Task Switching and Distractibility

Sarah Louise Brand

University College London

I, Sarah Louise Brand, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

ABSTRACT

In this thesis I examined the effects of task switching on people's ability to ignore irrelevant distractors. Load theory proposes that distractor interference critically depends on the availability of executive control to minimise the effects of irrelevant stimuli (e.g. Lavie, 2000). Much work on task switching suggests that task switching demands executive control in order to prepare for and implement a switch between tasks (e.g. Monsell, 2003; Rubinstein, Meyer, & Evans, 2001). I therefore hypothesised that the executive demand of a task switch will result in reduced ability to reject irrelevant distractors in selective attention tasks. The research reported provided support for this hypothesis by showing that task switching results in greater distractor interference as measured with the "flanker task" (e.g. Eriksen & Eriksen, 1974) and with the attentional capture task (e.g. Theeuwes, 1990), even when there was no overlap between the stimuli and responses for the two tasks, and when task-repeated and switch trials were presented within the same block (in AAABBB designs). This research also showed that dissociable executive demands were involved in switching tasks (AAABBB), compared with mixing tasks (ABAB versus AAA), and these executive demands were found to control rejection of distractors in the flanker task and attentional capture task, respectively. In addition, task switching reduced internal distraction by task-unrelated thoughts. The contrast between the effects of task switching on internal versus external sources of distraction further supported the involvement of executive control in task switching. Finally, individual differences in operational span capacity predicted the magnitude of task switching costs and flanker interference effects, suggesting the involvement of executive control in both abilities. Overall, this research highlights a new consequence of task switching on selective attention and distractibility, supporting predictions derived from prevalent views on the role of executive control in task switching and selective attention.

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

ACKNOWLEDGEMENTS

CHAPTER 1

General Introduction

1.1 PREFACE

In order to efficiently perform even simple everyday tasks, the ability to rapidly shift attention from one task to another is essential. For example, talking on the phone, whilst driving, may require shifts in attention from the road to the conversation, and vice versa. Performance in both tasks might be detrimentally affected because the need to shift attention between tasks limits the ability to selectively attend to only task-relevant information. Driving may be subject to greater distraction from irrelevant visual information, such as a brightly coloured coat on a pedestrian, when switching attention between driving and talking on the phone, compared to when focused solely on driving.

In this thesis I investigate the implications of load theory for performance in selective attention tasks when executive control is loaded with a task switch. I review evidence for the role of executive resources in the control of selective attention predicted by load theory. I then review the literature regarding a role for executive control in switching between two tasks, followed by a discussion of previous research investigating the effects of task switching on distractor interference. Lastly, I introduce the current study, which extends previous evidence supporting a role for executive control in selective attention. Most of this previous research focused on the effects of working memory load on selective attention. The current study investigates the effect on selective attention performance of specifically loading executive control via a task switch.

1.2 EXECUTIVE CONTROL OF SELECTIVE ATTENTION

A large body of research has investigated the ability to selectively attend to relevant information and selectively ignore irrelevant information (e.g. distractors; for reviews see Kahneman & Treisman, 1984; Lavie & Tsal, 1994). This research was for a long time split between authors contending that attentional selection occurred at an early stage of perceptual processing (e.g. Broadbent, 1958), and those who argued for a later stage of selection, occurring after (at least some) semantic processing had taken place (e.g. Deutsch & Deutsch, 1963). Load theory (Lavie, 2000, Lavie, Hirst, De Fockert, & Viding, 2004) was originally proposed as an answer to the early versus late selection debate, accounting for the mixed findings regarding early versus late selection. When the perceptual load of a visual display is high then load theory predicts that target processing will consume attentional resources, leaving none left over to process irrelevant information: this is early selection. Conversely, when perceptual load is low, load theory argues that attentional resources spill over to irrelevant items in the visual environment, and these items will be perceived and filtered out by later processes such as memory or response selection: this is late selection.

More recently, load theory has been extended to include the mechanism by which late selection occurs (e.g. Lavie, 2000; Lavie, Hirst, De Fockert & Viding, 2004). Lavie and colleagues have suggested that executive control is required in order to actively maintain priorities between task relevant stimuli and task irrelevant distractors. This is a late selection mechanism because although perception of task irrelevant distractors cannot be reduced, their interference on behaviour can be minimised. Evidence for this late selection mechanism comes from recent selective attention literature, which suggests that distractor processing can be determined by load on

executive processes, for example working memory maintenance (Lavie, 2000; Lavie et al., 2004). Greater load on these processes should increase distraction in selective attention tasks because executive control cannot ensure low-priority irrelevant information does not control attention.

Lavie and colleagues (Lavie, 2000; Lavie et al, 2004) manipulated working memory load by comparing low load blocks, in which a digit order to be maintained in working memory was the same on all trials (e.g. always "6789"), and high load blocks, in which subjects were requested to maintain a different memory set on each trial (e.g. "4672" "3925" etc). Distractor interference effects in the flanker task (shown in greater RTs when the distractor was incongruent versus congruent), which was performed during the maintenance interval of the working memory task, were greater when a high working memory versus low working memory load was being maintained. These studies strongly support the contention that executive load increases interference from distractors in a selective attention task.

De Fockert, Rees, Frith, and Lavie (2001) provide more direct, causal evidence for a role of executive processes in controlling selective attention. A selective attention task was performed concurrently with the working memory load task described above (maintaining a digit order in working memory). As above, greater interference from distractors was found under conditions of high versus low working memory load. Neuroimaging results indicated both greater activity in areas associated with executive control (i.e. prefrontal areas) and greater activity in areas implicated in the processing of faces (e.g. fusiform gyrus, right inferior occipital lobe, and left lingual gyrus) under high executive load. The discovery of increased activity associated with the presence of distractor faces under high executive load strongly supports the contention that executive load modulates distractor suppression.

Lavie and de Fockert (2005) studied the effects of the demand on executive control of maintaining representations in working memory (working memory load) on interference from an irrelevant, singleton distractor in a visual search task (attentional capture). Greater processing of the irrelevant singleton distractor when attempting to attend to a predefined target was found under conditions of high (e.g. maintain the order 5739) versus low (maintain the order 1234) working memory load, further supporting the theory that executive functions play an important causal role in successful performance in selective attention tasks.

The above studies strongly suggest that executive resources act to control selective attention. A task thought to directly measure the demand on executive control resources is task switching. I now review the evidence supporting a critical role for executive control resources in switching between tasks.

1.3 EXECUTIVE CONTROL AND TASK SWITCHING

Task switching has come to have a central role in studies investigating the role of executive resources in preparing for performance of a task (e.g. Logan & Gordan, 2001; Meiran, 1996; Rogers & Monsell, 1995). Executive control is involved in monitoring ongoing cognitive processes, activating relevant representations and procedures, and suppressing irrelevant, distracting representations and procedures (Oberauer et al., 2003). These control processes should be involved in switching the cognitive system between the performance of two tasks.

A task requires its own 'recipe' (or "task-set", e.g. Allport et al., 1994; Rogers & Monsell, 1995; Monsell, Yeung, & Azuma, 2000; Rubinstein, Meyer, & Evans, 2001), including the rules of the task and stimulus-response mappings (such as: look for targets

in one position, ignore distractors in another position; if letter X appears press one key, if Z press another). Executive control should be involved in coordinating switching between two tasks, including the manipulation and maintenance of task-sets. Executive control is needed to activate the current task-set, as well as to inhibit the previous task-set to disengage from it and ensure it does not compete with the relevant task-set for control of behaviour. The reconfiguration of a task-set when switching from one task to another (namely: selecting, linking and configuring processes required to perform the task; Rogers & Monsell, 1995) should also require executive control. In addition, this 'task-set reconfiguration' may also involve the retrieval by executive control processes of task-related information from long-term memory (LTM) on switch, but not pure, trials (Mayr & Kliegl, 2000). I now review the literature investigating whether such executive processes are involved in task switching.

1.3.1 <u>Effects of the interval between tasks on the task switch cost</u>

The time interval between the response to one task and the stimulus of the other (response-stimulus interval; RSI) allows for both the decay of task-sets and processes that carry over from the performance of the previous task (task-set inertia; Allport, Styles, & Hsieh, 1994), as well as for active preparation of the next task to be performed in cases of foreknowledge about which task will be performed next. Such active preparation should heavily depend on executive control (e.g. task-set reconfiguration), as previously discussed. Providing a sufficiently long RSI should, in principle, allow for both full decay of previous task-sets and processes as well as full preparation of the following task. In line with this expectation, substantial reduction in, and sometimes complete elimination of, task switching costs occurs when there is sufficient preparation time, i.e. task switch costs reduce as RSI increases from 0 secs up to roughly 0.6 secs

(Allport et al., 1994; De Jong, 2000; Gopher, Armony, & Greenshpan, 2000; Meiran, 1996; Rogers and Monsell, 1995, Experiment 3). The effect of RSI duration on task switching cost is often termed the preparation effect. Whilst many authors agree with the idea that preparation effects reflect the involvement of executive control in task switching, for example, in cognitive reconfiguration of task rules (Meiran, 1996; 2000; Rogers & Monsell, 1995), or goal setting (Rubinstein, Meyer, & Evans, 2001; Sohn & Anderson, 2001), others argue that the preparation effect is to do with non-executive processes. These non-executive processes, such as perceptual processing of the cue, required only when the task (and therefore cue) switches (e.g. Logan & Bundeson, 2003), or the decay of interference from the activation of previous task-sets (Allport et al., 1994), also have time to complete before the switch trial when there is a longer RSI. So far, the studies reviewed cannot distinguish between the relative contributions to the preparation effect of two types of processes: top-down executive processes and bottom-up processes such as carryover of inhibition and/or activation associated with a recently performed task and perceptual cue processing.

In some cleverly conceived explicit task-cuing studies, Meiran, Chorev, and Sapir (2000) manipulated the response-cue interval (RCI) and the cue-stimulus interval (CSI) in order to investigate the relative contributions of executive processes and task-driven processes to the effect of RSI on task switch costs. Executive processes could not prepare for the upcoming switch until cue presentation because task order was randomised. The greater the RCI the more inhibition can decay and the smaller the expected task-driven component of the switch cost, and the greater the CSI the more preparation time for executive processes, and the smaller the expected top-down executive component of the switch cost. Increasing the RCI reduced switch costs, suggesting that inhibition previously associated with the current task-set did explain part

of the switch cost. However, there was a far greater reduction in switch costs with a greater CSI, suggesting the cue allowed executive processes to prepare for the task, and that this explained a far greater component of the switch cost. While task-driven processes, such as carry over of inhibition associated with the current task set in earlier trials, contribute to the switch cost, the time taken by executive processes contributes a far greater amount. Note that because task order was randomised, the cue was processed on every trial, even when the task repeated, and as such did not contribute to the task switch cost. Additionally, task switch costs have been revealed to occur without a cue switch (e.g. Logan & Bundeson, 2003; Mayr & Kliegl, 2003), suggesting that the task switch cost is not dependent on a cue switch on task switch trials.

Further support for the direct involvement of executive control in task switching comes from studies comparing the effect on task switching costs of manipulations altering the executive demand of a task switch with those altering task difficulty without demanding executive resources. For example, Rubinstein et al. (2001, see also Allport et al, 1994) demonstrated that only manipulations of task difficulty which affected executive control (e.g. rule complexity) increased or decreased the switch cost. Changes in task difficulty which did not affect executive control (e.g. stimulus discriminability) did not affect the switch cost. These findings suggest that it is not the general increase in task difficulty when switching versus repeating tasks which is responsible for the task switch cost, but rather that task switch costs are specifically due to the executive demand involved in task switch versus task repeat trials.

In all the above studies an unexpected finding was a residual switch cost that remained even when the RSI was increased to over 1 second (Allport et al., 1994; Meiran et al., 2000; Rogers and Monsell, 1995). All of the executive preparation for a switch should be able to complete before stimulus presentation, and a residual switch

cost which remains regardless of preparation time suggests executive processes cannot fully explain the switch cost (Allport et al., 1994). It has been argued that a component of executive preparation for a switch may be unable to complete until exogenously triggered by the stimulus for the current task (Rogers and Monsell, 1995). Indeed, Waszak, Hommel, & Allport's (2003) findings suggest a possible exogenous process that could trigger further top-down control after stimulus presentation. They found that when a stimulus associated with both task-sets is observed in one task, it can reinstate activation to the other previously associated task-set, resulting in activation of both the relevant and irrelevant task-set. Even when executive processes are fully prepared for a task switch, extra executive control may be triggered by exogenous processes (e.g. reinstatement of activation to previous task-sets) to resolve the extra task-set competition. The residual switch cost could, at least partly, reflect extra executive control triggered by exogenous processes.

In summary, there is strong support in the literature for the general involvement of executive control in preparing for a switch between tasks. This preparation effect on task switch costs may at least partly reflect the top-down activation and suppression of the relevant and irrelevant task-sets, respectively, by executive resources. I now discuss research supporting the contribution of the activation and inhibition of task-sets to the task switch cost in turn.

1.3.2 <u>Executive control and task-set activation</u>

There is much evidence in the literature supporting the claim that executive control in task switching is required in order to activate the correct task-set (e.g. Luria & Meiran, 2005; Mayr & Kliegl, 2000; Rogers & Monsell, 1995; Rubinstein, Meyer, & Evans, 2001).

Evidence for the activation of task-sets in working memory comes from response-congruency effects suggesting the task-set of the previous task affects performance of the current task (see Luria & Meiran, 2005). For example, when a response is correct for both the current and previous task-set, responses are faster than when the response is only related to the current task-set and opposite to the response for the previous task-set (e.g. Rogers & Monsell, 1995). These findings are taken as evidence that both the current and previous task-set are concurrently maintained in working memory during task switching, and executive control acts to readjust the activation of the task-sets as the requirement regarding which task to perform changes.

Mayr and Kliegl (2000, 2003) argue that it is more parsimonious to assume that task-sets are activated in LTM by executive processes (i.e. retrieved from LTM/updated into working memory) on switch trials, but not pure trials, rather than concurrently maintained in working memory. According to this view, the switch cost reflects the time taken by executive processes to retrieve task-sets from LTM on switch versus pure trials.

In support of their theory, conditions making greater demand on retrieval processes (such as retrieval of episodic versus semantic information) resulted in increased task switch costs, whilst other elements of task difficulty unrelated to retrieval demands did not affect task switch costs (Mayr & Kliegl, 2000; see also Allport et al., 1994; Rubinstein, Meyer, & Evans, 2001). Similarly, in Rubinstein, Meyer, and Evans' (2001) study, task switch costs were greater for conditions requiring the activation of a larger number of task rules, requiring more activation to activate the task-set, versus a smaller number of task rules. Azuma and Monsell (cited in Monsell et al., 2000) also found that extra time was needed to switch to the task requiring the activation of a larger number of more complex condition-action task rules. Importantly, the effect of

retrieval-demand on switch costs was eliminated by allowing time for preparation for the upcoming task (Mayr & Kliegl, 2000), strongly supporting the view that the endogenous preparation carried out during the preparation interval involves the retrieval of task-sets from LTM by executive control processes.

Within this LTM retrieval hypothesis, the response-congruency effects described above, which are taken by some to be irrefutable evidence that both task-sets are simultaneously actively maintained in working memory, can be accounted for as arising from exogenously cued retrieval of the irrelevant LTM response code upon stimulus presentation when stimuli cue both tasks. If task-sets are retrieved when cued by the stimulus and activation reinstated to them, then the activation applied to currently relevant task-sets will affect performance on later trials. Indeed, larger switch costs have been observed for primed stimuli (seen previously in a previous task) versus unprimed stimuli (not seen previously in a previous task; Allport et al., 1994; Allport & Wylie, 2000; Waszak et al., 2003). For example, Waszak et al. (2003, Experiment 1) observed greater switch costs for word reading when the specific word/picture Stroop stimuli had previously been seen in the picture naming task, than when they had not. This implies that when a stimulus seen in a previous task is presented in a new task (i.e. primed stimulus), it can trigger retrieval and reinstatement of the activation associated with the previous task-set, creating greater task-set competition and greater switch costs. This supports the view that the activation of task-sets in LTM accounts for at least part of the switch cost.

An interesting question is to what extent activating the correct task-set in LTM prepares the cognitive system for a task switch. If activation of task-rules is the only task preparation necessary prior to a task switch then providing sufficient task preparation time along with cues specifically supplying the task-rules, in order that they

no longer need to be activated by executive processes, should eliminate the preparation effect on task switch costs. Indeed, providing a long time for task preparation before a task stimulus appears, along with cues giving S-R mapping information eliminated both the effect of preparation interval and retrieval-demand on task switch costs (Mayr & Kliegl, 2000, Experiment 3). In other words, the amount of time given for executive processes to prepare for a task and the executive demands of retrieving task-sets from LTM only affected task switching costs when there was a need to activate task-sets in LTM. When this need was removed by providing task-set information in the cue, there was no longer an executive demand associated with a task switch. This suggests that endogenous preparation for a task switch acts only to activate the task-set in LTM and that this accounts for the fundamental demand on executive processes of switching between tasks. Although additional demands can also contribute to the switch cost, it seems that activating a task-set in LTM reflects an underlying process which must necessarily be carried out by executive processes prior to a switch to a new task.

1.3.3 <u>Executive control and task-set inhibition</u>

In addition to the fundamental requirement to activate the currently relevant task-set, executive control may also be required to suppress previously activated, now irrelevant, task-sets to ensure they cannot compete for behavioural control. Mayr and Keele (2000, Experiment 5) found that responses to the last trial in the sequence ABA are slower than in the sequence ABC, suggesting executive processes inhibit task A in order to switch away from it. When task A is encountered again this inhibition is still associated with it and overcoming this inhibition slows the response. In the sequence ABC there is no such inhibition to overcome and so responses to the third trial in this sequence are faster than in the sequence ABA.

Strong support for top-down inhibition of task-sets in task switching also comes from findings of asymmetries between the costs of switching to well learned (dominant) and less well learned (non-dominant) tasks. Using Stroop stimuli researchers observed switch costs for switches from non-dominant to dominant tasks but not the other way around (Allport et al., 1994, experiment 5; Allport & Wylie, 2000; Wylie & Allport, 2000). Similarly, switching from a non-dominant to dominant language in bilingual participants resulted in significant switch costs which were not revealed when switching from their dominant to their less dominant language (Meuter and Allport, 1999). These counterintuitive asymmetries, with task switch costs only revealed when switching to, but not from, a better learned task, can be explained by greater inhibition of dominant task-sets (due to their greater activation requiring greater inhibition in order for them to be disengaged from). When switching to a dominant task-set, which was suppressed while performing the non-dominant task, there is greater suppression to overcome and it will take longer for the task-set to gain a high enough level of activation to gain behavioural control. The inhibition of previous task-sets is strongly supported by these asymmetries.

However, studies by Rogers & Monsell (1995), Azuma & Monsell (reported in Monsell et al., 2000) and Rubinstein et al. (2001) address this issue. These studies found that the asymmetry of switch costs could be reversed, so that switch costs were greater for a switch from dominant to non-dominant tasks. This is the asymmetry predicted by a reconfiguration account of switch costs, with reconfiguration taking longer when switching to the less well-learned, non-dominant task. For example, Azuma and Monsell used Stroop stimuli and found that switch costs were greater when switching from the dominant to the non-dominant task. In this study the incongruent part of the Stroop stimulus was presented at delays of 160 or 320 ms, so that it was not initially

present to cue the other task-set. This manipulation eliminates the need to suppress the other task-set and as such eliminates the asymmetry in cost that is attributed to greater suppression of dominant versus non-dominant tasks. The reversal of asymmetry, that is the additional cost found now in a switch to the non-dominant task (versus dominant task), is easily explained in terms of greater activation of task-set rules that is needed in cases when these are less well learned (i.e. in non-dominant task).

In summary, the costs of switching to dominant and non-dominant tasks are contributed to by both activatory and inhibitory top-down executive control. Which asymmetry is observed may depend upon which task (dominant or non-dominant) requires greater activation.

1.3.4 <u>Executive capacity and task switch costs</u>

Another approach to investigating the role of executive control in task switching involves investigating the effects of executive demand on task switching. A series of dual-task studies found that task switching performance was disrupted by concurrent performance of secondary "central executive" tasks (Baddeley, Chincotta, & Adlam, 2001): holding a working memory load on-line was associated with prolonged RTs to switch trials.

Another experiment also revealed increased switch costs associated with a concurrent requirement for executive processes to maintain items in working memory (Hester & Garavan, 2005). In a primary task participants were shown a series of letters during the maintenance period of a working memory load task (maintain a set size of 2, 5, or 8 letters) and asked to respond via key presses to whether the letter in each trial was part of the memory set or not. On 25% of trials the letter appeared in another colour, indicating that a switch should be made from this primary task to a secondary

task, requiring either colour or vowel/consonant discrimination. Hester and Garavan (2005) revealed that the task switching cost to this secondary task was increased when the set size of items to be maintained in working memory was greater, suggesting a causal role of executive resources in the control of task switching.

Given that working memory load modulates task switching costs (Baddeley, Chincotta, & Adlam, 2001; Hester & Garavan, 2005) and despite the effect of working memory span on dual-task performance (e.g. Kane & Engle, 2000; see introduction to Chapter 6), it is interesting that most previous research has found no correlation between working memory (executive) capacity and task switch costs (Kane and Engle, 2000; Oberauer, SuB, Schulze, Wilhelm, & Wittmann, 2000; Oberauer, SuB, Wilhelm, & Wittmann, 2003; Miyake et al., 2000). For a more detailed review of the literature regarding the effects of working memory capacity on task switching see the introduction to Chapter 6.

In the experiments reviewed in Chapter 6, which did not reveal an effect of working memory span on the task switch cost, task switching involved a confound between task cues and switch cues (Kane and Engle, 2000; Oberauer et al., 2003; Miyake et al., 2000), such that a response could be retrieved simply based on a combination of the cue and stimulus (i.e. a combination of a certain cue and stimulus can be learned, and the correct response retrieved based on the combined cue, thus minimising or eliminating executive demand, see Arrington & Logan, 2004; Logan & Bundeson, 2003; Logan & Schneider, 2006). Kane and Engle separated task cues and stimulus cues such that correct responses could not simply be retrieved from memory by a combined cue-stimulus cue. In this way the requirement to activate the correct task-set in order to perform the current task was reinstated and thus the executive requirements of the task switch increased. Removing the specific task cues revealed a significant

effect of working memory span on task switching costs in both RTs and errors, with low spans showing greater task switching costs than high spans.

In summary, so long as a task switch specifically requires that a task-set be activated in order to perform the correct task then executive capacity can predict individual task switching costs. Given the evidence in the literature that working memory capacity tasks rely on executive control (e.g. Conway, Cohen, & Bunting, 2001; Kane, 2001; Kane, Bleckley, Conway, & Engle, 2001; Kane & Engle, 2001; for review see Kane, 2002), this finding strongly suggests that task switching requires input from executive resources.

1.3.5 <u>Evidence from Neuroscientific studies for the role of executive processes in task switching</u>

There is wide agreement that the prefrontal cortex (PFC) plays a role in executive control, including the coordination of goal-directed behaviour (Brass & Von Cramon, 2004; Dreher & Berman, 2002; Miller & Cohen, 2001), and maintenance of relevant information in the face of interference (Kane & Engle, 2002). Indeed, findings suggest that PFC neurons can maintain task-relevant information (Fuster, 1995), which is not affected by interference from distraction (Miller, Ericksen, & Desimone, 1996), and PFC sends projections to much of the neocortex (e.g. Pandya & Barnes, 1987; Pandya & Yeterian, 1990) suggesting PFC meets many of the requirements for executive control and the control of task switching. If task switching involves input from executive control then brain-imaging studies should find activation in this area during task switching, compared to task repetition.

Increased activation in dorsolateral prefrontal cortex (DLPFC) has been associated with switch versus pure trials (Braver, Reynolds and Donaldson, 2003;

MacDonald, Cohen, Stenger, and Carter, 2000) as well as activation in the inferior frontal junction (Brass and Von Cramon, 2002). Imaging has also shown increased activity in PFC associated with voluntary task preparation before a switch (Luks, Simpson, Feiwell, and Miller, 2002; Sohn, Ursa, Anderson, Stenger, and Carter, 2000), suggesting PFC activation is specifically associated with executive control in task switching. Further, Garavan et al. (2002) found that greater activation in the left PFC was associated with trials where subjects were more successful at holding a task-set in memory, suggesting that PFC activation could be associated with activating and maintaining task-sets. Yeung, Nystrom, Aronson, and Cohen (2006) found regions of the PFC which showed increased activation only when switching was to a particular task, possibly reflecting the maintenance of task-relevant information; as well as regions associated with more global control processes, such as task coordination, which were unaffected by the task switched to.

More specific evidence suggesting how top-down executive processes control task switching comes from a neuroimaging study comparing BOLD responses to task-sequence ABA versus ABC (Dreher & Berman, 2002). Behavioural data has found greater switch costs when performing sequence ABA than ABC, suggesting inhibition is applied by executive functions when switching from a task (Mayr & Keele, 2000). In support of the interpretation of the behavioural data, increased activity was found in the DLPFC associated with the sequence ABA than ABC.

Additional evidence supporting a role of prefrontal executive control in task switching comes from the finding that activity in two areas of the PFC (anterior cingulated cortex/pre-sensory motor area, and posterior cingulate) correlated with behavioural switching costs: larger switch costs occurred when activity was greater in these areas of the PFC (Yeung et al., 2006), suggesting that increased switch costs were

associated with instances when PFC was under greater demand. Interestingly, Yeung and colleagues also revealed that activity associated with the currently irrelevant task was directly associated with increased task switching costs. For example, on trials when the irrelevant task was a face task, the RT cost of switching to the other task increased as activation in the area associated with task-irrelevant face processing increased. This finding offers support for the commonly held contention that interference between tasks is a major contributor to the task switch cost.

The Neuroimaging evidence presented suggests frontal executive areas are associated with executive control and the control of task switching, supporting our hypothesis.

Evidence for the role of frontal cortex in task switching also comes from several studies that have shown that left frontal patients demonstrated greater switch costs than controls (Aron, Monsell, Sahakian, & Robbins, 2004; Keele & Rafal, 2000; Rogers, Sahakian, Hodges, Polkey, Kennard, & Robbins, 1998). Frontal patients also show impairments in tasks heavily involving components of task switching. These include: inhibition of task-sets and/or responses (Aron et al., 2004; Cohen, Barch, Carter, Servan-Schreiber, 1999); sustaining attention (Wilkins, Shallice, & McCarthy, 1987); switching attention in the Wisconsin Card Sorting Task (Milner, 1963; Ravizza & Ciranni, 2002); as well as the coordination of multiple tasks and the formulation/maintenance of task goals in real-life multiple sub-goal tasks (Shallice & Burgess, 1991). The neuropsychological evidence presented suggests a causal role for frontal executive areas in the control of task switching.

1.3.6 <u>Switch costs with stimuli affording only one task</u>

If executive processes control switching between tasks above and beyond resolving interference between competing task-sets, then a switch cost should be found when switching between any two tasks, even with entirely different stimulus sets and response mappings. Many authors argue that in order for there to be large and consistent switch costs, there must be overlap between stimuli (e.g. Allport et al., 1994, Experiment 4; Jersild, 1927; Spector & Biederman, 1976; Waszak, Hommel, & Allport, 2003). The basis of this argument is that a large contributor to switch costs is the interference when performing the current task caused by the stimulus cueing, in a bottom-up manner, both the current and the previous task-sets (e.g. Waszak, Hommel, & Allport, 2003). Indeed, when the stimulus is not associated with both task-sets task switch costs are often eliminated or, at the very least, reduced to an almost negligible amount (Allport et al., 1994, Experiment 4; Jersild, 1927; Spector & Biederman, 1976).

Another way in which priming can add to switching costs when stimuli are bivalent is to do with the variation of an irrelevant element of the target stimulus. For example, in Allport et al.'s (1994) experiments, when the relevant stimulus dimension (word identity, e.g. RED/BLUE) varied there was also variation in the irrelevant stimulus dimension (ink colour). The need to filter out this variation is know as Garner filtering (Garner, 1970; 1974). In the task switching paradigm when a stimulus affords two tasks Garner filtering may contribute to the switch costs because this filtering will be greater on trials where a switch has been made from the other task, in which case the irrelevant stimulus dimension has recently been primed (Rubin & Meiran, 2005). Rubin and Meiran (2005, Experiment 1) showed that switch performance was marginally significantly facilitated (i.e. switch costs were reduced) when there was no variation in the irrelevant stimulus dimension. This became a significant effect when only trials with

no preparation were analysed, strongly suggesting that these priming effects contribute to the switching cost, especially when there is no time for the dissipation of activation associated with the irrelevant stimulus attribute which was relevant in the previous task.

In some cases (e.g. when the switch is unpredictable and a cue is used to introduce a task switch) task switch costs may also be attributable to the extra time taken in switch trials to discriminate and interpret the cue regarding which task to perform (Monsell, 2003). These interference effects, due to conflicting response mappings to the same stimulus, would slow down RTs in the same manner as would making a single task more complex, without assuming any increase in the recruitment of executive control processes.

Despite these contributions to the switch cost, which rely on stimuli which afford both of the tasks switched between, switch costs have occasionally been observed with stimuli which are only associated with one task-set (Allport et al. 1994; Rogers & Monsell, 1995, Rubin & Meiran, 2006). Rogers and Monsell (1995, experiment 1) found a substantial switch cost of over 200 ms with character pairs only associated with one task-set, consisting of the task-relevant character as well as a task-neutral character: the irrelevant character did not afford the other task, although note here that the irrelevant character still varied across trials and as such still required Garner filtering. Allport et al. (1994, Experiment 4) also found small but consistent switch costs for univalent neutral Stroop stimuli (e.g. coloured X's for the colour naming task), although they also revealed situations in which univalent stimuli led to no switch costs. Interestingly, in this case there was no opportunity for Garner filtering so priming could not have contributed to the switch cost. In both these studies switch costs associated with stimuli affording only one task were significantly smaller than the costs associated

with those affording both tasks, probably reflecting the role played by activation of irrelevant task-sets in switch costs.

A recent study by Rubin and Meiran (2005), however, revealed similar switch costs when switching between tasks with overlapping stimuli, and those with stimuli which were entirely unrelated, strongly suggesting that, at least in their study, large and significant task switch costs can occur when stimuli do not afford both tasks. This study is discussed in more detail in the introduction to Chapter 3.

In summary, although attempts have been made to reveal significant task switch costs with stimuli which are entirely separate for both tasks, only one study has so far revealed large and significant task switching costs when stimuli for the two tasks do not overlap. My current hypothesis concerns the effect of executive control involved in a switch between any two tasks on task performance, and as such predicts large and consistent task switching costs when there is no overlap between task stimuli. As such, in the current study task switching will be measured using two tasks which do not overlap in their stimuli (Experiments 1 & 2) and, later, do not overlap in both their stimuli or responses (Experiments 3 – 14, see introduction to Chapter 3). I expect to find large and significant switch costs under these conditions.

1.4 TASK SWITCHING AND DISTRACTOR INTERFERENCE IN SELECTIVE ATTENTION TASKS

1.4.1 Effects of task switching on distractor interference

A study by Rogers and Monsell (1995, Experiment 1) reports findings relating task switching to greater interference from irrelevant information. In this study there were greater switch costs to stimulus pairs with a target and a response-incongruent irrelevant

character (350 ms) versus a response-congruent irrelevant character (309 ms). Both tasks required the same response-mappings, making it hard to interpret whether the increased switch cost was due to a specific effect of having to change the response-mapping (so that the target response is less certain and thus more open to interference by an irrelevant, incongruent distractor), or whether the effect is due to a general demand on executive control leading to greater distractibility during task switching, as hypothesised by load theory. Interestingly, in this study no distractor effect was found in the non–switch condition and thus the increased distractor interference in the task switch condition, which involved 4 versus 2 response mappings, may merely have been due to the response-stimulus associations being more vulnerable to distraction, and not the increase in executive demand.

A series of studies carried out by Lavie and colleagues (2000; 2004) provide more direct support for the contention that switching between tasks loads executive processes and increases interference from distractors. In some of the experiments carried out by Lavie and colleagues, manipulating working memory load involved increased demand on dual-task coordination. Working memory load was often manipulated by comparing low load blocks, in which the memory sets were the same on all trials (e.g. always "6789"), and high load blocks, in which subjects were requested to maintain a different memory set on each trial (e.g. "4672"). In the low load condition it is possible that the working memory task was not performed, but rather participants responded based on their long-term memory of the memory set for that block. Thus low load blocks may have simply involved performance of the selective attention task, compared to high load blocks, where performance of both the selective attention task and the working memory task was required. In this way there was a difference in the

high versus low blocks in terms of the executive load of dual-task coordination, which could explain the greater distraction revealed in high load blocks.

Lavie et al. (2004, experiments 4 & 5) investigated the effects of successive dual-task performance on distractor rejection. Greater interference effects were found from distractors in a selective attention flanker task (incongruent – congruent trials) when performing first a working memory task, and then a selective attention flanker task (dual-task condition), than when performing the selective attention flanker task alone (single-task condition, same procedure except did not respond to working memory task). These experiments provide some indirect support for the hypothesis that task switching should lead to greater distractor interference because the dual-task conditions required switching from the working memory task to the flanker task. However, these experiments combined a working memory task with the flanker task and as such their findings may also be explained by increased working memory load in the dual-task conditions due to working memory not entirely 'clearing up' by the time the flanker task appeared. Thus, in the current study I aim to investigate the effects on distractor processing of executive load caused by task switching per se.

1.4.2 Effects of task switching on reaction times and distractor interference in the absence of executive load

Although there is much empirical support for the involvement of executive control in task switching, and given that only one previous study has found task switching costs when both stimuli and responses do not overlap, my current study may not produce significant task switching costs, or may not load enough on executive control in order to produce increased distractibility. If this is the case, then different outcomes might be expected. The effects of parallel versus serial processing in switch versus pure blocks,

and greater carryover effects of the distractor part of the display in pure than switch blocks both might result in increased distractor interference in pure rather than switch blocks, contrary to the current hypothesis. It is also possible that in the absence of executive control requirements, the RTs in the current experiment involving irrelevant stimulus dimensions, might be increased in pure than switch blocks. I will discuss each of these possibilities in turn.

The response selection bottleneck theory of the psychological refractory period (Pashler, 1984; 1994; Pashler & Johnston, 1989) contends that whilst perceptual processing and response preparation can occur in parallel, a central processing stage responsible for response selection occurs serially, so that the response for the first task must be selected before the response to the second task. More recently, authors have argued that these limitations are not structural, but rather are strategic, for example, serial processing has been argued to be invoked under situations demanding executive control, such as in the presence of cross talk and increased error probability (e.g. Logan & Gordan, 2001; Meyer & Kieras, 1997a; 1997b). Luria and Meiran (2005) argue that task switching versus task repetition in the psychological refractory period (PRP) paradigm, involves greater executive load and as such results in more serial processing (see also Oriet & Jolicoeur, 2003). If task switching instigates partly serial processing then it is to be expected that distractor interference will *decrease* under task switching conditions compared to pure blocks.

Another possible difference between switch and pure blocks which would predict greater distractor interference in pure compared to switch blocks is based on the Garner filtering effect (Garner, 1970; 1974). As previously discussed, the presence of an irrelevant stimulus dimension which varies on every trial may require executive control in order to filter out the irrelevant trial variance. In switch trials in the current

experiments the irrelevant dimension has not been associated with a relevant response (i.e. an X distractor in the present trial is associated with an X target for a previous trial) for at least one trial (because a trial of the second task intervenes). However, in the pure blocks the irrelevant dimension will on average have been associated with an opposite but previously relevant response more recently. As such, in pure trials the executive control elicited to filter the irrelevant stimulus dimension may be greater than in switch trials, resulting in longer responses to incongruent versus congruent trials in pure versus switch blocks.

Lastly, and similarly to the above, if carryover effects of the irrelevant stimulus dimension, such as increased interference from the triggering of recently relevant but opposite responses, are present, and if the executive control involved in switching is small due to the absence of stimuli which cue both task-sets, then it might be expected that responses in the pure blocks would be longer than the responses in the switch blocks.

1.5 CURRENT STUDY: THE EFFECT OF TASK SWITCHING ON DISTRACTOR INTERFERENCE IN SELECTIVE ATTENTION TASKS

Participants performed a flanker task either alone, or when switching between that task and another task. In the flanker task subjects made speeded responses to a target letter and a distractor letter appeared in the periphery. Both letters were either an X or a Z, creating two different conditions; one where the distractor letter was the same as the target letter (congruent); and one where it was the other letter (incongruent, e.g. target is 'x', distractor is 'z'). The difference between the reaction times to the incongruent and

the congruent trials is taken as a measure of the amount of interference caused by the distractor letter on the processing of the target letter.

Load on executive control resources was manipulated by switching between tasks (high load), or repeating performance of the same task (low load). Jersild's (1927) original task switching method of comparing two block types, pure and alternating, was used (with the exception of Chapter 4). Interference effects from the distractors in the flanker task and attentional capture task were compared in switch as opposed to pure trials.

Each task had it's own unique stimuli, and thus stimuli only afforded one task. As discussed previously, this was in order to more directly measure the hypothesis that a switch between any two tasks should load on executive control, for example to coordinate switching and activate/inhibit task-sets, and as such result in significant task switch costs and reduced selective attention performance.

I predict that greater interference from irrelevant distractors in the flanker task will be found under conditions of high executive load, i.e. in the switch as opposed to pure trials.

In Chapter 2 I aim to provide support for the hypothesis that task switching reduces selective attention performance by comparing distractor interference in the flanker task when it is performed in a task switch as opposed to task repeat (pure) block. I then generalise the effect of task switching on distractor interference to a task which does not have a response congruency element, and investigate the effects of task switching on attentional capture by an irrelevant singleton.

In Chapter 3 I investigate the effects of response mappings on the interaction between task switching and distractor interference in both the flanker task and attentional capture task. Task responses for the two tasks are separated first onto four

separate response keys, and then so that each hand responds only to one task. In this way interference between the response-mappings of the two task-sets is minimised.

The effects of task mixing and task switching on distractor interference are then investigated in Chapter 4. Pure and switch trials are performed within the same block, so that the effects of between block differences are reduced and distractor interference effects can be more specifically attributed to task switching per se.

Task unrelated thoughts are another form of distraction thought to rely on executive input. In Chapter 5 the opposite effect of task switching on interference from external distractors and internal distractors is revealed.

Finally, in Chapter 6 the influence of individual differences in working memory capacity on task switch costs and distractor interference effects in the flanker task is used to further provide support for the hypothesis that both task switching and distractor interference draw on a shared executive resource.

CHAPTER 2

Distractor Interference During Task Switching

2.1 EXPERIMENT 1

In Experiment 1, distractor effects were compared in a flanker task under task switch and task repeat conditions. Participants were required either to switch between a visual search task and a flanker task (switch blocks), or to repeatedly perform only one of these tasks (pure blocks). The hypothesis that the demands placed by task switching on executive control reduce it's availability to control attention leads to the prediction that distractor interference in the flanker task will increase in task switch blocks compared to pure blocks.

2.1.1 <u>Method</u>

    <u>Participants</u>. Ten participants (18-35) with normal or corrected-to-normal vision from University College London were paid to participate.

    <u>Stimuli and Apparatus</u>. The experiment was run on a PC with a 12" SVGA monitor and a standard 102 keyboard. E-Prime version 1.1 (Psychology Software Tools Inc.) was used to create the stimuli, run the experiment and collect the data. The visual search task displays consisted of a circle of red shapes (located with a 2.1° radius from fixation to the centre of each shape) made up of four diamonds (1.4° point to point) and one target circle (1.2° diameter) presented on a black background. The target circle was equally likely to appear in each of the five positions. Each shape had a white line (0.5° x 0.15°) inside it, either vertically or horizontally aligned. The alignment of the line in each shape was randomly assigned. The flanker task stimuli were a target letter, appearing in one of six positions (3 to the left and 3 to the right of fixation, with a separation of 0.7° between each possible position), and a distractor letter appearing above or below fixation (1.7° from fixation to distractor edge). The target letter was

either X or Z and subtended 0.4° (width) x 0.65° (height) of visual angle. The distractor letter was also either an X or a Z and subtended 0.5° (width) x 0.8° (height) of visual angle. The target letter and distractor letter were both 0.1° of visual angle in thickness. All letters were presented in white on a black background. There were two conditions in the flanker task; congruent, where the target and distractor were both the same (i.e. both X or both Z), and incongruent, where the distractor letter was a different letter to the target (i.e. target is X and distractor is Z; target is Z and distractor is X). Congruent and incongruent trials were randomised within blocks.

Procedure. The switch block trials consisted of the sequence shown in Figure 1.
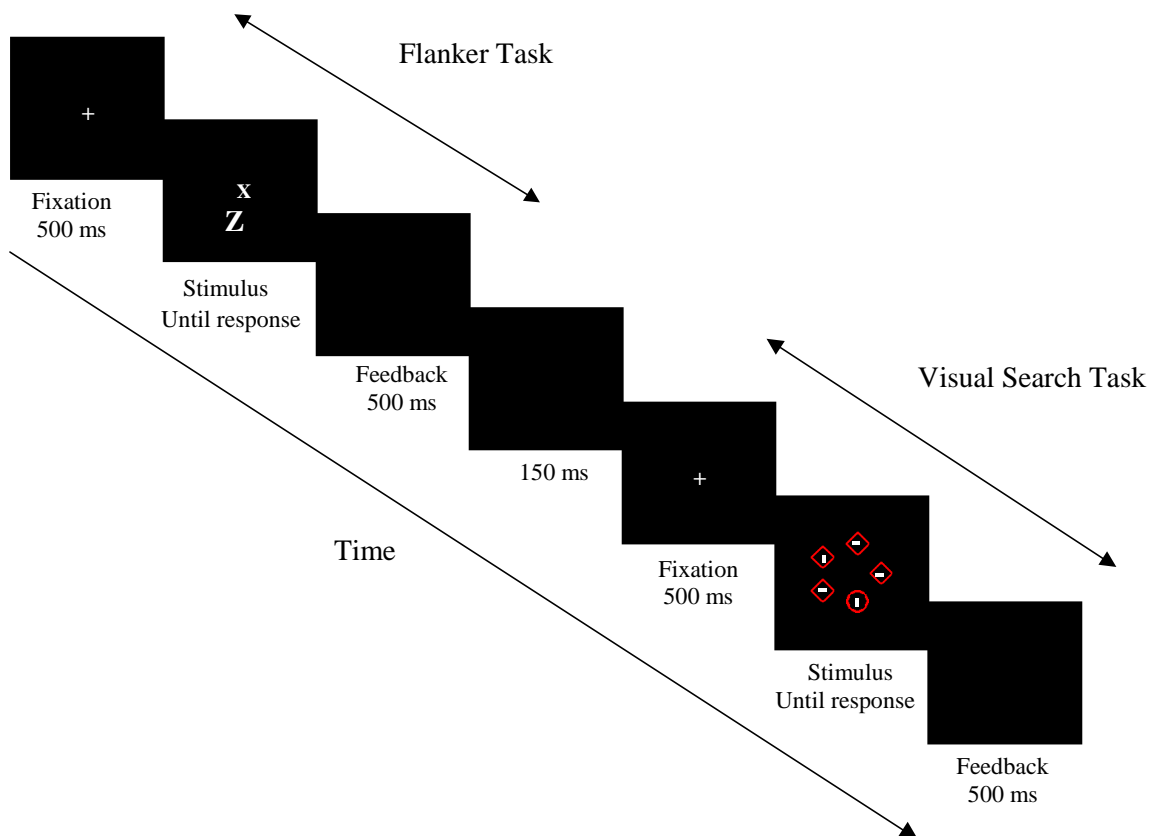
Figure 1: An example of the procedure in a switch block. In pure blocks the procedure for one task repeats.

For both tasks a fixation cross appeared for 500 ms, followed by the stimulus, which remained on the screen until response. Subjects pressed the 0 key on the number pad if the target letter in the flanker task was an X or if the line in the circle in the visual search task was horizontal, and the 2 key on the number pad if the flanker target was a Z or if the line inside the circle was vertical. Responses were made with the index and middle fingers of the right hand respectively. Feedback was a blank screen for 50 ms and a short auditory beep occurred in this time for an incorrect or no response, and this was followed by a blank screen of 150 ms.

In the flanker task target location, target identity (x or z) and congruency (congruent/incongruent) were counterbalanced to randomly occur with equal probability. In the visual search task target location and line orientation randomly occurred with equal probability.

Each block consisted of 80 trials mixed at random. In the switch blocks 40 randomly selected trials of each task were presented alternately (ABAB…). To match the number of trials for each task in the switch and pure conditions each subject performed 6 blocks of switch trials, and 3 pure blocks each of the two tasks. This created a total of 480 trials for each task: 240 in the pure and 240 in the switch blocks. A total of 12 experimental blocks were run, preceded by 2 practice blocks, one for each task, with 20 trials in each. Subjects did not practice switching between the tasks. Participants alternated between pure and switch blocks, half started with a pure block (half pure A and half pure B), and half started with a switch block followed by a pure block (half pure A and half pure B). The four block orders were counter-balanced across participants.

2.1.2 <u>Results</u>

Mean reaction times (RTs) and percentage error rates were calculated for each subject as a function of task condition (switch/pure) and distractor congruency in the flanker task (congruent/incongruent). Incorrect response trials and those longer then 2 s were excluded from the RT analysis in this experiment as well as in all the other experiments reported[1].

Table 1: Reaction times for the visual search task and the flanker task as a function of task condition (pure/switch) and congruency (congruent/incongruent).

| | Mean (SD) | Flanker Task | | | Visual Search Task |
		I	C	(I-C)	
Task condition					
Pure					
RT (ms)	*562 (158)*	*579 (163)*	*544 (153)*	*35*	*736 (158)*
Errors (%)	*4.5*	*6*	*3*	*3*	*6*
Switch					
RT (ms)	*766 (238)*	*808 (249)*	*724 (228)*	*84*	*882 (209)*
Errors (%)	*5*	*6*	*4*	*2*	*6*
Task switch cost					
RT (ms)	*204*				*146*
Errors (%)	*0.5*				*0*

I = incongruent, C = Congruent.

Visual search task. RTs were increased in the task switch versus pure blocks, $F (1, 9) = 30.9$, $MSE = 3909.9$, $p < 0.001$. Percentage error rates were the same in both task conditions ($F < 1$; see Table 1).

---

[1] The percentage of trials lost was smaller than 10% in all experiments.

Flanker task. A 2 (task condition) x 2 (congruency) within-subjects ANOVA performed on the flanker task RT data revealed longer RTs in switch than pure blocks, $F(1, 9) = 49.5$, $MSE = 8438.0$, $p < 0.001$, and longer RTs to incongruent versus congruent trials, $F(1, 9) = 43.0$, $MSE = 821.6$, $p < 0.001$, in the flanker task (see Table 1).

Critically, the significant interaction between switch and congruency, $F(1, 9) = 35.9$, $MSE = 160.9$, $p < 0.001$, indicated a larger congruency effect in switch versus pure trials in the flanker task, as predicted.

Since task switching led to slower RTs overall, congruency effects were also calculated as percentages of congruent trial RTs. A comparison of the percentage distractor effects between task conditions confirmed a significant increase from the pure (5%) to the switch (12%) blocks, $t(9) = 4.8$, $SEM = 0.011$, $p < 0.001$. This makes an account of the increase in distraction effects in the switch than pure blocks in terms of the scaling of RTs in the switch versus pure blocks unlikely.

An error ANOVA revealed a main effect of congruency, $F(1, 9) = 5.7$, $MSE = 0.001$, $p < 0.05$, with more errors in the incongruent trials, but no main effect of switch, $F(1, 9) = 3.0$, $MSE = 0.000$, $p = 0.12$, in the flanker task. There was no interaction between task condition and congruency in error rates in the flanker task ($F < 1$).

Key switch analysis. Switching tasks but repeating the same key press may require more input from executive control due to the need to reconfigure the response-mapping to the new task and inhibit the response for the previous task. Thus, one might expect a greater switch cost for these switches than for those involving a key switch. Indeed, there was a trend towards greater switch cost for switches involving no key switch ($M = 202$ ms) versus those involving a key switch ($M = 182$ ms), however, a 2 (task switch) by 2 (key switch) within subjects ANOVA was performed on the flanker

task RT data and this interaction did not reach significance, $F < 1$: Switch costs were not significantly increased when the current task involved the same key response to the previous task versus a different key response.

In conclusion, Experiment 1 provides preliminary support for the hypothesis that task switching leads to greater distraction in selective attention tasks. Experiment 1 supports the novel suggestion that the detrimental effects of task switching are not only restricted to slowed RTs, but that task switching also results in increased distractibility in the tasks switched between.

2.2 EXPERIMENT 2

In Experiment 2 I examine whether the effect of task switching on distractor interference could be generalised to another measure of distractor interference, which does not involve a response congruency manipulation. In Experiment 2 participants switched between an attentional capture task (similar to the visual search task used in Experiment 1, except that a singleton occurred in 50% of the trials), and a simple choice-response task (similar to the flanker task except with a neutral distractor). Longer RTs in singleton present than singleton absent trials (an attentional capture effect) would reveal that the singleton has captured attention away from the primary task (Theeuwes, 1991; 1992; 1994). Increased attentional capture in switch versus pure blocks would generalise the findings of Experiment 1 and support the hypothesis that task switching increases interference from distractors in two different types of task.

The hypothesis that task switching will reduce the ability to attend to targets and ignore distractors leads to the prediction that greater attentional capture will be found in switch (versus pure) trials, even though this task does not involve response competition.

2.2.1 <u>Method</u>

Participants. Eight participants (18-35) from University College London, all with normal or corrected-to-normal vision, were paid for their participation.

Stimuli. The flanker task was used as in Experiment 1 except that the target now subtended 0.6° x 0.4° of visual angle, and the distractor (which was always a neutral letter P) subtended 0.9° x 0.5°. The distance between the six possible positions of the target was 0.7° and the distractor appeared 1.7° (from fixation to distractor edge) above or below fixation. The attentional capture task was similar to the visual search task in Experiment 1 with the following exceptions: the stimulus was a circle of 9 shapes (radius: 3.3° of visual angle) made up of 8 diamond shapes and one circle shape. On half of the trials a colour singleton (one of the diamond non-targets presented in a different colour) was present in the display. The shapes could either be all green or all red, with the singleton appearing in the opposite colour (e.g. all green with red singleton). This added uncertainty as to the colour of the singleton and prevented subjects ignoring, for example, any green stimulus on each trial. In order to create uncertainty about the locations of the stimuli three different presentations of the stimuli were used. Each presentation was the same except that the circle of shapes was rotated clockwise by 0.5° in the second presentation, and 1° in the third presentation. Colour, display orientation, line orientation and singleton present/absent were randomised within blocks. Otherwise the block types and block orders were the same as in Experiment 1.

Procedure. The procedure was the same as that used in Experiment 1, except that to reduce overall experiment time no 150 ms blank screen appeared after each task response.

2.2.2 <u>Results</u>

The mean RTs and percentage error rates for each subject as a function of task condition (switch/pure) and singleton presence in the attentional capture task (present/absent) are presented in Table 2.

Table 2: Reaction times for the attentional capture task and the flanker task as a function of task condition (pure/switch) and singleton presence (present/absent).

	Attentional Capture Task				Flanker Task
	Mean (SD)	P	A	(P-A)	
Task condition					
Pure					
RT (ms)	*763 (100)*	*784 (111)*	*742 (89)*	*42*	*500 (46)*
Errors (%)	*4*	*5*	*3*	*2*	*3*
Switch					
RT (ms)	*869 (112)*	*918 (125)*	*820 (99)*	*98*	*667 (104)*
Errors (%)	*5*	*5*	*5*	*0*	*3*
Task switch cost					
RT (ms)	*106*				*167*
Errors (%)	*1*				*0*

P = Singleton present, A = Singleton absent.

<u>Flanker task.</u> As shown in Table 2, the flanker task RTs were increased under switch (vs. pure conditions), $F (1, 7) = 54.9$, $MSE = 2045.4$, $p < 0.001$. There was no significant difference between the error rates in the pure versus switch conditions, $F < 1$.

<u>Attentional capture task</u>. Two 2 (task condition) x 2 (singleton presence) within-subject ANOVAs were performed on the attentional capture RTs and percentage error rates. RTs were longer for switch than pure trials, $F (1, 7) = 21.7$, $MSE = 4121.0$, $p <$

0.01, and for singleton present versus singleton absent trials, $F(1, 7) = 36.2$, MSE = 1097.0, $p < 0.001$ (Table 2).

Critically, there was a significant interaction between task condition (switch/nonswitch) and singleton presence (present/absent), $F(1, 7) = 10.4$, MSE = 590.0, $p < 0.01$: A greater effect of singleton presence was found in switch trials than pure trials. Again, because the overall RTs increased in switch versus pure blocks, singleton effects were recalculated as proportions of singleton absent RTs and were still significantly greater in switch than pure trials, $t(7) = -3.1$, SEM = 0.020, $p < 0.01$, suggesting this increase in singleton effects was not attributable to the overall increase in RTs in switch versus pure blocks.

The error ANOVA revealed no difference between errors for pure and switch trials, $F < 1$, nor between singleton present versus singleton absent trials, $F < 1$, although a significant interaction in the errors between task condition and singleton presence, $F(1, 7) = 7.6$, MSE = 0.000, $p < 0.05$, showed a greater effect of capture on errors in the pure than switch blocks. Table 2 clearly shows that this interaction is due to less errors being made in the pure absent condition, as would be predicted.

Experiment 2 provides further support for the hypothesis that task switching results in reduced ability to attend to a target and discard distractors from entering higher levels of processing.

2.3 CHAPTER CONCLUSION

The experiments in Chapter 2 established that task switching increases distractibility in both a response competition flanker task and an attentional capture task. This provides preliminary support for the hypothesis that distractor interference effects will be

increased under task switch versus task repeat conditions. Increasing executive demand via the need to switch between two tasks resulted in increased distractor interference, suggesting that the executive resource loaded in task switching is also required to control distractor rejection in selective attention tasks, establishing support for Lavie's load theory of executive control as a late attentional selection mechanism.

CHAPTER 3

Response Mappings, Task Switching, and

Distractor Interference

3.1 INTRODUCTION

In this chapter I investigate the effect of task switching on distractor interference when the two tasks do not overlap in either their stimuli *or* their responses. As reviewed in the general introduction, with the exception of a recent study by Rubin and Meiran (2005), in previous studies the RT cost of switching between two tasks, which is attributed to the involvement of executive control in task switching, has only been revealed for switches between tasks overlapping in either stimuli (Meiran, 2000), response-mappings (Meiran, 2000; Rogers & Monsell, 1995, Experiment 4; Ruthruff, Remington & Johnston, 2001; Sumner & Ahmed, 2006), or more typically both (e.g. Rogers & Monsell, 1995). Indeed, in studies finding significant switch costs with task stimuli which do not overlap (Allport et al., 1994; Rogers & Monsell, 1995, for review see general introduction), there was overlap between the response-mappings for the two tasks, such that each response key was mapped to a response from both tasks. Due to the potential interference between response-mappings under these situations the switch costs in these studies may be due at least in part to the specific need to reconfigure stimulus-response mapping and inhibit current stimulus-response associations when switching from one task to another. Although these functions are likely to involve executive control, it is also possible to account for at least some of the RT cost associated with task switching in such a paradigm on the basis of the specific interference due to cross-talk, and potential negative effects of priming of the wrong response between conflicting response-mappings to the same stimulus (Allport & Wylie, 1999; 2000).

In support of the contribution of response-mapping overlap to task switch costs, Meiran (2000) revealed that overlap in response-mappings affected the switch cost, with

responses associated with both tasks appearing to account for the residual switch cost. However, large task switch costs revealed even when response-mappings do not overlap (Hester & Garavan, 2005) suggest response-mapping overlap is not a necessary prerequisite for task switch costs, although Hester and Garavan's study still presented stimuli affording both tasks, and thus task switch costs in this paradigm could still be contributed to by interference between task-sets related to the same stimulus.

So far none of the studies reviewed above and in the general introduction have revealed large and consistent task switching costs when both the stimuli and the responses are only associated with one task. The act of switching between two tasks, including monitoring correct task performance, activating/inhibiting task-sets, coordinating the two tasks, and shifting processing resources from one task-set to another, should involve executive control resources, regardless of whether the stimuli *or* the response-mappings for the two task-sets overlap.

In a recent study, Rubin and Meiran (2005) revealed large and consistent task switching costs when both stimuli *and* responses for each task afforded that task alone, and were unrelated to the other task. Switch costs for switches between these two tasks cannot be contributed to by factors related to re-mapping responses to the same key, nor stimulus-response mappings to the same stimulus, nor by interference from previous response-mappings on current response mappings due to both being activated by the same stimulus. Interestingly, in this paradigm task switch costs with stimuli affording both tasks were not significantly greater than those revealed for stimuli affording only one task. This study establishes that there can be large and significant task switch costs even when the stimuli and responses for the two tasks are entirely unrelated.

The experiments in the current chapter offer more direct support for the hypothesis that loading executive resources via task switching will increase distractor

interference. Task switches between two different tasks that share neither stimuli nor responses should tap more clearly into the higher-level executive control functions that are stipulated in load theory to be involved in distractor rejection. Specifically, Lavie (2000; Lavie et al., 2004) hypothesised that the demands placed on executive control when subjects need to coordinate two tasks involving different stimulus-processing priorities would detract from the availability of executive control to ensure that irrelevant low-priority distractors do not intrude on task performance.

Thus, this chapter aims to replicate the findings of greater distractor interference under task switch (versus task repeat) conditions, with both non-overlapping stimuli (as in Experiments 1 and 2) and non-overlapping response-mappings.

3.2 EXPERIMENT 3

Experiment 3 examines whether the findings of Experiment 1 can be replicated with different response-mappings for the two tasks. My hypothesis that task switching should impair the ability to ignore irrelevant distractors leads to the prediction that distractor interference in the flanker task will be greater in the task switching blocks than in the pure blocks, even when there is no overlap between the two task-sets in respect of stimuli or response-mappings.

3.2.1 Method

Participants. Nineteen undergraduates (18-35) from University College London participated. All had normal or corrected-to-normal vision and were paid for their participation.

Stimuli and Procedure. The stimuli were the same as those used in Experiment 1. The procedure was similar to that used in Experiment 1, with the exception that the response-mappings for the two tasks were mapped to four different keys as opposed to the same two keys. In the flanker task participants pressed 'C' (with the index finger of the left hand) if the target letter was a Z, and '5' on the numerical key pad (with the middle finger of the right hand) if the target letter was an X. In the visual search task subjects were asked to press 'D' (with the middle finger of the left hand) if the line in the circle was vertical, and '1' (with the index finger of the right hand) if it was horizontal.

3.2.2 Results

The mean RTs and percentage error rates as a function of the experimental conditions are presented in Table 3.

Table 3: Mean RTs for the flanker task and the visual search task as a function of task condition (pure/switch) and congruency (congruent/incongruent).

	Mean (SD)	Flanker Task			Visual Search Task
		I	C	(I-C)	
Task condition					
Pure					
RT (ms)	658 (148)	690 (168)	627 (132)	63	812 (184)
Errors (%)	6	8	5	3	3
Switch					
RT (ms)	912 (156)	971 (181)	853 (138)	118	980 (191)
Errors (%)	6.5	7	6	1	6
Switch cost					
RT (ms)	254				168
Errors (%)	0.5				3

I = incongruent, C = Congruent.

Visual search task. As can be seen in Table 3 the visual search RTs were longer in switch blocks than in pure blocks, $F (1, 18) = 81.3$, MSE = 3270, $p < 0.001$, thus establishing a significant task switching cost, and more errors were committed in switch than pure blocks, $F (1, 18) = 21.2$, MSE = 0.000, $p < 0.001$.

Flanker task. A 2 (task condition) x 2 (congruency) within-subject ANOVA on the RTs revealed longer RTs in the switch versus pure blocks, $F (1, 18) = 81.0$, MSE = 15112, $p < 0.001$, and in the incongruent versus congruent distractor conditions, $F (1, 18) = 39.5$, MSE = 3960, $p < 0.001$, revealing both a significant task switching cost and a significant effect of the congruency of the distractor on target RTs.

Importantly, there was a significant interaction between distractor congruency and task condition, $F (1, 18) = 17.0$, MSE = 837, $p < 0.001$: there were greater distractor effects in the task switch than in the pure task conditions (see Table 3) as predicted. As in previous experiments, because RTs were longer in switch than pure blocks, congruency effects were calculated as the percentage of the individual RT in the congruent distractor condition (M = 10% for pure blocks; M = 14% for switch blocks) and the interaction between task condition and congruency remained significant, $t (18) = -2.3$, SEM = 0.02, $p < 0.05$, thus making an account of the greater congruency effect in switch versus pure blocks in terms of a simple scaling effect unlikely.

The error ANOVA replicated the congruency effect, $F (1, 18) = 6.2$, MSE = 0.001, $p < 0.05$, with more errors committed in the incongruent than congruent trials. There was no effect of task switching on the error rates ($F < 1$). A numerical trend for a greater effect of congruency on errors in the pure than switch trials (2%) was revealed, but this did not reach significance, $F (1, 18) = 4.2$, MSE = 0.001, $p = 0.06$.

In conclusion, the findings suggest that switching between two tasks (as opposed to repeating performance of the same task) creates greater distraction in a selective

attention task, even when the task-sets of the two tasks do not overlap in their stimuli, nor in their responses.

3.3 EXPERIMENT 4

Experiment 4 aimed to replicate greater attentional capture from an irrelevant singleton in a visual search task when switching versus repeating tasks in conditions where the task-sets for the two tasks do not overlap in their response-mappings.

3.3.1 <u>Method</u>

<u>Participants</u>. Eight undergraduates from University College London aged between 18 and 30 and with normal or corrected-to-normal vision were paid for their participation.

<u>Stimuli and Procedure</u>. Stimuli were the same as in Experiment 2. The procedure was similar to that used in Experiment 2 but with one difference: Responses to the two tasks were mapped to different keys in the same way as in Experiment 3.

3.3.2 <u>Results</u>

Mean RTs and error rates were calculated for each subject as a function of task condition (switch/pure) and singleton presence in the attentional capture task (present/absent) and can be seen in Table 4.

Table 4: RTs for the attentional capture task and the flanker task as a function of task condition (pure/switch) and singleton presence (present/absent).

	Attentional Capture Task				Flanker Task
	Mean (SD)	P	A	(P-A)	
Task condition					
Pure					
RT (ms)	*716 (100)*	*735 (106)*	*696 (94)*	*39*	*465 (77)*
Errors (%)	*7*	*7*	*7*	*0*	*6*
Switch					
RT (ms)	*957 (196)*	*998 (205)*	*916 (186)*	*82*	*719 (128)*
Errors (%)	*4*	*4*	*4*	*0*	*4*
Task switch cost					
RT (ms)	*241*				*254*
Errors (%)	*- 3*				*-2*

P = Singleton present, A = Singleton absent.

Flanker task. As shown in Table 4, flanker task RTs were increased under switch (vs. pure) conditions, $F (1, 7) = 115.4$, $MSE = 2247.6$, $p < 0.001$, showing a significant task switching cost. Task condition was marginally significant in the error rates, $F (1, 7) = 5.2$, $MSE = 0.00$, $p = 0.06$, with more errors occurring in the pure blocks. As can be seen in Table 4 this was a small effect (2%) and as such is unlikely to reflect a speed-accuracy trade off large enough to explain the increase in RTs revealed in switch versus pure blocks.

Attentional capture task. A 2 (task condition) x 2 (singleton presence) within-subject ANOVA performed on the attentional capture RTs revealed significantly longer RTs in switch than pure trials, $F (1, 7) = 30.7$, $MSE = 15185.4$, $p < 0.001$, and significantly greater RTs for singleton present versus singleton absent trials, $F (1, 7) =$

28.0, MSE = 1046.4, p < 0.001: significant task switch costs and attentional capture effects were revealed.

Critically, there was a significant interaction between task condition (switch/nonswitch) and singleton presence (present/absent), $F (1, 7) = 22.9$, MSE = 163.7, $p < 0.01$. As illustrated in Table 4 this interaction reflects greater singleton capture effects in the switch than nonswitch blocks, as predicted. As in previous experiments, when the singleton effect was re-calculated as a proportion of singleton absent RTs the interaction remained significant (M = 6% for pure blocks; M = 9% for switch blocks), $t (7) = -3.4$, SEM = 0.010, $p < 0.05$, thus the effect of task condition on congruency effects is unlikely to result from a scaling effect due to increased RTs in the switch versus pure blocks.

An error ANOVA revealed only a main effect of task condition, $F (1, 7) = 14.8$, MSE = 0.00, $p < 0.01$, with greater errors in pure than switch trials ($F < 1$ for both the main effect of singleton presence and for the task condition versus singleton presence interaction). This 3% effect is not considerable enough to satisfactorily explain greater RTs in switch versus pure blocks as merely a speed-accuracy trade off. Additionally, to pre-empt further experiments, these results are replicated (Chapter 5, Experiment 13) without the presence of greater errors in pure versus switch trials, suggesting that a speed-accuracy trade-off is not responsible for the increased RTs in switch versus pure blocks in this experiment.

In conclusion, Experiment 4 replicated the findings of Experiment 2, showing greater interference effects from the irrelevant singleton in an attentional capture task in switch versus pure blocks; even when the task sets of the two tasks do not overlap in either response-mappings or stimuli. The results support the prediction that task

switching increases distraction even when the tasks switched between overlap in neither stimuli nor responses.

3.4 EXPERIMENT 5

Experiment 5 investigates the effect on distractor interference of switching between two tasks when responses to the two tasks are mapped to separate hands, so that the responses to one task are mapped to one hand and the responses to the other task are mapped to the other hand. The aim was to replicate the greater flanker effects in switch than pure blocks revealed by previous experiments, but with the responses to the flanker task mapped to the left hand and the responses to the visual search task mapped to the right hand. In this way, there is no overlap between the effecters of the responses for the two tasks.

3.4.1 Method

Participants. Eight undergraduates (18 to 30, with normal or corrected-to-normal vision) from University College London received payment in return for their participation.

Stimuli and Procedure. The stimuli were the same as in Experiment 3. The procedure was the same as Experiment 3, with the exception that responses to the two tasks were mapped to not only different keys, but also different hands. In the flanker task responses were made with the left hand, pressing the Z key if the target letter was a Z; pressing the X key if the target letter was an X. In the attentional capture task participants responded with the right hand, by pressing the 2 key on the number pad for a vertical line, and the 0 key on the number pad for a horizontal line.

3.4.2 <u>Results</u>

The mean RTs and percentage error rates as a function of task condition (switch/pure) and distractor congruency in the flanker task (congruent/incongruent) can be seen in Table 5.

Table 5: Mean RTs and percentage error rates for the visual search and flanker tasks in switch and pure blocks and distractor congruency in the flanker task (congruent/incongruent).

	Flanker Task				Visual Search Task
	Mean (SD)	I	C	(I-C)	
Task condition					
Pure					
RT (ms)	*550 (106)*	*567 (119)*	*532 (92)*	*34*	*671 (85)*
Errors (%)	*7*	*9*	*5*	*4*	*7*
Switch					
RT (ms)	*742 (130)*	*759 (139)*	*725 (121)*	*33*	*793 (90)*
Errors (%)	*10.5*	*12*	*9*	*3*	*7*
Switch cost					
RT (ms)	*192*				*122*
Errors (%)	*3.5*				*0*

I = Incongruent, C = Congruent.

<u>Visual Search task</u> Visual search task RTs were significantly increased under switch (vs. pure) conditions, $F_{(1, 7)} = 95.2$, $MSE = 625.6$, $p < 0.001$, a significant task switch cost, as shown in Table 5. There was no difference in the error rates between the two task conditions (both were 7%).

Flanker task. Two 2 (task condition) x 2 (flanker congruency) within-subject ANOVAs performed on the flanker task RTs and percentage errors revealed longer RTs for switch than pure trials, $F(1, 7) = 49.9$, $MSE = 5953.1$, $p < 0.001$, showing a significant task switch RT cost. The increase in RTs to incongruent trials versus congruent trials seen in Table 5 was marginally significant, $F(1, 7) = 5.2$, $MSE = 1762$, $p = 0.057$.

In addition, as can be seen in Table 5, distractor congruency effects were the same in task switch and pure blocks ($F < 1$ for the interaction). Further inspection of the data indicated that congruency effects in the pure trials (34 ms) were not significantly different to those in the pure blocks in Experiment 3 (50 ms), $t(20)$, $p = 0.79$, but the congruency effects were significantly different in the switch trials (33 ms in Experiment 5 versus 101 ms in Experiment 3), $t(20)$, $p < 0.05$. Switching in this experiment, unlike in Experiment 3, had no effect on distractor congruency effects and as such there was no interaction.

The error ANOVA replicated the main effect of congruency seen in the RTs, $F(1, 7) = 5.6$, $MSE = 0.001$, $p = 0.05$, with greater numbers of errors in incongruent versus congruent trials. There was no main effect of task condition, $F(1, 7) = 1.3$, $MSE = 0.006$, $p = 0.28$, and no interaction between task condition and congruency for error rates, $F(1, 7) = 2.1$, $MSE = 0.00$, $p = 0.20$.

In conclusion, Experiment 5 did not support my prediction that distractor interference will increase under conditions of task switching versus task repetition when there is no overlap in the responses. Next I test whether the failure to replicate the increase in distractor interference effects under task switching conditions is a general effect of separating responses between the two hands, or is specific to the response competition task.

3.5 EXPERIMENT 6

In Experiment 6 I investigated whether task switching increases attentional capture by an irrelevant singleton when the responses to the two tasks are separated, so each hand responds to only one task.

3.5.1 <u>Method</u>

<u>Participants.</u> Twelve undergraduates from University College London aged between 18 and 30 and with normal or corrected-to-normal vision were paid to participate in the experiment.

<u>Stimuli and Procedure.</u> The stimuli and procedure were the same as in Experiment 4 with the exception that responses to the two tasks were mapped not only to different fingers, but to different hands, in the same way as in Experiment 5.

3.5.2 <u>Results</u>

The mean RTs and error rates as a function of task condition (switch/pure) and singleton presence in the attentional capture task (present/absent) are shown in Table 6.

Table 6: Mean RTs and percentage error rates for the attentional capture task and the flanker task as a function of task condition (pure/switch) and singleton presence (present/absent).

	Attentional Capture Task				Flanker Task
	Mean (SD)	P	A	(P-A)	
Task condition					
Pure					
RT (ms)	*784 (128)*	*808 (139)*	*761 (118)*	*47*	*483 (41)*
Errors (%)	*5.5*	*6*	*5*	*1*	*5*
Switch					
RT (ms)	*879 (150)*	*918 (158)*	*840 (143)*	*78*	*662 (129)*
Errors (%)	*5.5*	*6*	*5*	*1*	*4*
Task switch cost					
RT (ms)	*95*				*179*
Errors (%)	*0*				*-1*

P = Singleton present, A = Singleton absent.

Flanker task. As can be seen in Table 6 the flanker task RTs were increased under switch (vs. pure) conditions, $F_{(1, 11)} = 32.2$, MSE = 5668.2, $p < 0.001$, showing a significant task switching cost, but there was no main effect of task condition in the errors, $F_{(1, 11)} = 0.48$, MSE = 0.00, $p = 0.50$.

Attentional capture task. A 2 (task condition) x 2 (singleton presence) within-subject ANOVA on RTs showed a task switch cost, $F_{(1, 11)} = 17.2$, MSE = 6288.7, $p < 0.01$, and a significant capture effect, $F_{(1, 11)} = 75.6$, MSE = 614.1, $p < 0.001$ (see Table 6): RTs were significantly increased for task switch versus pure blocks and singleton present versus singleton absent trials.

Most importantly, a significant interaction, $F_{(1, 11)} = 6.9$, MSE = 400.7, $p < 0.05$, indicated that the effect of singleton presence was greater in switch trials than pure

trials. This interaction remained significant when the singleton effects were re-calculated as proportions of singleton absent RTs (M = 6% for pure trials; M = 9% for switch trials), t (11) = -2.2, SEM = 0.15, p < 0.05, making an account for this effect in terms of a scaling effect due to increased RTs in switch versus pure blocks unlikely.

The error ANOVA found no significant main effects (singleton presence, F (1, 11) = 2.5, MSE = 0.001, p = 0.15; task condition, F < 1) and no significant interaction between task condition and singleton presence (F < 1).

Experiment 6 replicated the results of Experiment 4, despite the separation of the tasks to different hands. The findings of Experiment 6 demonstrate that singleton capture effects are increased under conditions of task switching, even when the response-mappings for the two tasks switched between do not overlap between hands.

3.6 CHAPTER CONCLUSIONS

Greater interference from distractors in the flanker and attentional capture tasks was revealed in task switch (vs. pure) blocks when the responses to the two tasks were mapped to different response keys, replicating the findings from Experiments 1 and 2 when there is no overlap between the response mappings of the two tasks. However, when the responses to one task were mapped to one hand, and the responses to the other task were mapped to the other hand, increased distractor interference in switch versus pure blocks was replicated in the attentional capture task, but not in the flanker task.

An interesting question is why separating responses between the hands eliminated the effect of task switching on selective attention performance in the flanker task, but not in the attentional capture task. One possibility is that task switching affects the two selective attention tasks at different stages of distractor processing. For

example, the effect of task switching on distractor interference in the flanker task may occur at the response selection stage, where the opposing response of the distractor in an incongruent trial competes for control of behaviour. Task switching may act to increase interference between responses at the response selection stage, so long as there is overlap between responses, such that the previous tasks responses compete with the current tasks responses for behavioural control. Greater interference at the response selection stage would allow the distractor to more effectively compete for behavioral control under task switch conditions because executive resources would be directed towards not only rejecting the distractors response, but also the responses to the previous task. When the responses are separated such that there is a clear distinction between the responses to the two tasks (e.g. left hand = flanker task, right hand = visual search task) then this extra interference when task switching is removed.

Note that the simple addition of a greater number of responses in switch versus pure blocks is unlikely to itself result in the effect of task switching on distractor interference because, to look ahead, these effects are also revealed when the pure and switch trials occur within the same block. In this case it is likely that responses to both tasks are held active across the block, and as such there will be no difference in the number of responses held active during task switch and task repeat trials, but only in the recency of making responses to the other tasks, and thus the activation level of the competing responses.

Whilst the effect of task switching on the ability to selectively attend to a target in the flanker task may occur at the response competition stage, the effect of task switching on singleton capture (which was not affected by removing response-mapping interference) may occur at another stage of higher level functioning, such as target selection. For example, when executive resources are less available due to task

switching, the singleton target representation may be less strongly maintained in working memory, thus allowing the distractor representation to interfere more effectively with target selection, slowing responses to trials on which an irrelevant singleton is present compared to trials where it is absent. I return to this point in Chapter 4.

These findings make an important contribution to task switching research, supporting Rubin and Meiran's (2005) finding of significant task switch costs with both stimuli affording, and responses related to, only one task. As discussed previously, earlier research only established a task switching cost with tasks that had either overlapping stimuli (Meiran, 2000) or response-mappings (Meiran, 2000; Rogers and Monsell, 1995, Experiment 4; Ruthruff, Remington, & Johnston, 2001; Sumner & Ahmed, 2006), and typically both (e.g. Rogers and Monsell, 1995).

CHAPTER 4

The Effect of Task Switching on Distractor

Interference when Pure and Switch Trials are in

the Same Block

4.1 INTRODUCTION

The aim of Chapter 4 is to further break down the executive control demands of task switching, with a view to more specifically attributing the greater distractor interference effects in switch trials to a particular element of executive control. To this end, the contribution of the mixing cost to my task switching costs in Chapters 2 and 3 was removed, and the effects of the executive demands of task switching versus task mixing on distractor interference were assessed and compared.

The task switching cost revealed in previous chapters can be further divided into a specific task switching cost and a task mixing cost (Kray & Lindenberger, 2000; Meiran, Chorev, & Sapir, 2000; for review see Rubin and Meiran, 2005). The specific task switching cost measures the difference in the time taken to respond to pure and switch trials when both trial types are displayed within the same block. The task mixing cost measures the difference in reaction times to repeated-task trials in a between-block design, where repeated-task trials are presented in a pure block, and repeated-task trials in a within-block design, where repeated-task trials and switch trials are presented in the same block. Thus, the task mixing cost measures the effect of mixing task A within a block with task B compared to performing task A alone in a 'pure' block.

Support for the distinction between the task switching cost and task mixing cost comes from a behavioural double dissociation regarding the effects of age and ADHD on task switch versus task mix costs: Old age had a strong effect on the mixing cost, but a relatively weak effect on the task switching cost (Kray & Lindenberger, 2000), whereas children with ADHD showed increased task switching costs, but normal mixing costs (Cepeda, Cepeda, & Kramer, 2000).

Originally, the mixing cost was thought to reflect processes such as working memory demands (storage of two versus one task-set), division of attention between perceptual dimensions, degree of arousal and effort, response criterion, and so on (Meiran, 1996; Rogers & Monsell, 1995). However, the mixing cost may be an important measure of executive demand because it compares a condition where task performance can almost be performed automatically (pure trials in pure blocks), with a condition in which task performance occurs in a control demanding environment (nonswitch trials in AAABBB blocks; Rubin & Meiran, 2005).

An interesting question, then, is whether the mixing cost and switching cost measure different aspects of executive control, and, if so, how much each contributes to the overall task switch cost. Indeed, recent accounts suggest that the specific task switching cost comparing switch and nonswitch trials within a block loads on transient executive control processes operating on a trial by trial basis (Braver, Reynolds, & Donaldson, 2003; Logan & Bundeson, 2003; Mayr & Kliegl, 2003), for example triggered by interference between task-sets. Mixing tasks within a block, on the other hand, may load more sustained or global control processes which operate across blocks (Braver et al., 2003; Koch, Prinz, & Allport, 2005; Kray & Lindenberger, 2000), such as the maintenance or sustained activation of two task-sets in a mixed block compared to one in a pure block.

Whilst this simple distinction is tempting, some doubt has been cast by work carried out by Rubin and Meiran (2005). They showed large mixing costs when stimuli afforded both tasks, but small and non-significant mixing costs when the stimuli afforded only one task (see also Mayr, 2001), suggesting that the mixing cost reflects the transient control processes triggered by interference between task-sets, rather than sustained control processes. In contrast, switching costs were large and significant for

both stimulus types, suggesting that the switching cost was not contributed to by these transient control processes. Note, however, that many previous studies have found that when the stimulus is not associated with both task-sets, task switch costs are often eliminated or, at the very least, reduced to an almost negligible amount (Allport et al., 1994, Experiment 4; Jersild, 1927; Spector & Biederman, 1976) suggesting that some aspect of overall task switch costs does rely heavily on transient control processes triggered by interference between tasks-sets. Rubin and Meiran (2005) also found no effect of working memory load on the task mixing cost nor on the specific task switching cost, suggesting the sustained control processes involved in maintaining task-goals and/S-R mappings in working memory does not contribute to these costs. However, this study does not suggest that other sustained control processes are not involved in the control of task switching or task mixing costs.

The research reviewed above supports a different role of executive control in task switching versus task mixing costs. To this end, the current experiments aim to investigate whether it is the executive demand required by mixing tasks or switching to a new task, or both, which affects distractor interference. Investigating the effect of task switching on distractor interference without the mixing cost will either: i) have no effect on task switch costs and selective attention performance because mixing cost did not load executive control in these experiments; ii) reduce overall (but not specific) task switch costs by removing the contribution of task mixing, but have no effect on the difference in selective attention performance between pure and switch trials because it is the executive demand of switching tasks which is responsible for the increased distractor interference effects in task switch blocks; iii) reduce overall task switch costs, as above, and facilitate selective attention performance by removing the additional executive demand of mixing tasks, suggesting the executive demand of mixing tasks

was responsible for some of the greater distractor interference effects in task switch blocks; iv) reduce the overall task switch cost and eliminate the difference in selective attention performance between pure and switch trials, suggesting the executive demand of mixing tasks is responsible for the effect of task switch blocks on distractor interference effects.

In my prior experiments the contributions of the executive demand of switching versus mixing tasks to the detrimental effect of task switch blocks on selective attention performance could not be assessed. In the current chapter I investigate how the executive demands of task mixing versus task switching affect selective attention performance. By presenting both pure and switch trials within the same block I investigate the effects of specific task switching (without the presence of the task mixing cost) on distractor interference effects. Task mixing does not contribute to the task switch cost under these conditions because pure and switch trials are no longer compared between one-task and two-task blocks. Thus, by comparing task switch costs and distractor interference effects between experiments I can assess the relative contributions of task switching and task mixing to task switch costs and selective attention performance. Repeat-task trials occurring within the same block as switch trials will be referred to as nonswitch trials, and repeat-task trials occurring in pure blocks in previous experiments will be referred to as pure trials.

4.2 EXPERIMENT 7

Experiment 7 aims to more specifically attribute the effect on distractor processing to task switching per se, rather than to additional executive demand which might result from mixing tasks, or the contribution from other between block differences, such as

effort and arousal. Thus, in Experiment 7 only switch blocks with the trial order AAABBB were presented. In this way a comparison could be made between the distractor interference effects in switch trials (the first trial A following 3 trial Bs, and vice versa) and non-switch trials (the second trial in each 3-trial sequence) within the same block.

I predict that in an AAABBB design there will be significant switch costs, as well as greater distractor interference effects in switch (vs. nonswitch) trials. Mixing costs will be assessed by comparing nonswitch trials in the AAABBB design with pure trials in the pure blocks in previous chapters.

4.2.1 Method

Participants. Ten subjects (18-35) from University College London with normal or corrected-to-normal vision were paid for their participation.

Stimuli and Procedure. The stimuli were the same as in Experiment 3 and the procedure was similar to that in Experiment 3, with the exception that trials were presented in an AAABBB order in every block. In each of 12 AAABBB blocks 3 of one task and then 3 of the other task were randomly selected without replacement, and this sequence repeated until 80 trials had been performed. The blocks alternated between blocks starting with task A and blocks starting with task B. The task beginning the first block was task A for half of the participants and task B for the other half.

4.2.2 Results

The mean RTs and percentage error rates as a function of the experimental conditions can be seen in Table 7.

Table 7: Mean RTs and percentage errors for the flanker task and the visual search task as a function of task condition (pure/switch) and congruency (congruent/incongruent) when trials were presented in AAABBB blocks.

	Flanker Task				Visual Search Task
	Mean (SD)	I	C	(I-C)	
Task condition					
Nonswitch					
RT (ms)	*668 (68)*	*691 (74)*	*647 (73)*	*44*	*915 (109)*
Errors (%)	*3*	*5*	*2*	*3*	*3*
Switch					
RT (ms)	*969 (164)*	*1025 (165)*	*913 (166)*	*112*	*1143 (136)*
Errors (%)	*8.5*	*8*	*9*	*-1*	*8*
Switch cost					
RT (ms)	*301*				*228*
Errors (%)	*5.5*				*5*

I = incongruent, C = Congruent.

Visual search task. As shown in Table 7, RTs were longer in switch versus pure blocks, $F (1, 9) = 41.1$, MSE = 6339.1, $p < 0.001$, revealing a significant task switching RT cost in the AAABBB design. There was also a non-significant trend in the error rates, $F (1, 9) = 3.6$, MSE = 0.003, $p = 0.09$, with more errors in the switch than nonswitch trials.

Nonswitch trial RTs in Experiment 7 (915 ms) were not significantly longer than pure block trials in Experiment 3 (812 ms), $t (27) = -1.6$, $p = 0.12$, although there was a numerical trend in the direction predicted by a task mixing cost.

Flanker task. A 2 (task condition) x 2 (congruency) within-subject ANOVA revealed significantly greater RTs in switch versus pure blocks, $F (1, 9) = 57.7$, MSE =

15574.7, p < 0.001, and in the incongruent versus congruent trials, F (1, 9) = 41.4, MSE = 1484.9, p < 0.001, as before.

Most importantly for my hypothesis there was a significant interaction between task condition and distractor congruency, F (1, 9) = 23.6, MSE = 487.0, p < 0.001: distractor effects were more than doubled in the switch versus pure trials in the AAABBB block design (see Table 7). This interaction remained significant when the data were analysed as proportions for the switch and pure trials, t (9) = 2.3, SEM = 0.023, p < 0.05, suggesting that the increased distractor interference in switch trials was not due to the prolonged RTs in switch versus pure trials.

In the error rates there was a marginally significant effect of task condition, F (1, 9) = 5.0, MSE = 0.005, p = 0.053, with greater errors in switch versus nonswitch trials, as can be seen in Table 7. There was no effect of congruency nor an interaction between task condition and congruency in the errors (F < 1 for congruency main effect: F (1, 9) = 2.9, MSE = 0.001, p = 0.12, for the interaction between task condition and distractor congruency).

Nonswitch RTs in Experiment 7 (668 ms) were not significantly different from the pure trial RTs in Experiment 3 (658 ms), t (27) = -0.2, p = 0.84, suggesting that there was no effect of mixing tasks on the flanker task RTs. T-tests comparing Experiments 3 and 7 showed no significant difference between task switch costs (254 ms and 301 ms, respectively), t (27) = -1, p = 0.34, and no significant difference between distractor interference effects in the pure versus nonswitch trials (64 ms and 44 ms, respectively), t (27) = 0.9, p = 0.36. These findings further suggest that any additional executive demand of mixing tasks did not affect task switch costs and distractor interference effects in the flanker task in Experiment 3.

Experiment 7 thus replicated the finding of greater distractor interference in switch versus pure trials in Experiment 3 but with both trial types occurring within the same block. Experiment 7 suggests that the increase in distractor interference effects under task switching conditions is not due to the executive demand involved in mixing tasks, but rather the executive demand involved in switching between tasks.

4.3 EXPERIMENT 8

In Experiment 8 I examined whether increased attentional capture by an irrelevant singleton when task switching can also be found in switch versus pure trials when both are presented within the same block.

4.3.1 Method

Participants. Twelve subjects (18-35, with normal or corrected-to-normal vision) from University College London were paid for their participation.

Stimuli and Procedure. The stimuli and procedure were the same as those used in Experiment 4, with the exception that trials were presented in an AAABBB order in every block. The AAABBB block design was the same as in Experiment 7 except that there were 6 blocks in which the AAABBB sequence repeated until 288 trials had been performed.

4.3.2 Results

Mean RTs and percentage error rates as a function of task condition (nonswitch/switch) and singleton presence in the attentional capture task (absent/present) can be seen in Table 8.

Table 8: Mean RTs and percentage error rates for the attentional capture task and the flanker task as a function of task condition (nonswitch/switch) and singleton presence (sin absent/sin present) when trials were presented in AAABBB blocks.

		Attentional Capture Task			Flanker Task
	Mean (SD)	P	A	(P-A)	
Task condition Nonswitch					
RT (ms)	923 (156)	956 (155)	889 (164)	67	556 (70)
Errors (%)	4	4	4	0	2
Switch					
RT (ms)	1080 (184)	1101 (180)	1058 (195)	43	848 (148)
Errors (%)	4	4	4	0	4
Switch cost					
RT (ms)	157				292
Errors (%)	0				2

P = Singleton present, A = Singleton absent.

Flanker task. As can be seen in Table 8, RTs were longer in switch than in nonswitch trials in the flanker task, $F (1, 11) = 99.8$, MSE = 5126.5, $p < 0.001$, showing a significant task switching cost. The percentage errors in the flanker task were increased in the switch versus nonswitch trials, but this was not significant, $F (1, 11) = 3.5$, MSE = 0.00, $p = 0.09$.

There was a significant effect of mixing tasks in the AAABBB design on the flanker task RTs, $t (18) = -3$, $p < 0.01$, with nonswitch trial RTs (922 ms) significantly increased compared to pure trial RTs in Experiment 4 (716 ms).

Attentional Capture task. Two 2 (task condition: switch/nonswitch) x 2 (singleton presence: present/absent) within-subjects ANOVAs were performed on the RT data and percentage error rates. The RT ANOVA revealed significant effects of task

condition, F (1, 11) = 57.9, MSE = 5166.3, p < 0.001, with longer RTs in switch versus nonswitch trials, and also singleton presence, F = 8.5, MSE = 36465.2, p < 0.05, with longer RTs in the singleton present versus absent trials, thus establishing both a task switching cost and attentional capture by an irrelevant singleton.

However, there was no interaction between task condition and singleton presence, F (1, 11) = 2.1, MSE = 768.0, p = 0.17.

Error rates were the same under all conditions (see Table 8).

A possible explanation for the lack of interaction here is that the increase in attentional capture effects in task switch versus pure task blocks resulted from the executive demand of mixing tasks, rather than that of switching tasks. Indeed, there were significantly longer RTs in the nonswitch trials in Experiment 8 (922 ms) versus pure trials in Experiment 4 (716 ms), t (18) = 3.3, SED = 62.5, p < 0.01, establishing that there was a significant effect of mixing tasks on attentional capture task RTs. However, although there was a strong numerical trend, there was no significant interaction between mixing task condition and singleton presence, F (1, 18) = 1.2, MSE = 1580, p = 0.3, with singleton effects not significantly greater in nonswitch (67 ms) compared to pure trials (39 ms).

The RT cost of switching to the attentional capture task in the AAABBB within-blocks design in Experiment 8 (157 ms) was reduced compared to the between-blocks design in Experiment 4 (241 ms), t (18) = -1.9, SED = 43.4, p = 0.07, showing that the mixing cost explains some of the task switch cost revealed between pure and switch blocks in Experiment 4. The reduction in task switching cost in the within- versus between-block design is mostly attributable to the mixing cost, rather than the relatively smaller non-significant increase in the RTs to switch trials in Experiment 8 (1080 ms) versus Experiment 4 (957 ms) design, t (18) = 1.4, SED = 86.0, p = 0.17.

In an attempt to rule out the mixing cost as an account of the increased attentional capture effects revealed in previous experiments, I now aim to facilitate performance in nonswitch trials. This manipulation, if successful, may reveal an increase in singleton capture effects under task switching versus nonswitching conditions. In Experiment 9 I attempt to facilitate performance in the attentional capture nonswitch trials in an AAABBB design.

4.4 EXPERIMENT 9

In Experiment 9 the amount of practice on the attentional capture task was increased in order to facilitate performance of the attentional capture nonswitch trials. In Experiment 9 the number of AAABBB blocks was increased from 6 to 12.

4.4.1 Method

Participants. Eight undergraduates (18-35) with normal or corrected-to-normal vision from University College London were paid for their participation.

Stimuli and Procedure. The stimuli and procedure were the same as those used in Experiment 8, with the exception that the number of AAABBB blocks was increased from 6 to 12.

4.4.2 Results

The mean RTs and percentage error rates as a function of task condition (nonswitch/switch) and singleton presence in the attentional capture task (absent/present) are shown in Table 9.

Table 9: Mean RTs and percentage error rates for the attentional capture task and the flanker task as a function of task condition (nonswitch/switch) and singleton presence (sin absent/sin present) with 12 AAABBB blocks.

	Attentional Capture Task				Flanker Task
	Mean (SD)	P	A	(P-A)	
Task condition					
Nonswitch					
RT (ms)	861 (110)	889 (114)	832 (109)	57	539 (84)
Errors (%)	7	6	7	-1	5
Switch					
RT (ms)	1053 (171)	1082 (166)	1023 (180)	59	913 (166)
Errors (%)	7	7	6	1	9
Switch cost					
RT (ms)	192				374
Errors (%)	0				4

P = Singleton present, A = Singleton absent.

Flanker task. Table 9 shows the significant effect of task condition in both the flanker task RTs, $F (1, 7) = 69.3$, MSE = 8084.1, $p < 0.001$, with longer RTs in switch than nonswitch trials; and percentage error rates, $F (1, 7) = 13.1$, MSE = 0.001, $p < 0.01$, with more errors committed in switch than nonswitch trials.

There was a nonsignificant trend towards a mixing cost in the flanker task RTs, $t (14) = -1.9$, $p = 0.085$, with longer RTs in the nonswitch (548 ms) versus pure (462 ms) trials in Experiment 4.

Attentional Capture task. Two 2 (task condition) x 2 (singleton presence) within-subject ANOVAs performed on the RT data and percentage error rates revealed increased RTs in switch versus nonswitch trials, $F (1, 7) = 26.1$, MSE = 11361.1, $p < 0.001$, and in singleton present versus singleton absent trials, $F (1, 7) = 33.1$, MSE =

819.2, p < 0.001, replicating the significant task switch costs and singleton capture effects revealed in Experiment 8.

However, the singleton capture effect again did not differ in the switch versus nonswitch trials (F < 1, see Table 9) in the AAABBB design, even with increased practice of the attentional capture task.

The error ANOVA replicated neither of the main effects (F < 1 for both the task condition and singleton presence main effects) and there was no interaction between task condition and singleton presence, F (1, 7) = 1.9, MSE = 0.00, p = 0.21.

As predicted, increasing practice of the tasks reduced RTs in the nonswitch attentional capture trials (by 61 ms from Experiment 8), but this reduction was not significant, t (18) = -0.96, p = 0.36. In other words task switch costs to the attentional capture task were not significantly increased in Experiment 9 compared to Experiment 8, t (18) = 0.87, p = 0.4, and RTs to the nonswitch trials in Experiment 9 were still significantly greater than the RTs to the pure trials in Experiment 4, t (14) = 2.8, p < 0.05: there was still a significant mixing cost. However, note that the non-significant increase in switch cost from Experiment 8 to 9 (35 ms) was enough for the RT cost of task switching in Experiment 9 (192 ms) to no longer be significantly different from that in Experiment 4 (between-blocks; 241 ms), t (14) = -0.85, p = 0.4.

Once again there was a nonsignificant numerical trend towards greater attentional capture in the task mix (nonswitch trials, 57ms) than no task mix (pure trials in Experiment 4, 39 ms) conditions. This trend did not reach significance, F (1, 14) = 1.4, MSE = 460, p = 0.26.

In summary, Experiment 9 still did not find any effect of task switching on attentional capture, despite increasing the amount of practice on the attentional capture task and somewhat increasing the task switching cost.

4.5 EXPERIMENT 10

Experiment 10 aimed to facilitate repetition trial performance in the attentional capture task in the AAABBB design in order to increase the cost of a switch between tasks. In Experiment 10 the number of repetitions of the attentional capture task prior to nonswitch trials in a within-block design was increased. In this way the attentional capture nonswitch trials were made more similar to the attentional capture pure trials in Experiment 4.

In Experiment 10 the two tasks were presented in 9A3B (…AAAAAAAAABBB…) blocks, with task A being the attentional capture task.

4.5.1 Method

Participants. Ten undergraduates (18-35) from University College London with normal or corrected-to-normal vision were paid for their participation.

Stimuli and Procedure. The stimuli and procedure were the same as Experiment 8, with the exception that trials were presented in the order …AAAAAAAAABBB… (9A3B), where A is the attentional capture task. Trials included as nonswitch trials for the attentional capture task were in positions 5 – 8 in each run of 9 trials. In this way nonswitch trials occurred after 4 previous repetitions of the attentional capture task.

4.5.2 Results

The mean RTs and percentage error rates as a function of task condition (nonswitch/switch) and singleton presence in the attentional capture task (absent/present) can be seen in Table 10.

Table 10: Mean RTs and percentage error rates for the attentional capture task and the flanker task as a function of task condition (nonswitch/switch) and singleton presence (sin absent/sin present) when trials were presented in AAABBB blocks.

	Attentional Capture Task				Flanker Task
	Mean (SD)	P	A	(P-A)	
Task condition					
Nonswitch					
RT (ms)	*889 (110)*	*928 (117)*	*849 (104)*	*79*	*539 (73)*
Errors (%)	*6.5*	*6*	*7*	*-1*	*4*
Switch					
RT (ms)	*1306 (308)*	*1355 (325)*	*1256 (299)*	*99*	*1040 (242)*
Errors (%)	*6*	*7*	*5*	*2*	*8*
Switch cost					
RT (ms)	*417*				*501*
Errors (%)	*-0.5*				*4*

P = Singleton present, A = Singleton absent.

Flanker task. As can be seen in Table 10, there were longer RTs in the switch than nonswitch trials in the flanker task, $F(1, 9) = 72.4$, $MSE = 17283.2$, $p < 0.001$, and more errors made in switch versus nonswitch trials, $F(1, 9) = 52.2$, $MSE = 0.00$, $p < 0.001$.

There was a significant effect of mixing tasks on nonswitch RTs in the flanker task, $t(16) = -2.1$, $p = 0.05$, with longer RTs in nonswitch (539 ms) than pure trials in Experiment 4 (462 ms).

Attentional Capture task. Two 2 (task condition) x 2 (singleton presence) within-subject ANOVAs found significantly greater RTs in switch versus nonswitch trials, $F(1, 9) = 29.7$, $MSE = 58579.3$, $p < 0.001$, and significantly greater RTs in the singleton present versus singleton absent trials, $F(1, 9) = 45.6$, $MSE = 1739.2$, $p < 0.001$, again

replicating significant task switch costs and singleton capture effects in a within-block design.

However, although there was a numerical trend for greater attentional capture in task switch versus nonswitch trials (see Table 10) this did not reach significance ($F < 1$).

The error ANOVA did not replicate the main effects of task condition ($F < 1$), nor singleton presence, $F(1, 9) = 3.51$, $MSE = 0.00$, $p = 0.09$. However, there was a significant interaction between singleton presence and task switch condition, $F(1, 9) = 5.3$, $MSE = 0.00$, $p < 0.05$: the error singleton effect (singleton present errors – absent errors) was larger in the switch than nonswitch trials. Thus, the effects in the errors provide some support for the current hypothesis.

Increasing the number of attentional capture trials occurring prior to the nonswitch attentional capture trials in Experiment 10 did not significantly reduce nonswitch trial RTs (889 ms versus 923 ms in Experiment 8), $t(20) = -0.58$, $p = 0.58$. Note that, as in Experiment 9, RTs to the nonswitch trials were still significantly different to those in Experiment 4 (716 ms), $t(16) = 3.5$, $p < 0.05$: there was still a significant cost associated with mixing tasks.

Critically, in Experiment 10 there was a significant interaction between mixing cost and singleton presence, $F(1, 16) = 5.9$, $MSE = 611$, $p < 0.05$, with significantly greater singleton capture effects revealed in the nonswitch trials (79 ms) compared to pure trials in Experiment 4 (39 ms). This result strongly supports the view that the executive demand of mixing tasks is responsible for increased attentional capture in switch blocks versus pure blocks in previous experiments, rather than the executive demand directly associated with a switch between tasks.

As predicted, task switch costs were significantly increased in Experiment 10 in comparison to Experiment 8, $t(20) = 3.5$, $p < 0.01$. Interestingly, the task switch cost in

Experiment 10 (417 ms) was also significantly greater than in the between-block task switch cost in Experiment 4 (241 ms), $t(16) = 1.9$, $p < 0.05$. Despite this successful increase in task switch costs, singleton capture effects on RTs were still not significantly increased in switch versus pure trials, and the increase in the capture effect with switching on errors was fairly small, when these trials were presented in a within-block design. This supports the view that it is the need to mix two tasks within the same block that effects attentional capture by an irrelevant singleton, and not the specific need to switch between tasks.

Further support that the specific task switch cost does not affect singleton capture effects comes from the increase in task switch costs in Experiment 10, versus Experiments 8 and 4, which was not accompanied by a concurrent increase in singleton capture effects in Experiment 10 versus Experiment 8, $t(20) = 1.4$, $p = 0.16$, nor Experiment 4, $t(16) = 1.6$, $p = 0.14$. The presence of a mixing cost in previous experiments which did reveal increased attentional capture in switching versus pure blocks again strongly suggests that it is the executive demand associated with mixing tasks which affects selective attention performance on the attentional capture task.

Although nonswitch trial RTs were not reduced to a significant degree it was the significant increase in the switch trial RTs in Experiment 10 (1305 ms) compared to Experiment 8 (1080 ms), $t(20) = 2.12$, $p < 0.05$, and the between-block design in Experiment 4 (957 ms), $t(16) = 2.77$, $p < 0.05$, which was largely responsible for the increased task switch cost. Thus, in Experiment 10 the increase in the number of trials prior to a nonswitch trial did not increase task switching costs by facilitating nonswitch trial performance. Rather, increasing the frequency of the attentional capture task (compared to the other task) seems to increase the RT cost of a switch to the attentional capture task. Note that this frequency effect on specific task switch costs was not due to

the attentional capture task becoming the better learned task due to increased practice (see Allport, Styles, & Hsieh, 1994; Monsell, 2003; Yeung & Monsell, 2003), because switch performance was also significantly decreased in the flanker task in Experiment 10 versus Experiment 8, $t(20) = 2.3$, $p < 0.05$, and versus Experiment 4, $t(16) = 3.4$, $p < 0.01$.

It is possible that the increased task switch cost in Experiment 10, due to the increase in switch RTs, resulted from the difficulty in monitoring how many repetitions of the attentional capture task were left before a switch to the flanker task was required. Under these conditions the strategy of not preparing for task switches in advance may have been easier than monitoring when a task switch was due. Although there were only 3 trials of the flanker task it would be economical to apply the same strategy to both tasks throughout the blocks, rather than attempt to switch strategy when switching tasks. Preparation for a switch allows some of the work by executive resources to be carried out prior to the task switch and as such reduces switch costs. By not preparing for a switch the amount of work to be done by executive resources on switch trials (i.e. in preparing the system for the new task) is increased.

Experiment 10 suggests that the smaller difference between switch trials and nonswitch trials in Experiment 8 versus switch and pure trials in Experiment 4, reflected in significantly smaller task switch costs in Experiment 8, were not responsible for the elimination of the interaction between task condition and singleton presence: Although task switch costs in Experiments 9 and 10 were increased and were thus not smaller (indeed in Experiment 10 were significantly larger) than in Experiment 4, the interaction between task condition and singleton capture still did not approach significance in a within-block design.

Experiment 10 made an alternative account for the greater attentional capture in the switch versus pure blocks as due to habituation to the singleton in the pure blocks in Experiment 4 unlikely. In the between-block design in Experiment 4, repeated performance of the attentional capture task in the pure blocks may have resulted in habituation to the irrelevant singleton, reducing the attentional capture observed in the pure blocks compared to the switch blocks. Allowing sustained, repetitive performance of the attentional capture task in the within-block design should allow habituation to the singleton in nonswitch trials and thus increase the difference in singleton effects between nonswitch and switch trials. Experiment 10 did not significantly increase the difference in singleton capture effects between switch and nonswitch trials, thus suggesting habituation to the singleton distractor was not responsible for the greater singleton capture in switch than pure trials in Experiment 4.

In summary, in Experiment 10, switching to the first of a run of 9 attentional capture task trials increased the RT cost of switching compared to Experiments 8, 9 and 4. However, Experiment 10 did not find significantly greater singleton capture effects in switch versus pure trials in a within-block design, despite this increase in task switch costs. Interestingly, Experiment 10 revealed a significant effect of mixing tasks on the singleton capture effect, suggesting that the need to mix tasks within a block loads executive resources required to ensure an irrelevant singleton does not capture attention. These finding strongly support the view that the increase in attentional capture effects when comparing switch and pure blocks is due to the executive demand of mixing tasks, rather than the executive demand specifically associated with switching from performance of one task to performance of another.

4.6 CHAPTER CONCLUSIONS

Task switching reduced selective attention performance in the flanker task when both the trials involving a switch between tasks, and those requiring the previous task to be repeated, were presented within the same block. However, task switching under these conditions had no effect on attentional capture by an irrelevant singleton. Despite manipulations which successfully increased the cost of the specific task switches on general task performance, the ability to avoid distraction from an irrelevant singleton distractor remained the same on switch and nonswitch trials. Revealingly, the requirement to mix tasks within a block did increase capture by an irrelevant singleton, suggesting that it is the executive demand associated with mixing tasks which resulted in the effect of task switching on capture effects in previous experiments, rather than that of the specific need to switch between two tasks. Whilst the effect of task switching on flanker task performance is due to the executive demand incurred by a specific switch from one task to another, the effect of task switching on attentional capture is due to the extra executive demand required when mixing tasks.

As discussed in the introduction to this chapter, many authors have argued for a differentiation between slow, sustained executive processes involved in mixing tasks and more transient executive processes involved in switching the cognitive system from one tasks performance to another (Braver, Reynolds, & Donaldson, 2003; Koch, Prinz, & Allport, 2005; Kray & Lindenberger, 2000; Logan & Bundeson, 2003; Mayr & Kliegl, 2003; although see also Rubin & Meiran, 2005). Selective attention performance in the attentional capture task is heavily reliant on the ability to actively maintain representations of the target and distractor. The ability of sustained executive processes to maintain the abstract identity of the distractor (i.e. ignore any singleton which is not

the target, or ignore any colour singleton) and suppress it and/or monitor for the presence of the distractor singleton, should be directly predictive of the amount of singleton capture by an irrelevant singleton. In this way, attentional capture effects might be affected only by limitation in the availability of sustained executive processes which may be loaded by mixing tasks. This could explain why selective attention performance in the attentional capture task was unaffected by task switching once the requirement to mix tasks was present in both pure and switch trials. In comparison, the flanker effect relies on a more transient control process of response competition resolution which must be completed anew on every trial. Thus, whilst flanker task performance relies on maintenance of the task-set also, the interference from the irrelevant distractor specifically depends on the availability of transient response-conflict resolution control processes at the response-selection stage, such as those required for a switch between two tasks.

It is important to note that in the previous chapter I argued that flanker effects occur at the response competition stage and attentional capture effects occur at a later stage of processing. I made this argument on the basis that the effect of task switching on flanker effects, but not on attentional capture effects, was eliminated when responses to the two tasks were separated between the hands. These double dissociations in the effects of response mappings and the effects of switching versus mixing blocks on distraction in the flanker versus attentional capture tasks strongly support a distinction in the executive resource required for performance of the two selective attention tasks.

In light of the suggestion that attentional capture is mediated by executive resources involved in controlling mixing, rather than switching, tasks, the failure of manipulations aimed at facilitating nonswitch trial performance in order to increase task switching costs, and thus reveal an effect of task switching on attentional capture, can

be explained: the nonswitch RTs reflected the cost of mixing tasks, and as such were not reduced by manipulations which were not designed to reduce the cost of mixing tasks.

Another possible explanation of the mixing cost, other than the executive demand of mixing tasks, might be that it is due to the carryover of specific interference effects in the switch trials to the nonswitch trials. Whilst it has been revealed previously that, for example, stimulus-response mappings of the previous task carryover across a number of trials (for review see Allport & Wylie, 2000; Goshke, 2000; Monsell, 2003) this is only the case when the stimuli cue the response-mappings for both tasks. In the current experiments the stimulus is different in each task and does not cue the response-mappings of the previously performed task, and there is no overlap between response-mappings, suggesting carryover effects are not responsible for the mixing costs revealed.

Note that the effect of first trial performance on task switch costs is not assessed here, but this is another contributor to task switch costs which is confounded between pure and switch trials in the current experiments. Future work could further separate the executive demand of task switching and assess more directly which demands in switch blocks are responsible for the detrimental affect on selective attention performance.

The current findings support the distinction in the literature between sustained executive control of mixing tasks, and transient executive control of switching tasks. As discussed above, the results suggest that the mixing cost results from sustained executive demand which also affects the more sustained executive requirements of the attentional capture task; and that the specific task switching cost results from the more transient executive demand involved in both switching between tasks and performing the flanker task.

In summary, Chapter 4 revealed both significant task switching and task mixing costs as well as distractor interference effects in both the flanker task and attentional capture task. Whilst task switching affected interference from distractors in the flanker task, it was rather the executive demand of task mixing which was responsible for the previously found effect of task switching on attentional capture by an irrelevant singleton.

CHAPTER 5

Task-Unrelated Thoughts During Task

Switching

5.1 INTRODUCTION

Another form of distraction on the performance of a primary task which may be affected by a switch between tasks is task-unrelated thoughts (TUTs), or mind wandering. TUTs are thoughts occurring during the performance of a task which are unassociated with carrying out the task, and can be considered as intrusions, or distractions, from internally generated processes whilst a task is being executed. Recent studies provide evidence that TUTs require executive control resources, and as such I hypothesise that TUT should also be affected by a switch between tasks.

Much evidence in the TUT literature supports a role of executive control in mind wandering. Studies have repeatedly revealed that the extent to which primary tasks interfere with TUTs depends upon the level of executive demand made by the task: more executive demand in the primary task results in less TUTs and vice versa (Antrobus, 1968; Filler & Giambra, 1973; Teasdale et al., 1993; 1995). Decreasing the executive demands of pursuit rotor and memory tasks by increasing practice (independent of fatigue) has also been associated with increased TUT frequency (Teasdale et al., 1995). Smallwood, Obonsawin, and Reid (2003) hypothesised that block duration mediated changes in TUTs would be reduced for fluency tasks, which rely heavily on controlled processing and are thus not readily automated, compared to other less control-demanding (verbal encoding and vigilance) tasks. Whereas the executive demand of the verbal encoding and vigilance tasks reduced with block length as they became more automated, the fluency task required the same executive input throughout the block. TUTs in the tasks more given to automation increased with block length, but there was no effect of block length on TUTs in the fluency task. Thus, TUTs reflected the availability of executive resources, increasing as the executive demands of

the tasks more prone to automation decreased, and staying the same for the fluency task, where the executive demand of the task did not reduce with practice.

Random generation of numbers, argued by Baddeley (1996) to involve executive control in order to suppress the use of an automatic response pattern (such as odd numbers), was also less random when TUTs were concurrently reduced, suggesting these two tasks share a requirement for executive control (Teasdale et al., 1995).

Studies using the sustained attention to response task (SART), a go/no go task, where participants respond to the numbers 0-9 with a key press but suppress responding to one number, usually the number 3, provides further evidence that executive control is involved in TUTs. The SART task gives a measure of failures in controlled processing: When the SART becomes more automated, and is less under the direct control of executive resources, there will be more errors in suppressing the response to the no go target, especially when the target is more infrequent. Evidence that errors on the SART reflect a drift of attention from the primary task comes from studies showing that SART errors both predict (Robertson et al., 1997), and are predicted by (Manly et al., 1999) questionnaire measures of absentmindedness. Faster SART RTs are associated with experimental blocks in which TUTs occur compared to those where attention remains directed towards the primary task (Smallwood et al., 2004), supporting the view that TUTs result in more automated task performance due to less executive control of the primary task. Increased TUTs (measured retrospectively) are also associated with increased errors during blocks where executive control is disengaged from the task (i.e. blocks where RTs were faster) suggesting the pre-potent response was stronger and therefore more automated.

Further support for the reliance of TUTs on executive control comes from five experiments showing a large and consistent decrease in TUTs as age increases

(Giambra, 1989). Increasing age is associated with an overall decline in executive functioning (e.g. Salthouse et al., 1998) and thus this finding supports the suggestion that reduced executive control results in reduced experience of TUTs.

Imaging studies also support a role for frontal-executive control in TUTs, indicating that TUTs share cognitive and neural mechanisms with task-related thought processes (Christoff, Ream, and Gabrieli, 2004). Comparing periods of rest (where TUTs are free to occur) with periods where a simple cognitive task is engaged in, Christoff et al. (2004) identified activity associated with rest in higher cortical regions such as rostrolateral prefrontal cortex, temporopolar cortex, parahippocampus, parietal and visual cortical areas. Interestingly, rest has frequently been used as a baseline in the past for comparing activation whilst performing a cognitive task. Studies have shown that certain areas do not show a difference in activation during higher cognitive tasks when rest is used as a baseline, such as complex memory retrieval, problem solving, and the Wisconsin Card Sorting Task, all tasks which consistently activate the rostrolateral prefrontal cortex (e.g. Christoff et al., 2001; Christoff, & Gabrieli, 2000; Goldberg et al., 1998). However, critically, activation differences are seen in the same tasks when compared to a baseline using an unrelated secondary task (e.g. Buckner et al., 1996; Ragland et al., 1998). These findings suggest that activations in this prefrontal area are associated with brain activity present during both higher level cognitive tasks and rest, supporting a role of executive control in 'rest' conditions, where TUTs are free to occur.

In addition, some studies have shown striking similarities between the patterns of activation present when at rest and those associated with particular higher cognitive functions. For example, activation associated with both an episodic memory task and a rest condition was found in higher cortical regions, including prefrontal and parietal association cortices (Andreasen et al., 2004). Post-experiment interviews revealed that

rest was an active process involving freely wandering past recollection, future plans, and other personal thoughts and experiences. Binder et al. (1999) found similar areas associated with both a semantic retrieval task and rest. They argue that rest is associated with semantic knowledge retrieval, representation in awareness, and manipulation of represented knowledge. These studies strongly suggest that rest (time in which participants are free to experience TUTs) is associated with regions (such as the prefrontal cortex) and activities (such as manipulation of knowledge) thought to be heavily involved in executive control.

More specifically, prefrontal executive areas appear to be heavily involved in TUTs when there is awareness of the contents of the mind wandering episode, but not when there is no awareness of the content of the mind wandering episode (Smith et al., 2006). TUTs with no thought content awareness were associated with activations in areas related to long-term memory storage (such as hippocampus). It should be noted that executive control areas are not always involved unless TUT is associated with thought content awareness. This suggests that frontal-executive resources may not be involved in the initiation of TUTs, but rather in the control and coordination of information in awareness during a mind wandering episode (e.g. Smallwood & Schooner, 2006).

In summary, a combination of behavioural and neuroscientific evidence supports the view that content-aware TUTs rely on frontal-executive resources. I therefore hypothesise that a reduction in the availability of these resources, via the requirement to switch between tasks, should result in reduced frequency of report of TUTs. Note that this predicted reduction in interference from an internal source of distraction (TUTs) is contrary to the revealed increase in interference from an external source of distraction (visual distractors) during task switching versus task repetition. Investigating the effect

of executive load on TUTs offers a comparison between the role of executive control in inhibiting external distractors versus supporting internal distraction, offering insight into the dissociation between distraction from internal and external sources.

I tested this hypothesis by measuring TUTs via probe questions, occurring at the end of each short block of experimental trials, asking whether participants had any task-unrelated thoughts during task performance of the block of trials prior to the probe. Participants were informed that a TUT could be any specific thought which was unrelated to performance of the primary task, such as considering what they would have for dinner. In this way, participants only reported TUTs in which they were aware of the contents of their mind wandering episode. These types of TUT are those which appear to rely most heavily on input from frontal-executive control resources and, as such, should be most susceptible to interference from tasks also relying on these resources, such as task switching.

5.2 EXPERIMENT 11

Experiment 11 aimed to establish the effect of task switching on the experience of task-unrelated thoughts. It is predicted that the frequency of report of TUTs will be lower under conditions of task switching versus task repetition.

5.2.1 <u>Method</u>

<u>Participants</u>. Eight participants (18-35) from University College London with normal or corrected-to-normal vision were paid to participate.

<u>Stimuli and Procedure</u>. The stimuli were the same as those used in Experiment 3. The procedure was similar to that used in Experiment 3, with two exceptions: firstly,

the flanker task distractor was always response-neutral (the letter P); and secondly, each

of the twelve blocks of trials (six pure and six switch blocks) was divided into two

separate blocks, creating 24 blocks of 48 trials. After each of the 24 blocks participants

were asked whether they had had any TUTs during the preceding block. Participants

pressed Y for yes and N for no on the computer keyboard. The TUT probe occurred 12

times after switch blocks and twelve times after pure blocks (6 times after pure flanker

task blocks and 6 times after pure visual search task blocks).

5.2.2 Results

Table 11 shows mean RTs, percentage error rates and frequency of report of TUTs as a

function of task condition in the three tasks. TUTs are presented as the proportion of yes

answers to the TUT probe after pure and switch blocks.

Table 11: Mean RTs for the visual search task and flanker tasks and proportion of yes

responses to TUT probe as a function of task condition (pure/switch).

Mean (SD)	Flanker Task	VS Task	TUTs
Task condition			
Pure			
RT (ms)	655 (153)	913 (220)	0.80 (0.30)
Errors (%)	4	5	
Switch			
RT (ms)	934 (368)	1262 (303)	0.50 (0.20)
Errors (%)	4	5	
Task switch cost			
RT (ms)	279	349	- 0.30
Errors (%)	0	0	

Visual search task. As shown in Table 11, visual search RTs were longer in switch blocks than in pure blocks, $F_{(1, 7)} = 35.4$, $MSE = 13768.5$, $p < 0.01$, revealing a significant task switch cost. There was no effect of task condition on percentage errors which were the same in pure and switch trials (see Table 11). As can be seen in Table 11, overall visual search RTs were significantly slower than flanker task RTs, $t_{(7)} = -7$, $SEM = 41$, $p < 0.001$.

Flanker task. Task condition again had a significant effect on RTs, $F_{(1, 7)} = 11.9$, $MSE = 26137.8$, $p < 0.05$, with longer RTs revealed in the switch versus pure blocks: a task switch cost. Again, there was no effect of task condition on percentage errors, which, as can be seen in Table 11, were the same in both pure and switch conditions.

Task-unrelated thoughts. As predicted, there was a significant effect of task condition on frequency of report of TUTs, $F_{(1, 7)} = 14.4$, $MSE = 0.02$, $p < 0.01$, with a higher frequency of TUTs reported after pure versus switch blocks (see Table 11), establishing that task switching significantly reduced the frequency with which TUTs were reported.

Since overall RTs were significantly greater in the pure blocks of the visual search versus flanker task, suggesting greater task difficulty in the visual search task, I examined the effect of a different source of general task difficulty on TUTs: Was there a reduced rate of TUTs when task difficulty increased, i.e. in the visual search task? There was no significant difference between the TUTs reported after pure blocks of the flanker task than pure blocks of the visual search task, $t_{(7)} = -1.8$, $p = 0.11$, although there was a numerical trend towards *increased* TUT report after the pure blocks of the visual search task (0.85) than flanker task (0.71). Note that the direction of the numerical trend is contrary to that which would be expected if general task difficulty were responsible

for the revealed decrease in TUTs in switch versus pure trials. This suggests that it is specifically the executive demand of switching between two tasks which results in a reduced frequency of report of TUTs, rather than general task difficulty. I return to this point in Experiment 13, where this trend became significant.

Experiment 11 established support for my hypothesis that fewer TUTs will be experienced under conditions of task switch versus task repeat conditions.

5.3 EXPERIMENT 12

In Experiment 12 I directly contrasted the effects of task switching on external versus internal distraction. I predict both increased distractor interference in the flanker task and, conversely, reduced distraction from TUTs under task switch versus task repetition conditions.

5.3.1 Method

Participants. Ten participants (18-35) with normal or corrected-to-normal vision from University College London were paid for their participation.

Stimuli and Procedure. The stimuli and procedure were the same as Experiment 11, with the exception that the distractor in the flanker task was not a neutral P, but either an X or a Z, creating the opportunity to observe the effects of the response-competitive distractor on target RTs.

5.3.2 Results

Table 12 shows mean RTs, percentage error rates and frequency of report of TUTs as a function of the experimental conditions. TUTs are presented as the proportion of yes

answers to the TUT probe. Two participants were removed from the analysis because their flanker effects in the pure blocks were very large (310 and 323 ms) compared to the group average (M = 46 ms, SD = 78 ms).

Table 12: Mean RTs for the visual search and flanker tasks and proportion of yes responses to TUT probe as a function of task condition (pure/switch) and congruency in the flanker task (congruent/incongruent).

	Mean (SD)	Flanker Task			VS Task	TUTs
		I	C	(I-C)		
Task condition						
Pure						
RT (ms)	811 (237)	834 (219)	788 (261)	46	934 (296)	0.70 (0.30)
Errors (%)	9	11	6	5	7	
Switch						
RT (ms)	1138 (553)	1209 (553)	1066 (557)	143	1296 (654)	0.40 (0.30)
Errors (%)	8	9	6	3	5	
Switch cost						
RT (ms)	327				362	-0.30
Errors (%)	-1				-2	

I = incongruent, C = congruent.

Visual search task. Visual search RTs were longer in switch than pure blocks, $F (1, 9) = 8.2$, MSE = 79917.2, $p < 0.01$, revealing a significant task switching cost. More errors were committed in the pure than switch blocks, $F (1, 9) = 6.4$, MSE = 2.5, $p < 0.05$, although this 2% difference is unlikely to account for the RT task switch cost as a speed-accuracy trade-off, especially since significant task switch related RT costs were revealed in Experiment 11 in the visual search task without any difference in errors between task conditions.

As can be seen in Table 12, overall RTs were significantly greater in the pure visual search task trials compared to pure flanker task trials, $t(9) = 2.5$, $p < 0.05$.

Flanker task. A 2 (task condition) x 2 (congruency) within-subject ANOVA revealed significantly longer RTs in both the switch versus pure blocks, $F(1, 9) = 10.4$, $MSE = 103215.8$, $p < 0.05$, and in the incongruent versus congruent distractor conditions, $F(1, 9) = 39.3$, $MSE = 2281.2$, $p < 0.001$, establishing both a significant task switching cost and a significant congruency effect in the flanker task.

Critically, as predicted, there was an interaction between task condition and distractor congruency, $F(1, 9) = 5.6$, $MSE = 4230.0$, $p < 0.05$, with greater distractor effects in task-switch than pure task conditions, replicating Experiment 3 (see Table 12). When the congruency effects were calculated as proportions of the congruent RTs, in order to eliminate the possibility of explaining the results in terms of a scaling account, the increase in congruency was still marginally significant, $t(9) = -1.7$, $p = 0.065$, one-tailed.

The error ANOVA only replicated the congruency effect, $F(1, 9) = 7.4$, $MSE = 0.001$, $p < 0.05$, with more errors occurring in the incongruent versus congruent trials, (for task condition, $F(1, 9) = 1.2$, $MSE = 0.001$, $p = 0.31$, for the interaction between flanker congruency and task condition, $F(1, 9) = 3.9$, $MSE = 0.000$, $p = 0.08$).

Task-unrelated thoughts. Table 12 clearly shows the significant effect of task condition on frequency of report of TUTs, $t(9) = 6.2$, $SEM = 0.04$, $p < 0.001$: as predicted, more TUTs were reported in pure blocks than switch blocks.[2]

---

[2] When this analysis was performed on all 12 participants including the two outliers TUTs were still significantly greater in pure than switch blocks, $F(1, 11) = 23.1$, $MSE = 0.13$, $p < 0.01$. All other ANOVAs were also performed on all 12 participants with only one difference in the results to those reported above. With all 12 participants the congruency x task condition interaction was not significant, $F(1, 11) = 2.3$, $MSE = 5074$, $p = 0.16$, showing no significant effect of task switching on distractor interference effects.

Due to the significant increase in RTs in the pure trials in the visual search task versus the flanker task, TUTs were compared between these two conditions to examine the effect of task difficulty on TUTs. There was no significant difference in TUTs between the flanker task (0.63) and visual search task (0.70), $t < 1$, supporting the view that it is specifically the executive demand of a task switch which is responsible for the decrease in TUTs in switch versus pure trials.

Experiment 12 offers support to the hypothesis that task switching will conversely increase distraction from external sources, such as flanker interference, whilst decreasing distraction from internal sources, such as TUTs.

5.4 EXPERIMENT 13

In Experiment 13 I examined whether the dissociation between increased external distractor interference and decreased internal distractor interference under task switch conditions can be replicated with a different measure of external distractor interference, namely the attentional capture task. I predict that task switching will result in increased interference from singleton distractors, partnered with decreased interference from TUTs.

5.4.1 <u>Method</u>

<u>Participants</u>. Eight participants (18-35) with normal or corrected-to-normal vision from University College London were paid for their participation.

<u>Stimuli and Procedure</u>. The stimuli and procedure were the same as Experiment 4, with the exception that each of the 12 experimental blocks was split into two and

each of the subsequent 24 blocks was followed by a TUT probe, following the procedure of Experiment 11.

5.4.2 Results

Table 13 shows mean RTs, percentage error rates, and proportion of positive TUT report following the probe, as a function of task condition (pure/switch) and singleton presence (absent/present). One participant was removed from the analysis because their singleton effect in the pure condition was abnormally large (210 ms) compared to the group mean ($M = 54$ ms, $SD = 69$ ms).

Table 13: Mean RTs for the visual search and flanker tasks, and proportion of yes responses to TUT probe, as a function of task condition (pure/switch), singleton presence (absent/present).

	Attentional capture task				Flanker task	TUTs
	Mean (SD)	P	A	(P-A)		
Task condition						
Pure						
RT (ms)	*890 (119)*	*917 (123)*	*863 (121)*	*54*	*530 (53)*	*0.50 (0.30)*
Errors (%)	*5*	*6*	*4*	*2*	*4*	
Switch						
RT (ms)	*1145 (210)*	*1208 (213)*	*1082 (214)*	*126*	*860 (207)*	*0.40 (0.30)*
Errors (%)	6	6	6	0	3	
Switch cost						
RT (ms)	*255*				*330*	*-0.10*
Errors (%)	*-1*				*-1*	

A = singleton absent, P = singleton present.

Flanker task. RTs were significantly affected by task condition, $F_{(1, 7)} = 19.8$, MSE = 21976.1, $p < 0.01$, being longer in switch blocks than in pure blocks, revealing a significant task switching cost. No difference in percentage errors between switch and pure blocks, $F < 1$, was revealed. Also note that pure trial RTs in the flanker task were significantly faster than in the visual search task, $t_{(7)} = -9.0$, SEM = 40, $p < 0.001$.

Attentional capture task. A 2 (task condition) x 2 (singleton presence) within-subject ANOVA revealed significantly longer RTs in the switch versus pure blocks, $F_{(1, 7)} = 26.2$, MSE = 19914.1, $p < 0.01$: a significant task switching cost. Longer RTs were also revealed in the incongruent versus congruent distractor conditions, $F_{(1, 7)} = 16.4$, MSE = 3633.1, $p < 0.01$, showing a significant effect of singleton presence on RTs.

An interaction between singleton presence and task condition, $F_{(1, 7)} = 10.7$, MSE = 959.1, $p < 0.05$, replicated the findings of greater singleton effects in task-switch than pure task conditions observed in Experiment 4, supporting the prediction that externally generated distraction would increase in switch versus pure blocks. This increase in singleton effects under task switch conditions was significant even when the possibility of explaining the RT interaction by a scaling account was addressed by calculating the congruency effects as proportions of the congruent RTs, $t_{(7)} = -2.6$, $p < 0.05$, one-tailed.

The error ANOVA did not replicate any of these effects: $F_{(1, 7)} = 2.6$, MSE = 0.00, $p = 0.15$, for the main effect of task condition; $F_{(1, 7)} = 2.5$, MSE = 0.00, $p = 0.16$ for the main effect of singleton presence; $F_{(1, 7)} = 2.4$, MSE = 0.00, $p = 0.28$ for the interaction between flanker congruency and task condition.

Task-unrelated thoughts. Contrary to the findings of Experiment 12, there was no difference in the frequency of TUTs after pure blocks versus switch blocks, $F < 1$, as can clearly be seen in Table 13.[3]

Interestingly, although there was no effect of switch on TUTs, there were significantly more TUTs reported after the visual search task (0.52) than after the neutral flanker task (0.37), $t(7) = -3.0$, $SEM = 0.05$, $p < 0.05$, suggesting that, contrary to the reduction in TUTs after loading executive control with a task switch, increasing another source of task difficulty actually increased the number of TUTs reported. This dissociation between the effects of task switching and another source of task difficulty on TUTs supports the view that it is specifically the executive load of task switching which increases external and decreases internal distraction on switch trials, and not another source of task difficulty in switch versus pure blocks. Despite this significant increase in TUTs after the visual search pure trials compared to flanker task pure trials, there was still no effect of switching on TUTs when comparing the switch trials to the visual search task pure trials, $t(7) = -1.5$, $SEM = 0.08$, $p = 0.20$. However, the increase in TUTs with increased task difficulty could result simply from the prolonged RTs in the visual search task: longer blocks of visual search than flanker pure trials would have resulted in a longer time in which TUTs could occur before the probe after the visual search task than flanker task pure blocks. Alternatively, greater vigilance in the flanker task might have resulted in both faster RTs and less TUTs. Without further experiments the effect of visual search task difficulty on TUTs is purely post hoc and any explanations are speculative.

---

[3] When the outlier was included in the analyses all results were the same as reported here (there was still no difference in TUTs between the pure and switch trials, $F(1, 8) < 1$) with the exception that the interaction between singleton presence and task condition was only marginally significant, $F(1, 8) = 4.6$, $MSE = 1470$, $p = 0.064$.

It is important to note that Experiment 13 replicates the findings of Experiment 4 with no significant differences in the percentage errors rates. Experiment 13 suggests that the greater task switch RT costs and the greater singleton capture RT effects in switch than pure trials revealed in Experiment 4 are not due to a speed-accuracy trade-off.

Experiment 13 failed to replicate the decrease in TUTs during task switching which was revealed in Experiments 11 and 12.

5.5 CHAPTER CONCLUSIONS

Reducing the availability of executive control by switching between the flanker task and a visual search task conversely increased distraction from external sources and reduced internal distraction. Whilst prevention of distraction from external visual distractors is controlled by executive resources, these resources appear not to be involved in the prevention of distraction from internal distractors. Instead, executive control is required in order to generate and/or control internal distraction in the form of TUTs.

Interestingly, switches between the attentional capture task and a neutral flanker task did not result in less frequently reported TUTs. Whilst this at first seems surprising, given that previous experiments suggest that attentional capture effects rely on executive control processes required in mixing tasks, it may be that TUTs rather rely on the executive control processes involved in switching between tasks, which are relied on for successful flanker task performance. Performance of both the switch requirement

and the flanker task would produce a far greater load on these (possibly more transient) executive processes than the combined performance of the attentional capture task and task switching because the attentional capture task does not load on these particular executive processes. Indeed, if executive control were simply involved in the initiation of TUTs then this might involve only transient control processes.

The TUT measure used in the current study may be more sensitive to the availability of transient executive processes compared to sustained executive processes, because the TUT probe asks only whether participants experienced TUTs in the block prior to the TUT probe. The elements of TUTs which might be affected by more sustained control processes, such as the length and depth of processing involved in the mind wandering episode, are not measured using the current method. An interesting avenue for future research would be to measure the contents and length of TUTs, rather than purely their presence or absence. These aspects of mind wandering might load more on the sustained executive control associated with attentional capture and thus reveal a dissociation between the effects of task switching on TUTs and attentional capture.

Note that Experiment 12 also suggests that increased distraction from external distractors in switch conditions is not due to increased task difficulty: increasing executive load (and concurrently task difficulty) only increases distraction if this distraction is from external sources. If it were the case that increasing task difficulty necessarily resulted in increased distraction then both external and internal distraction would be increased. Additionally, another source of task difficulty, as reflected by significantly greater RTs in the visual search than flanker task in Experiments 11 and 12, was not associated with decreased TUTs. These findings support the view that it is

specifically the executive demand associated with a switch between tasks which reduces

TUTs in switch versus pure blocks.

CHAPTER 6

Individual Differences in Working Memory Capacity, Task Switching Cost, and Distractibility

6.1 INTRODUCTION

In Chapter 6 I examined how individual differences in working memory capacity relate to the task switch cost and distractibility in selective attention tasks. Working memory capacity was assessed using the operation span task (Ospan), which measures the availability of executive resources to control performance of a primary task (e.g. maintain task relevant information and task goals) in the face of distraction (e.g. from an ongoing task, such as manipulating numbers in equations; e.g. Engle, 2002). If it is the case that task switching and distractor rejection in selective attention tasks both rely on executive resources, then lower Ospan scorers should show greater RT deficits in conditions involving switching tasks and interference from distractors.

Tasks relying on executive control in order to respond to a target in the face of distraction, such as the antisaccade task, the Stroop task, and the dichotic listening task, correlate with working memory span score. In a colour-word Stroop task (e.g. Stroop, 1935), under conditions where maintenance of the task goal (to name the colour and avoid reading the word) was made difficult (i.e. in a 75% congruent condition where reading the word gave the correct answer in 75% of trials) low span's performance was detrimentally affected on incongruent trials, with low-spans making nearly twice as many errors as high-spans. However, when the task goal was easy to maintain (i.e. in a 0% and a 50% congruent condition) there was no such advantage (Kane & Engle, 2003). Low working memory spans were less able to maintain the task goal of naming the colour in the face of interference from the more practised task of reading the word.

In a dichotic listening task, where participants attend to information in one ear whilst ignoring the information in the other ear, 65% of low-spans heard their name when it occurred in the unattended stream, compared to only 20% of high-spans: low-

spans were less able to reject the distracting information and focus on the current task goal (Conway, Cohen, & Bunting, 2001).

The antisaccade task requires inhibition of the strong tendency to shift attention to sudden onsets. Participants fixate centrally and targets appear on either the left or right side of fixation. Critically, before stimulus onset there is a sudden onset cue which can appear on the side where the target will appear, called the prosaccade condition, or on the opposite side, called the antisaccade condition. The automatic tendency of the visual system to orient to the cue (both with eye movements and attention) facilitates task performance in the prosaccade condition, but is detrimental to task performance in the antisaccade condition. Whilst no difference has been revealed for low- and high-working memory spans on task performance in the prosaccade condition, participants who score low (vs. high) on the working memory span task were more detrimentally affected by the need to avoid making a conflicting response when performing the antisaccade condition (Kane, Bleckley, Conway, & Engle, 2001), again supporting the view that low-spans have less executive control to maintain target information in the face of distractor interference.

Further studies have suggested that whereas high-spans use their executive control ability to protect them from distractor interference, low-spans cannot or do not. Under conditions of cognitive load (i.e. dual-task performance) high-span's performance was reduced to that of low span's, but low-span performance was unaffected (Kane & Engle, 2000).

Interestingly, despite the effect of executive capacity (working memory span) on dual-task performance (e.g. Kane & Engle, 2000), and the findings reviewed in the general introduction that varying working memory load modulates task switching performance (Baddeley, Chincotta, & Adlam, 2001; Hester & Garavan, 2005), most

previous research has found no correlation between working memory capacity and task switch cost (Kane and Engle, 2000; Oberauer, SuB, Schulze, Wilhelm, & Wittmann, 2000; Oberauer, SuB, Wilhelm, & Wittmann, 2003; Miyake et al., 2000). Oberauer et al. (2003) revealed that task-set switching variables, taken as a measure of executive supervision processes, were only weakly related to other working memory functions, such as storage/processing and coordination, suggesting that the underlying cause of RT slowing in switch trials cannot be attributed to general working memory capacity. Similarly, no positive correlation was revealed between a latent 'mental-set-shifting' variable statistically extracted from three different switching tasks (the plus-minus task, Jersild, 1927; the letter-number task, Rogers & Monsell, 1995; and the local-global task) and Ospan (Miyake et al., 2000). Miyake and colleagues argue that this mental-set-shifting latent variable, and information updating and monitoring (loaded on by the Ospan) are executive functions which are separable, and performance on tasks requiring different executive functions will not necessarily correlate. Using three numerical Stroop tasks and four experiments with the Rogers and Monsell (1995) alternating runs task, Engle and colleagues also failed to reveal any effects of working memory span on task switching RT costs (Kane & Engle, 2000). These findings are a little surprising, given that the research just reviewed supports working memory span as a measure of the ability of executive control to activate/maintain task-relevant information in the face of interference from task-irrelevant information (e.g. Conway, Cohen, & Bunting, 2001; Kane, Bleckley, Conway, & Engle, 2001; Kane & Engle, 2000; 2001). Task switching should involve this general executive control capacity and the lack of relationship between working memory capacity and task switching ability casts doubt on the idea of a general resource for maintaining information in the face of distraction (e.g. Oberauer et al., 2003).

However, in these previous experiments, which did not reveal an effect of working memory span on the task switch cost (Kane and Engle, 2000; Oberauer et al., 2003; Miyake et al., 2000), task switching involved a confound between task cues and switch cues. For example, using the classic Rogers and Monsell (1995) alternating runs paradigm (AABB…), where a specific location cued which of two tasks should be performed on the stimulus (letter/digit pairs), Kane and Engle (2002) failed to find an effect of working memory span on task switch RT costs, and Oberauer et al. (2003) found only a weak correlation between task switching and working memory tasks. Logan and colleagues (e.g. Arrington & Logan, 2004; Logan & Bundeson, 2003; Logan & Schneider, 2006) have argued that combining the task cue and the stimulus cue in this type of paradigm allows the correct answer simply to be retrieved from long term memory based on the reinstatement of the previous stimulus-location-response binding episode. If the top right location cued a response to the letter in the letter/digit pair, then whenever the stimulus 3A appeared in the top right location then the answer was always, for example, A. Thus, there is no executive requirement to activate the correct task-set, simply the need to retrieve the correct stimulus-location-response mapping from memory. Task switch costs in this theory are considered to reflect the cost of encoding the new task cue in the switch trial, as compared to repeating the same task, which requires no cue-encoding. Note that executive control involved in retrieval from LTM, in this argument, is the same across pure and switch trials and, as such, cannot explain the switch costs revealed.

In order to reveal an effect of working memory capacity on task switching the availability of a composite cue which can trigger retrieval of the correct response without the need to activate the correct task-set must be removed. In such a way, the

executive demands of a task switch will be increased and task switching should rely more heavily on the availability of executive control.

Kane and Engle (2004) addressed this issue in a cleverly conceived experiment in which task cues and stimulus cues were separated such that correct responses could not simply be retrieved from memory, and thus increased the executive requirements of task switching. Switching was cued by location, as in previous experiments, with the difference that there were only three possible locations and two possible tasks. As such, each location did not itself cue a particular task, rather the correct task was cued simply by the *change* in location. For example, in this paradigm, although the top position was associated with one task on one trial, the next time the stimulus appeared in the top location it cued the other task, (Kane & Engle, 2004). Removing the specific task cues in this way (and so removing the possibility to respond using the stimulus-location-response binding recalled from memory) increases the executive load of switching. This manipulation revealed a significant effect of Ospan on task switching costs in both RTs and errors, with low spans showing significantly greater task switch costs compared to high spans.

Whilst previous studies have investigated the effects of working memory span on distraction in tasks such as the antisaccade, Stroop, and dichotic listening tasks, which involve responding in line with a task goal whilst avoiding distraction from invalid cues, strong response tendencies and salient information, respectively, no studies at the time of testing had investigated the effect of working memory span on distractor interference effects in the response competition task. However, Heitz and Engle (2007), in an elegant study investigated the mechanism by which working memory capacity affects distractor interference. They revealed no interaction between working memory span and either RTs or errors on the flanker task, but high working memory spans

reached peak performance in the incongruent trials in terms of accuracy significantly faster than low spans. They argue that the difference between the working memory span groups reflects slower attentional focusing in the low than high spans. As such they suggest that executive control will only affect flanker task RTs when responding occurs within the response time frame in which visual attention has started, but not yet finished, focusing. In terms of the current study, I claim, instead, that whilst the time taken to constrict the window of attention may modulate the effect of working memory span on distractor interference effects, this does not rule out an effect of working memory span on overall distractor interference effects in RTs or errors. Consider that in the current study, unlike the study of Heitz and Engle (2007) where there was considerable time pressure to perform the flanker task as fast as possible, accuracy was emphasised as more important than speed in responding to the flanker task. Thus, in incongruent trials, high spans, due to their attention focusing more quickly and so leaving the distractor outside of their window of attention, will more quickly reach a level of certainty regarding the correct response to the flanker task compared to low spans. This will reduce high spans distractor interference RT effects compared to low spans.

The current study investigates the effect of working memory span on task switching costs and distractor interference effects in the flanker task. If both task switching and distractor interference rely on executive control then low working memory span should correlate with larger task switching costs and greater interference from distractors.

6.1 EXPERIMENT 14

In Experiment 14 I investigate how individual differences in working memory span effect task switching costs and distractor interference effects. The hypothesis that executive load results in larger costs of task switching in terms of both RTs and distractor interference effects leads to the expectation that individuals with low working memory span (low-spans) will show more interference from irrelevant distractors and greater effects of switching on RTs than high-spans. I predict greater distractor interference effects in the flanker task along with greater task switching costs for low-versus high-spans.

6.1.1 Method

Participants. Sixty two participants (18 – 35) with normal or corrected to normal vision, who responded to an advert in the Gumtree online magazine, or were undergraduate students from University College London, were paid for their participation.

Materials. The standardised Automated Operation Span task (Ospan; Unsworth, Heitz, Schrock, & Engle, 2005) was presented on a computer screen. Subjects responded by writing the words they remembered on a standardised Automated Operation Span response sheet (Unsworth, Heitz, Schrock, & Engle, 2005).

Stimuli and Procedure. The stimuli and procedure were the same as in Experiment 3, except participants also performed the Automated Operation Span task (Ospan). Participants were randomly divided so that half of the participants performed the Automated Operation Span task immediately before the RT experiment, and half immediately after the RT experiment. Participants were presented with serially

presented equation-word trials (e.g. IS (2 + 6) – 3 = 5 ? Cloud). On each trial participants read the equation out loud, gave their answer out loud (yes or no), and then read the word out loud (e.g. "Is 2 plus 6 minus 3 equal to 5? Yes. Cloud."). After each equation-word trial was completed the experimenter pressed a key and the next trial was presented on the screen. Equation-word trials were presented and completed by the participant in sets of between 2 and 5. Participants were blind as to how many equation-word trials would be in each set. After each set participants saw 3 question marks in the centre of the screen which was the cue to write down all of the words they remembered from that set on the standardised response sheet. The partial-credit unit (PCU) scoring method was used to score the Ospan (see Conway et al., 2001)[4]. For each set of words recalled, a proportion score was given, so that if a subject scored 3 out of 5 on one set they scored 0.6 for that set. The final score was the average of the proportions on each of the 12 sets.

6.1.2 Results

Overall results. Table 14 shows the overall RTs and percentage errors for the flanker task as a function of task condition and congruency.

---

[4] The all or nothing method (ANL; the sum of recalled words only from those sets recalled fully and in the correct order) used by Engle and colleagues (e.g. Kane and Engle, 2003) was not used because the range of ANL Ospan scores in my population (4-37 out of a possible 60) was more limited than that established by Engle and colleagues on student populations across America (2-54; see Kane and Engle, 2003, page 51). This was a result of my population being mostly gathered from the general population, and not all students. High spans in my population had a range of 15-37, compared to the normal high span range of 19-54, strongly suggesting that my population had limited variance in their working memory ability. Thus, the ANL scoring method resulted in reduced variance in the Ospan score (with only 14 unique ANL values in the low and high span groups combined). Using the PCU method increased the variance in the scores, resulting in 23 unique PCU values for the low and high spans combined and high spans scored up to 0.98 out of 1.00. NB: results were the same using both scoring methods, with two exceptions: i) congruency x Ospan was only marginally significant with the ANL method (p = 0.06), possibly due to the ceiling effect in the ANL scores; ii) none of the correlations with Ospan were significant with ANL, due to the reduced variance in ANL versus PCU scores.

Table 14: RTs and percentage errors in the flanker task and visual search task as a function of task condition and congruency.

	Mean (SD)	Flanker Task			Visual Search Task
		I	C	(I-C)	
Task condition					
<u>Pure</u>					
RT (ms)	*692 (125)*	*737 (134)*	*647 (121)*	*90*	*824 (151)*
Errors (%)	*5.5*	*7*	*4*	*3*	*6*
<u>Switch</u>					
RT (ms)	*938 (165)*	*995 (175)*	*881 (160)*	*114*	*1031 (189)*
Errors (%)	*4.5*	*6*	*3*	*3*	*3*
<u>Switch cost</u>					
RT (ms)	*246*				*207*
Errors (%)	*-1*				*-3*

I = incongruent, C = Congruent.

Visual search task. Two within-subjects ANOVAs performed on the upper and lower tiertiles of the population (N = 42) revealed a significant effect of task condition on both the visual search RTs, $F (1, 41) = 167$, MSE = 5367, $p < 0.001$, and errors, $F (1, 41) = 45$, MSE = 0, $p < 0.001$. This result replicates the task switch cost revealed in previous experiments but with a large sample size.

Flanker task. RT and error data were analysed with two within-subjects ANOVAs performed on the upper and lower tiertiles of the population (N = 42). The RT ANOVA revealed a significant effect of task condition, $F (1, 41) = 371$, MSE = 6862, $p < 0.001$, with longer RTs in switch compared to pure trials, replicating the task switch cost with this large sample size. Longer RTs in the incongruent than congruent trials also established a significant effect of congruency, $F (1, 41) = 188$, MSE = 2303, p

< 0.001, replicating the detrimental effect of incongruent distractors on RTs in selective attention tasks.

There was a significant interaction between task condition and congruency, $F(1, 41) = 8$, MSE = 741, $p < 0.01$, with a greater effect of incongruent distractors in the switch than pure trials. This interaction was not replicated when the flanker effect was taken as a proportion of the congruent RTs in pure (14%) and switch (13%) trials, $t(41) = 0.8$, SEM = 0.01, $p = 0.4$, thus not ruling out the scaling effect as an explanation for the increased flanker effects in the switch condition, where RTs were significantly longer than in the pure condition. However, given that my population, sampled from a mostly non-student population, had a ceiling effect in Ospan compared to a large number of previous student populations sampled by Engle and colleagues (see Kane & Engle, 2003; see footnote 2, p. 110), it is possible that these participants performed less well on the selective attention task in the pure blocks compared to the student populations used in my previous experiments. Indeed, percentage distractor interference effects in the pure blocks in the current experiment (14%) were significantly increased compared to the student population sampled in Experiment 3 (9%), $t(59) = -2.0$, $p = 0.05$, where the range of working memory spans would have been more similar to the student populations used by Engle and colleagues (see Kane & Engle, 2003). This significant increase in pure percentage flanker effects in Experiment 14 reduces the difference between the flanker percentages in the pure and switch conditions and eliminates the previously revealed significant difference in percentage flanker effects between pure and switch blocks.

Individual differences in Ospan. High- and low-span participants were identified on the basis of their performance on the Automated Operation Span task. Following the method of Conway et al. (2001), the overall partial-credit score of each participant was

converted into a z-score. Based on these z-scores the group was split into three tiertiles: participants in the top tiertile (Ospan z-score higher than 0.7) were included in the high working memory span group; those in the bottom tiertile (Ospan z-score of less than -0.7) were included in the low Ospan group. Low-span scores ranged from 0.59 to 0.73 ($\underline{M}$ = 0.67, sd = 0.05, n = 24) and high-span scores ranged from 0.85 to 0.98 ($\underline{M}$ = 0.89, sd = 0.04, n = 18).

Table 15 shows the flanker task RTs and percentage errors for both Ospan groups as a function of task condition and congruency.

Table 15: RTs and percentage errors in the flanker task and visual search task as a function of task condition, congruency and working memory span group

	Mean (SD)	Flanker Task			Visual Search Task
		I	C	(I-C)	
Low Ospan					
Task condition					
Pure					
RT (ms)	702 (113)	754 (123)	651 (110)	103	834 (131)
Errors (%)	5	6	4	2	5
Switch					
RT (ms)	975 (159)	1037 (170)	912 (154)	126	1049 (207)
Errors (%)	4.5	6	3	3	3
Switch cost					
RT (ms)	273				215
Errors (%)	-0.5				-2
High Ospan					
Task condition					
Pure					
RT (ms)	678 (141)	713 (147)	642 (136)	71	811 (178)
Errors (%)	6.5	8	5	3	6
Switch					
RT (ms)	890 (166)	938 (170)	841 (165)	97	1005 (165)
Errors (%)	5.5	7	4	3	4
Switch cost					
RT (ms)	212				194

Errors (%)	*-0.5*	*-2*

I = Incongruent, C = Congruent.

     Visual search task. Although the low Ospan group showed slower overall RTs (942 ms) compared to high spans (908 ms), this numerical trend was not significant, t < 1. Overall percentage errors were also not significantly different between low (4) and high (5) spans, t (40) = 1.3, p = 0.20. A numerical trend for low spans to show greater RT costs when task switching (see Table 15), also did not reach significance: Ospan did not affect the RT nor error task switch cost in the visual search task, t < 1 for both RTs and errors.

     Flanker task. A numerical trend towards slower overall RTs in the low (838 ms) versus high (783 ms) Ospan groups did not reach significance, t (40) = 1.3, p = 0.20. Overall errors in the flanker task were also not significantly different for low (4.75) and high (6) spans, t (40) = 1.4, p = 0.16.

     A 2 (task condition) x 2 (congruency) x 2 (Ospan: high/low) mixed measures ANOVA was performed on the RT data for the flanker task. As predicted there was a significant interaction between Ospan and task condition, F (1, 40) = 6.2, MSE = 6087, p < 0.05, with task switching costs significantly greater in the low span group than in the high span group. In addition, when the full range of Ospan scores was taken into account in the assessment of the correlation between Ospan and task switch cost, there was a significant negative correlation between Ospan score and task switch cost, r = -0.31, n = 62, p < 0.05, as can clearly be seen in Figure 2: as Ospan scores increased task switch costs decreased.
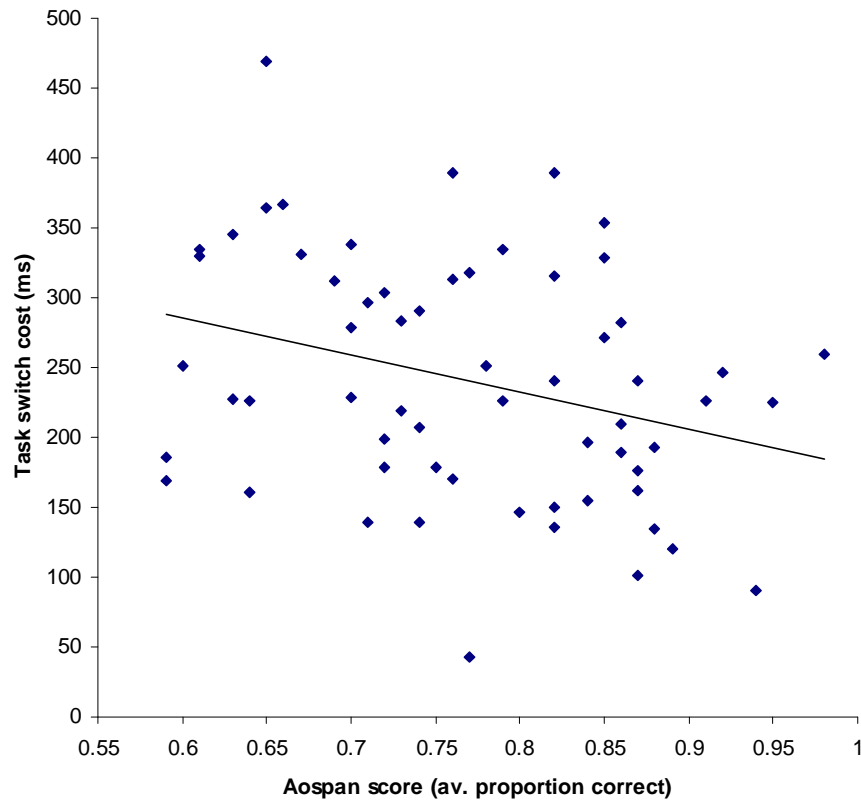
Figure 2: Task switching costs in the flanker task as a function of Ospan score.

Table 15 also demonstrates the significant interaction between Ospan and congruency in the flanker task RTs, $F (1, 40) = 4.4$, $MSE = 2127$, $p < 0.05$, with low spans showing greater RT interference in the presence of incongruent distractors than high spans, as predicted. The correlation between Ospan and congruency effects did not reach significance, $r = -0.20$, $n = 62$, $p = 0.12$, although the nonsignificant trend for increased congruency effects with increased Ospan score can be seen in Figure 3. Given that there was a significant interaction between Ospan group (low and high) and congruency, the lack of correlation is likely due to the inclusion of the middle range Ospan scorers who were not included in the Ospan score tiertile analysis.
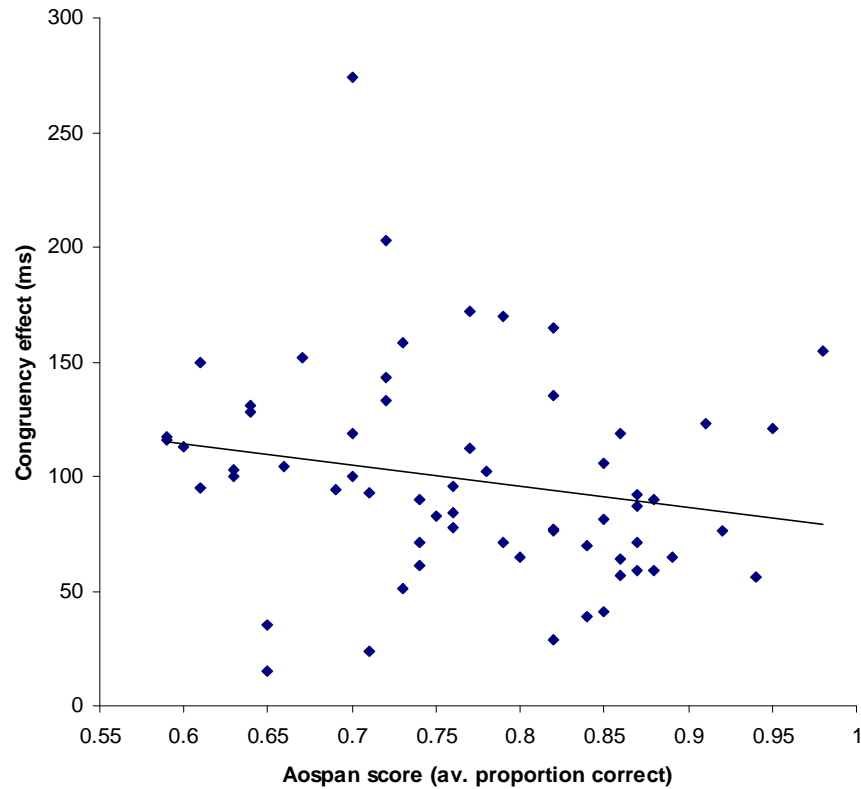
Figure 3: Congruency effects (incongruent – congruent RTs) as a function of Ospan score.

There was no 3-way interaction between Ospan, task condition, and congruency, $F < 1$: Both high and low scorers on the Ospan task showed a similar effect of task switching on distractor interference effects (low spans showed a 23 ms increase in distractor interference in switch versus pure blocks, and high spans showed an increase of 26 ms).

For all interactions between the flanker task percentage errors and working memory span $F < 1$.

It is interesting to note that high-spans in the switching blocks behaved similarly to low-spans in the pure blocks, with no significant difference between distractor interference effects in low span pure blocks (103 ms) and high span switch blocks (97

ms), t (40) = -3.7, p < 0.001, suggesting that the requirement to task switch artificially removed the advantage in ignoring distractors seen in high-span compared to low-span participants.

The results of Experiment 14 support the prediction that low Ospans will show greater task switching costs and greater congruency effects than high Ospans.

6.2 CHAPTER CONCLUSIONS

Both the ability to efficiently switch between tasks and to respond to a target and reject distractors in a selective attention task were detrimentally affected in participants with low working memory span (executive capacity), when compared to those with a relatively high executive capacity. This supports the prediction that task switching and the ability to selectively attend to a target and reject distractors both rely on executive control. The greater executive capacity of individuals with high working memory spans allowed them to more effectively avoid distraction and preserve their RT performance, to some degree, from being affected by the requirement to switch between two tasks (compared to the low-span participants).

Task switching may serve to artificially eliminate the advantage high span individuals benefit from when rejecting distractors in a selective attention task, by reducing their executive capacity to that of low spans. Interference from distractors was the same for the high spans when they performed a switch between tasks as it was for the low spans when they simply repeated performance of one task. Thus, once a task switch has been performed by high spans, they have similar executive capacity available for performing the selective attention task as low spans under no executive demand, and as such will not perform differently on a selective attention task.

Perhaps surprisingly, performance on a selective attention task in individuals with relatively low working memory spans was not more detrimentally affected than high spans performance when there was the additional demand of carrying out a switch between tasks compared to when performing one task repeatedly. Despite task switching reducing high spans to low spans normal performance, when low spans then performed a task switch, their selective attention performance was affected to a similar degree by task switching as was that of the high spans. Kane and Engle (2000) revealed a reduction in high-span's ability to avoid proactive interference under cognitive load, but conversely to in the current study, this was coupled with no effect of cognitive load, leading them to suggest that low spans do not use executive control to avoid distraction, unlike high-spans. If the low-span participants in the current study were not using their executive control to avoid distraction in the flanker task, then reducing the availability of executive control in task switch conditions should not have affected their performance. As it was, there was no significant difference in the effect of task switching on distractor interference effects between low- and high-spans: low-span's selective attention performance was affected by task switching to the same extent, if not more, than the high-span's. These findings, in juxtaposition to Kane and Engle's, suggest that while high-span's use their relatively greater executive ability to aid in rejecting interference from distractors, low-span's also use their executive control, although perhaps less effectively or with smaller resources, to protect them, to some extent, from distraction. A similar executive demand from the requirement to switch tasks, therefore, resulted in a similar reduction in selective attention performance for both working memory span groups.

Whilst it appears that high span's executive capacity did not save them from the effects of task switching on distractor interference, alternatively, it is possible that there

was a ceiling effect, with low-spans under task switching conditions in the presence of an incongruent distractor reaching the point at which greater distraction no longer increased RTs. Whilst there was no significant difference, the low spans did show a slightly higher difference in congruency effects between switch and pure conditions (low spans 31 ms; high spans 24 ms). Additionally, the ceiling effect in operational working memory span scores in the current population may have hidden a difference between high and low operational working memory span scorers by reducing the difference between the high and low span groups.

Interestingly, the interaction between working memory span and task switching was only revealed in the flanker task, but not in the visual search task. Perhaps high-spans directed their extra capacity onto the harder task and prepared more for the task containing the distractor interference: the flanker task. Kane and Engle (2002) argue that executive attention's core function is to maintain target representations and block distractor interference, supporting the idea that executive resources might be directed towards the task containing interference from distractors.

The way in which reduced executive capacity limits selective attention ability has been recently argued to reflect the time taken by executive control to focus the visual attentional window. Low working memory span participants reach peak performance (in terms of accuracy) more slowly than high spans, suggesting that the difference between high and low spans in selective attention performance may at least partly reflect the speed at which individuals can adjust the size of the focus of attention (Heitz & Engle, 2007). This is an interesting proposal given our findings, and suggests more specifically that at least part of the effect of working memory span on selective attention performance could be due to high spans extra executive capacity resulting in them more quickly constricting their visual attention. This would allow high span

participants to more quickly reject the distractor in incongruent trials, due to it more quickly being outside of the focus of attention. The data partly support this, with the reduction in interference from distractors in the high spans resulting from a reduction in RTs on incongruent trials compared to low spans. The effect of loading executive resources with a requirement to switch between two tasks on selective attention performance may, therefore, reflect a reduction in the speed at which depleted executive resources can constrict the focus of attention in switch compared to pure trials.

In conclusion, it seems that the executive control resources required to perform a switch between tasks are shared, at least to some extent, by attending to a target in the face of distraction. When the ability to use this executive capacity, or perhaps even its availability, is reduced in individuals with low working memory spans, then performance on both task switching and selective attention tasks is detrimentally affected. However, further research is required to investigate whether high spans executive capacity will save them from the effects of task switching on selective attention performance when the possibility of a ceiling effect on low spans performance under task switching is eliminated, and a high span group with a higher, more normal (see Kane & Engle, 2003), mean operational working memory span score used.

CHAPTER 7

General Discussion

7.1 OVERVIEW AND IMPLICATIONS OF FINDINGS

7.1.1 Executive control of selective attention

The experiments in this thesis provide support for the hypothesis that loading executive control will reduce selective attention performance by reducing the availability of executive resources to control distractor rejection. Chapter 2 established that under conditions of task switching (believed to load on executive control resources, for review see Monsell, 2003), selective attention performance was detrimentally affected in two selective attention tasks (the flanker task and the attentional capture task).

In Chapter 3 these findings were extended to situations in which not only the task stimuli (as in Experiments 1 and 2), but also the responses to the two tasks were entirely separate and non-overlapping. Interestingly, whilst the effect of task switching on selective attention performance in both the flanker and attentional capture task replicated when responses were mixed between the two hands (so that each hand made responses to both tasks), when the response mappings of the two tasks were separated between the hands (so that each hand responded to one task only) task switching only affected selective attention performance in the flanker task, but not in the attentional capture task. I will return to this point in section 7.1.8.

Chapter 4 more clearly investigated the effect of executive control on selective attention performance by inter-mixing the conditions of task repeat and task switch in the same block in an AAABBB… design. This design reduced the possible contributions of between block effects to the task switching cost. Large and significant task switch costs and distractor interference effects were still revealed under these conditions, suggesting that it is specifically the executive demand of a switch between tasks which results in the reaction time and distractibility costs of task switching.

Chapter 4 also suggested that the two selective attention tasks rely on control input from different executive resources. Whereas the flanker task appears to rely on input from the (possibly transient) executive resources also required for a switch between tasks, the attentional capture task appears to rely, rather, on the (possibly more sustained) executive resources required by mixing tasks within a block (see section 7.1.8).

Chapter 5 made a distinction between the roles of executive control in rejecting distraction from external (e.g. visual distractors) versus internal (e.g. task-unrelated thoughts) sources. This chapter demonstrated that task switching has opposing effects on internal versus external distraction: whereas task switching increases interference from external visual distractors, it decreases interference from internal distraction in the form of TUTs.

The effect of individual differences in working memory capacity on task switching and selective attention performance was revealed in Chapter 6. High working memory capacity appeared to protect individuals, to some extent, from the detrimental effects of task switching and from distraction in the flanker selective attention task.

7.1.2 <u>An additional cost of task switching</u>

The current study highlights a novel cost of switching between two tasks, namely greater distractibility in a task when switching between performance of that task and another task than when performing one task alone. There is an extensive literature addressing the effect of task switching on reaction times in the tasks switched between, but no study has specifically addressed the effects of task switching on selective attention performance. This novel finding has important implications for selective attention research: clearly, one of the determinants of the ability to ignore distractors is

the extent to which a task is performed in isolation, or performed inter-mixed with other tasks.

7.1.3 Executive control in task switching

Despite a large body of research it has remained a contentious issue to what extent executive control can account for the costs associated with task switching. The current study provides support for the role of executive control in task switching in several ways: firstly, task switching affected another task thought to load on executive control: selective attention ability (Lavie, 2000; Lavie et al., 2004), suggesting this aspect was shared between the two tasks; secondly, even when task switching occurred in conditions which were not conducive to the carryover of activation associated with previous task sets, triggered by overlapping stimuli or responses, task switching still instigated a considerable RT cost, suggesting the cost is due to a more general resource that is loaded by task switching; thirdly, task switching affected two different types of distraction, namely task-unrelated thoughts and distractor interference, in opposite ways, as would be predicted by task switching loading on executive control resources; and lastly, individual differences in operational working memory capacity, believed to reflect executive control ability (e.g. Engle, 2002), predicted task switching performance.

The current findings do not rule out contributions to the task switch cost of priming or carryover of activation/inhibition associated with a previous task-set. Indeed, switch costs are likely to reflect a combination of factors, including, primarily, the requirement for executive resources to control a switch between tasks, the need for executive control to mix tasks within a block, as well as the contribution of other costs under more specific circumstances, such as the cost associated with performing the first

trial of a task and carryover of activation associated with a previous task-set, to name but a few. The current study strongly supports an important contribution to task switch costs of the executive control demand of switching between tasks.

7.1.4 Task mixing costs versus specific task switching costs

The current study suggests that the overall task switching cost, when measured between blocks, may be contributed to not only by the specific requirement to switch between tasks, but also by the RT cost associated with mixing tasks within a block (Kray & Lindenberger, 2000; Meiran, Chorev, & Sapir, 2000; for review see Rubin and Meiran, 2005). The mixing cost is measured by comparing the pure trial RTs in a pure block, and the nonswitch trial RTs in an AAABBB block. Chapter 4 revealed that whilst there was a large contribution to the between-task task switch cost from a specific task switch cost in the experiments in Chapters 2 and 3, there was also a contribution from the cost of mixing tasks. In other words, RTs in the pure trials in pure blocks were faster than in the nonswitch trials in AAABBB blocks, reflecting a cost associated with mixing tasks within the same block. In the task switching literature many authors argue that this mixing cost reflects an executive demand associated with mixing tasks, because it involves comparing a condition where response can be almost automatic and one where response occurs in a task context demanding of control (Rubin & Meiran, 2005), and thus mixing tasks incurs a RT cost. Indeed, support for this contention from the current study comes from the finding that attentional capture by an irrelevant singleton is modulated by the requirement to mix tasks within a block.

Interestingly, in the literature there is a distinction made between the executive demand required by switching tasks, and the executive demand required by mixing tasks (Braver, Reynolds, & Donaldson, 2003; Koch, Prinz, & Allport, 2005; Kray &

127

Lindenberger, 2000; Logan & Bundeson, 2003; Mayr & Kliegl, 2003). Whereas the specific task switching cost is argued to load on transient control processes (Braver, Reynolds, & Donaldson, 2003; Logan & Bundeson, 2003; Mayr & Kliegl, 2003), mixing tasks, on the other hand, is contended to load on more sustained or global control processes (Braver et al., 2003; Koch, Prinz, & Allport, 2005; Kray & Lindenberger, 2000, although see Rubin & Meiran, 2005), such as the storage and maintenance of task rules in WM. Firstly, the current findings support a distinction between the executive demands of task switching and task mixing by showing that the contributions of these differential aspects of executive control to the task switching cost can be dissociated. Additionally, the finding that the flanker task and attentional capture task are differentially affected by load on these different executive demands supports the view that the executive demands for task switching and task mixing are dissociable and might be divided between transient (implicated in the flanker task) and sustained (implicated in the attentional capture task) control processes, respectively. This point is further clarified in section 7.1.3.

7.1.5 <u>Task switching with stimuli and responses affording only one task</u>

In Chapter 3 the effect of task switching on selective attention performance was extended to situations in which neither the task stimuli (as in Chapter 2) nor task responses overlapped between the two tasks. Previous research suggested that task switching only incurred a RT cost when either responses or stimuli were shared between tasks (Meiran, 2000; Rogers & Monsell, 1995, Experiment 4; Ruthruff, Remington & Johnston, 2001; Sumner & Ahmed, 2006). Contrary to much of the task switching literature, and in support of Rubin and Meiran's (2005) more recent finding of large and significant task switch costs even when stimuli and responses do not overlap, task

switching in the current study detrimentally affected task performance even when the two tasks were entirely separate. This supports a more general demand made by task switching on executive control of coordinating two different tasks.

7.1.6 <u>The effect of task switching on external versus internal distraction</u>

Chapter 5 demonstrated an additional and contrary effect of loading executive control with a task switch additional to reaction time costs and distractor interference effects in selective attention tasks: task switching led to reduced interference from internal distraction (mind wandering episodes). This is an interesting finding as it suggests that contrary to the costs associated with task switching, in reaction times and ignoring external distractors, loading executive control makes one less likely to experience mind wandering, which could be considered a benefit under some circumstances. In some senses, however, this may be considered a cost, because mind wandering plays an important role in novel and stimulus-independent human thought and behaviour.

7.1.7 <u>The effect of task switching on distractor interference: greater executive demand in switch versus pure trials or stronger task-set representations in pure versus switch trials?</u>

When performing the selective attention tasks after a switch from another task the task-set representation stored in working memory will be less well established than when repeating the same task due to the need to reconfigure the task-set anew on the switch trial. This raises the interesting possibility that increased distractor interference in switch versus pure trials could be explained by a less well established task-set in the selective attention task on the switch compared to pure trials. When a task-set is less

129

well established the distinction between the target and distractor will be less clear, thus increasing competition from the distractor to control behaviour.

However, when a task-set is less well established, so would be the associations of each stimulus and response. Take, for example, the flanker task, where a consistent increase in distractor effects was found during task switching. The reduction in stimulus-response associations with a less clear task-set should impact both the target and the distractor stimulus. Hence, a less well established task-set might result in prolonged overall RTs in both the congruent and incongruent trials due to the target being less strongly associated with the correct response. More importantly, *smaller* response competition effects from a distractor might be expected in this situation, given that the distractor will be less strongly associated with a competing response in the incongruent trials.

Additionally, it seems more parsimonious to assume, based on the combination of previous findings that task switching loads executive control (e.g. Monsell, 2003), and that loading working memory results in increased distractor interference (e.g. Lavie 2000; Lavie et al., 2004), that it is the executive demand of switching tasks which results in reduced distractor interference.

Support for the executive demand of a task switch being responsible for the revealed reduction in selective attention ability, without the confound of a less well established task-set in switch versus pure trials, comes from my finding that task mixing results in increased distractor interference in the attentional capture task. As discussed in Chapter 4, the literature suggests that the requirement to mix tasks loads on executive control (Braver et al., 2003; Koch, Prinz, & Allport, 2005; Kray & Lindenberger, 2000). Investigating the effect of task mixing on attentional capture by an irrelevant singleton involves comparing two conditions (pure trials in the between block design and

nonswitch trials in the AAABBB within block design) in which the current task-set should be similarly established in working memory, but in which executive demand is greater in nonswitch compared to pure trials due to a more control demanding task context (e.g. Rubin & Meiran, 2005). After performance of the initial trial of a new task in the AAABBB design (i.e. the switch trial), the task-set should be fully 'set', so that on subsequent performance of the task in the nonswitch trial the task-set will be as well established as in the pure trials in the between block design. Indeed, the task switch cost for a predictable switch is seen only on the first trial of a task (Rogers & Monsell, 1995). Thus, the effect of task mixing on distractor interference cannot be explained by a less well established task-set in nonswitch compared to pure trials, suggesting that the effect of both task mixing and task switching on distractor interference is rather due to the executive demand associated with switching and mixing tasks.

7.1.8 <u>Executive control in the attentional capture and flanker tasks: evidence for the involvement of separable control processes</u>

There are two lines of evidence proffering support for the view that the attentional capture task and flanker task rely on control from different executive processes. Firstly, as outlined above, detrimental flanker task performance in task switch conditions in Chapter 3 depended on the presence of shared responses between hands: when the responses to the two tasks were further separated so that one task was mapped to one hand, and one to the other, flanker task performance was unaffected by task switching. Conversely, the capture of attention by an irrelevant singleton was still greater in switch compared to pure trials, even when the responses to the two tasks were separated between hands. This dissociation suggests that performance on the two selective attention tasks reflects the operation of different aspects of executive control. Distractor

rejection in the flanker task was not affected by a switch when that switch did not introduce further interference between responses, i.e. the responses were mapped to separate hands. The executive control requirements of distractor rejection in the flanker task may centre around the resolution of (and indeed may be triggered by) response-competition. The effect of task switching on attentional capture, by contrast, may rely on interference at a later stage of processing, and as such would be unaffected by the elimination of additional interference at the response-competition level when task switching. The executive control required to avoid attentional capture by an irrelevant singleton may rely on another aspect of executive control.

Further elucidation of a possible distinction between the executive control required by each selective attention task was provided by Chapter 4, where the previous within-block cost of task switching was separated into two constituent components; the specific cost of switching to a new task compared to repeating tasks, and the cost of mixing two tasks within the same block compared to performing one task. The experiments reviewed in Chapter 4 provide evidence that the distinction between the seemingly different executive requirements of the flanker and attentional capture tasks, as tentatively suggested by the findings of Chapter 3, could be mapped to the distinction between the executive requirements of task switching and task mixing. Rejection of a distractor in the flanker task required the availability of those executive resources which were loaded by switching between tasks, whilst avoiding capture of attention by an irrelevant singleton required the availability of those executive resources involved in mixing tasks within a block. This double dissociation suggests that these two tasks may map onto the different aspects of executive control hypothesized in the literature to reflect transient (task switching) or sustained (task mixing) control processes (Braver et al., 2003; Koch, Prinz, & Allport, 2005; Kray & Lindenberger, 2000; Logan &

Bundeson, 2003; Mayr & Kliegl, 2003). Perhaps the transient control processes involved in task switching are required by response interference resolution in the flanker task. Conversely, the more sustained control process required by mixing tasks may act to maintain representations of the target feature in the presence of a salient but irrelevant singleton feature, making it essential for successful performance of the attentional capture task.

Combined, these two lines of evidence suggest a distinction between (possibly transient) executive control required by performance of the flanker task and switching between tasks, and (possibly more sustained) executive control required by performance of the attentional capture tasks and the requirement to mix more than one task within a block.

7.1.9 Individual differences in executive capacity predict task switching and selective attention performance

Individuals with low operational working memory capacity showed greater RT costs of task switching and reduced selective attention performance (Chapter 6). In support of the hypothesis tested in this thesis, individuals who had high executive capacity were able to use their extra capacity to protect them to some extent from the cost of switching tasks and the interference from distractors in the flanker task, compared to those with low executive capacity.

Performing a switch between tasks may reduce the executive capacity of high spans to that of low spans, and thus artificially eliminate the advantage high span individuals benefit from in performing a selective attention task. High spans demonstrated similar interference from distractors when performing a switch between tasks as low spans when they simply repeated performance of one task. Thus, once a

high span performs a task switch, the executive capacity available to high spans for performing the selective attention task is similar to that available to low spans under no executive demand, and as such high and low spans did not perform differently on a selective attention task under these conditions.

Interestingly, the effect of operational working memory span on task switching performance was only revealed in the flanker task, but not in the visual search task. It is possible that high-spans directed their extra capacity onto the flanker task, since this was the more taxing on executive resources, due to the presence of the response-competitive distractor. Indeed, the main function of executive capacity may be to maintain target representations and block distractor interference (Kane and Engle, 2002), and thus it is likely that executive resources will be directed towards the task containing greater interference.

An interesting question is what mechanism allows participants with greater executive capacity to more easily reject distractors in a selective attention task. The effect of working memory span on selective attention performance could, at least partly, be due to high spans extra executive capacity enabling them to more quickly constrict their visual attention (Heitz and Engle, 2007), and thus more quickly reject the distractor in incongruent trials, because it more quickly ends up outside the focus of attention. Loading executive resources with a requirement to switch between two tasks may, therefore, reduce the speed at which depleted executive resources can constrict the focus of attention in switch compared to pure trials, and thus effect selective attention performance.

7.1.10 <u>Task difficulty</u>

If increasing task difficulty, regardless of executive load, necessarily resulted in increased distraction, then in situations where task switching increases, and executive demand does not, there should be no effect on distractibility. In Chapter 5, rates of TUTs, a form of internal distraction, were decreased by task switch compared to task repeat conditions, but were not decreased by task difficulty when compared between the two tasks: the task associated with longer RTs, and thus greater task difficulty, was associated with increased, rather than decreased rates of TUT compared to the easier task. This suggests that differences in task difficulty are not responsible for the decrease in TUTs after task switching.

In addition, TUTs were reduced in situations when task switching demanded executive control, whereas distractor interference was increased under these circumstances. If task difficulty results in increased distraction then both internal and external distraction should increase as task difficulty increased. This was clearly not the case. Instead, internal versus external distraction were conversely affected by task switching as would be predicted by a theory suggesting that the availability of executive control is reduced under task switch conditions.

These findings suggest that the effect of task switching on distractor interference is related to executive control, and not simply task difficulty.

In summary, my overall findings combine to offer strong support for a critical role of executive control in preventing distractor interference and allowing mind wandering, and establish preliminary evidence that different aspects of executive control are involved in different selective attention tasks.

7.2 IMPLICATIONS OF CURRENT RESEARCH FOR EVERYDAY LIFE

7.2.1 Detrimental effects of everyday 'multi-tasking'

The current research strongly suggests that performance of everyday tasks will be detrimentally affected when attempts are made to switch attentional resources from one task to another. A good example is driving and talking on the phone. Switching between driving and a conversation will result in not only slowed reaction times to visual stimuli, such as signs and traffic lights, but also to a greater likelihood that irrelevant items in the visual scene (such as a bright red jacket worn by a pedestrian) will capture attention, stealing attentional resources away from the main task of driving. Perhaps less importantly in the current example, the conversation would also suffer from slow responses and distraction, especially during moments of driving which are particularly demanding, such as negotiating a complicated roundabout. Note that conversations in which the other person is unaware of the needs of the driving (such as a person on the other end of a phone) may result in greater deficits because the other person will not stop talking or demanding your attention when driving requirements increase. Thus, according to the current findings, the demands of a phone conversation whilst driving would not be alleviated by the use of a hands free kit.

Chapter 6 also suggests that the extra time taken on and greater distractibility in everyday tasks when trying to switch between tasks would be more pronounced for people whose executive capacity is lower, i.e. those with low operational working memory spans, as well as in situations already demanding high levels of executive control, such as finding a parking space in a busy car park full of pedestrians and other cars.

7.3 FUTURE RESEARCH

7.3.1 <u>Executive control, rejecting distractors, and switching between tasks</u>

Although the current work highlights the importance of general executive control availability for distractor rejection, and even distinguishes different executive control requirements for the flanker task and attentional capture task, the precise nature of the executive involvement in distractor rejection remains unclear. Further research is required to more specifically highlight the aspects of executive control important in attending to targets whilst ignoring distractors.

Behavioural methods may be fruitful in order to elucidate more precisely which aspects of executive control are involved in avoiding distraction in the flanker task and attentional capture task. Investigating a wider array of selective attention tasks would allow comparison of the effects of loading different aspects of executive control (for example that required by task mixing and that required by task switching) on different selective attention tasks. Similarities between tasks which load one type of executive control or the other would serve to highlight the specific role of each of these types of executive control. For example, if slower, sustained executive control involved in target maintenance is loaded in task mixing, then task mixing should interfere with target performance only in those selective attention tasks in which distractor rejection critically relies on maintenance of target and/or distractor representations, for example this type of control should not affect the Posner cueing task, in which the distractor is unrelated to the target representation (attention is captured by a location cued by a central cue). On the other hand, if a simple task switch relies on transient control processes involved in resolving interference between responses, then only performance on selective attention tasks in which distractors create response competition, such as the

Stroop task, or some other transient interference, will be affected by a simple task switch.

Another avenue would be to investigate whether the individual differences in executive capacity which affected distractor rejection performance in the flanker task, also affect attentional capture by irrelevant singletons. Given that operational working memory span is thought to reflect the ability to maintain targets in the face of interference from distracting information, which should reflect similar sustained control processes to those which I have hypothesised to be involved in attentional capture task performance, I would expect that operational working memory span would indeed affect performance in the face of interference from irrelevant singleton distractors.

In regards to task switching, the current research highlights the contributions of the specific executive demand of task switching and task mixing, and the effects of these executive demands on selective attention performance. An interesting direction for future research would be to further dissect the executive demand of task switching, such as the additional RT costs associated with performing the first trial in a run, and the effects of these demands on selective attention performance.

7.3.2 <u>Complementary neuroscientific research</u>

If activation in the frontal lobe is increased during task switching (e.g. Brass and Von Cramon, 2002; Braver, Reynolds and Donaldson, 2003; MacDonald, Cohen, Stenger, and Carter, 2000), then in situations in which task switching leads to an incorrect or slowed response, there should be relatively greater activation in areas associated with processing the distractor. This would provide further evidence that task switching loads frontal executive resources, and that this reduces the availability of these resources to

reject distractors and so is associated with increased activation associated with distractors in selective attention tasks.

Whilst the issue of executive capacity is an area of fruitful research, it has remained elusive as to what exactly operational working memory span measures. Is it the total amount of an executive resource available to each individual, is it the ability of each individual to effectively use the executive capacity they have, does it reflect differences between individuals in the way in which they allocate executive control resources? Although these questions are perhaps out of reach given the knowledge and current techniques available, it is important to begin directing research towards answering these questions. Neuroimaging techniques might be useful in elucidating the mechanisms involved in determining working memory capacity. For example, if working memory capacity reflects the amount of executive control actively exerted in response to task demands, then individuals with high operational working memory span might show a greater *increase* in frontal cortex activity in situations demanding extra executive control, such as switching tasks versus repeating tasks, than individuals with low operational working memory spans. Conversely, if high working memory capacity reflects more efficient use of limited executive resources, then high operational working memory span might be associated with a smaller increase in frontal activity under switch compared to repeat conditions. In this way high working memory capacity would protect against distractor interference because more efficient use of a limited resource results in greater 'leftover' working memory (executive) capacity for distractor rejection. Combining this research with behavioural research measuring distractibility would provide behavioural correlates to compare brain activity with.

Finally, if different aspects of executive control are involved in different selective attention tasks, then it might be expected that activation associated with

executive control of the two tasks have different frontal locations. For example, the ACC has often been implicated in the resolution of transient interference triggered by response competition. This area might be more activated in the flanker task, than in the attentional capture task. Areas previously associated with sustained maintenance of target/distractor representations in working memory should similarly show relatively greater activation during performance of the attentional capture task.

In summary, the current research provides support for the control of selective attention by executive resources and offers a strong basis for interesting and fruitful further research.

REFERENCES

Allport, A., Styles, E. A., & Hsieh, S. (1994). Shifting intentional set: Exploring the dynamic control of tasks. In C. Umilta & M. Moscovitch (Eds.), *Attention and performance XV* (pp. 421-452). Cambridge, MA: MIT Press.

Allport , A., & Wylie, G. (1999). Task-switching: Positive and negative priming of task set. In G. W. Humphreys, J. Duncan, & A. M. Treisman (Eds.), *Attention, space, and action: Studies in cognitive neuroscience* (pp. 273 – 296). Oxford: Oxford University Press.

Allport , A., & Wylie, G. (2000). 'Task-switching', stimulus-response bindings and negative priming. In S. Monsell & J. Driver (Eds.), *Control of cognitive processes: Attention and performance XVIII* (pp. 35 – 780). Cambridge, MA: MIT Press.

Altmann, E. M. (2007). Comparing switch costs: Alternating runs and explicit cueing. *Journal of Experimental Psychology: Learning, Memory and Cognition, 33 (3),* 475–483.

Antrobus, J. S. (1968). Information theory and stimulus-independent thought. *British Journal of Psychology, 59*, 423–430.

Arrington, C. M. & Logan, G. D. (2004). Episodic and semantic components of the compound-stimulus strategy in the explicit-task cueing procedure. *Memory and Cognition, 32*, 965-976.

Aron, R. A., Monsell, S., Sahakian, B. J., & Robbins, T. W. (2004). A componential analysis of task-switching deficits associated with lesions of left and right frontal cortex. *Brain, 127,* 1561-1573.

Baddeley, A. D. (1996). The psychology of memory. In A. D. Baddeley, B. A. Wilson & F. N. Watts (Eds.), *Handbook of memory disorders* (pp. 3-25). John Wiley & Sons: Chichester.

Baddeley, A. D., Chincotta, D., & Adlam, A. (2001). Working memory and the control of action: Evidence from task switching. *Journal of Experimental Psychology: General, 130 (4),* 641-657.

Baddeley, A. D., & Hitch, G. (1974). Working memory. In G. A. Bower (Ed.), *The psychology of learning and motivation* (Vol. 8, pp. 47-89). New York: Academic Press.

Binder, J. R., Frost, J. A., Hammeke, T. A., Bellgowan, P. S. F., Rao, S. M., & Cox, R. W. (1999). Conceptual processing during the conscious resting state: a functional MRI study. *Journal of Cognitive Neuroscience, 11*, 80–93.

Brass, M., & Von Cramon, D. Y. (2002). The role of the frontal cortex in task preparation. *Cerebral Cortex*, *12*, 908-914.

Brass, M., & Von Cramon, D. Y. (2004). Decomposing components of task preparation with fMRI. *Journal of Cognitive Neuroscience, 16 (4)*, 609-620.

Braver, T. S., Reynolds, J. R., & Donaldson, D. I. (2003). Neural mechanisms of transient and sustained cognitive control during task switching. *Neuron, 39*, 713-726.

Broadbent, D. E. (1958). *Perception and communication*. London: Pergamon.

Buckner, R. L., Raichle, M. E., Miezin F. M., & Petersen, S. E. (1996). Functional anatomic studies of memory retrieval for auditory words and visual pictures. *Journal of Neuroscience, 16*, 6219–6235.

Cepeda, N. J. Cepeda, M. L., & Kramer, A. F. (2000). Task switching and attention deficit hyperactivity disorder. *Journal of Abnormal Child Psychology, 28 (3)*, 213–226.

Christoff, K., & Gabrieli, J. D. E. (2000). The frontopolar cortex and human cognition: Evidence for a rostrocaudal hierarchical organization within the human prefrontal cortex. *Psychobiology, 28*, 168-186.

Christoff, K., Prabhakaran, V., Dorfman, J., Zhao, Z., Kroger, J. S., Holyoak, K. J., & Gabrieli, J. D. E. (2001). Rostrolateral prefrontal cortex involvement in relational integration during reasoning. *NeuroImage, 14*, 1136-1149.

Christoff, K., Ream, J. M., & Gabrieli, J. D. E. (2004). Cognitive and neural basis of spontaneous thought processes. *Cortex, 40 (4-5)*, 623-630.

Cohen, J. D., Barch, D. M., Carter, C. S., & Servan-Schreiber, D. (1999). Schizophrenic deficits in the processing of context: Converging evidence from three theoretically motivated cognitive tasks. *Journal of Abnormal Psychology, 108*, 120-133.

Conway, A. R. A., Cowan, N., & Bunting, M. F. (2001). The cocktail party phenomenon revisited: The importance of WM capacity. *Psychonomic Bulletin and Review, 8*, 331-335.

Conway, A. R. A., & Engle, R. W. (1996). Individual differences in working memory capacity: More evidence for a general capacity theory. *Memory, 4 (6)*, 577-590.

Daneman, M., & Carpenter, P.A. (1980). Individual differences in WM and reading. *Journal of Verbal Learning and Verbal Behavior, 19*, 450-466.

De Fockert, J. W., Rees, G., Frith, C. D. & Lavie, N. (2001). The role of working memory in visual selective attention. *Science, 291*, 1803-1806.

De Jong, R. (2000). An intention–activation account of residual switch costs. In: S. Monsell and J. Driver (Eds.), *Control of Cognitive Processes: Attention and Performance XVIII* (pp. 357–376). MIT Press, Cambridge, MA.

Deutsch, J. A. & Deutsch, D. (1963). Attention: Some theoretical considerations. *Psychological review, 70*, 80-90.

Dreher, J. C., & Berman, K. F. (2002). Fractionating the neural substrate of cognitive control processes. *Proceedings of the National Academy of Science, USA, 99*, 14595-14600.

Engle, R. W. (2001). What is working memory capacity? In H. I. Roediger, J. S. Nairne, I. Neath, & A. M. Suprenant (Eds.), *The nature of remembering: Essays in honor of Robert G. Crowder* (pp. 297-314). Washington DC: American Psychological Association Press.

Engle, R. W. (2002). Working memory capacity as executive attention. *Current Directions in Psychological Science, 11 (1),* 19-23.

Engle, R. W., Cantor, J., & Carullo, J. J. (1992). Individual differences in WM and comprehension: A test of four hypotheses. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18,* 972-992.

Engle, R. W., Nations, J. K., & Cantor, J. (1990). Is "working memory capacity" just another name for word knowledge? *Journal of Educational Psychology, 82*, 779–804.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. A. (1999). Working memory, short term memory and general fluid intelligence: A latent variable approach. *Journal of Experimental Psychology: General, 128,* 309-331.

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters on the identification of a target letter in a nonsearch task. *Perception & Psychophysics, 16*, 143-149.

Filler, M. S., & Giambra, L. M. (1973). Daydreaming as a function of cueing and task difficulty. *Perceptual and Motor Skills, 37*, 503 –509

Fuster, J. M. (1995). *Memory in the cerebral cortex*. Cambridge, MA: MIT Press.

Garavan, H., Ross, T. J., Murphy, L., Roche, R. A., Stein, E. A. (2002). Dissociable executive functions in the dynamic control of behaviour: inhibition, error detection, and correction. *Neuroimage, 17,* 1820-1829.

Garner, W. R. (1970). The stimulus in information processing. *American Psychologist, 25*, 350-358.

Garner, W. R. (1974). Attention: the processing of multiple sources of information. In E. C. Carterette, & M. P. Friedman (Eds.), *Handbook of Perception*, New York: Academic Press.

Giambra, L. M. (1989). Task-unrelated-thought frequency as a function of age: a laboratory study. *Psychology and Aging, 4 (2)*, 136–143.

Goldman, T. E., Berman, K. F., Fleming, K., Ostrem, J., Van Horn, J. D., Esposito, G., Mattay, V. S., Gold, J. M., & Weinberger, D. R. (1998). Uncoupling cognitive workload and prefrontal cortical physiology: a PET, rCBF study. *Neuroimage, 7*, 296-303.

Gopher, D., Armony, L., & Greenshpan, Y. (2000). Switching tasks and attention policies. *Journal of Experimental Psychology: General, 129*, 308-339.

Goschke, T. (2000). Involuntary persistence and intentional reconfiguration in task-set switching. In: S. Monsell and J. Driver (Eds.), *Control of cognitive processes: Attention and performance XVIII* (pp. 331–355). MIT Press, Cambridge, MA.

Heitz, R. P., & Engle, R. W. (2007). Focusing the spotlight: Individual differences in visual attention control. *Journal of Experimental Psychology: General, 136 (2),* 217–240.

Hester, R., & Garavan, H. (2005). Working memory and executive function: The influence of content and load on the control of attention. *Memory & Cognition, 33*, 221-233.

Jersild, A. T. (1927). Mental set and shift. *Archives of Psychology, 89.*

Kahneman, D. & Treisman, A. (1984). Changing views of attention and automaticity. In R. Parasuraman & D. R. Davies (Eds.), *Varieties of attention* (pp 26-61). New York: Academic Press.

Kane, M. J., Bleckley, M. K., Conway, A. R. A., & Engle, R. W. (2001). A controlled-attention view of WM capacity. *Journal of Experimental Psychology: General, 130,* 169-183.

Kane, M. J., & Engle, R. W. (2000). WM capacity, proactive interference, and divided attention: Limits on long-term memory retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26,* 336-358.

Kane, M. J., & Engle, R. W. (2002). The role of prefrontal cortex in working-memory capacity, executive attention, and general fluid intelligence: An individual-differences perspective. *Psychonomic Bulletin and Review, 9 (4)*, 637-671.

Kane, M. J., & Engle, R. W. (2003). Working-memory capacity and the control of attention: The contributions of goal neglect, response competition, and task set to Stroop interference. *Journal of Experimental Psychology: General, 132 (1),* 47-70.

Kane, M. J. & Engle, R. W. (2004). *Working-memory capacity and executive control of task-set switching*. Invited paper at the Second International Conference on Working Memory, Kyoto, Japan.

Keele, S. W., & Rafal, R. (2000). Deficits of task set in patients with left prefrontal cortex lesions. In S. Monsell & J. Driver (Eds.), *Control of cognitive processes: Attention and performance XVIII* (pp. 35-70). Cambridge, MA: MIT Press.

Klein, K., & Fiss, W. H. (1999). The reliability and stability of the Turner and Engle working memory task. *Behavior research methods, instruments, & computers, 31 (3)*, 429-432.

Koch, I., Prinz, W., & Allport, A. (2005). Involuntary retrieval in alphabet-arithmetic tasks: Task-mixing and task-switching costs. *Psychological Research 69 (4)*, 252-261.

Kray, J. and Lindenberger, U., 2000. Adult age differences in task-switching. *Psychology and Aging 15*, 126–147.

Lavie, N. (2000). Selective attention and cognitive control: Dissociating attentional functions through different types of load. In S. Monsell & J. Driver (Eds.), *Control of cognitive processes: Attention and performance XVIII* (pp. 175-194). Cambridge, MA: MIT Press.

Lavie, N., & de Fockert, J. W. (2005). The role of working memory in attentional capture. *Psychonomic Bulletin & Review, 12,* 669-674.

Lavie, N., Hirst, A., de Fockert, J. W. & Viding, E. (2004). Load theory of selective attention and cognitive control. *Journal of Experimental Psychology: General, 133 (3)*, 339-354.

Lavie, N. & Tsal, Y. (1994). Perceptual load as a major determinant of the locus of selection in visual attention. *Perception & Psychophysics, 56,* 183-197.

Logan, G. D., & Bundesen, C. (2003). Clever homunculus: Is there an endogenous act of control in the explicit task cuing procedure? *Journal of Experimental Psychology: Human Perception and Performance, 29,* 575- 599.

Logan, G. D., & Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychological Review, 108*, 393-434.

Logan, G. D., & Schneider, D. W. (2006). Priming or executive control? Associative priming of cue encoding increases "switch costs" in the explicit task-cuing procedure. *Memory and Cognition, 34*, 1250–1259.

Luks, T. L., Simpson, G. V., Feiwell, R. J., & Miller, W. L. (2002). Evidence for anterior cingulated cortex involvement in monitoring preparatory attentional set. *Neuroimage, 17*, 792-802.

Luria, R., & Meiran, N. (2005). Increased control demand results in serial processing: Evidence from dual-task performance. *Psychological Science, 16 (10)*, 833-840.

MacDonald, A. W., Cohen, J. D., Stenger, V. A., & Carter, C. S. (2000). Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. *Science*, *288*, 1835-1838.

Manly, T., Robertson, I. M., Galloway M., & Hawkins, K. (1999). The absent mind: Further investigations of sustained attention to response, *Neuropsychologia, 37*, 661–670.

Mayr, U. (2001). Age differences in the selection of mental sets: The role of inhibition, stimulus ambiguity, and response-set overlap. *Psychology and Aging, 16*, 96-109.

Mayr, U., & Keele, S. W. (2000). Changing internal constraints on action: The role of backward inhibition. *Journal of Experimental Psychology: General, 129,* 4-26.

Mayr, U., & Kliegl, R. (2000). Task-set switching and long-term memory retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26*, 1124-1140.

Mayr, U., & Kliegl, R. (2003). Differential effects of cue changes and task changes on task-set selection costs. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29*, 362-372.

Meiran, N. (1996). Reconfiguration of processing mode prior to task performance, *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22*, 1–20.

Meiran, N. (2000). Reconfiguration of stimulus task sets and response task sets *during* task switching. In S. Monsell & J. S. Driver (Eds.), *Attention and performance XVIII: Control of cognitive processes* (pp. 377-399). Cambridge, MA:MIT Press.

Meiran, N., Chorev, Z., & Sapir, A. (2000). Component processes in task switching. *Cognitive psychology, 41,* 211-253

Meuter, R. F. I., & Allport, A. (1999). Bilingual language switching in naming: Asymmetrical costs of language selection. *Journal of Memory and Language, 40*, 25-40.

Meyer, D. E., & Kieras, D. E. (1997a). A computational theory of executive control processes and human multiple-task performance: Part 1. Basic Mechanisms. *Psychological Review, 104*, 3-65.

Meyer, D. E., & Kieras, D. E. (1997b). A computational theory of executive control processes and human multiple-task performance: Part 2. Accounts of Psychological Refractory-Period Phenomena. *Psychological Review, 104*, 749-791.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience, 24,* 167-202.

Miller, E. K., Ericksen, C. A., & Desimone, R. (1996). Neural mechanisms of visual working memory in prefrontal cortex of the macaque. *Journal of Neuroscience*, *16*, 5154-5167.

Milner, B. (1963). Effects of different brain lesions on card sorting. *Archives of Neurology, 9*, 90-100.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex frontal lobe tasks: A latent variable analysis. *Cognitive Psychology, 41,* 49-100.

Monsell, S. (2003). Task Switching. *Trends in Cognitive Sciences, 7 (8)*, 341-342.

Monsell, S., Yeung, N. P., & Azuma, R. (2000). Reconfiguration of task-set: Is it easier to switch to the weaker task? *Psychological Research, 63*, 250-264.

Oberauer, K., Süß, H.-M., Schulze, R., Wilhelm, O., & Wittmann, W. W. (2000). Working memory capacity - facets of a cognitive ability construct. *Personality and Individual Differences, 29*, 1017-1045.

Oberauer, K., Süß, H.-M., Wilhelm, O., & Wittmann, W. W. (2003). The multiple faces of working memory - storage, processing, supervision, and coordination. *Intelligence, 31*, 167-193.

Oriet, C., & Jolicoeur, P. (2003). Absence of perceptual processing during reconfiguration of task-set. *Journal of Experimental Psychology: Human Perception and Performance, 29*, 1036-1049.

Pandya, D. N., & Barnes, C. L. (1987). Architecture and connections of the frontal lobe. In E. Perecman (Ed.), *The Frontal Lobes Revisited* (pp. 41-72). New York: IRBN.

Pandya, D. N., & Yeterian, E. H. (1990). Prefrontal cortex in relation to other cortical areas in rhesus monkey-architecture and connections. *Progress in Brain Research*, *85*, 63-94.

Pashler, H. (1984). Processing stages in overlapping tasks: Evidence for a central bottleneck. *Journal of Experimental Psychology: Human Perception and Performance*, *10*, 358-377.

Pashler, H. (1994). Graded capacity sharing in dual-task interference? *Journal of Experimental Psychology: Human Perception and Performance*, *20*, 330-342.

Pashler, H. & Johnston, J. (1989). Chronometric evidence for central postponement in temporally overlapping tasks. *Quarterly Journal of Experimental Psychology*, *41A*, 19-45.

Perrett, E. (1974). The left frontal lobe of man and the suppression of habitual responses in verbal categorical behaviour. *Neuropsychologia, 12*, 323-330.

Ragland, J. D., Gur, R. C., Glahn, D. C., Censits, D. M., Smith R. J., & Lazarev, M. G. (1998). Frontotemporal cerebral blood flow change during executive and declarative memory tasks in schizophrenia: A positron emission tomography study, *Neuropsychology 12*, 399–413.

Ravizza, S. M., & Ciranni, M. A. (2002). Contributions of the prefrontal cortex and basal ganglia to set shifting. *Journal of Cognitive Neuroscience, 14 (3)*, 472-483.

Rees, G., Frith, C. D., & Lavie, N. (1997). Modulating irrelevant motion perception by varying attentional load in an unrelated task. *Science, 278*, 1616-1619.

Robertson, I. H., Manly, T., Andrade, J., Baddeley, B. T., & Yiend, J. (1997). 'Oops!'" Performance correlates of everyday attentional failures in traumatic brain injured and normal subjects. *Neuropsychologia, 35 (6)*, 747–758.

Rogers, R. D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General*, *124*, 207-231.

Rogers, R. D., Sahakian, B. J., Hodges, J. R., Polkey, C. E., Kennard, C., & Robbins, T. W. (1998). Dissociating executive mechanisms of task control following frontal lobe damage and Parkinson's disease. *Brain, 121,* 815-842.

Rubin, O., & Meiran, N. (2005). On the origins of the task mixing cost in the cuing task-switching paradigm. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31 (6),* 1477-1491.

Rubinstein, J. S., Meyer, D. E., & Evans, J. E. (2001). Executive control of cognitive processes in task switching. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 763-797.

Ruthruff, E., Remington, R. W., & Johnston, J. C. (2001). Switching between simple cognitive tasks: The interaction between top-down and bottom-up factors. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 1404-1419.

Salthouse, T. A., Fristoe, N., McGuthry, K. E. & Hambrick, D. Z. (1998). Relation of task switching to speed, age, and fluid intelligence. *Psychology and Aging, 13,* 445-461.

Shallice, T., & Burgess, P. W. (1991). Deficits in strategy application following frontal lobe damage in man. *Brain, 114,* 727-741.

Smallwood, J., Davies, J. B., Heim, D., Finnigan, F., Sudberry, M. V. O., Connor, R. C., & Obonsawain, M. C. (2004). Subjective experience and the attentional lapse. Task engagement and disengagement during sustained attention. *Consciousness and Cognition***,** *4*, 657-690.

Smallwood, J., Obonsawin, M.C., & Reid, H. (2003). The effects of block duration and task demands on the experience of task unrelated thought. *Imagination, Cognition and Personality, 22*, 13-31.

Smallwood, J., & Schooler, J. W. (2006). The restless mind. *Psychological Bulletin, 132 (6)*, 946-958.

Smith, R., Keramatian, K., Smallwood, J., Schooler, J., Luus, B., & Christoff, K. (2006). Mind-wandering with and without awareness: An fMRI study of spontaneous thought processes. *Paper presented at the 28th Annual Conference of the Cognitive Science Society.*

Sohn, M. H., & Anderson, J. R. (2001). Task preparation and task repetition: Two-component model of task switching. *Journal of Experimental Psychology: General, 130*, 764-778.

Sohn, M. H., Ursa, S., Anderson, J. R., Stenger, V. A., & Carter, C. S. (2000). The role of prefrontal cortex and posterior parietal cortex in task switching. *Proceedings of the National Academy of Sciences, 97*, 13448-13453.

Spector, A., & Biederman, I. (1976). Mental set and mental shift revisited, *American Journal of Psychology, 89*, 669–679.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*, 643-662.

Sumner, P., & Ahmed, L. (2006). Task switching: The effect of task recency with dual and single affordance stimuli. *The Quarterly Journal of Experimental Psychology, 59,* 1255-1276.

Teasdale, J. D., Proctor, L., Lloyd, C. A., & Baddeley, A. D. (1993). Working memory and stimulus-independent thought: Effects of memory load and presentation rate. *European Journal of Cognitive Psychology, 5*, 417-433.

Teasdale, J. D., Dritschel, B. H., Taylor, M. J., Proctor, L., Lloyd, C. A., Nimmo-Smith, I., & Baddeley, A. D. (1995). Stimulus-independent thought depends on central executive resources. *Memory and Cognition, 23 (5)*, 551–559.

Theeuwes, J. (1991). Cross-dimensional perceptual selectivity. *Perception and Psychophysics, 50*, 184-193.

Theeuwes, J. (1992). Perceptual selectivity for colour and form. *Perception and Psychophysics, 51,* 599-606.

Theeuwes, J. (1994). Stimulus-driven capture and attentional set: Selective search for color and visual abrupt onsets. *Journal of Experimental Psychology: Human Perception and Performance, 20*, 799-806.

Turner, M. L., & Engle, R. W. (1989). Is working memory capacity task dependent? *Journal of Memory and Language, 28,* 127-154.

Unsworth, N, Heitz, R. P., Schrock, J. C., & Engle, R. W. (2005). An automated version of the operation span task. *Behavior Research Methods, 37 (3)*, 498-505.

Waszak, F., Hommel, B., & Allport, A. (2003). Task-switching and long-term priming: Role of episodic stimulus-task bindings in task-shift costs. *Cognitive Psychology*, *46*, 361-413.

Wilkins, A. J., Shallice, T., & McCarthy, R. (1987). Frontal lesions and sustained attention. *Neuropsychologia, 25*, 359-365.

Wylie, G. & Allport, A. (2000). Task switching and the measurement of "switch costs". *Psychological Research, 63*, 212–233.

Yeung, N., & Monsell, S. (2003). The effects of recent practice on task switching. *Journal of Experimental Psychology: Human Perception and Performance, 29 (5)*, 919-936.

Yeung, N., Nystrom, L. E., Aronson, J. A. A., & Cohen, J. D. (2006). Between-task competition and cognitive control in task switching. *The Journal of Neuroscience, 26 (5)*, 1429-1438.