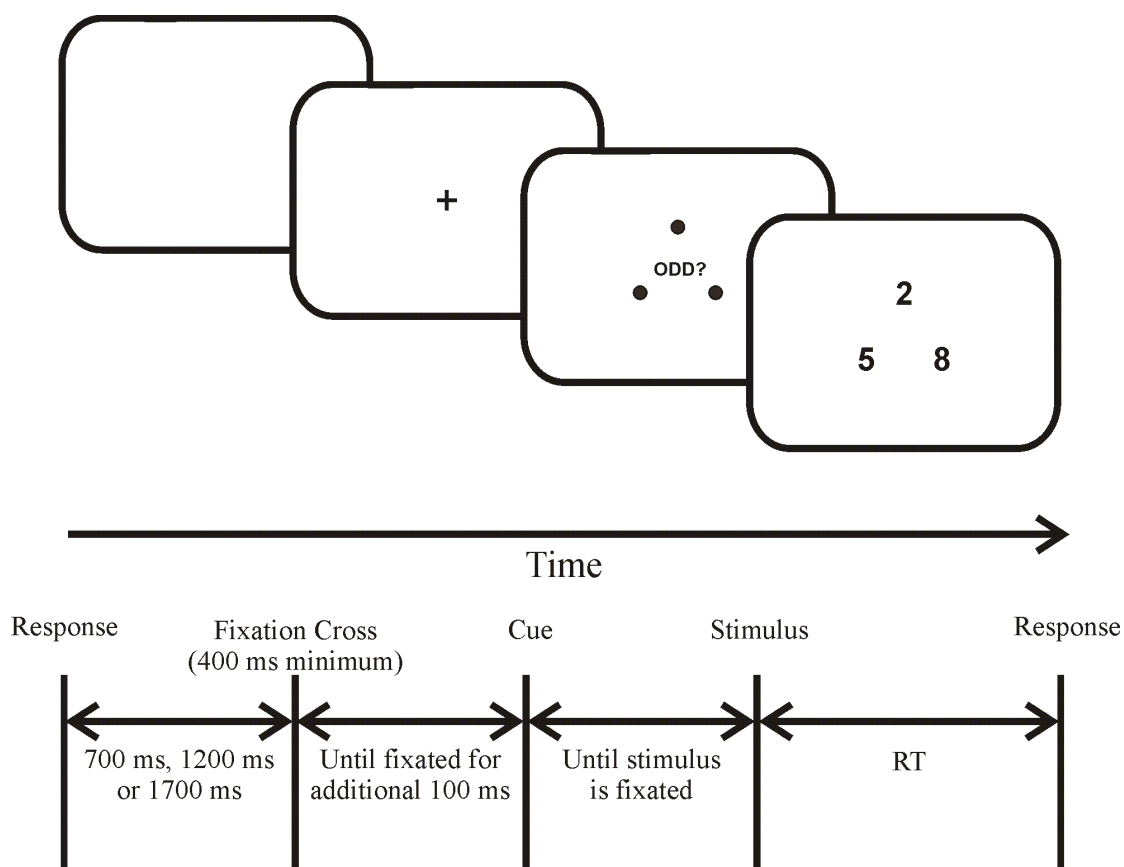


Figure 5.1. The time-course of one trial with example displays. The dots used to identify where the digits would eventually appear were presented in light blue.

The tasks were equiprobable, so the task switch:repeat ratio was 2:1. 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.

Before the eye-tracking session, participants practiced the three tasks in an 8-trial block each, followed by a 74-trial task-switching block in which only one digit was presented centrally on each trial. Location-task mappings and the gaze-contingent timing of the cue-stimulus interval were then introduced in two further practice blocks of 74 trials each, identical to the experimental blocks which followed.

Eye-tracking

An EyeLink 1000 eye-tracker (SR Research, Ottawa, Canada) recorded the movements of the right eye from the onset of the blank screen until response; it was calibrated before each 74-trial block. Four square regions (side = 2°) were delineated as containing ‘relevant’ information for the three digits in the stimulus and the cue. The proportion of all fixations to land in these regions on both switch and repeat trials was 91.19%. The first two trials in each block, trials with RT > 2500 ms (1.14%) and trials following an error were omitted from all analyses. Error trials were also omitted from RT and eye-tracking analyses.

Only fixations initiated after cue onset were analyzed. The 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) was submitted to statistical analysis.

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

Results

Cue-stimulus interval (CSI)

Participants spent more time fixating the cue before initiating an eye-movement away from it on switch (746 ms) than on repeat trials (679 ms). In order to assess the extent to which preparation influenced performance, trials were grouped into quartiles according to the duration of this ‘self-generated CSI’. This was computed separately for each condition in every participant to ensure that no single participant or condition contributed more data points to any CSI quartile. The mean CSIs for the quartiles were: 466 ms, 558 ms, 671 ms, 1134 ms. All performance and eye-tracking data were analysed including these as levels of the factor CSI.

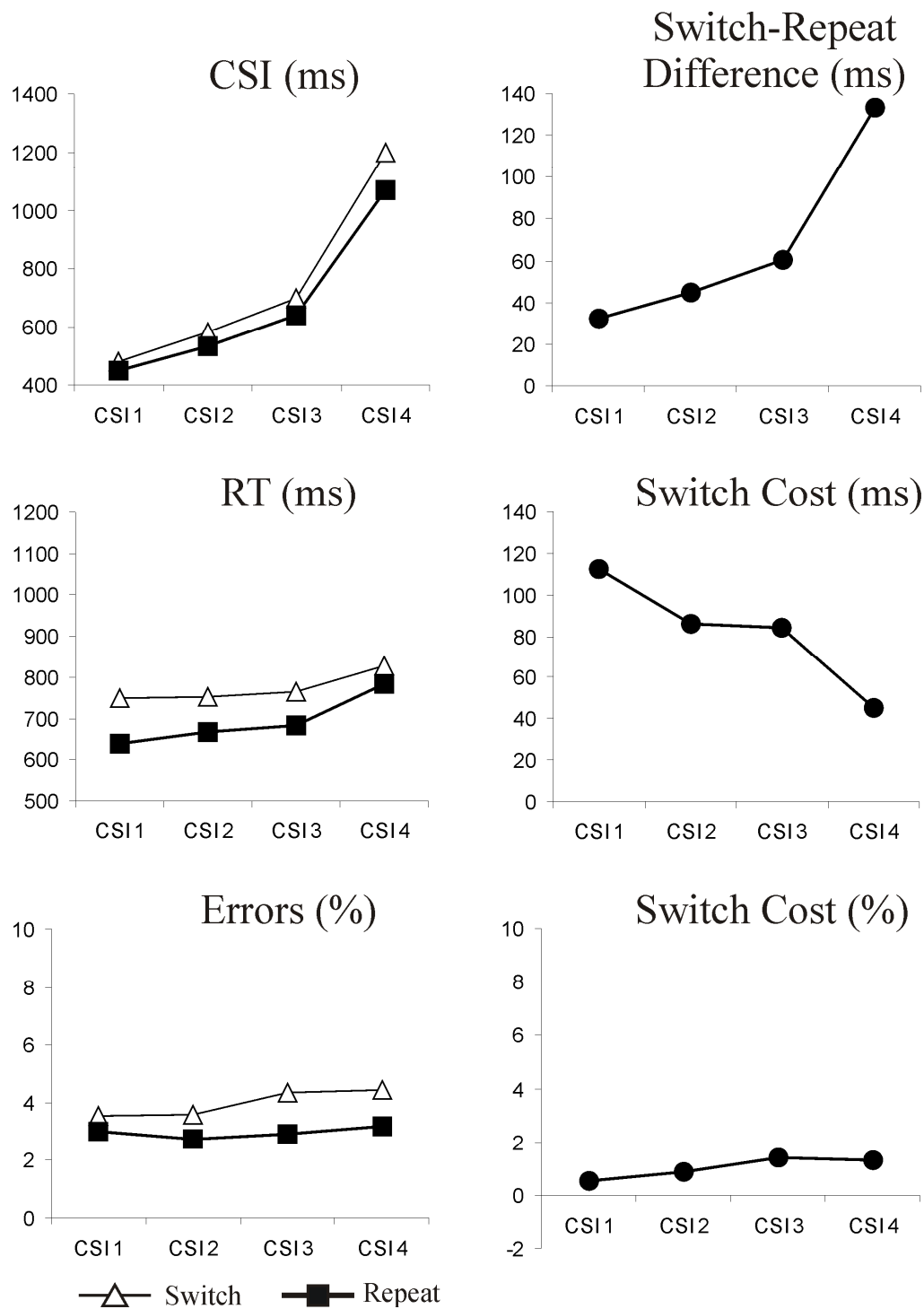


Figure 5.2. Mean cue-stimulus interval (CSI) (top), RT (middle) and error rate (bottom) as a function of CSI and transition (switch, repeat). The column on the right shows the (switch-repeat) difference for the CSI durations and switch costs for the behavioral data.

Figure 5.2 shows the mean CSIs, RTs and errors averaged across all three tasks and RFIs. The CSI durations were submitted to an ANOVA with factors switch, CSI, task and RFI which found a reliable main effect of switch, $F(1,17)=33.62$, $p<0.001$, indicating that the cue was fixated for 68 ms longer on switch than repeats trials. The

switch-repeat difference in CSI duration increased from 32 ms at the shortest CSI to 133 ms at the longest (switch by CSI interaction, $F(3,51)=9.95$, $p=0.005$). Nonetheless, the effect was reliable for all quartiles (main effect of switch at CSI 1: $F(1,17)=47.83$, $p<0.001$; CSI 2: $F(1,17)=56.02$, $p<0.001$; CSI 3: $F(1,17)=38.04$, $p<0.001$; CSI 4: $F(1,17)=17.64$, $p=0.001$), suggesting that switching was associated with delayed orienting of task-relevant spatial attention for a very large portion of the entire distribution of CSIs. There were no other reliable interactions involving the factor switch in the analysis of CSI durations.

RT and errors.

An ANOVA with the factors switch, CSI, task and RFI on the RTs found a reliable switch cost of 82 ms, $F(1,17)=32.80$, $p<0.001$, which reduced with the self-imposed time allowed for preparation from 112 ms at the shortest CSI to 45 ms at the longest, $F(3,51)=8.34$, $p<0.001$ (switch by CSI interaction). The ‘residual’ switch cost was statistically significant in the longest CSI quartile, $F(1,17)=6.81$, $p=0.018$.

It is possible that the effects involving the factor CSI reflect not the time available for preparation, but the response-stimulus interval (RSI; time available for passive dissipation) which also increased at longer CSIs; these were necessarily confounded in the current design. To determine whether there is a detectable effect of RSI (which varied with RFI, CSI and, to a much lesser extent, the fixation cross-to-cue interval) we selected a subset of trials for which the RSI was within one standard deviation of the median RSI for the condition (collapsed across all three tasks). This resulted in a systematic variation in RSI with RFI (mean RSIs in order of increasing RFI were: 1858 ms, 2374 ms, 2895 ms) but the CSI was comparable for each RFI within a CSI quartile. The mean CSIs in order of increasing RFI for CSI quartile 1 were: 472 ms, 468 ms, 473 ms; CSI 2: 552 ms, 555 ms, 560 ms; CSI 3: 650 ms, 657 ms, 676 ms; CSI

4: 900 ms, 954 ms, 1003 ms. CSI 4 was excluded from the analyses which examined the effect of RFI within each CSI because the CSI duration substantially varied as a function of RFI in this quartile thereby confounding the time available for preparation and the time available for passive dissipation. An ANOVA with the factors RFI and switch on the RTs from each of the three shortest CSI quartiles (only including those trials selected as described above) found that the effects of RFI on overall performance were modest and did not systematically reduce as a result of the RFI: the switch cost in order of increasing RFIs for CSI 1 was: 100 ms, 140 ms, 118 ms; CSI 2: 69 ms, 102 ms, 96 ms; CSI 3: 53 ms, 80 ms, 86 ms. Neither the main effect of RFI nor its interaction with switch approached significance for any of the CSIs (all F 's < 2). The results from this analysis suggest that the reduction in switch cost with increasing CSI cannot be explained by passive dissipation and is therefore a consequence of active (endogenous) preparation.

However, a non-significant result in the ANOVA cannot be taken as evidence in favour of the null hypothesis (i.e., that performance is equal at all RFIs). We therefore used Bayesian statistics to estimate the likelihood that the null hypothesis is supported using the method proposed by Masson (2011). We computed the Bayes factors and the posterior probabilities of H_0 and H_1 using the sums of squares for the main effect of RFI and the RFI by switch interaction¹ for each CSI quartile (see Table 5.1). According to Raftery's (1995) classification of evidence based on probabilities into "weak" (0.5 – 0.75), "positive" (0.75 – 0.95), "strong" (0.95 – 0.99) and "very strong" (>0.99) there is 'positive' to 'strong' evidence in favour of H_0 and the evidence in favour of H_1 was less than 'weak' supporting the notion that the reduction in switch cost with CSI reflected

¹ Although Masson (2011) did not provide a method for computing n for interactions with >2 levels in a given factor, I followed the advice of Masson following a personal communication with my supervisor: $n \times (\text{df factor 1}) \times (\text{df factor 2})$. Although this method remains controversial it was the best strategy available at the time.

the time available for preparation and not the time available for passive dissipation of the previous task set.

Table 5.1.

Sums of Squares (Effect and Error) and the Posterior Probabilities of the Null Hypothesis (H_0) and Alternative Hypothesis (H_1) for the RTs as a function of CSI.

Comparison		CSI 1	CSI 2	CSI 3
RFI	Sum of Square (effect)	11595.72	1432.02	5905.41
	Sum of Square (error)	113174.61	162305.32	233047.26
	p H_0	0.861	0.968	0.958
	p H_1	0.139	0.032	0.042
RFI by Switch	Sum of Square (effect)	7154.46	5509.13	5788.22
	Sum of Square (error)	102720.54	155589.54	222953.78
	p H_0	0.915	0.951	0.958
	p H_1	0.085	0.049	0.042

A reliable switch cost was also found in the errors, $F(1,17)=5.13$, $p=0.037$, with participants making 1.0% more errors on switch than on repeat trials. This effect was not modulated by preparation, $F(3,51)<1$, but there was a reliable interaction between switch and task, $F(2,34)=4.88$, $p=0.014$. The error switch cost was 1.8% in the odd/even task, $F(1,17)=8.89$, $p=0.008$, 1.2% in the low/high task, $F(1,17)=5.04$, $p=0.038$, and 0.07% in the inner/outer task, although the latter was not reliable, $F(1,17)<1$.

Eye-tracking

Figure 5.3 shows the dwell time in the three stimulus regions described above (see Method) as a function of transition and CSI². We estimated the apparent delay in appropriate attention orientation on switch trials relative to repeats by first selecting a 200 ms window³ on the repeat curve starting from the 20 ms bin half way between cue onset and the first bin in which dwell time (averaged over participants) exceeded 95%

² The apparent discrepancy between the mean CSI duration (initial fixation landing time) and the dwell time curves in Figure 5.3 (early fixations at the longest CSI are prior to the mean latency of the first fixation at the shortest CSI) is due to considerable variability between participants/conditions in the self-selected CSIs.

³ Because the portion of the dwell time curve with maximal rise in CSI quartile 4 was considerably longer than the other CSIs, we used a 400 ms window there.

of the maximum of the entire dwell-time function (see Fig. 5.3, left panels, for the window boundaries). For the dwell-time (y axis) value at every 2 ms point (the resolution of recording – 500 Hz) on the repeat curve we estimated the delay in the switch curve reaching this value using non-linear interpolation as introduced in Chapter 2 and applied in all the subsequent chapters. The estimated switch-related delays in order of increasing CSI quartile were: 131 ms, 85 ms, 63 ms, 186 ms. Four one-sample t-tests (one for each CSI) found that the estimated delay was reliable for all CSIs (CSI 1: $t(17)=5.74$, $p<0.001$; CSI 2: $t(17)=6.51$, $p<0.001$; CSI 3: $t(17)=4.65$, $p<0.001$; CSI 4: $t(17)=2.53$, $p=0.021$). A follow up ANOVA with the factor CSI found that the differences in the delay in appropriate attention orientation with CSI quartile did not reach significance, $F(3,51)=2.19$, $p=0.154$.

The dwell time on the currently irrelevant regions (Fig. 5.3, right panel) was analysed in two contiguous 500 ms windows starting 200 ms after cue onset. ANOVAs with the factors switch, CSI, task and RFI were run on the dwell time in the early and late windows separately. Both analyses found a tendency to fixate the irrelevant regions more on switch trials than repeats (early window, $F(1,17)=18.90$, $p<0.001$; late window, $F(1,17)=20.11$, $p<0.001$). The effect was reduced at longer preparation intervals in both windows (early, $F(3,51)=10.10$, $p<0.001$; late, $F(3,51)=4.22$, $p=0.017$), but remained reliable (or approached significance) in all but the longest CSI quartile (early window: main effect of switch in CSI 1, $F(1,17)=26.49$, $p<0.001$; CSI 2, $F(1,17)=4.90$, $p=0.041$; CSI 3, $F(1,17)=3.32$, $p=0.086$; CSI 4, $F(1,17)<1$; late window: CSI 1, $F(1,17)=11.83$, $p=0.003$; CSI 2, $F(1,17)=10.72$, $p=0.004$; CSI 3, $F(1,17)=21.51$, $p<0.001$; CSI 4, $F(1,17)=1.54$, $p=0.232$). There was also a reliable interaction between switch, CSI and task in the early window, $F(6,102)=4.43$, $p=0.003$, which approached significance in the late window, $F(6,102)=2.02$, $p=0.075$. The follow-up analyses by task found a systematic reduction in the tendency to fixate the irrelevant regions on switch trials

relative to repeats with increasing CSI only for the inner/outer task in the early window, $F(3,51)=11.85$, $p<0.001$, (switch by CSI interaction).

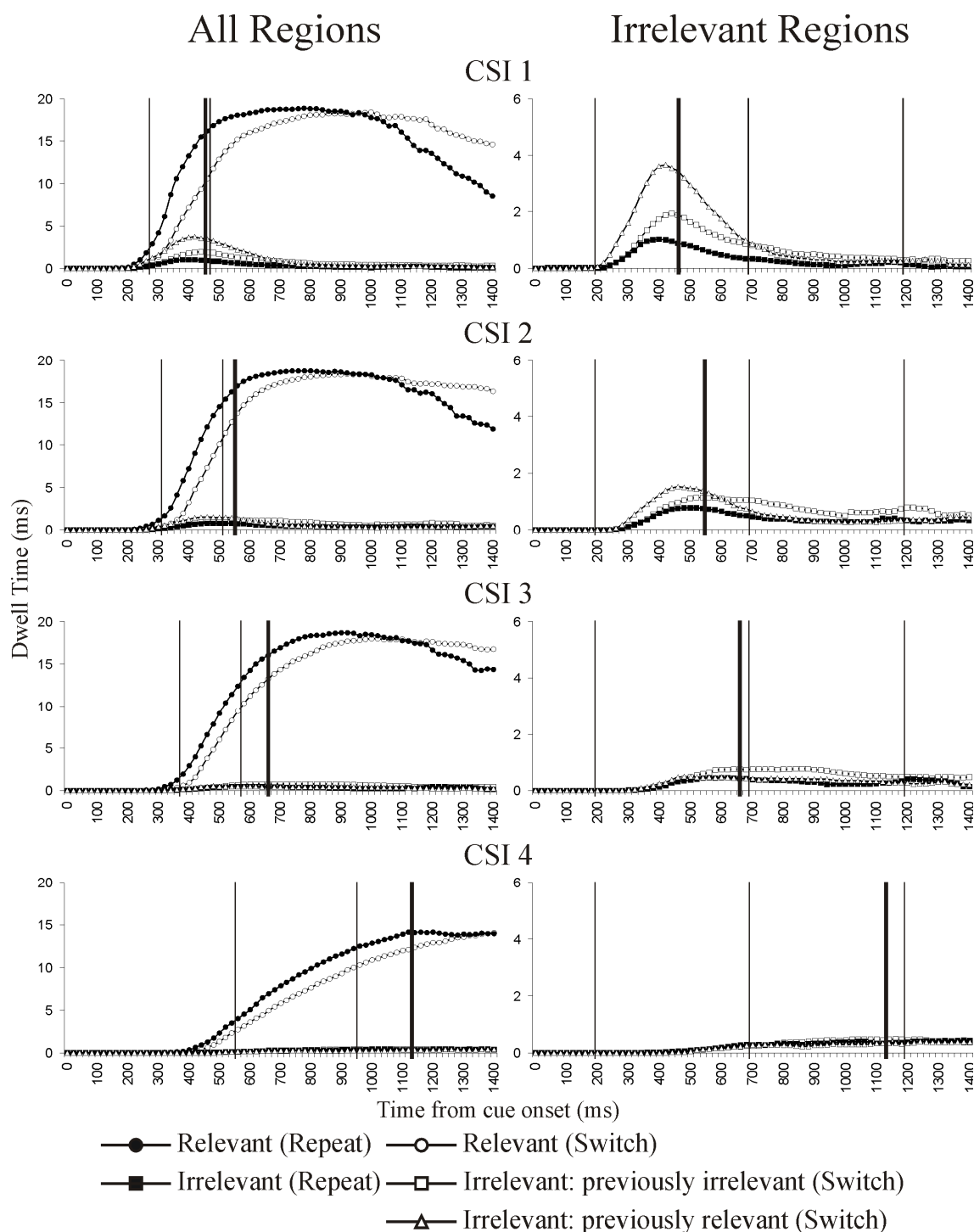


Figure 5.3. Dwell time per 20 ms (see text for definition) for 1420 ms following cue onset as a function of CSI quartile, transition (switch, repeat) and task-relevance of stimulus region. The left panel shows the fixations on both the relevant and irrelevant regions, whereas the right panel shows only the fixations on the irrelevant regions (with the scale adjusted accordingly). Thick vertical lines indicate the mean stimulus onset time, thin vertical lines show the time-windows used for statistical analysis.

In an effort to capture attentional inertia, we submitted to an ANOVA the dwell time in the currently irrelevant regions on switch trials with the factors previous relevance (previously relevant, previously irrelevant), CSI, task and RFI, for the same time-windows as above. In the early window the tendency to fixate the previously relevant region over the other irrelevant region was marginally significant, $F(1,17)=4.16$, $p=0.057$, and reduced as a function of CSI, $F(3,51)=7.19$, $p=0.005$. Inspection of Figure 5.3 (right panels) shows that the tendency to fixate the previously relevant region over the other irrelevant region in the early window was present in the shortest CSI quartiles but reversed somewhat in the longest (mean differences are presented in Table 5.3). Follow up ANOVAs for each CSI quartile found that the main effect of previous relevance was reliable only in the shortest CSI (CSI 1, $F(1,17)=7.93$, $p=0.012$; CSI 2: $F(1,17)<1$; CSI 3, $F(1,17)=1.68$, $p=0.212$; CSI 4, $F(1,17)<1$). In order to confirm that attentional inertia had been eliminated at the longer CSIs, Bayesian statistics were computed for the dwell time in the irrelevant regions for each CSI quartile in the same way as for the RTs (see above). Inspection of Table 5.2 shows that the evidence for H_1 was ‘strong’ for CSI 1 only and that evidence for H_0 was ‘positive’ to ‘very strong’ at the three longest CSIs indicating that attentional inertia was only present in the shortest CSI and was eliminated at the longer CSIs.

Table 5.2.

Sums of Squares (Effect and Error) and the Posterior Probabilities of the Null Hypothesis (H_0) and Alternative Hypothesis (H_1) for Dwell Time on the Irrelevant Regions on Switch Trials as a function of CSI.

	CSI 1	CSI 2	CSI 3	CSI 4
Sum of Square (effect)	50101.60	2192.48	185.86	0.03
Sum of Square (error)	107413.56	42664.87	1876.76	465.60
pH_0	0.035	0.936	0.868	0.973
pH_1	0.965	0.064	0.132	0.027

Table 5.3 shows the mean difference in dwell time between the currently irrelevant regions on switch trials averaged across all three tasks for the early and late

windows. Although neither the main effect of RFI, $F(2,34) < 1$, nor its interaction with previous relevance, $F(2,34) < 1$, were reliable in the omnibus ANOVA for the early window, in order to ascertain whether the reduction in this index of attentional inertia with increasing CSI reflected the duration of the preparation interval, rather than passive dissipation of the previous task-set parameters, follow up analyses were performed for the three shortest CSIs with the factors RFI and previous relevance (using only the subset of trials selected in the same way as for the corresponding RT analysis above). Although the main effect of RFI approached significance in the shortest CSI, it was not reliable in the longer CSI quartiles (main effect of RFI at CSI 1, $F(2,34) = 3.13$, $p = 0.061$; CSI 2, $F(2,34) = 1.92$, $p = 0.168$; CSI 3, $F(2,34) = 2.42$, $p = 0.104$) and the RFI by previous relevance interaction did not approach significance in any CSI (all F 's < 1) suggesting that the effect of CSI was explainable predominantly by the duration of the preparation interval rather than the time available for passive dissipation of attentional settings.

Table 5.3.
Mean (Standard Error) Difference (Previously Relevant-Previously Irrelevant) in Dwell Time in the Currently Irrelevant Regions on Switch Trials in the Early and Late Time Windows as a Function of CSI and RFI.

	RFI	CSI 1	CSI 2	CSI 3	CSI 4
Early Window	700	28.74 (9.95)	5.21 (7.5)	-0.69 (1.81)	0.18 (0.77)
	1200	22.43 (9.02)	5.53 (5.82)	-3.49 (1.4)	-0.3 (1.05)
	1700	23.44 (9.13)	4.87 (4.87)	-0.37 (1.64)	0.07 (0.6)
	Mean	24.87 (8.83)	5.2 (5.57)	-1.51 (1.17)	-0.02 (0.58)
Late Window	700	-3.75 (2.52)	-10.07 (4.93)	-6.15 (3.25)	-1.28 (2.54)
	1200	-1.66 (3.08)	-3.69 (5.18)	-13.21 (2.82)	-3.37 (2.76)
	1700	-3.65 (3.04)	-12.41 (4.84)	-1.97 (4.57)	-4.13 (1.94)
	Mean	-3.02 (1.81)	-8.72 (3.47)	-7.11 (2.84)	-2.93 (1.48)

In order to confirm that the reduction in this measure of attentional inertia was due to the time available for preparation and not the time available for passive dissipation of the previously relevant attentional settings, Bayesian statistics were computed in the same way as for the RTs (see above). Inspection of Table 5.4 shows

that the evidence in favour of H_0 is ‘positive’ for the main effect of RFI and ‘positive’ or ‘strong’ for the RFI by previous relevance interaction and the evidence in favour of H_1 is less than ‘weak’ for both comparisons at all CSIs indicating that RFI did not substantially affect performance.

The ANOVA run to investigate attentional inertia in the late window found an overall tendency to fixate the previously relevant region *less* than the other irrelevant region, $F(1,17)=7.82$, $p=0.012$. The previous relevance by CSI interaction approached significance, $F(3,51)=2.48$, $p=0.088$, but inspection of Table 5.3 shows that there was not a systematic modulation of this effect by CSI. Follow up ANOVAs demonstrated that the tendency to fixate the previously relevant region less than the other irrelevant region was reliable only in CSI quartiles 2 and 3 (main effect of relevance in CSI 1, $F(1,17)=2.78$, $p=0.114$; CSI 2, $F(1,17)=6.39$, $p=0.022$; CSI 3, $F(1,17)=6.27$, $p=0.023$; CSI 4, $F(1,17)=3.91$, $p=0.064$).

Table 5.4.

Sums of Squares (Effect and Error) and the Posterior Probabilities of the Null Hypothesis (H_0) and Alternative Hypothesis (H_1) for Dwell Time on the Irrelevant Regions in the Early Window on Switch Trials as a function of CSI.

Comparison		CSI 1	CSI 2	CSI 3
RFI	Sum of Square (effect)	1411.59	776.01	355.28
	Sum of Square (error)	7665.70	6873.23	2495.35
	pH0	0.632	0.84	0.766
	pH1	0.368	0.16	0.234
RFI by Previous Relevance	Sum of Square (effect)	65.00	554.26	177.87
	Sum of Square (error)	15460.16	11941.93	3030.41
	pH0	0.971	0.941	0.928
	pH1	0.029	0.059	0.072

Discussion

We investigated the robustness of attentional inertia in a task-cuing experiment in which the duration of the preparation interval was controlled by the participant. Participants were able to initiate the stimulus onset by shifting their gaze from the cue to one of the elements of the compound stimulus with no limit imposed on the time

available for preparation. The unconventional features of the current design (e.g., the gaze-contingency of displays) did not greatly alter the behavioural effects commonly reported in task switching experiments: switch cost, its reduction with preparation and its residual component. It could be argued that the pattern of RTs suggest a *repetition benefit* rather than a switch cost (i.e., repeat trials benefit from carryover of task-set parameters as opposed to switch trials suffering due to the cost of active reconfiguration) because the primary difference between switch and repeat RTs over CSIs appears to be in the performance on repeat trials. However, an alternative interpretation is that performance worsens on both trial types as participants use additional preparation time (suggesting that they take longer to prepare when they struggle with the task) coupled with an improvement in performance over CSIs on switch trials (indicating that the time they use to prepare when they struggle is effectively used to actively switch between task-sets). The research reported in Chapter 2 indicated that task switching is associated with inertia in spatial attention (preferential fixation of the previously relevant stimulus element on switch trials) and delayed fixation of the currently relevant stimulus element. By imposing no time limit on preparation we were able to eliminate the former but not the latter.

Our measure of attentional inertia (the preferential fixation of the previously relevant region over the other irrelevant region on switch trials) was only significant in the early window and only in the shortest CSI quartile. Conventional statistics revealed no inertia for the longer CSI quartiles and Bayesian statistics indicated this null effect was robust. There was however an increased general tendency to fixate the task-irrelevant regions (irrespective of relevance on the preceding trial) during switches relative to repeats. This tendency may reflect weaker (and noisier) activation of attentional settings on switch trials or increased distractibility or some combination of the two. There was little effect of RFI (as assessed orthogonally to CSI) on fixations on

the irrelevant regions suggesting that passive dissipation of attentional settings had little or no impact on across-trial attentional dynamics.

In order to assess the effects of preparation we divided the trials into quartiles based on the self-generated CSI. Because the time allowed by the participants for preparation was necessarily confounded with the time available for passive dissipation, we introduced extra variability in RSI by varying the onset of the fixation cross (RFI). The analysis of the effect of RFI and its interaction with switching in each CSI quartile ensured that the reduction in switch cost with increasing CSI did indeed reflect preparation and not passive dissipation.

The analysis of CSI durations (i.e. the time spent fixating the cue) showed that the time taken to initiate an eye-movement away from the cue was longer on switch than repeat trials and that this difference grew in the longer CSI quartiles. Together with the finding that attentional inertia was reduced by preparation and altogether absent at longer CSIs suggests that effective reconfiguring of attentional parameters takes time but it can result in the elimination of inertia in spatial attention. Despite the fact that the switch-repeat difference in the time it took to initiate an eye-movement away from the cue was greater for the longest CSI quartile, the switch-induced delay in fixating the task-relevant region was not notably different across CSI quartiles. The likely reason for this is the greater number of fixations on the task-irrelevant regions (particularly the previously-relevant) on the trials with the shorter CSIs.

In conclusion, the present set of results suggests that the tendency to fixate the previously (but no longer) relevant region during a task-switch – an index of task-dependent carryover of spatial attentional settings – can be eliminated by preparation. Its apparent ‘residual’ (asymptotic) component, which I reported in Chapter 2, may be due to strategic adjustments in the ‘speed-accuracy’ trade-off in conditions of time-limited preparation intervals. It is worth noting that the mean CSI in the longest CSI

quartile in the present study roughly equalled the mean of the two longest CSIs in the experiments reported in Chapter 2 (1020 ms and 1420 ms) for which there was clear attentional inertia. Thus similar preparation intervals resulted in markedly different fixation patterns depending on whether it was determined intrinsically (the present study) or extrinsically (Chapter 2). Presumably, when the duration of the preparation interval is determined extrinsically (even if the interval is long) participants feel compelled to reorient attention before the appropriate settings have been updated for the current task-goal (at least on a proportion of trials). Furthermore, a fixed CSI does not allow the cognitive control system to adjust the preparation interval according to the self-perceived readiness (or according to the need for more preparation), which likely occurs when the CSI is under the participant's control. Nonetheless, preparation remains a time-consuming process whether the preparation interval is determined extrinsically or intrinsically. Indeed, the delay in appropriate orienting of attention (indexing the time taken for reconfiguration of task-relevant attentional settings) seems to be broadly consistent (at least within each experimental paradigm) whatever the duration of the preparation interval.

6

Spatial attention in task switching with stimuli containing task-specific features

Introduction

In all of the experiments documented thus far in this thesis, each composite stimulus was constructed from three digits (indo-arabic numerals) placed at the corners of an invisible equilateral triangle. This was intended to ensure that each stimulus element could only be selected via (task-related) spatial attention and not attention to dimensions or specific perceptual features associated with particular classes of stimuli. The experiment described in this chapter re-introduces the possibility of attentional selection via perceptual features in order to investigate the extent to which (endogenous) spatial selection can block (post stimulus) capture of attentional selection via (exogenous) task-relevant perceptual salience.

Two recent reports which used eye-tracking to investigate an attentional component of task-set (Longman et al., 2013; Mayr et al., 2013) both documented task-switch-induced handicaps in attentional selection via locations and features. However, neither study obtained an online record of reconfiguring attention prior to stimulus onset. In Experiments 1 and 2 (Chapter 2) I used eye-tracking to investigate the time-course of orienting spatial attention during the preparation interval. In addition to reporting a task-switch-induced delay in appropriate attention orientation, I also describe an analysis only possible with >2 tasks (thus absent in the previously reported eye-tracking studies) which showed that a task switch resulted in a stronger tendency to fixate the previously (but no longer) relevant attribute than the other (previously irrelevant) irrelevant attribute, suggesting ‘attentional inertia’ over and above mere distractibility. Furthermore, the use of four preparation intervals showed attentional

inertia to have a residual component (it persisted into the longest CSI) which an earlier investigation that used two CSIs (Longman et al., 2013) could only suggest.

In addition to the above-mentioned eye-movement effects, the design I introduced in Chapter 2 allowed the analysis of three types of response congruence: the digit at the relevant location afforded the responses for the relevant or the irrelevant tasks (which we referred to as ‘within-location’ congruence); the three digits each afforded responses according to the tasks associated with the respective locations (‘cross-location’ congruence); the digits at irrelevant locations afforded the responses according to the task at the relevant location (‘flanker’ congruence). Each of these types of congruence had three levels; for example flanker congruence had the levels: congruent (all three digits were associated with the same response), incongruent (the two irrelevant digits were associated with a response that conflicted with the correct response) and semi-congruent (the intermediate case, where one of the irrelevant digits required the same response as the relevant digit). These analyses revealed that there was little or no effect of cross-location congruence or flanker congruence; only within-location congruence had a (relatively modest) effect on performance. This shows that, despite the substantial early tendency to misallocate attention to the no longer relevant locations, the digits at irrelevant locations were not processed enough to influence response selection. This conclusion is supported by the absence of a detectable tendency to fixate the irrelevant digits after stimulus onset on long CSI trials.

The above finding suggests that, once deployed appropriately spatial attention effectively blocked the processing of features at the irrelevant locations during a task-switch. The present investigation aims to further test the effectiveness of such spatial selection in task-switching by introducing a further potential contributor to task-set inertia. In the experiments described in Chapter 2, all three elements of the compound stimulus were homogenous with respect to their features – they were all digits. In the

present study the constituent elements of the compound stimulus come from perceptually different classes: digits, letters and objects (the associated tasks are three semantic categorizations specific to these domains: odd vs. even, vowel vs. consonant and living vs. man-made). The differential features of the digits, letters and objects require the activation of the respective sets of features in order to perform the respective categorisations. I reasoned that the carry-over (inertia) in the activation of these features may result in an extra ‘pull’ of attention towards the previously (but no longer) relevant stimulus attribute during a task switch, which could be reflected in (1) response congruence effects¹, and/or (2) increased post-stimulus fixations on the previously (but no longer) relevant attribute.

I preserved the spatially predictable stimulus layout used in the rest of the experiments documented in this thesis in order to permit pre-stimulus orientation of spatial attention, thus giving spatial attention a ‘head start’, particularly on long CSI trials. The key question is whether spatial selection during a task-switch is sufficiently robust to block processing of irrelevant stimulus attributes in conditions where task-set inertia comprises both spatial (location) settings (as in Chapter 2) and non-spatial (feature) settings (as in Longman et al., 2013).

Method

Participants

12 students from the University of Exeter (7 female, mean age = 20.67) were paid £10 (£5 per hour) for their participation and awarded up to a maximum additional

¹ Note that, unlike our previous paradigm (Chapter 2), the present design allows only for analysis of cross-location congruence effects; because each stimulus affords only one of the three categorizations (e.g., a digit cannot be classified as a vowel/consonant or as living/man-made), there cannot be within-location congruence and flanker congruence.

payment of £3.60 by winning bonus points for improving performance throughout the experiment.

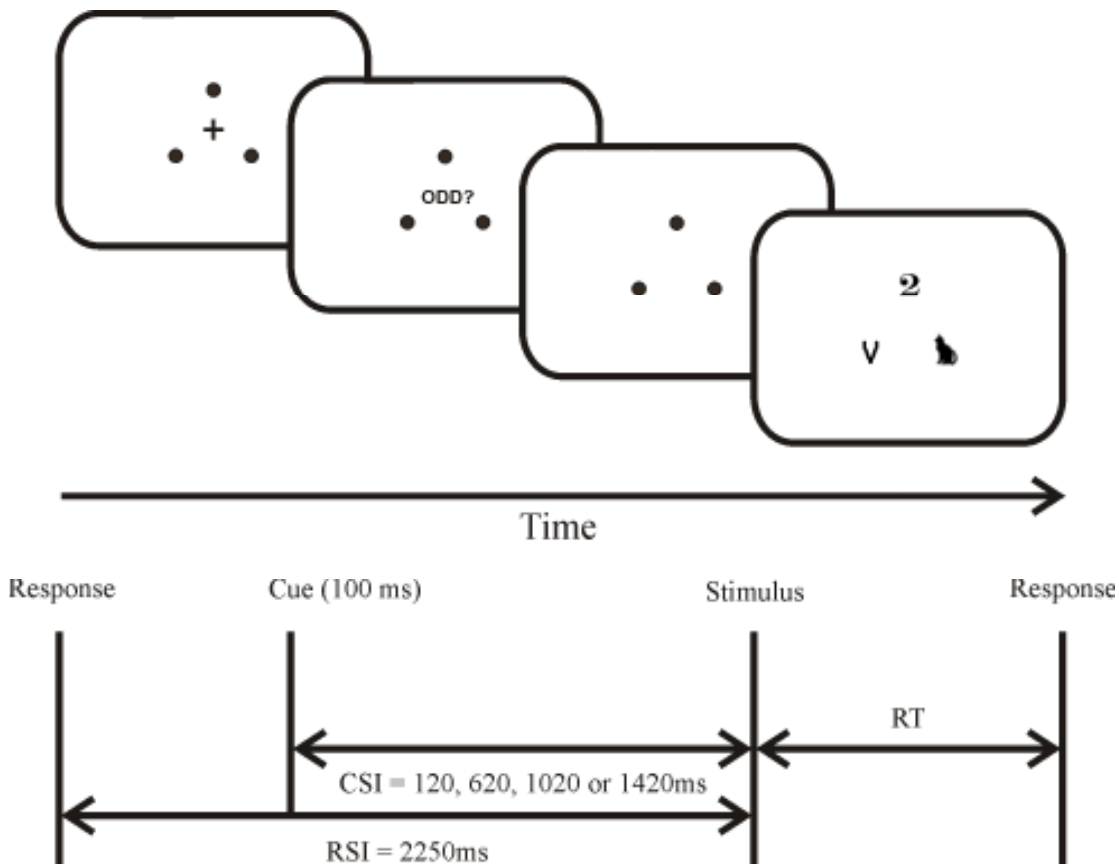


Figure 6.1. The time-course of one trial with example displays. The dots used to identify where the digits would eventually appear were presented in light blue.

Tasks, stimuli and procedure

The experiment was run using E-Prime (Psychology Software Tools Inc., Sharpsburg, USA) on a flat-screen (zero curvature) 17" CRT monitor placed ~57 cm from the participants' eyes (at this distance 1° of visual angle corresponds to ~1 cm on the monitor). 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 three part of the stimulus would eventually appear (see Fig. 6.1). A task-cue ('ODD?' or 'EVEN?' for the digit classification task, 'VOWEL?' or 'CONSNT?' for the letter classification task, 'LIVING?' or 'MADE?' for the object classification task,

subtending up to 1.0° horizontally, 0.3° 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, thus unconfounding task switching and cue switching (cf. Logan & Bundesen, 2003; Monsell & Mizon, 2006). CSI (120 ms, 620 ms, 1020 ms or 1420 ms) was constant within a 74-trial block, but varied from block to block; the order of CSIs within the 4-block sequences, of which a 16 block session was composed, was Latin-square-balanced over participants. The response-stimulus interval was 2250 ms regardless of CSI (to avoid confounding preparation with passive decay of control settings from the previous trial, cf. Meiran, 1996), except following an error when “ERROR” was displayed for an extra 1000 ms.

The stimulus comprised one digit, one letter and one object (each subtending up to 1.0° horizontally, 1.0° 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 stimuli were larger than in our previous experiments in order to maximise the interference from competing attributes while maintaining sufficient separation between the stimulus components to encourage eye-movements. The cue specified both the location of the item to be classified and the classification rule to apply: odd vs. even; vowel vs. consonant; living vs. man-made; with each task mapped to a single location throughout the experiment (counterbalanced over participants). The stimulus was displayed until one of two keys (‘c’ or ‘m’ on a standard QWERTY keyboard) was pressed with the left (odd, vowel, living) or right (even, consonant, man-made) index finger. Stimuli were generated by first defining the level (e.g., odd, vowel, living) of each item and then randomly selecting an item from the appropriate set (digits: 2-9; letters: A, E, I, U, F, H, J, V; objects: silhouette of cat, dog, fly, snail, drill, jug, lamp, tape dispenser, see Fig. 6.2) with one constraint: there could be no exact repetition from the previous trial of the whole stimulus (the same three items in the same locations).

Stimuli were also controlled to ensure that the combinations of categories of the three items (e.g. odd, consonant, living) were equiprobable for each task and transition type. The tasks were equiprobable, resulting in a 2:1 switch/repeat ratio.

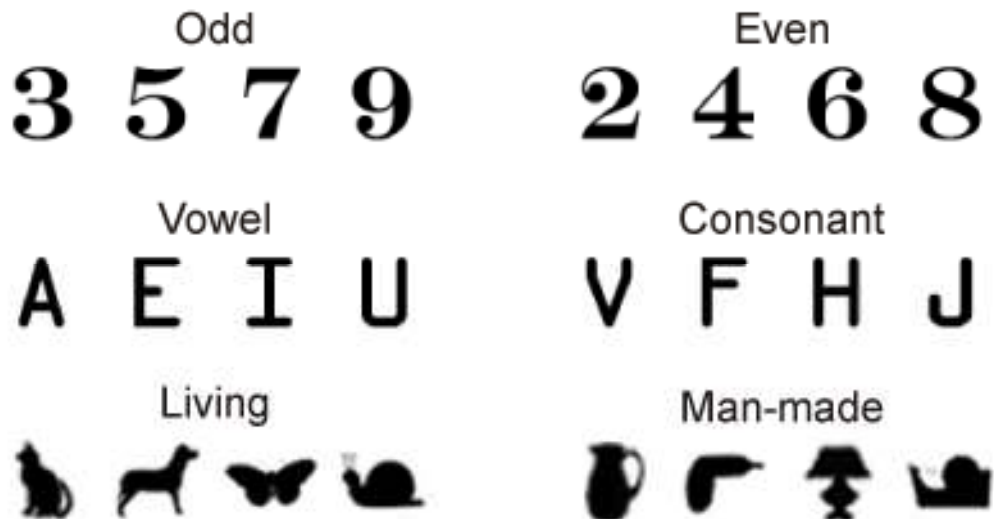


Figure 6.2. The complete stimulus set divided into appropriate classifications. Stimuli were selected to maximise perceptual differences between groups but minimize differences within groups to ensure each item should be fixated in order to make a correct response.

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, participants practiced each task in 8-trial blocks followed by a 74-trial task-switching block with each item displayed centrally. Task-location associations were subsequently introduced in a further task-switching block of 74 trials, identical to the experimental blocks which followed.

Eye-tracking

An EyeLink 1000 eye-tracker (SR Research, Ottawa, Canada) recorded the 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 delineated as containing

‘relevant’ information for the three items in the stimulus and the cue. On task-repeat trials, 89.92% of all fixations occurred within these regions; on task-switch trials, 89.77%. Blocks with >20% of trials containing no fixations in any of the three stimulus regions (suggesting poor calibration) were discarded (only one block from one participant was discarded due to this precaution). The first two trials in each block, trials with RT>2500 ms (0.46%), trials with no fixations on the cue (5.43%) and trials following an error were omitted from all analyses. Error trials were omitted from RT and eye-tracking analyses.

Only new fixations following cue onset were analyzed. Two measures 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 in the respective region within the respective time-window); (2) the ‘launch time’ of the first eye movement away from the cue limited to those trials on which the currently relevant region was the first to be fixated.

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

Results

RT and errors

Effects of switching. Mean response times (RTs) and error rates, averaged across all three tasks, can be found in Figure 6.3. An ANOVA with the factors switch (switch, repeat), CSI and task found a reliable switch cost in the RTs, $F(1,11)=49.08$, $p<0.001$, reflecting a performance overhead of 70 ms on switch trials relative to repeats. The switch cost reliably reduced as preparation time increased (CSI=120 ms: 115 ms; CSI=620 ms: 64 ms; CSI=1020 ms: 65 ms; CSI=1420 ms: 40 ms; Switch by CSI interaction: $F(3,33)=4.81$, $p=0.012$). There was also a reliable ‘residual’ switch cost at

the two longest CSIs (CSI=1020 ms: $F(1,11)=27.99$, $p<0.001$; CSI=1420 ms: $F(1,11)=32.30$, $p<0.001$) and although the switch cost continued to reduce as preparation time increased between the two longest CSIs, this further reduction merely approached significance (CSI by Switch interaction: $F(1,11)=3.90$, $p=0.074$). Switch also reliably interacted with task, $F(2,22)=8.41$, $p=0.002$, with the largest switch cost in the number task (115 ms) and the smallest in the object task (26 ms; letter task: 69 ms). There were no reliable effects or interactions involving the factor switch in the errors.

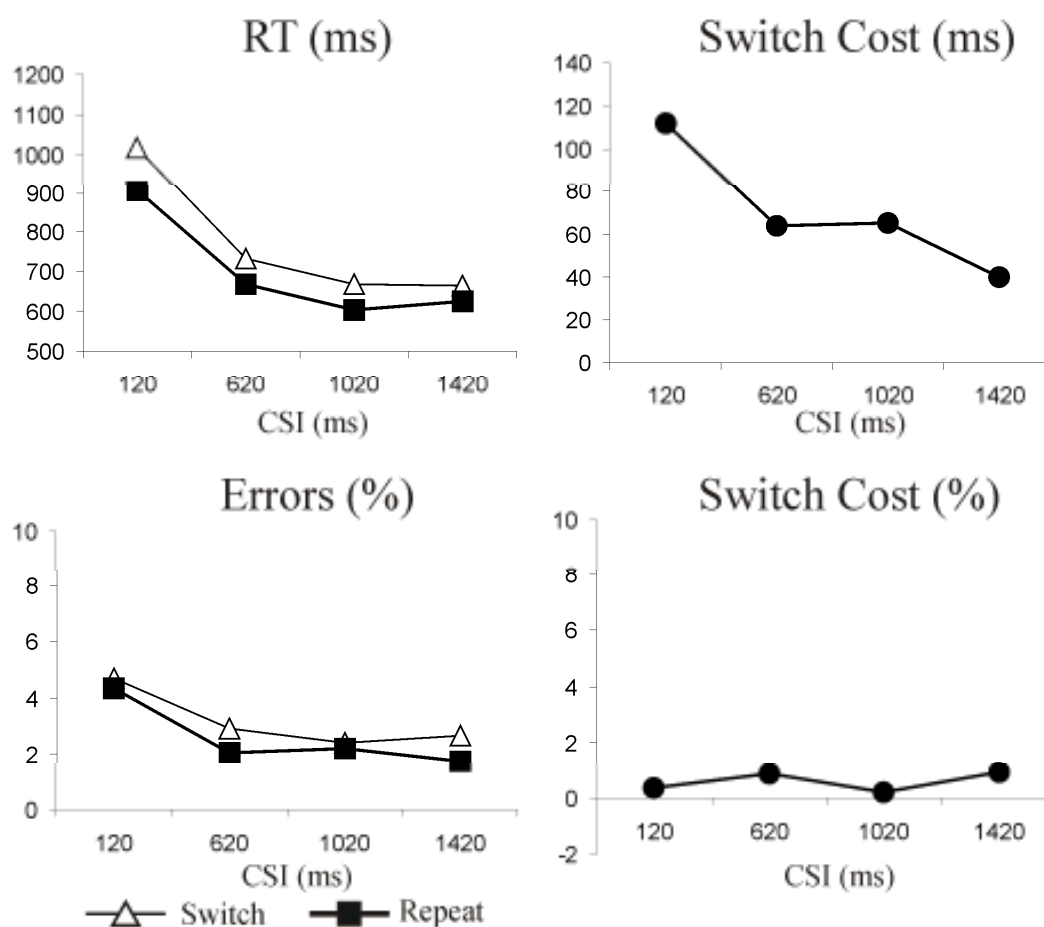


Figure 6.3. Behavioral data: mean RT, error rate and switch costs (right), as a function of cue-stimulus interval (CSI) and transition (switch vs. repeat).

Response congruence. To examine whether the irrelevant attributes of the stimulus were processed sufficiently to activate responses, we analysed (cross-location) response congruence with three levels (congruent, semi-congruent, incongruent; see Introduction). The small reversed congruency effect in the RTs (congruent: 740 ms,

semi-congruent: 736 ms, incongruent: 731 ms) did not approach significance, $F < 1$. In the errors the pattern was less straightforward (congruent: 2.39%, semi-congruent: 3.11%, incongruent: 2.82%) but was also non-significant, $F(2,22)=1.50$, $p=0.244$.

It is possible that a reliable congruence effect was not recorded because the data were diluted by the inclusion of both of the irrelevant elements in the analysis. Previous research (e.g., Chapter 2; Mayr et al, 2013) has demonstrated that the most likely irrelevant region to be fixated (processed) is the region which was relevant on the previous trial. By limiting the congruence analysis to switch trials and only considering these two stimulus elements (currently relevant and previously relevant) it is possible to investigate the extent to which processing of the previously relevant stimulus element affected response selection. An ANOVA on the RTs and errors from these trials with the factors congruence and CSI found a small congruence effect in the expected direction for the errors (congruent: 3.03%; incongruent: 3.28%) but a small reversed congruency effect for the RTs (congruent: 774 ms; incongruent: 769 ms); neither effect approached significance ($F_s < 1$).

N-2 sequence effects. A further phenomenon merits some consideration. ‘Backward inhibition’ (or ‘n-2 repetition cost’) – poorer performance on the third trials in a CBA sequence compared to an ABA sequence where A, B and C represent three tasks – is commonly accepted as the best evidence of task-set inhibition (e.g., Kiesel et al., 2010; Mayr & Keele, 2000). Our design and trial sequence (where tasks were equated for n-2 sequences) permitted an assessment of this effect. An ANOVA on switch trials with the factors ‘transition from trial n-2’ (switch, repeat), CSI and task found that the main effect of transition did not approach significance for RTs or errors ($F_s < 1$), but the interaction between transition and CSI did (RT: $F(3,33)=3.80$, $p=0.019$; errors: $F(3,33)=4.05$, $p=0.020$). In the RTs this represented a small but unreliable n-2 repetition *benefit* in all CSIs except CSI=620 ms which had a marginally reliable 41 ms

n-2 repetition cost, $F(1,11)=4.75$, $p=0.052$. In the error data $CSI=120$ and $CSI=1420$ had small n-2 repetition benefits and $CSI=620$ and $CSI=1020$ had small repetition costs. The only CSI with a reliable effect of n-2 transition in the errors was $CSI=1020$ ms, $F(1,11)=5.55$, $p=0.038$. Mean n-2 repetition costs for RTs and errors can be found in Table 6.1.

Table 6.1. Mean (Standard Error) N-2 Repetition Cost (n-2 Repeat Minus n-2 Switch) for RT and Errors at each CSI.

	CSI (ms)							
	120		620		1020		1420	
RT (ms)	-25.94	(17.14)	40.67	(19.49)	-11.36	(13.23)	-0.75	(14.65)
Errors (%)	-1.68	(1.02)	0.53	(0.78)	1.62	(0.72)	-0.76	(0.59)

Because there were no systematic effects of either response congruence or backward inhibition, neither were analysed for the eye-tracking data.

Eye-tracking.

Task switch-induced delay and attentional inertia. Dwell time on each stimulus region as a function of task-relevance and CSI can be found in Figure 6.4. To analyse the apparent delay in attention to the currently relevant region we estimated its duration in the same way as described in Experiment 1 (Chapter 2; see Fig. 6.4 for time-window boundaries). One sample t-tests on the estimated delays in fixating the task-relevant region for each CSI (estimated delay in order of increasing CSI: 82 ms, 61 ms, 60 ms, 62 ms) found them to be reliable at every CSI (in order of increasing CSI: $t(11)=3.36$, $p=0.006$; $t(11)=2.62$, $p=0.024$; $t(11)=3.52$, $p=0.005$; $t(11)=2.84$, $p=0.016$). An ANOVA with the factor CSI found no significant effect of the preparation interval on the magnitude of the delay, $F(3,33)<1$.

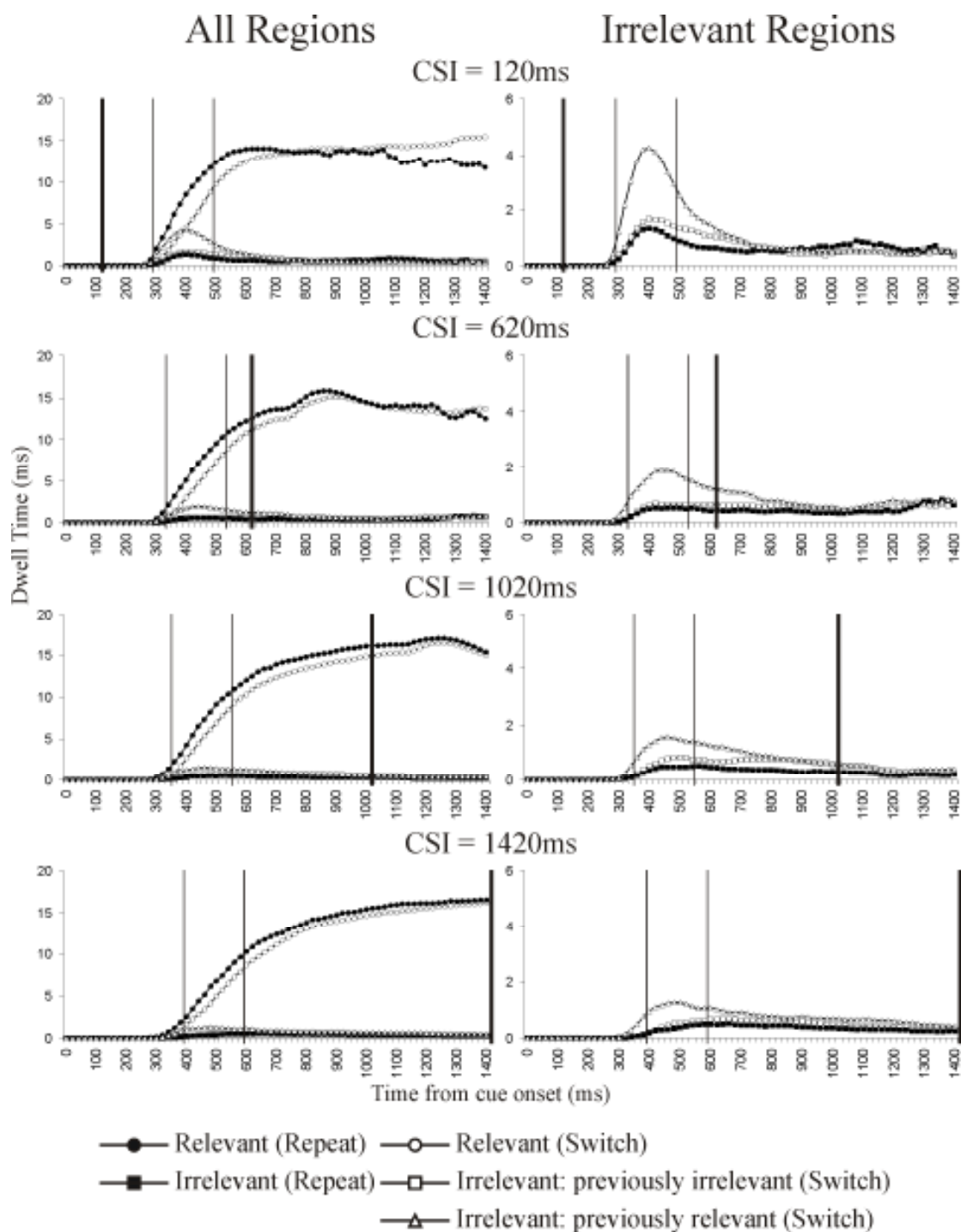


Figure 6.4. Dwell time per 20 ms bin (see text for definition) for 1420 ms following cue onset as a function of CSI, transition (switch, repeat) and task-relevance of stimulus region. The left panel shows the fixations on both the relevant and irrelevant regions, whereas the right panel shows only the fixations on the irrelevant regions (with the scale adjusted accordingly). Thick vertical lines 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 analysis of the dwell time on the currently irrelevant regions in the same 200 ms windows (Fig. 6.4. right column) found the previously reported measure of

attentional inertia (Chapter 2). On switch trials, participants tended to fixate the currently irrelevant region that was relevant on the previous trial more than the irrelevant region which was not (main effect of relevance: $F(1,11)=8.34$, $p=0.015$). This effect reduced in conditions with longer preparation intervals (relevance by CSI interaction: $F(3,33)=7.71$, $p=0.005$) and, although there was a numerical tendency suggesting that the effect remained in the longest CSIs, follow-up ANOVAs found that the effect was only reliable in the two shortest CSIs: main effect of relevance at CSI=120: $F(1,11)=15.09$, $p=0.003$; CSI=620: $F(1,11)=6.16$, $p=0.030$; CSI=1020: $F(1,11)=3.18$, $p=0.102$; CSI=1420: $F(1,11)=3.40$, $p=0.092$).

Although part of the delay in selecting the appropriate region is due to fixations on the irrelevant regions, it is also evident in the ‘launch time’ of the first saccade to leave the cue, even when the analysis is limited to the trials on which the first saccade to leave the cue landed directly in the currently relevant region (Fig. 6.5). An ANOVA on the mean launch times found a delay of 29 ms on switch trials relative to repeats (main effect of switch, $F(1,11)=11.73$, $p=0.006$). This seemed to be unaffected by the duration of the preparation interval (switch by CSI interaction, $F(3,33)<1$), but there was a reliable switch by task interaction, $F(2,22)=10.40$, $p=0.001$, representing a greater delay in the digit and letter tasks; for the object task the delay was non-significantly reversed (launch times were 6 ms faster on switch trials than repeats, $F(1,11)<1$). There was also a reliable three-way interaction between switch CSI and task, $F(6,66)=3.33$, $p=0.026$, indicating that the delay in launch times was in the expected direction for the two shortest CSIs in the objects task, and was only reversed in the two longest CSIs. In the other two tasks, the delay was in the expected direction in all CSIs.

These results are consistent with our previous findings that selection of the task-relevant stimulus location is delayed on switch trials relative to repeats, even when the analysis is limited to those trials where fixation was appropriately deployed from the

outset, and that when attention is misallocated on switch trials, there is a tendency to fixate the location that was relevant on the previous trial more than the irrelevant region which was not.

Whilst the above eye-movement analyses confirm the previously documented attentional effects, the principle aim of the current study is to investigate whether attention is attracted by stimulus attributes that were relevant on the previous trial even if attention has already been appropriately oriented to the currently relevant region.

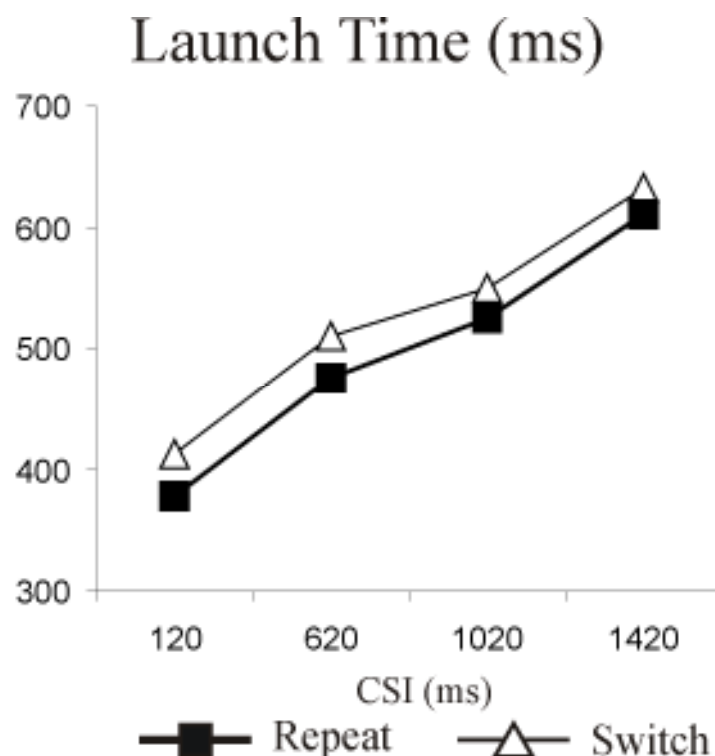


Figure 6.5. Mean ‘launch time’ of the first saccade to leave the cue (limited to those trials where the first saccade terminated in the currently relevant region) as a function of CSI and transition.

Post-stimulus dwell time. In order to distinguish between pre- and post-stimulus shifts of attention analysis of post-stimulus dwell time was limited to fixations initiated after stimulus onset (see Fig. 6.6). Post stimulus dwell time was analysed in a 300 ms window starting from 100 ms following stimulus onset (because in the shortest CSI post-stimulus fixations could reflect either initial orienting of spatial attention

and/or its subsequent reorienting, this CSI was omitted from further analysis leaving only three).

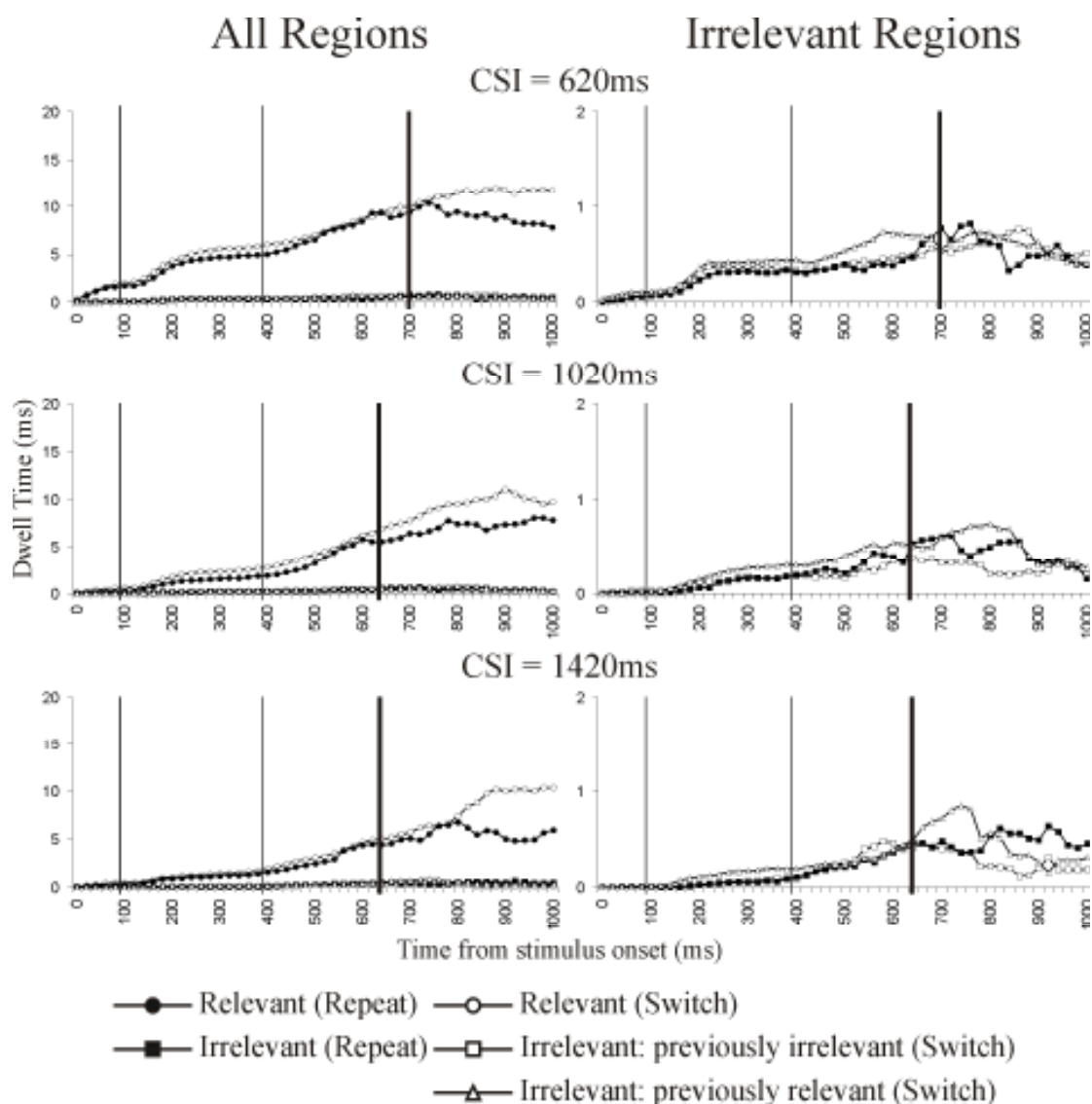


Figure 6.6. Mean dwell time from fixations initiated post-stimulus for 1020 ms following stimulus onset plotted as in Figure 6.4. Thick vertical lines show the mean RT and thin vertical lines the time-windows used for statistical analysis.

A switch by CSI by task ANOVA on the relevant dwell time in the critical time window found a reliable main effect of switch $F(1,11)=9.55, p=0.010$, indicating that more time was spent fixating the relevant region on switch trials than repeats. There was also a reliable switch by task interaction $F(2,22)=14.90, p<0.001$. Follow up ANOVAs found that the tendency to fixate the relevant region more on switch trials than repeats

was statistically significant in the digit task, $F(1,11)=32.57$, $p<0.001$, but not the letter task, $F(1,11)=2.32$, $p=0.156$, and although the tendency reversed slightly in the object task, this reversal was not reliable, $F(1,11)<1$.

Despite very small numbers of new fixations on the irrelevant regions after stimulus onset there was a marginally reliable tendency, on switch trials, for participants to fixate the previously (but no longer) relevant region more than the other irrelevant region, even after stimulus onset, $F(1,11)=4.58$, $p=0.056$. Although the relevance by CSI interaction was not reliable, $F(2,22)<1$, follow up ANOVAs run to test the extent to which post-stimulus attentional inertia was modulated by the duration of the preparation interval found that the effect approached significance only for the two longest CSIs (main effect of relevance at CSI=620 ms, $F(1,11)<1$; CSI=1020 ms, $F(1,11)=3.79$, $p=0.078$; CSI=1420 ms, $F(1,11)=4.34$, $p=0.061$).

Between-experiment analyses.

In order to investigate the extent to which task-specific stimulus attributes attract attention relative to perceptually homogenous stimuli I compared the RT, errors and post-stimulus fixations data from this experiment with those from my earlier report (Experiment 2, Chapter 2) in which three number classification tasks were performed on stimuli which were about half the size of the current stimuli (subtending 0.4° horizontally, 0.5° vertically) but presented at the same (centre-to-centre) distance from each other and all other aspects of the experimental design were identical. To ensure an ‘apples to apples’ comparison only the data from the odd/even task from both experiments were subjected to the between-experiments analyses which included experiment as a between subjects factor.

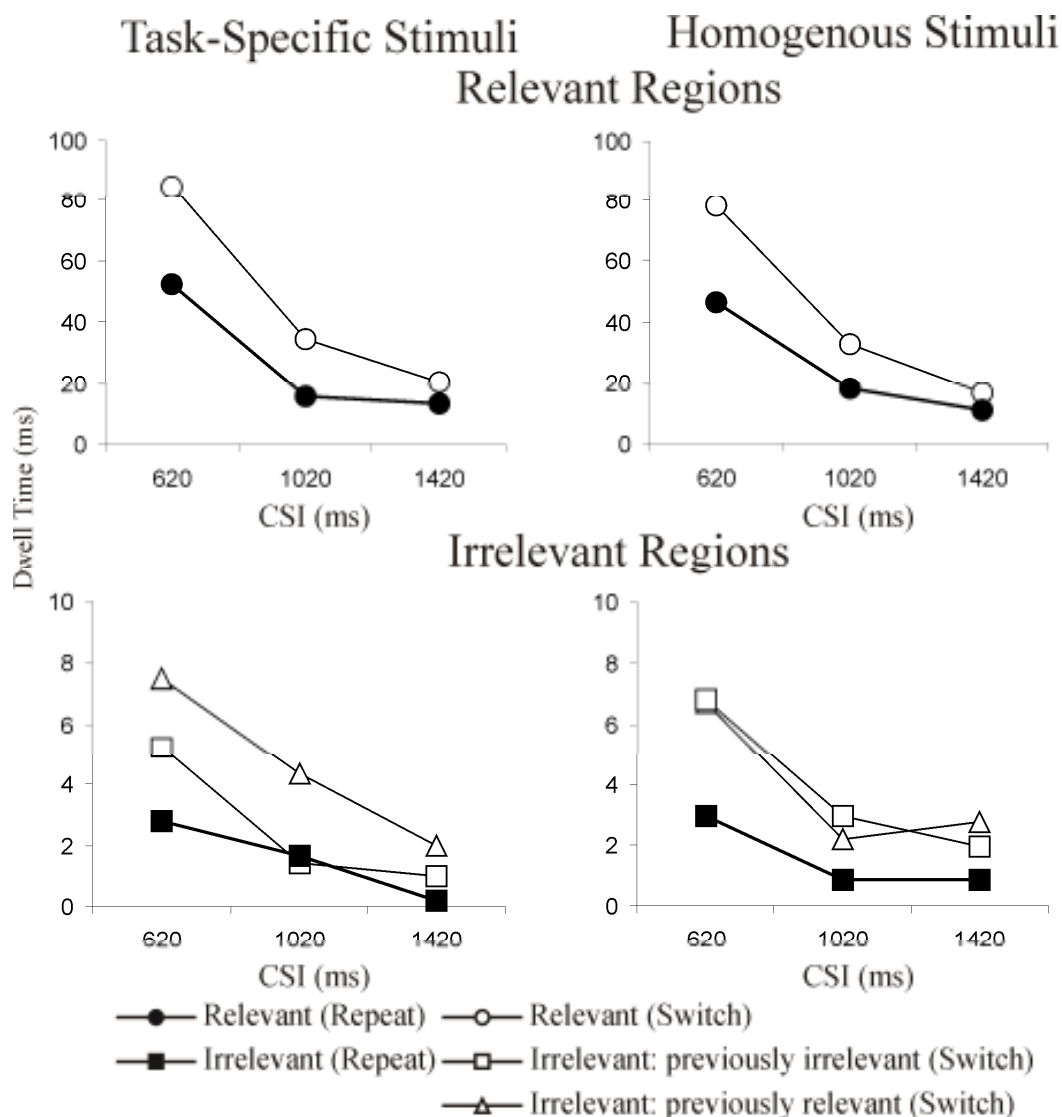


Figure 6.7. Mean post-stimulus dwell time in the critical time window (the maximum possible dwell time in the critical time window was 300 ms) as a function of CSI, transition and task relevance of stimulus region for the odd/even task with task-specific (left) and homogenous (right) stimuli.

There were no reliable effects or interactions involving the factor experiment in the RT or errors data indicating a comparable level of performance between experiments. The RT (errors) switch cost with task-specific stimuli was 115 ms (1.46%) and 121 ms (2.29%) with homogenous stimuli. Figure 6.7 shows the post-stimulus dwell time in the critical time window for the two experiments. The analysis of the post-stimulus dwell time in the currently relevant region found no reliable effects or interactions involving the factor experiment (all F 's < 1). Inspection of Figure 6.7 shows that there was a greater tendency to fixate the previously (but no longer) relevant region

over the other irrelevant region on switch trials with task-specific stimuli than with homogenous stimuli and the interaction approached significance, $F(1,34)=3.24$, $p=0.081$. Follow up ANOVAs performed for each CSI found that the difference between experiments was only reliable at CSI=1020 ms (relevance by experiment interaction at CSI=620 ms, $F(1,34)<1$; CSI=1020 ms, $F(1,34)=6.51$, $p=0.015$; CSI=1420 ms, $F(1,34)<1$).

There is a possibility that participants might have relied on the features of the stimulus elements rather than/as well as the location of the elements to select the relevant attribute. This may have resulted in less optimal orienting pre-stimulus and, hence, greater attentional inertia post-stimulus. To examine this alternative interpretation of the post-stimulus inertia, two further between-experiment analyses were performed. First, if participants were inclined to use the features of the stimulus to guide attention then one would expect longer latencies for the mean launch time of the first saccade to leave the cue and land directly on the currently relevant element relative to when only spatial attention could be used. Second, because the stimuli were larger and afforded responses in only one task in the current experiment it is possible that attention was not allocated with the same precision (participants may not have felt the same need to fixate a small area while suppressing perception of the other stimulus elements) relative to when the stimuli were perceptually homogenous.

Although the launch time of the first relevant saccade was later with task-specific stimuli at all CSIs (mean launch time in order of increasing CSI for task-specific stimuli: 395 ms, 494 ms, 542 ms, 614 ms; homogenous stimuli: 386 ms, 457 ms, 499 ms, 523 ms) the ANOVA on these data found that the difference was not reliable (main effect of experiment: $F(1,34)=2.57$, $p=0.118$). However, there was a reliable interaction between CSI and experiment, $F(3,102)=3.65$, $p=0.019$, and between switch, CSI and experiment, $F(3,102)=2.88$, $p=0.040$, indicating a difference in the

launch time slopes over CSIs in each transition condition for the two experiments. Follow up ANOVAs for each transition separately found a reliable interaction between CSI and experiment for the repeat trials only, $F(3,102)=5.64$, $p=0.002$ (switch trials: $F(3,102)<1$). However, independent samples t-tests performed on the launch times at each CSI for the repeat trials found the difference to be reliable at the longest CSI only (in order of increasing CSI: $t(34)=0.13$, n.s.; $t(34)=1.02$, n.s.; $t(34)=1.15$, n.s.; $t(34)=3.14$, $p=0.004$). The mean launch times for repeat trials, in order of increasing CSI, for task-specific stimuli (homogenous stimuli) were: 368 ms (365 ms), 459 ms (428 ms), 516 ms (470 ms), 592 ms (467 ms); and for switch trials: 422 ms (407 ms), 529 ms (485 ms), 567 ms (529 ms), 636 ms (578 ms).

A straightforward measure of the accuracy of fixations is the proportion of fixations that landed outside (suggesting poor targeting) of the three regions around the stimulus elements plus a fourth region around the cue throughout the entire experiment. Overall, in the current experiment 10.08% of all fixations landed outside of these regions on task-repeat trials; 10.23% on task-switch trials (6.07% and 6.84% respectively when the stimuli were perceptually homogenous). Independent samples t-tests found that the difference was statistically significant when the task repeated ($t(34)=3.25$, $p=0.005$) and when it switched ($t(34)=3.09$, $p=0.006$).

Discussion

In a task-cuing experiment we attempted to examine attention to task-irrelevant stimulus attributes by presenting composite stimuli made of three perceptually distinct attributes, each associated with its own task and location. Eye movements were compared to those recorded during an experiment in which the stimulus elements were perceptually homogenous and afforded responses in all three classification tasks (three digits presented at predictable locations). Previous studies by Longman et al., (2013) and

Mayr et al. (2013) did reveal a substantial post-stimulus handicap associated with a task-switch on trials with long preparation intervals, but in these studies advance spatial selection of the task-relevant attribute was either not possible (Mayr et al., 2013), or not strongly encouraged and documented (Longman et al., 2013). Here, I examined the post-stimulus ‘pull’ of feature-based attention by task-irrelevant attributes in conditions when spatial selection of the relevant attribute is not only possible, but strongly encouraged and documented.

I found the familiar behavioural effects commonly reported in task switching experiments (switch cost, its reduction with opportunity for preparation, and its residual component). As in my previous investigation with homogenous elements of the compound stimulus, the congruence of the responses afforded by the irrelevant attributes of the stimulus and the responses afforded by the relevant attribute (cross-location response congruence) did not detectably influence performance, even though in the present experiment the irrelevant stimulus elements were twice the size and hence somewhat more discriminable in parafoveal vision.

I confirmed the recently reported attentional effects associated with switching between tasks (inertia of spatial attention, delay in attending the relevant stimulus attribute; Chapter 2). Additional analyses, intended to investigate the extent to which attention is captured by previously relevant stimulus attributes, found some new fixations initiated after stimulus onset. There was a reliable tendency to fixate the relevant region more on switch trials than repeats and, despite being very small in number, the time spent fixating the previously (but no longer) relevant element on switch trials was greater than the time spent fixating the other irrelevant element. This tendency approached significance at the two longest CSIs and was greater in the present design than in our earlier experiment (Experiment 2, Chapter 2) that used compound

stimuli made of perceptually homogenous attributes (though reliably so only for one of the two longest CSIs, 1020 ms).

Thus, the results from the analyses of post-stimulus eye-movements show that the change from compound stimuli made of perceptually homogenous attributes to compounds made of elements that possess different perceptual features resulted, on switch trials, in a somewhat greater tendency to attend to the previously relevant attribute after the stimulus onset. This may suggest some form of inertia in feature-based attention, possibly coupled with (re)activation of the previously (but no longer) relevant task-set by the associated set of perceptual features (e.g., digit features activating the odd-even task-set). It therefore seems that orienting spatial attention to the relevant location (which eye-movement analyses during the CSI showed to be as effective in the current experiment as in our previous investigation with homogenous attributes) does not altogether block perceptual processing of the attribute at the irrelevant location, but it does attenuate it considerably – behavioural analyses found no sign of the irrelevant attributes influencing response selection.

Two final analyses were intended to assess the possibility that participants were less concerned with spatial selection before stimulus onset, relying to some extent on the perceptual features of the stimulus elements to guide attention because the task-specific features were available and easy to select. There was some evidence to support this interpretation. The mean launch time of the first correctly targeted saccade was slower in the current experiment relative to an experiment with perceptually homogenous stimulus elements, though reliably so only on repeat trials at the longest CSI. The analysis used to assess the accuracy of the fixations found that more fixations landed outside the analysis regions (for the stimulus and the cue) in the current experiment than when the stimulus elements were perceptually homogenous. This means that the issue of whether spatial selection was less effective post-stimulus in the

current experiment was due to non-spatial attributes (features) eliciting inertia, or the spatial attention being more 'lax' during the CSI, remains unresolved. Further research examining the limits of spatial attention in task switching will need to avoid the strategic effects which could not be ruled out in the present experiment.

General discussion

The primary aim of this thesis was to systematically investigate anticipatory control of attentional selection of perceptual attributes in task switching. To this end a new task-cueing paradigm was developed in which the stimulus display consisted of three elements each consistently associated with a different location and task. This enabled the use of eye movements as an on-line measure of task-related spatial attention at a high temporal resolution both before and after stimulus onset. The two experiments reported in Chapter 2 were designed to establish whether, and how, cueing a change of task impacts on spatial attention above and beyond a mere change of relevant location. Experiments 3 and 4, reported in Chapter 3, investigated the extent to which spatial attentional settings cease to be ‘bound’ to (accessed via) other components of task-set under conditions designed to uncouple them. Experiment 5, reported in Chapter 4 combined eye-tracking with ERPs to investigate the temporal relationship between reconfiguration of spatial orientation and of other task-set components. Experiment 6, reported in Chapter 5, examined whether the carry-over of attentional settings from the preceding trial (‘attentional inertia’) can be overcome when participants are given ultimate control over the duration of the preparation interval. Finally, Experiment 7, reported in Chapter 6, examined whether anticipatory re-orienting of spatial attention during a task switch effectively suppresses the processing of irrelevant stimulus elements when each element has task-specific features (affords only one task). What follows is a summary of the key findings from these experiments (presented in italics), along with a discussion of the theoretical implications and some of the questions which remain unanswered.

Experiments 1 and 2 (Chapter 2)

Findings: Task switching delays preparatory fixation of the currently relevant stimulus element. This delay cannot be explained by task-independent changes in the location of the relevant element, is not confined to the trials with slow orienting (long fixation latency) and does not arise predominantly from fixation errors (because, when the first eye-movement leaving the cue is correctly targeted, it is also delayed by a task switch); the delay also predicts the switch cost both over and within individuals.

The results from Experiments 1 and 2 demonstrate that switching tasks has a substantial impact on spatial attention and, at least in the current paradigm, switch-induced delays in spatial selection of the relevant stimulus element contribute to the performance overhead measured by reaction time (the switch cost). The large switch-induced delay in spatial attention did not reduce significantly at the longer CSIs (unlike the small delay elicited by location switching in the control condition). Hence the delay induced by a task-switch evidently indexes a time-consuming process probably reflecting reconfiguration of task-relevant spatial attention parameters (in the face of interference from the attentional settings of the previously relevant task), over and above any small cost of overcoming the carryover of oculomotor settings from the previous trial. Only at the shortest CSI was there a statistically detectable delay in the location switching condition suggesting that the sudden onset of the stimulus display (120 ms after the cue onset) might have ‘captured’ the participants’ attention before the cue had been fully interpreted (so that carryover of oculomotor settings from the previous trial would likely determine the target of the first saccade).

A related finding from Experiment 1 was that, when the arbitrary cues referred only to locations and not tasks, the analysis of the latency of the first eye-movement away from the cue showed that cue encoding took no longer on (location) switch trials than when the relevant location repeated. This result is at odds with Logan and

colleagues' (e.g., Logan & Bundesen, 2003; Schneider & Logan, 2005, 2007) view that the (task) switch cost in the standard (task-) cuing paradigm can largely be explained by cue encoding time. If this were the case then cue priming on repeat trials should result in comparable switch-induced delays in the latency of the first saccade to leave the cue whether it refers to a location, a task or both. It could be argued that the meaning of the cue in the task switching condition is more complex and it may therefore benefit from cue encoding more than the location switching (control) condition (though one would expect at least some benefit of priming of cue encoding in the location switching condition). The problem with such amendments to the 'priming of cue encoding' account is that 'cue encoding' then becomes more or less identical to the notion of activating the task goal, widely seen as a constituent of TSR.

An interesting behavioural observation in Experiments 1 and 2 is that there was little evidence on task (or location) switch trials of the irrelevant elements being processed to a level that would activate responses either in the relevant task ('flanker' congruence) or in the tasks associated with the respective locations ('cross-location' congruence). Thus, it appears that once the relevant element of the stimulus was selected, this spatial filtering was robust enough to block (or strongly suppress) processing of the irrelevant stimulus elements. I return to this finding later in the discussion of Experiment 7.

Finding: When the task switches, attention tends still to be 'pulled' towards the previously (but no longer) relevant stimulus element: the effect I have termed 'attentional inertia'. Attentional inertia is reduced, but not eliminated (in these two experiments) with opportunity for preparation.

By using three tasks it was possible to analyse, on switch trials, the extent to which attention was oriented towards the previously (but no longer) relevant stimulus

element rather than the other irrelevant element. A clear tendency for misoriented fixations to go to the previously relevant location was seen at all CSIs, albeit reducing at the longer CSIs, and this “attentional inertia” effect was much larger in the task-switching condition than the location-switching control condition (in which the small effect disappeared at the long CSI). This suggests that carryover of task-relevant attentional settings from trial $n-1$ can influence the orientation of attention on trial n , even with ample time to prepare – though subsequent experiments (Experiments 5 and 6) showed that preparation can not merely reduce but eliminate this tendency given a self-generated or less variable preparation interval (see below). It should be noted that (with the exception of Experiment 6) CSI duration was blocked in all of the experiments reported in this thesis. This leaves open the possibility that the effects I refer to as ‘preparation’ might actually reflect a more passive process (i.e., the participants are simply less quick to act when they know that the preparation interval is long, thus reducing the likelihood of making premature saccades). Of course, the best way to achieve this is by using the available time to prepare an appropriate saccade. The finding that the launch time of the first appropriately targeted saccade increases in conditions with longer preparation intervals coupled with the finding that attentional inertia was eliminated when the participants could self-select the duration of the preparation interval is consistent with the idea that participants were using the time to actively prepare. However, only by introducing a condition in which CSI was randomised within a block can strong claims be made regarding the effect of active preparation on attentional selection. Although the idea of task-set inertia is common currency in the task switching literature, previous research has focused on inertia as affecting a later stage of processing (e.g., response selection). Using eye-tracking to measure inertia in spatial attention provides a robust method to investigate the

contribution of carryover of the previous perceptual parameter settings (in this case spatial orienting) to the interference reflected in the residual cost.

In addition to occasional fixations of the previously relevant region, one might anticipate other signs of attentional inertia. For example, even in correctly targeted eye-movements, one might expect the saccadic trajectory to ‘curve’ towards the previously-relevant location, much as saccadic trajectories deviate away from or toward a concurrent distractor (e.g. McSorley, Haggard, & Walker, 2006). I examined this possibility using data from Experiment 2¹, but found little indication of inertia in the geometry of saccadic paths, possibly because the trajectories were rather short and the range of possible eye-movements relatively limited in these experiments. Further research using more widely separated stimulus elements and/or more complex stimulus configurations may be useful for examining this possibility.

One may also ask whether, in addition to being prone to task-set related inertia, the spatial attention system is just more generally distractible during a task switch. Such a question cannot be answered conclusively by the experiments presented in this thesis. Although fixations on the stimulus element/s not relevant on the previous trial can be examined, this would not be a clean measure of distractibility, because it may reflect longer-lag carryover or associative effects, and is not independent of fixations on the previously relevant location. A good measure of distractibility could be obtained by presenting on some trials a distracting stimulus element that is never task-relevant, and is preferably trial-unique to avoid associative effects.

Another phenomenon which the experiments reported in this thesis did not investigate thoroughly is whether saccades on switch trials were targeted as accurately as on repeat trials. Dwell time in a particular region can indicate which stimulus element was being attended, but it is tacit about the spatial distribution of fixations within a

¹ I am grateful to Cristian Munteanu, a computer science student working as an intern with Dr Lavric, for helping to program these analyses.

region. The number of fixations landing within the analysis regions was reported for each experiment and are summarised here for repeat (switch) trials: Experiment 1, task switching: 95.06% (94.27%); location switching: 93.95% (93.97%); Experiment 2: 93.93% (93.16%); Experiment 3: 94.24% (93.99); Experiment 4: 94.45% (93.96); Experiment 5: 92.8% (92.43%); Experiment 6: 91.19% (91.19%); Experiment 7: 89.92% (89.77%). Although fixations were generally (slightly) better targeted on repeat trials, the difference between switch and repeat trials was so small in each case that these data provide little evidence that targeting was detectibly poorer when the task switched. However, a more detailed analysis could be accomplished in a number of ways, for instance, by measuring the distance of fixation coordinates from the centroids of the stimulus regions, by computing measures of spatial dispersion of fixation coordinates or by examining the number of corrective saccades within regions.

The findings from Experiments 1 and 2 indicate that, although early stages of attentional selection are susceptible to carryover of attentional settings from the previous trial, they are also accessible to top-down control. This conclusion is evidently at odds with the claims of some researchers from the visual attention literature (e.g., Mortier et al., 2005; Theeuwes et al., 2006) but is consistent with the findings of others who suggest that all stages of processing are accessible to top-down control (e.g., Found & Müller, 1996; Rangelov et al., 2012). Perhaps the current findings can be used to resolve the differences between these two opposing views by formalising the relationship between bottom-up carryover and top-down control of early stages of attentional selection.

Experiments 3 and 4 (Chapter 3)

Findings: The extent to which the need to change task-set is reflected in delays and inertia in spatial attention depends on the strength of the coupling of attention to other

parameters of task-set. Under certain conditions spatial attention can be (nearly) completely decoupled from the rest of task-set, which reduces (or eliminates) the switch-induced attentional handicaps but substantially increases the switch cost. However, the 'natural' (or default) state seems to be for attentional selection to be coupled with task set; only quasi-exogenous location cues (arrows or words pointing to the relevant locations in the stimulus) employed together with instructions and training that prioritised location selection over task selection, overrode the coupling completely.

An intriguing finding in these experiments is that, when task and attentional set are decoupled, the dramatic reduction (and elimination) of attentional delays and inertia comes at the price of an equally dramatic increase in the performance (RT) switch cost. Although the current data cannot provide an explanation for the latter effect, I speculate that there may be at least four possibilities here. First, there is the possibility that some TSR processes run in parallel (though see below the discussion of Experiment 5 suggesting seriality at least for some stages of TSR). For instance, the task goal and task-relevant attentional settings may be activated in parallel. Decoupling these components might postpone the reconfiguration of other task-set components until attentional selection is complete (though if this were the case one might expect to see a further reduction in switch cost at the longest CSIs). Second, a coupled system may be more compatible with cascaded processing. For instance the task-goal may be activated before task-relevant stimulus selection has been completed. This might not be possible when the components become decoupled. Third, fixation of the task-relevant stimulus element might 'boost' activation in other (later) task-set components. Such an advantage might be eliminated when attentional selection is decoupled. Finally, it is possible that only one construct can be reconfigured at a time (either the whole task-set or only one aspect of it – in this case spatial attention). Decoupling spatial attention from other task-set components forces their reconfiguration to be performed serially (cf.

Kieffaber et al., 2013; Vandierendonck et al., 2008). However, because Experiment 5 suggests seriality in the reconfiguring of spatial attention vs. other task-set components reflected in the switch-related ERP posterior positivity, it is not clear why serially reconfiguring attentional set and then other task-set components which are decoupled is less effective than serially reconfiguring them when they are coupled.

Attentional selection is not the only component process which can potentially be decoupled from (and encouraged at the expense of) other task-set components.

Although the experiments described in this thesis specifically focus on attentional selection several theoretical models of cognitive control make a distinction between two (e.g., Logan & Gordon, 2001; Meiran et al., 2000, 2008) or three (e.g., Rangelov et al., 2012) distinct stages of processing accessible to top-down control. Experiments 3 and 4 demonstrate that the modulation of at least early perceptual selection processes can be decoupled from other task-set components. It remains to be seen whether components from later stages of processing can also be decoupled and how this might influence performance. For example, in an experimental design in which the responses for each task are mapped to different hands (e.g., Astle et al, 2008a; Poljac & Yeung, 2014), it might be possible to decouple preparation of the relevant hand from other task-set components; one could encourage (via appropriate cues and instructions) selection of the hand before selection of the task.

Experiment 5 (Chapter 4)

Findings: The timing of the switch-induced posterior positivity in the fixation-locked ERP (it always follows the first relevant fixation) suggest that some stages of TSR are serial with spatial orienting being prioritised over (at least some of the) other components of task-set. The earlier switch-induced negativity seen in this experiment

(but not in most task-cueing experiments) may be a correlate of preparatory spatial orienting.

This experiment (which contained the methodological innovation of combining EEG and eye-tracking measures of task-set preparation) revealed distinct switch-induced ERP effects preceding (central-parietal negativity) and following (parietal-occipital positivity) the onset of the first fixation on the task-relevant stimulus element during the preparation interval. Thus, the TSR processes indexed by the switch-induced positivity do not appear to run in parallel with but to follow the reconfiguration of the spatial attention component of task-set. I speculated in Chapter 4 that the positivity may reflect in this experiment the loading into (or activating in) working memory of the relevant semantic categories and/or S-R rules. However, because the positivity is also elicited by switches of perceptual dimensions, or features of a dimension, in the absence of a change in response set (Kieffaber et al., 2013; Rushworth et al., 2002), it cannot be related specifically to reconfiguring semantic categories or S-R rules. Instead it may reflect loading into WM of any relevant task-set parameters that cannot be applied ('used') immediately, before the stimulus arrives. This interpretation of the positivity is consistent with the fact that it is unlikely to reflect the reorienting of spatial attention – spatial attention parameters can be both reconfigured and applied (relevant location selected) well in advance of the stimulus. A corollary of this interpretation is that during a task switch WM is updated in two stages ('sweeps') – first one loads the parameters that can be applied immediately, then the parameters that have to wait for stimulus onset. The switch-induced negativity preceding the fixation may reflect the first stage and the switch-induced positivity the second.

Experiment 6 (Chapter 5)

Findings: The attentional inertia reflected in the residual tendency to orient to the location associated with the previous task can be eliminated when there are no limits placed on the time available for preparation. The same is not true for the switch-induced delay in orienting attention.

The carryover of attentional settings could be overcome if participants were given ultimate control over the duration of the preparation interval. Nonetheless, a residual switch cost remained at long preparation intervals showing that inertia in attentional selection was not the only contributor to the asymptotic component of task-set. Intriguingly, attentional inertia was also eliminated in Experiment 5, where the preparation interval was not under the participant's control and the longest CSI was 1000 ms. This would seem to suggest that the effect can be eliminated by means other than allowing participants to take longer when needed. Perhaps the answer lies in the efficiency with which participants use the preparation interval (cf. De Jong, 2000). In Experiments 1-4 there were four CSIs, each used equally often. In Experiment 5 there were only two CSIs, and 75% of trials had a CSI of 1000 ms. Perhaps this led to a more optimal criterion on the speed-accuracy continuum of initiating an eye-movement; i.e., the fixation of the task-relevant location is, under these conditions, only launched when any residual equivocation with respect to its target has been overcome. In Experiment 6 the same effect may have been achieved by (implicitly) encouraging participants to move towards the accuracy end of the continuum (however, the data summarised above indicate that fixation accuracy was not noticeably better in these two experiments than those preceding them). It remains unclear whether carryover of parameters in later stages of processing might be overcome in a similar way; the latter point is beyond the scope of this thesis which focuses on an early (perceptual selection) stage but offers an intriguing area for further research.

That ultimate control over the preparation interval did not eliminate (or even reduce) the switch-induced delay in fixating the relevant region suggests that (when the task demands it) reconfiguration of this component is an essential time-consuming process on switch trials. In addition to overcoming perseveration of attentional settings from the previous trial, it is likely that the delay in orienting indexes ‘activation’ of the currently relevant settings. Further research is necessary to document the specific processes indexed by delays in attentional selection and the extent to which they can be explained by overcoming perseveration alone.

Experiment 7 (Chapter 6)

Finding: When each of the three stimulus elements afforded only one task, and hence possessed task-specific features, the tendency to fixate the previously relevant element was somewhat greater than in the earlier experiments, in which each element was a digit affording all three tasks, so that the elements were not differentiated by their perceptual features. This may reflect extra inertia of non-spatial (feature) attributes of the stimuli, or reduced use of spatial filtering to select the relevant element.

With perceptually distinct stimulus sets (digits, letters, objects) there was a greater tendency (though significantly so only in one of the two longest CSIs) to fixate after stimulus onset on switch trials the previously relevant stimulus element (compared to the irrelevant element that was also irrelevant on the previous trial) relative to when the stimulus elements were perceptually homogenous. However, the irrelevant elements were still not processed enough to influence response selection (as evidenced by the lack of a reliable response congruence effect). Along with recent findings from the literature (e.g., Elchlepp et al., submitted; Longman et al., 2013; Mayr et al., 2013) these results may suggest that inertia of non-spatial attention to dimensions leads to extra fixations on the previously relevant stimulus element on switch trials (cf. Meiran et al.,

2008). However, the analysis of the latency of launching an eye-movement towards the relevant location suggests the above conclusion could be premature. The observation that participants took substantially longer to launch an eye-movement which resulted in a relevant fixation in this experiment (relative to the experiments with homogenous stimulus features) is consistent with an alternative interpretation of the inertia observed in post-stimulus fixations in the current experiment – that participants felt they could rely on feature-based selection and felt less compelled to engage in (early) location-based selection. As a comparison, in Mayr et al.'s (2013) eye-tracking experiment the stimuli were of a comparable size (1.2°) to those used in the current experiment (1.0°) and they reported that the probability of fixations landing on the currently relevant element were $\sim 50\%$ suggesting that the stimuli were large enough to be discriminable without a fixation. A more 'lax' orienting could explain the increased inertia in the post-stimulus interval. Indeed, there is some evidence of such 'lax' orienting in the analysis of the proportions of fixations landing outside of the regions encompassing the stimulus elements and the cue – this proportion was larger with heterogeneous elements than with homogenous elements. Because the stimuli were twice the size of those used in the earlier experiments with perceptually homogenous stimuli, another possible explanation for the 'lax' orienting might be that participants simply did not need their attention to have such a precise focus. Further work that eliminates such strategic effects (whatever the reasons) is needed to determine the effectiveness of spatial 'filtering' on switch trials.

It should also be noted that Experiment 7 used only 12 participants (whereas Experiments 1-4 used 24 participants per condition). By doubling the number of participants in Experiment 7 some of the ambiguity in the results might be resolved but there remain important differences between this and Experiment 2, which I used for comparison, other than the number of participants used (e.g., the size of the stimuli).

Nonetheless, by using only 12 participants I was able to draw some relevant conclusions which encourage further investigation of the relationship between spatial attention and attention to features in task switching (which was my primary aim). The same reasoning also applies to the number of participants used in Experiments 5 and 6 where smaller numbers were adequate in order to conclusively investigate the effects of interest (e.g., in Experiment 5, 12 participants was ample to partition the EEG according to fixation latencies).

Other remaining issues

This thesis describes an investigation into the dynamics of spatial attention in task-switching. It documents several phenomena (some more surprising than others) about the interplay between task-set control and spatial orienting. A key question that cannot be answered yet is: to what extent do these phenomena and conclusions generalise to other forms of attention (e.g., non-spatial attention, attention in other sensory modalities)? The research that speaks to other forms of attentional selection in task-switching, as reviewed in Chapter 1, is still relatively limited; it suggests that other forms of attention can also be reconfigured in advance of the stimulus, that there is inertia in attending to dimensions in task-switching, and that non-spatial attentional set can, under some conditions, be decoupled from the rest of task-set. However, these other forms of attentional selection in task switching still await systematic investigation.

As well as being able to generalise the findings to other forms of attention, another avenue for research might be to investigate the extent to which they can be generalised to other task-set components at later stages of processing (e.g., transformation rules, response selection/execution). Although advance reconfiguration and parameter inertia have been extensively studied for later stages of processing, their precise relationship remains unclear.

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