FLEXIBLE BEHAVIOR UNDER CONTROL? NEURAL AND BEHAVIORAL EVIDENCE IN FAVOR OF A TWO-COMPONENT MODEL OF TASK-SWITCHING

by

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The ability to rapidly change from one course of action to another, i.e. "flexible behavior", is a hallmark of human cognition. Laboratory observations of switch costs, an increase in reaction time and errors when alternating between tasks compared to repeating a task, have been argued to be a measure of endogenous control during flexible behavior. However, alternative models suggest no such reconfiguration processes are necessary to account for performance in these task-switching situations. The first part of this dissertation uses neuroimaging to address whether reconfiguration processes do in fact occur in the explicit cuing variant of the task-switching paradigm. Using a 4:2 mapping between cues and tasks, we found neuroanatomical evidence for a dissociation between cue-switch (left prefrontal and lateral parietal) and task-switch (medial precuneus and cerebellar) related areas, consistent with the claim of endogenous control during task selection. The second portion explores whether automatic, long-term memory (LTM) processes can explain the "switch cost asymmetry", the fact that switch costs are larger when switching into a dominant task rather than into a competing non-dominant task. We modified an alternating runs task-switching paradigm to include either long or short response-to-stimulus intervals (RSIs) after each pair of trials (i.e., AA-AA-BB-BB), thereby inducing selection costs not only at the point of a task-switch (i.e., AA-BB), but also between same-task pairs (i.e., AA-AA). Using spatially compatible versus incompatible response rules and Stroop word versus color naming, we found asymmetric effects not only at task-change transitions, but also at task-repeat transitions when the RSI was long (presumably inducing frequent losses of task set). In two additional experiments, an asymmetry for long RSIs was obtained even when competing tasks were separated into alternating single task blocks, but not when the tasks were compared in a between-subject design. This pattern supports the idea that the asymmetry arises from interference effects occurring in LTM traces. The combined results of this dissertation characterize task-switching processes not as an "either-or" phenomenon in regards to the question of control, but rather as the interplay between top-down, executive functions and bottom-up, long-term memory priming mechanisms.

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CHAPTER I

EXAMINATION OF CONTROL IN TASK-SWITCHING

How are our actions and behaviors initiated and guided? While this age-old question touches on deep-rooted philosophical questions (such as the nature of the will) it has only been in the last century or so that researchers have attempted empirical investigations of such issues of "control." As one might imagine, investigations of such a nebulous concept have proven difficult. First then, it is necessary to define what we even mean by the term control. This alone has proven no easy task, as even definitions of the concept are contentious.[1] On one hand, control is a seemingly simple concept to understand, even a dictionary definition gleams some insight into its usefulness as a psychological concept: "the power to influence or direct behavior or the course of events," (The New Oxford American Dictionary). While this definition is clearly aimed at the control of people, its essence – to direct behavior—is, in the simplest sense, the same conception by which we will use the term.

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[1] Researchers often speak of "executive processes," the "central executive", "executive control", "executive function" or "executive attention" despite generally referring to the same concept. Use, hereafter, of any of these terms can, for our intents and purposes, can be considered synonymous.

A return to this question of what constitutes control, with a more formal operationalization of control processing, will follow. But before doing so, it is imperative to also touch upon the issues of how and when control processes might come about in the first place. Consider the following example illustrating some basic principles of control:

> Before heading into the office for the day you remember you need to cash an important, expiring check. At the end of an exhausting day, you recall this "check cashing task" that needs completing and rush out of the office to make it to the bank before closing. You get into your car and make your way towards the bank, which also happens to be mostly along the same route as to your home. All is going smoothly and you have even reminded yourself during the drive that you need to stop at the bank your way home. Mid route however, you receive an important call on your cell phone and become engrossed in conversation. Distracted by the call, you find you have made an error in your route by turning right, towards your home, instead of making a left at the last intersection, which would have taken you onto the street your bank is located. You correct your error, but not for some time after discovering your blunder and by the time you make it to the bank you find to your consternation that it has closed.

This anecdote, while possibly a bit farcical, illustrates a number of factors involved in controlled behavior, or in this case, "failure of control" (Monsell, 1996). First and foremost, controlled action is required in the face of automaticity. That is, control is required to overcome highly familiar and routinized behaviors, such as taking the familiar direction home (turning right) over the less familiar, less practiced turn towards the bank. Also, a critical decision ("response") was required in the face of a familiar stimulus in the example, i.e. the intersection. Note however that the critical stimulus in this case, the intersection, did not by itself afford the appropriate behavior, rather it presented an equivocal choice—turn left or turn right. The stimulus then is said to have been "ambiguous" to the correct response in this case. Consider in contrast a "T" junction onto a one-way street where only one correct response would have been possible. Related to the concept of automatic behavior, the "turn right" response was also more strongly elicited by the intersection due to its familiarity. In other words it was a more "prepotent" response than the "turn left" option. Another critical point that can be drawn from this example is that the "correct" behavior in such situations is highly dependent on the current context. The context in this case is determined by the desired goal ("going to the bank"). However, keeping the desired goal state in mind is highly susceptible to interference, as demonstrated by the likely loss of this goal by the distracting phone call or overriding of this goal by a competing goal ("drive home") that may have been elicited by a particularly prepotent stimulus-response association (turn right at this intersection to go home; S-R association or S-R mapping).

The above example also illustrates some of the basic conditions under which control is required for appropriate action. The set of components required to perform a desired action, in other words the configuration of goals, rules, responses, have been termed "mental sets" (Mayr, 2003) or "task-sets" (Monsell, 1996), sharing similar characteristics of earlier concepts such as "schemas" (Norman and

Shallice, 1986). Selecting then between mental-sets has been argued to require a reconfiguration of the cognitive system, in other words, an act of endogenous control (for a review, see Rubinstein, Meyer, & Evans, 2001; Monsell, 2003; Mayr, 2003). Putative cognitive processes that fall under the control rubric are numerous and include, but are not limited to: inhibition, switching, dividing or allocating attention, resolving conflicting between competing representations, planning, manipulation of items in working memory and task-switching. It is the last of these concepts, task-switching, that forms the focus of our investigation.

While we just listed some exemplar processes that have been argued to constitute control functions, we still need a more formal working definition of the term. As aforementioned, the exact usage of the term is not agreed upon, but overarching notions of control include those processes involved in the organization, hierarchy and direction of action. Control functions then are those processes that occur particularly in situations that require novel or flexible behavior guided by internal goals, as compared to purely "bottom-up" driven behavior (e.g. Pennington and Ozonoff, 1996). As such, control processes are oft considered non-automatic, slow (relative to automatic processes), effortful and require use of cognitive resources (e.g. Schneider & Shiffrin, 1977). While this descriptive overview of control admittedly may raise as many questions as it answers, it, in the least, provides a *general* framework that can be referred to for definitions of control.

The purpose of this dissertation though is not to define control, but rather examine the supposed control, and/or "control-less," processes that occur in contexts requiring the rapid selection between mental sets. This chapter (I) summarizes some basic principles of the so-called "task-switching" paradigm, as well as outlines two broad classes of models that present differing accounts of these effects. These two explanations can be broadly grouped into control-based versus low-level, associative priming explanations. Evidence in favor of both accounts is further detailed in Chapter II, along with a review of neuroimaging studies that have attempted to separate components of switching. Chapter III provides our neuroimaging evidence in support of a two-component model of task-switching. Chapter IV presents behavioral data consistent with associative, long-term memory (LTM) explanations of the switch cost asymmetry effect. Integrating these results, the final chapter argues in favor of a LTM retrieval account of task-switching, composed of both top-down (control) and bottom-up (automatic associative retrieval) influences on selection.

Basic Findings and Terminology of Task-Switching

How might these so-called control processes be investigated empirically? The task-switching paradigm has gained popularity recently as an ostensible "window" into control processes. It has been known for some time that alternating between two simple choice reaction time (RT) tasks, incurs both a slowing of reaction times and an increase in the number of errors committed, an effect known as the *switch cost*. Jersild (1927) was the first to report this finding in a study that required participants to either alternate between addition or subtraction operations on a series of digits within a list, or simply repeatedly perform addition (or subtraction) on subsequent digits within a list. Lists that required alternating between operations ("tasks") took longer to complete as those lists that required repeating the same operation.

Spector and Biederman (1976) extended the Jersild (1927) finding by showing these observed switch costs were much less pronounced when visual cues were present that indicated the appropriate operation on each set of digits (i.e. "+" or "-" symbols) than when these operators were not present. Stimuli in which only one possible response is possible, or afforded, such as when operation symbols were present in the Spector and Biederman (1976) study, are known as *univalent* or *unambiguous* stimuli. Conversely, the condition in which these symbols are not present, or any such situation in which the desired response is not afforded by the external stimulus itself, are known as *bivalent* (or multivalent really as more than two choices might be possible) or *ambiguous* stimuli. Such ambiguous situations, which again lead to larger switch costs, arguably require an endogenous control process needed to identify the appropriate task.

Further evidence in favor of endogenous control processes as a critical determinant of switch costs comes from the so-called *preparation effect*. If participants are informed, either by a cue or by a predictable task sequence, of the upcoming task and given a substantial amount of time (~600 or more milliseconds) between successive cues or stimuli, a substantial reduction of switch costs is observed (e.g. Rogers & Monsell, 1995). The existence of this preparation effect has been argued in favor of the idea that "reconfiguration" of the relevant task-set must occur whenever there is a change in task. Sufficient time between tasks then is thought to allow for these control processes to take place during this interval, thus reducing the time needed to do so after target presentation. It should be noted, however, that switch costs are not completely eliminated with preparation time, even with several second long intervals. This remaining cost is known as the *residual switch cost.*

Switch costs have been replicated across a range of different tasks and stimuli type. Additionally, switch costs have been reliably observed in varied paradigms in addition to the somewhat informal "alternating lists" method employed by Jersild (1927). For example, Rogers and Monsell (1995) devised a novel method for examining switch costs, known as the *alternating runs* methodology. In their paradigm, two tasks are performed within the same block of trials in runs of same-task trials that alternate in a predictable manner (e.g. AAAABBBB). One advantage of this method is the ability to measure discrete RTs on a trial-by-trial basis, as opposed to the global assessment of RT of the list method. Additionally, task-switches and repetitions can be assessed within the same block. This led to the finding that RTs on no-switch (repeat) trials within single-task blocks (such as in a repetition list) are actually faster than when no-switch trials are performed in the same block as another task (such as in an alternating runs design); this is known as the *mixing* or *global selection* cost. Another popular method of assessing switch costs is by the task-cuing (also known as random cuing) paradigm that presents task in an unpredictable sequence, with tasks indicated by the current cue (generally a letter or word cue) presented either before or concomitant with the stimulus (target). This methodology allows for tight control over parameters. For example, the preparation time can be varied via the cue-to-stimulus interval (CSI). Whereas the interval between tasks can be manipulated via the response-to-cue (RCI) interval, allowing for "passive decay" of the preceding task-set (e.g. Meiran, 1996; Mayr & Kliegl, 2000).

But is switching between tasks really special? That is, is the selection process(es) required between tasks really any different than the within-task selection that must occur (e.g. selecting the appropriate S-R mapping) in any choice RT task? In fact, within-task difficulty does not generally interact with switch costs, supporting the idea that selection between tasks is independent from selection within tasks (e.g. Mecklinger, von Cramon, Springer, & Matthes-von Cramon, 1999; Rogers and Monsell, 1995; Mayr & Kliegl, 2000; Gopher, Armory, & Greenshpan, 2000; Rubinstein et al., 2001). Neuroanatomical evidence also supports this distinction. Patients with left-frontal cortical damage exhibit profound deficits in switching tasks, but not in other difficult, control functions such as inhibition (Mayr, Diedrichsen, Ivry, & Keele, 2006). Additionally, neuroimaging studies have show switch selective areas, independent of task-selective areas (Yeung, Nystrom, Aronson, & Cohen, 2006).

Before moving on to accounts of switching, some additional effects from the task-switching literature warrant introduction here, as they will become highly relevant in later discussions. First of these is the *congruency effect*. Recall that in the case of ambiguous stimuli, dimensions relevant to both tasks are visible concurrently. Thus, the correct response for the current task can potentially be mapped to the same response as the other, non-relevant task, (i.e. "congruent" trials) or to a different response then is afforded by this stimulus in the context of the former task (i.e. "incongruent" trials). For example, say participants switch between color and shape discrimination tasks, responding with a "left" keypress to red or square objects and a "right" keypress to green or circle objects. Thus, in this example, a green circle would be a congruent trial, since a "right" response is required for either task, whereas a green square would be incongruent, since a "right" response would be required if the color task is current, but a "left" response when the shape task is current. Incongruent trials typically show longer RTs than congruent trials on switch trials; congruency effects however cannot account for the entirety of switching effects as congruent and neutral stimuli also show significant switch costs (Rogers and Monsell, 1995). Interference from preceding task sets has also been used to explain the so-called switch cost asymmetery effect. This is the finding that switching into a highly dominant or "strong" task, such as Stroop word naming shows larger switch costs than switching to a less dominant, "weaker" task, such as Stroop color naming (e.g. Allport, Styles, & Hsieh, 1994). Further examination and an alternate explanation of this effect will follow in subsequent sections (Chapter IV contains an in-depth assessment of the switch cost asymmetry effect).

"Control-Like" Accounts

How can we account for these various effects related to task-switching? Can current models accurately explain all aspects of these phenomena? We have already touched on the idea that switching requires the "resetting" of the cognitive system to update the current task-set. But what exactly might this consist of? Possibilities include: shifting the attentional focus from one perceptual dimension of a feature to another (e.g. Meiran, 2000), activating the current task-set and/or inhibiting the currently irrelevant task-set (e.g. Mayr & Keele, 2000; Arbuthnott & Frank, 2000) and retrieval and updating of the current task goals and rules from LTM (e.g. Mayr & Kliegl, 2000; 2003; Rubinstein et al., 2001). Such processes could all fall under the rubric of "control" processing, given their likely conscious, effortful and non-automatically elicited nature.

The preparation effect has been argued as critical is the postulation that switching requires reconfiguration and control processes, as aforementioned. However, might we better elucidate these potential mechanisms involved in preparation? One intuitive possibility for such a beneficial operation that might occur during preparatory intervals is verbal self-instruction. For instance, participants might verbalize the upcoming task or even rehearse the relevant rule mappings. Goschke (2000) presented initial findings consistent with this idea. In this study, participants were required in one condition to verbalize the upcoming task with a relevant word label (e.g. "shape" if shape discrimination was the forthcoming task) during the preparation (CSI) interval, whereas in the other condition an irrelevant task word (e.g. a particular day of the week) was verbalized. As expected, reduced switch costs, as a function of CSI, were seen for the task-relevant label condition, but not when an unrelated verbal response was produced, suggestive of a critical function of language during preparation.

Other investigators have used articulatory suppression (AS) tasks, requiring the continued repetition of a familiar word or sequence (e.g. “the”), concurrent with task performance to examine the potential role of verbalization in switching. Articulatory suppression is thought to selectively impair phonological loop processing, while leaving executive control processes proper relatively unaffected (Baddeley, Lewis & Vallar, 1984). Highly reliable, negative effects of AS on switch costs have been found across a number of paradigms and stimuli types. Moreover, these effects were apparent only when ambiguous stimuli (operator signs absent) were used and larger with less direct compared to more direct (i.e. letters instead of word cues) task cues (e.g. Baddeley, Chincotta, & Adlam, 2001; Emerson & Miyake, 2003; Saeki & Saito, 2004). Given these results, particularly the preparation and ambiguity effects, it was argued that verbal self-cuing might guide endogenous control during task switching (e.g. Miyake & Emerson, 2003).[2]

The LTM Retrieval Account

Consistent with this purported function of verbalization in cuing the upcoming task, is the proposal that switching is in essence a problem of selecting the correct task-set from long-term memory (Mayr & Kliegl, 2000; Rubinstein et al., 2001). Mayr and Kliegl (2000) in fact hypothesized that much of what can be done to "reconfigure" the system is to retrieve or reload the relevant task-set into working memory from long-term memory in a controlled, endogenous manner. To test this idea, they implemented an alternating runs design and varied the degree of within-task retrieval difficulty by using either a semantic or episodic retrieval task. As expected, a retrieval-demand effect was seen, such that switching to the episodic task (high retrieval) incurred larger switch costs than switching to the semantic task (low retrieval). The authors interpreted this increase in switch costs as a result of the increased interference present between the high retrieval demands of the primary task (episodic retrieval) and the putative retrieval of task-set information when a switch in task is required. Moreover, in a second experiment, the

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[2] Although see Bryck and Mayr (2005) for evidence suggestive of a general (i.e. non-specific to switch trials) role of verbalization, particularly when sequencing demands of task order are high.

authors found a difficulty manipulation of the primary tasks, not thought to affect retrieval demands (reversed word order), did not similarly increase switch costs. This suggests the results of the first experiment cannot be explained simply by some general difficulty difference between the tasks.

Mayr and Kliegl (2000) hypothesized that what needs to be retrieved specifically are the explicit rules for the upcoming task. To test this, they presented subjects with the a cue prior to stimulus presentation which consisted of the relevant rule for the upcoming task, that is the response assignments required on the upcoming trial (e.g. "bottom-top"). As expected, this manipulation successfully reduced switch costs, as well as eliminated the retrieval-demand effect, compared to a control condition with no cue. Additionally, increasing the preparation time (CSI) reduced the retrieval demand effect; however simply increasing the passive decay time between trials (RCI, which does not allow for preparation, e.g. Merian, 1996) did not reduce the retrieval demand effect.

Consistent with this finding, Rubinstein et al. (2001) showed that switch costs increased with tasks requiring a more complex rule than those requiring a simpler rule. The authors interpreted this result in terms of retrieval difficulty, arguing that complex rules are harder to retrieve than simpler rules. In summary, Mayr and Kliegl (2000) suggest that task-set reconfiguration processes require the retrieval of the relevant rules from LTM and loading these into working memory (WM) before an act of selection can occur. Based on these observations, Mayr and other (Mayr & Kliegl, 2000; 2003; Mayr, 2003) have proposed a LTM retrieval model of task-switching. The basic tenets of this idea suggest that working memory, at least in demanding task-switching situations, is able to hold only one task-set representation, including the relevant rules (e.g. S-R mappings), on-line at any given time. In other words, activating a representation in working memory is akin to selecting this task (Mayr & Kliegl, 2000; Mayr, 2003). This single-task constraint is likely not due to capacity limitations (Rubinstein et al., 2001), but might be an effective means of reducing between task competition that arises when two, or more, task-sets are relevant for performance (Mayr & Kliegl, 2000, Rubinstein et al., 2001). This constraint has the side-effect then, at least for rapid back-and-forth switching situations, that performance of a new task requires the purging of the old task-set and the activation of the now relevant task-set. Thus re-retrieval of the now relevant features of the new task, likely the rules required of this task (e.g. "green color = right response"), from LTM is required. A more in-depth account of this model will be considered in later chapters, but for now it is important to note this model has the ability to parsimoniously account for the host of task-switching effects thus far discussed.

"Control-Less" Accounts

However, can control accounts accurately explain all of the phenomena observed in switching studies? For one, recall that preparation time reduces, but does not fully eliminate switch costs, i.e. residual costs are leftover (e.g. Allport et al., 1994). If switch costs can be explained wholly by endogenous control processes, adequate preparation time should be sufficient for these processes to occur before stimulus presentation, thereby effectively eliminating switch costs. Additional findings are also difficult to explain by imparting only control mechanisms, as such, alternative mechanisms have been posited. For example, Allport et al. (1994) argued that the existence of residual costs could be explained by what they termed task-set inertia (TSI). This concept can be likened to a type of proactive interference (PI) of conflicting S-R mappings between tasks. This conceptualization of task-switching situations suggests that the former task, in a sequence of tasks, provides positive priming of the current task. While this would provide a benefit in the case of a task repetition, it should induce interference in the case of a task-switch. Additionally, negative priming needs to be overcome on switch trials, since the now relevant task was presumably suppressed on the preceding trial (where it was irrelevant). The TSI account gains support by its ability to explain the asymmetry effect (described above). If we presume that performance on the non-dominant task requires relatively more suppression of the dominant task than vice-versa, than switching into the dominant task requires reactivating a task-set that was just previously strongly inhibited. Conversely, little suppression is presumed while performing the dominant task, so switching into the non-dominant task requires little overcoming of suppression. Hence, switching to the non-dominant takes less time than switching into the dominant task. Allport et al. (1994) also investigated what would happen to switch costs if there was no interference present, such as when subsequent S-R mappings did not overlap, yet participants still alternated between two tasks. Consistent with the idea of TSI, switching costs were greatly reduced in such a case where task-sets were dissimilar (Allport et al., 1994).

However, how long might activation or suppression of the preceding task-set last? Longer response times have in fact been observed for alternating between dissimilar (i.e. non-overlapping stimuli and S-R mappings) tasks if, in a previous experimental condition (completed a few minutes previously) participants performed tasks that directly competed with the two currently relevant tasks (Allport et al., 1994). Similar results have been found with other paradigms. For example, it has been shown that the "Simon effect" (i.e. a cost when stimuli and responses match) can actually be eliminated or even reversed if prior to the location-irrelevant Simon task, subjects first performed a location-relevant task (S-R compatibility task) with incompatible mappings (Proctor & Lu, 1999; Tagliabue, Zorzi, Umilta, & Bassignani, 2000). This reversal can persist for quite some time (up to 600 trials later). These results suggest that associations built in an earlier context can have a lasting (i.e. LTM based) influence on the current context if features (S-R associations in this case) overlap, or partially overlap. Presumably, these features are automatically retrieved due to this overlap with previous stimuli/tasks. As such, these effects are difficult to explain via purely control mechanisms of switching (Allport & Wylie, 2000).

Such results form the basis of a class of accounts of task-switching that can be referred to as associative retrieval models. Examination of such "bottom-up" processing in task-switching, and control in general, is oft overlooked. Perhaps this is due to the influence of hierarchical and stage-like models of information processing, which tend not to consider the role "lower" levels of behavior can have on "higher" levels (e.g. Sternberg, 1969, Norman and Shallice, 1986, Koechlin, Ody, & Kounelher, 2003; Rubinstein et al., 2001). However, evidence emerging in the past few years has suggested a considerable role of LTM processes during task-switching. Extending these findings, Waszak, Hommel and Allport (2003) showed that this long-term priming of stimulus/task features can be quite specific. They used a picture-word Stroop task with stimuli consisting of a picture of a highly namable object and a word embedded within this picture (typically incongruent with the picture). Participants first responded based on the picture feature of the stimuli, then in a later block, they responded by naming the word. Critically, the experimenters also manipulated the stimuli previously presented to participants during the word-reading task by either repeating stimuli seen previously (while performing the picture-naming task) or by presenting novel stimuli not previously in the experiment. The critical result from this study was that previously seen stimuli incurred significantly larger switch costs than unprimed stimuli. Waszak et al. (2003) interpreted this result as reflecting "binding" or integration between task sets and low-level features. It seems even non-relevant features (the non-attended to features of a stimulus) could become integrated with task context. Additionally, these priming effects were seen even after long intervals (up to 100 trials) between the first presentation of a prime and its probe trial. This suggests the representation of these bound representations must have resided in LTM. Not only did these associations persist over time, but item specific interference increased with the number of presentations during the probe (picture-naming) phase. Thus, these associations between task and stimuli seem to be strengthened in LTM with repeated exposure, and as such, produced greater interference during switching.

A similar interpretation was given by the results of a study by Mayr and Bryck (2005). The introduced a design which allowed for disambiguating rule (task) changes and S-R associations (because certain S-R associations could occur under two different rules). The critical finding here was that complete S-R associations produced benefits only when the rule also repeated, but incurred costs when the rule changed. This result provides another example suggestive of task sets becoming integrated with lower levels features.

This interpretation of stimulus features forming integrated representations is similar to other conceptualizations, outside of the task-switching literature, of bounded representations. For example, Logan's "instance theory" of memory (e.g. Logan, 2002) suggests that during task performance, a residual "instance" of a particular episode is encoding and stored in a memory trace that contains features of that particular event, such as the particular S-R mapping executed, stimulus features, etcetera. This concept of integrated representations is also in line with notions of "object files" from the visual perception and attention literature (e.g. Kahneman, Treisman, & Gibbes, 1992) and "event files" from the perception and action literature (e.g. Hommel, 2004). These traces then can include many features of the encoded episode and the general context in which it occurred, such as the intended goal, stimulus, rule and response executed (e.g. Logan, 1988; Hommel, 2004;

Mayr & Bryck, 2005). One critical, additional, property of these "event files" is that only *attended* features are included in a memory trace, or "instance" (Logan, 2002). However, Neill (1997) extends this idea a bit by assuming that actively ignored distractors (in a negative priming task) can also be included in traces as "to-be-ignored" items.

To summarize, these studies are consistent with the idea that codes representing task-relevant features can reside in LTM and can have a profound effect on presumed "control" function of switching. It should be noted that the preceding accounts should really be qualified as those that *deemphasize* control processing during task-switching, but do not necessarily claim no such processing exists in a task-switching environment. However, they do point out limitations with current models that suggest the entirety of switch costs can be explained solely by the time taken to complete control functions.

CHAPTER II

EVIDENCE FOR SEPARABLE COMPONENTS OF TASK-SWITCHING

The preceding chapter introduced the concept of control, a putative method of empirical measurement of renewed interest (the task-switching paradigm) as well as a brief overview to what degree this methodology may actually measure "control." Accounts that emphasize control were compared to those than emphasize low-level, priming and associative memory accounts of switching. One such prominent, as of yet discussed, "priming" account was presented by Logan and Bundenson (2003). They essentially claim that task switching, at least in the cuing paradigm, can be reduced simply to cue-switching. However, Mayr and Kliegl (2003), using a very similar paradigm found differing results and subsequently reached a differing conclusion. These initial studies investigating "cue-switching" compared to "task-switching", along with follow-up studies and interpretations are outlined in the following. Results from a functional magnetic reasoning imaging (fMRI) study investigating the neural correlates of cue-switching versus task-switching, as well as a review of relevant neuroimaging results from task-switching studies in general, are also presented.

Behavioral Studies of Cue-Switching Versus Task Switching

One standard version of the task-switching paradigm, the aforementioned task-cuing design, entails presenting participants with a cue indicating which task is to be performed on a trial in advance of the actual stimulus presentation. (e.g. Merian, 1996). This methodology has the advantage of allowing for the exact manipulation of many of the timing variables present during switching. Perhaps foremost of these, is the cue-to-stimulus interval (CSI), which allows for an assessment of the role of preparation during target stimulus has been shown to reduce, although not eliminate, switch costs (e.g. Rogers and Monsell, 1995). Presumably, longer CSIs allow participants to prepare for an upcoming switch in tasks once the cue has been presented. Given the cue information, participants should be able to extrapolate the upcoming task-set parameters, which might include the relevant task rules (e.g. set of S-R mappings). What or how exactly participants prepare for an upcoming task is open to debate, but it is generally agreed upon that this preparation is an intentional act of reconfiguration, likely reflecting a endogenous control process(es).

However, two groups of researchers documented a potential problem with the standard procedure of the explicit task-cuing design. Both Mayr and Kliegl (2003) and Logan and Bundeson (2003) pointed out that a change in task also requires a change in the cue. As such, the cuing design cannot differentiate potential effects of changing cues from changing tasks (task-sets) with standard measures of switch cost (task-switch minus repeat trials). It is possible then that the typical switch costs observed in cuing studies result from processes required to re-encode the cue on a switch trial, or conversely, benefits from repeating the same cue on a no-switch trial, rather than switching task-sets. It is therefore of great theoretical importance to determine whether switch costs arise simply due to a change in cues, a change in tasks, or both. For example, according to the previously discussed LTM-view of switching (e.g. Mayr & Kliegl, 2000, 2003), either a change in cue or change in task constitutes a change in the retrieval pathway into the correct set of rules—proposed as a critical determinant to switch costs. Thus, it is critical to determine whether there are separable components associated with a change in a cue compared to a change in task.

Both groups (Mayr & Kliegl, 2003; Logan & Bundesen, 2003) tested this idea by introducing a new variant of the task-cuing paradigm with a 4 to 2 mapping between cues and tasks (i.e. two separate cues linked to each of the tasks). This design allows for the assessment then of changes in the cue that are independent of changes in tasks (i.e. a trial in which the same task was cued as the previous one, but via the other cue), a condition labeled “cue-switch” by Mayr and Kliegl (2003). To test whether “true” task-switching effects exist, i.e. a cost associated only with a change in a task, the authors compared task-switch trials (change in cue and task) with cue-switch trials, which they called “task-switch” costs[3]. Again, this novel design allowed for delineating the effects of a change in cue from a change in task and was directly tested by comparing cue-switch costs (cue-switch versus no-switch trials) from “true” task-switch costs (task-switch versus cue-switch trials).

Using two arbitrary (i.e. not semantically related to the tasks) single letter cues per task, a color and a shape task, Mayr and Kliegl (2003) found a strong cue-switch effect (~ 250 ms) and a somewhat smaller, but robust, task-switch effects (~ 150 ms) in several experiments. Further, they showed evidence that these two effects were separate from one another and likely reflect two independent components of task-switching. For one, the cue-switch effect, but not the task-switch cost, seemed to be sensitive to preparation as the cue-switch cost decreased with increasing CSI. Additionally, only the cue-switch effect was sensitive to practice effects, as cue-switch trial RTs decreased over blocks compared to no-switch trials. On the other hand, negative response repetition effects, longer RTs to trials in which a

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[3] Logan and Bundesen (2003) used different terminology. They labeled trials in which neither the cue nor the task changed as “cue repetition”, trials in which only the cue changed as “task repetitions” and trials in which the task and cue changed as “task-switch” trials. To simplify and avoid confusion, we will use the terms *no-switch*, *cue-switch* and “true” *task-switch* to refer to these respective conditions.

response was repeated compared to changed, occurred in task-switch, but not in cue-changes conditions.

Mayr and Kliegl (2003) also examined the locus of the "backwards inhibition" effect, the fact that a task that was recently performed induces a cost compared to a more novel task on the current trial and is generally regarded as reflective of inhibitory processing induced by the recently relevant task (Mayr & Keele, 2000). With the standard explicit cuing paradigm, researchers are not able to sort out whether the inhibitory processing results at the level of cue encoding, or the actual task-set representation; the modified 4:2 cue-to-task mapping paradigm should be able to shed light onto this question. To test this, in Experiment 3 of Mayr and Kliegl (2003), a third task was introduced (size), again cued by two separate letters. This allowed the authors to examine potential differences in backwards inhibition costs on trials in which the task was the same on the current trial as the task on n-2 trials, but differed in whether the cue repeated or changed on the critical trial compared to the n-2 trial. Inhibition at the level of cue processing would predict an increase in RT only in the case where the same cue repeated on the current trial as the n-2 trial. However, the results were consistent with inhibitory effects at the task-set level representation, as RT costs for trials in which the task repeated on the current trial as the n-2 trial were only apparent when a change in cues occurred.[4] This finding suggests that backwards inhibition affects the task-switch component, but not the cue-switch component of switching.

To summarize the results of Mayr and Kliegl (2003), they successfully delineated cue-switch from task-switch effects using the 4:2 cues-to-task explicit cuing paradigm. Further, they argued these two components are independent of one another, as cue-switching was affected by preparation and practice effects, while task-switching was affected by response repetition and backwards inhibition effects, but not vice-versa. They characterize these two components as having very different functions. The cue-switch, given its sensitivity to CSI, likely reflects intentional, preparatory processes that act to reconfigure the cognitive system for a task-set switch, whereas the task-switch stage likely involves the relatively automatic "application" of rules or S-R mapping once the target stimulus is present. They frame this in terms of the "LTM retrieval" view of switching, which argues a large portion of switch costs are attributable to the need to retrieve the relevant rules from LTM in order to establish the current task-set, which is largely what

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[4] Interestingly, backwards inhibition effects were not seen in n-2 task repeat trials in which the cue also repeated. This is inconsistent with the earlier work of Mayr and Keele (2000). See Mayr and Kliegl (2003) for a possible explanation of why they failed to see this effect in their Experiment 3. Regarding our discussion, the critical finding is that backwards inhibition appears to occur at the task-switch "application" stage, and not at the cue-switch stage.

one can do to prepare for an upcoming task-switch, as argued by Mayr and Kliegl (2000). The LTM view of switching is further discussed in Chapter V. The practice effects on cue-switching, the authors argue, in consistent with an intentional, retrieval process as the cue-task associations were arbitrary to begin with, but over practice these associations were likely strengthened. According to the retrieval view of switching, this is akin to strengthening the retrieval pathway between a given cue and its corresponding task, which should make it easier to bring relevant information into working memory. However, there is no reason to believe practice should affect the theorized relatively automatic application of rules once already loaded into working memory during the task-switching phase. The fact that negative response repetition effects and backwards inhibition effects were seen on task-switch trials, but not cue-switch trials, was also consistent with the view these comprise two, independent stages during switching.

As aforementioned, Logan and Bundesen (2003) used a very similar methodology to differentiate cue-switch from task-switch effects. The used digits as stimuli and tasks alternated between determining the magnitude (lower or higher than ‘5’) or the parity (odd or even) of the stimulus. Two cues per task were used which were words semantically related to the task, (e.g. “magnitude” and “high-low” for judging the magnitude of the digit). Robust cue-switch effects were seen (ranging from 95 to 168 ms) as in Mayr and Kliegl (2003), however, much smaller task-switch effects were observed (between 14 to 35 ms) in the Logan and Bundesen (2003) study. Logan and colleagues replicated this general finding of robust cue-switching, but virtually absent task-switching costs in several follow-up studies (Logan & Bundesen, 2004; Arrington & Logan, 2004; Schneider & Logan, 2005, 2006). These authors claim then that no "true" task switch effects occur during switching, but can be explained solely by changes in cues— repetition of the same cue produces priming benefits (i.e. no-switch trials), while changing the cue incurs a cost, whether it is a cue-switch or task-switch trial seems not to matter. This priming account thus requires no need to assume reconfiguration, or endogenous control, processes by the system when switching tasks (Logan & Bundesen, 2003).

Schneider and Logan (2005) provide an explicit model of their priming account of switching in the task-cuing paradigm. Their model explains performance based on two major mechanisms: priming of cue encoding and retrieval from LTM of a compound cue. Cue encoding processing is the time needed to process the current task cue into a useful representation in working memory (short-term memory in their terminology). The activation level of cues in working memory is thought to decay in the time intervening between trials. Once a cue has been encoded, retrieval of the appropriate response category from LTM can then be completed. This retrieval process, the authors argue, is mediated by a compound retrieval cue, formed by the task cue and target stimulus on each trial. Selecting the correct response depends then on the combined strength of the association between the cue and the response category and the association between the target and the response category. Differences in cue encoding time based on the transition type is the major determinant of the cue-switch and task-switch effects observed in their version of the 4:2 cue-to-task cuing paradigm.

The Schneider and Logan (2005) model accounts for cue-switch and task-switch results based on semantic/associative priming mechanism as follows. First off, it is assumed that cues indicating the same task have a fairly high level of association with one another (e.g. "odd" and "even"), but across task pairs are only weakly associated with one another (e.g. "odd" and "low"), assumptions that are supported by free association norms (Nelson, McEvoy, & Schreiber, 1999, as cited in Schneider & Logan, 2005). Logan and Scheinder (2006) also provide empirical evidence that associated cues can prime each other, independent of the association of the cue to the stimuli and task. The authors found that pairs of highly semantically related cues (e.g. "queen" and "king") produced faster RTs than conditions in which the pair of cues had a low association to one another (e.g. "queen" and "salt") on cue-switch trials. Note the cues used here were not semantically related to the magnitude and parity tasks used (Logan & Schneider, 2006a). Differences between transition types arise then due to priming effects between cues during the cue-encoding phase via the Schneider and Logan model. In the case of a no-switch (i.e. cue-repeat) trial, RT will be fast based on fast cue encoding processing due to the high residual activation of the same cue (i.e. repetition priming) on each trial. In a cue-switch trial, cue-encoding processes will be intermediately fast due to associative priming between similar cue (e.g. "odd" and "even"), but not as fast as in the cue repetition condition, which can thereby explain the cue-switch effect (cue-switch trials slower than no-switch trials). The "true" task-switch effect can be explained then by the intermediate strength associative priming mechanisms occurring for a cue-switch (e.g. "odd" to "even") compared with no priming on a task-switch trial (e.g. "odd" to "high").

How then does this model explain the large true task-switch effects seen with arbitrary cues (e.g. Mayr & Kliegl, 2003)? Logan and Bundesen (2004) tackled this question by manipulating the semantic relatedness of the cues used and found true task-switch effects with arbitrary cues (i.e. letters), but small to no task-switch effects with meaningful cues. Logan and Bundesen (2004) added the argument into their priming model that using arbitrary cues requires associating these cues with a "mediator" (e.g. a task name like "color"), whose representation must first be retrieved before retrieving the relevant response category from LTM. Thus, according to this interpretation, true task-switch effects are due to the repetition of the same mediator in the case of a cue-switch trial, whereas in a task-switch trial, a different mediator is retrieved. See Logan and Schneider (2006b) for evidence in favor of this idea. The critical aspect of this model then is the fact that a series of component processes—encoding the cue, encoding the target, retrieving the response category, selecting the response –occurs on every trial, independent of the transition type. This single-task set assumption does not require reconfiguring the system to a new set of processes after a change in tasks occurs. In other words, this model of switching is "control-less", in that it does not necessitate the incorporation of any executive functions to explain switch cost phenomena.

The use of arbitrary versus meaningful cues proved to be a critical experimental difference that can account for the difference between substantial true task-switch effects seen in Mayr and Kliegl (2003) and the small to absent true task-switch effects in Logan and Bundesen (2003). Schneider and Logan (2006) and Monsell and Mizon (2006) both illuminate another notable experimental difference between these two studies is the probability of a task-switch occurrence. Consider for a moment the number of unique cue-task pairs configurations possible in each of the three transition types with four cues to two tasks. If all possible configurations are used, there are four possible no-switch and cue-switch pairs, but eight possible task-switch pairs. For example, let us label the cues for one task as "1" and 2" and the cues for the other task as "3" and "4." We can see then that the unique configurations for no-switch transitions are limited to 1-1, 2-2, 3-3, and 4-4. Similarly, cue-switch transitions have only four unique configurations: 1-2, 2-1, 3-4 and 4-3. However, tasks-switch possibilities double to eight: 1-3, 1-4, 3-1,4-1, 2-3, 3-2, 2-4 and 4-2. While Mayr and Kliegl (2003) chose to balance the proportion of switch types (.33 for each) in their experiment by only using half of the possible task-switch transition types (i.e. only one cue-cue type, not it's reversal), Logan and Bundesen (2003) used all eight possibilities, thereby creating an over-proportionate amount of task-switches overall (occurring 50% of the time, while no-switch and cue-switches each could occur 25% of the time). Both Monsell and Mizon (2006) and Schneider and Logan (2006) manipulated the probability of switching in a series of studies and found that low-probability of switching conditions led to robust true task-switch effects, while higher probabilities of switching lead to little or no true task-switch effects, replicating Mayr and Kliegl (2003) and Logan and Bundeson (2003), respectively.

This finding did little to clarify the question of reconfiguration versus priming, as the results were again interpreted very differently. Monsell and Mizon (2006) claim that *strategic* differences in the way participants perform during low and high probability switching situations could account for these observed differences in true task-switch effects. The authors argue that under high switch likelihood situations, participants may simply adopt a strategy of assuming a switch in task will occur on the next trial and therefore prepare, i.e. reconfigure, for the opposite task on each trial. If participants employed this strategy on all, or even a majority of, trials, it would have the effect of reducing RTs when an actual change in task did occur (i.e. task switch trials), since presumably the reconfiguration process could begin, or even finish, before the stimulus appeared. This strategy would of course have negative consequences on trials in which the task did not change (i.e. no-switch and cue-switch) trials. The combined effects of lower task-switch trials and increased cue-switch trials due to this strategy could explain the lack of true task-switch costs, but large cue-switch effects when switching probability was kept high.

However, Schneider and Logan (2006) interpreted their results in the context of their cue-encoding priming model and claim that the relative frequencies of cues led to differences in the amount of priming seen. In other words, if certain cue-cue transitions are more frequent than others, these instances will have a greater change of being recalled from memory on a given trial if the current cue is similar to past events, a la Logan's instance theory (Logan, 1988). So, in Schneider and Logan's (2006) high switching probability (p = .7) condition, task-switch cue transitions, (e.g. odd-even to high-low) are more frequent than no-switch (e.g. odd-even to odd-even) or cue-switch (e.g. odd-even to magnitude) transitions and this greater occurrence during performance in the experiment would lead to more/stronger instances of these particular cue-cue configurations. The odd-even cue in this case will become more associated with task-switch transitions and this stronger association will lead to more activation of the relevant task-switch cues (high-low and magnitude) on the next trial. This higher activation will then lead to priming of cue-encoding if the next trial is in fact a task-switch, leading to faster task-switch trial RT and subsequently lower true task-switch effects (Schneider and Logan, 2006). Schneider and Logan (2006) do not rule out the possibility that strategic changes could be occurring in participants when transition probabilities are manipulated. In this scenario, priming would still result from advance activation of the next cue; however, instead of the automatic retrieval of instances, this activation of cues would result from participants expectancy of what the next transition type would be, based presumably on the probability of transitions experienced during the experiment.

The plausibility of both of these interpretations, combined with the confound of switching probability and frequency of cue-cue transitions in both studies, leaves open the question of what accounts for probability effects on true task-switch and cue-switch costs. Mayr (2006) introduced a strategy-based interpretation of these effects similar to the Monsell and Mizon (2006) model, termed the task-level adaptation account, with an added wrinkle. Mayr (2006) argues that participants may in fact employ different strategies based on probability differences during task performance, but this strategy may not be an adaptation to switching per se, rather an adaptation to the likelihood of a task-switch given a change in cues. The methodological differences between Mayr and Kliegl (2003) and Logan and Bundesen (2003) not only result in an overall switching probability difference, but also result in a difference in this conditional probability of a task change occurring given a cue change ($p = .5$ in Mayr and Kliegl, 2003 and $p = .67$ in Logan and Bundesen, 2003). If participants are able to make a fast judgment regarding cue information on a given trial, if confronted with a change in cue, participants are likely to engage in reconfiguration processes and prepare for a change in task if a high conditional probability exists that a change in cue will produce a change in tasks.

Mayr (2006) independently manipulated specific cue-cue transition frequencies and conditional cue-task switch probabilities to directly test the task-level adaptation account from the cue priming account in a 4:2 cues-to-task explicit cuing paradigm. As noted above, task-switch conditions have eight unique cue-cue transition types, while cue-switch and no-switch only have four each. Mayr (2006) took advantage of this fact by manipulating the frequency of half of the task-switch transitions types (labeled task-switch-2) in a between-participant manner, while leaving the probability of the other half of task-switch transitions types (labeled task-switch-1), cue-switch and no-switch transitions types identical within each group. The high frequency group was presented task-switch-2 transitions 40% of the time and task-switch-1 transitions 20% of the time, while the low frequency group was presented with task-switch-2 10% and task-switch-1 transitions 30% of the time. Note this also results in a higher conditional probability of a task change given a cue change in the high probability group (p=.75) compared to the low probability group (p=.57). Cue-switch and task-switch effects were examined across the two groups. Task-switch-1 only trials were used to measure costs as cue-cue transition frequencies should not affect the results as these transitions type frequencies were identical to cue-switch and no-switch frequencies in each group. As predicted, participants were affected by overall switching probability, as task-switch effects were smaller and cue-switch effects were larger in the high task-switch-2 probability group. Recall that adapting a strategy of preparing for a switch would have the effect of reducing task-switch times (when one was "correct" that a switch would occur), but increase cue-switch times (when one was "incorrect" about a task switch and reconfiguration of the current task was then required). Furthermore, the cue-priming model would predict that task-switch transition types with a higher frequency in each group (i.e. task-switch-1 for the low probability group and task-switch-2 for the high probability group) would be primed and thus produce faster times and less errors than the lower probability types for each group. However this was not the case, as frequency effects (difference scores) were found to be either very small or actually reversed and unreliable in all cases. The results from Mayr (2006) thus provide evidence in favor of the task-level adaptation account over the cue-priming model of probability effects in the cuing paradigm. More generally, these results also provide support for the dissociation of cue-switching from task-switching components and are consistent with an explanation of switch-costs reflecting reconfiguration processes.

Additional empirical and modeling work has examined the independence between cue-encoding and task-related processing by requiring participants to make two responses after the typical no-switch, cue-switch and task-switch transition types in the 4:2 cues-to-task paradigm. Altmann (2006), for example, had participants respond to cues in pairs of trials, with the cue only appearing at the beginning of the pair. This allowed for examination of cue-switch and task-switch effects on the second trial in a pair that should, the author argues, be independent of critical cue-encoding processing (according to the cue-priming model) since the cue is no longer present at this point. Robust task-switch effects, but no cue-switch effects, were seen on Trial 2 conditions, suggesting that additional processing occurs during task-switching that can not simply be accounted for by changes in the cue (Altmann, 2006). Moreover, Altmann (2006) attempts to fit both a cue-priming model and behavioral performance in the standard 1:1 cues-to-task cuing paradigm to the 4:2 cuing paradigm without tremendous success.

Arrington, Logan and Schneider (2007) also attempted to separate cue-encoding from target processing to examine whether true task-switching effects occur independently of cues. They required participants to make a response not only to the target, as in typical task cuing paradigms, but also to the cue itself before the target appeared. Arrington et al. (2007) make the assumption then that the two components occur serially and in fact find evidence consistent with successful separation of cue-switch and task-switch processing as cue-switch effects were limited to cue-encoding RTs, at least when the cue-response required making a decision about which task was cued. In these successful separation conditions, task-switch effects were seen in target RTs, which argues against the cue-priming model as these effects could not be due to cue-encoding given the successful isolation of cue-encoding processes to the cue-response period. Arrington et al. (2007) admit that this is counter to the Schneider and Logan (2005) cue-priming model and suggest that true task-switching effects do exist.

Thus far, we have reviewed evidence that supports the idea that switch costs, at least as measured in the cuing paradigm, do not solely reflect task-set changes—in fact, a simple change in the cue indicating the next task, with or without a corresponding change in task, has been shown to be a large determinant of switch costs. However, current explanations of this cue-switch effect, along with the labile task-switch effect, posit differing mechanisms. One view advances the concept of a two-component system, with one stage involved in the retrieval of task rules and the other in the application of these rules given stimulus presentation. The opposing view puts forth a single priming model that determines the correct response in switching via the compound cue-to-response and target-to-response associations strength. Thus, the degree of association between cues on successive trials will determine the amount of priming of the relevant retrieval pathway required for a response. Further, these cue-switch and task-switch effects are modulated by the arbitrariness of the cues used, as well as the probability of switching. Both models, thus far, have been able to account for these effects. However, the single-priming accounts seem to be making amendments that allow for the existence of at least *some* task-switch specific processes, tipping the scales in favor of two-components models. Nevertheless, a consensus has by no means been reached. Brain imaging during performance of a 4:2 cues-to-task cuing paradigm may then held elucidate the degree of separableness of these two components.

Neuroimaging Studies of Task-Switching

Before describing our experimental method in detail, we first review studies that have examined task-switching, or task-switching like (i.e. S-R reversal tasks), performance during functional magnetic resonance imaging (fMRI) scanning. We will be paying special attention to a number of variables and results from these studies that are particularly relevant to our study (Experiment 1); these include the inter-trial interval (ITI) used between trials, whether the experiment was attempting to separate components of switching (e.g. isolating the preparatory component of switching, or an attempt to separate cue from task switching), the types of cues used (number, arbitrary/semantic) and the behavioral switch cost obtained during scanning.

Early fMRI studies of task-switching generally found areas of activation consistent with notions of the cortical areas critical to "cognitive control." For instance, prefrontal cortex areas thought to be involved in working memory and executive functions such as dorsolateral and ventrolateral PFC (DLPFC and VLPFC, respectively) have reliably been observed when contrasting switch versus repeat trials (e.g. Dove, Pollmann, Schubert, Wiggins, & von Cramon 2000; Kimberg, Aguirre, & D'Esposito, 2000; Sohn, Ursu, Anderson, Stenger, & Carter, 2000; Braver, Reynolds, & Donaldson, 2003; Brass & von Cramon, 2002; 2004; Barber & Carter, 2005; Badre & Wagner, 2006; Ruge, Brass, Koch, Rubin, Meiran, & von Cramon, 2005), although see Yeung, Nystrom, Aronson and Cohen (2006) for evidence that lateral PFC activity might be limited to task-specific processing and not to some general switching mechanism. Other prefrontal regions have shown activity in several switching studies that also tested conflict resolution and/or monitoring, such as the anterior cingulate cortex (ACC; Yeung et al., 2006; Dreher & Berman, 2002; Barber & Carter, 2005; Wager, Jonides, & Reading, 2004) and frontopolar regions thought to be responsible for hierarchical control (e.g. Pollmann, Weidner, Muller, von Cramon, 2000; Koechlin et al., 2003). Additional frontal regions, albeit in the more posteriorly located premotor cortex, supplementary and pre-supplementary motor areas (SMA and preSMA, respectively), areas implemented in motor planning and preparation, have been reported (Dove et al., 2000; Brass & von Cramon, 2004; Ruge et al., 2005; Forstmann, Brass, Koch, & von

Cramon, 2005; Badre & Wagner, 2006). Prefrontal regions tended to lateralize to the left hemisphere, although activity was certainly not limited to the left hemisphere and some of the left dominant activity could be accounted for the prevalence of verbal type stimuli used in these studies. In addition to frontal cortex, posterior parietal cortex, including bilateral precuneus and intraparietal suclus (IPS) areas have consistently been activated in switching studies (Dove et al., 2000; Kimberg et al., 2000; Brass & von Cramon, 2004; Barber & Carter, 2005; Slagter,Weissman, Giesbrecht, Kenemans, Mangun, Kok, et al., 2006; Forstmann et al., 2005; Ruge et al., 2005; Badre & Wagner, 2006; Gruber, Karch, Schlueter, Falkai, & Goschke, 2006).

While this broad fronto-parietal network of activity gives us an overview of areas involved in task-switching, several studies have attempted to further clarify the neural properties of switching. Namely, most of these attempts have focused on trying to separate the theorized "preparation " stage from the target induced "execution" stage. The most common of approach to this has been simply to isolate the preparatory period, although some researchers have also attempted to examine both components within single experiments. Unfortunately, the findings reported regarding preparation in task-switching are far from conclusive. Many of the initial studies attempting to isolate preparatory neural components during switching were unable to detect reliable areas of activation specific to switch trials during preparation (e.g. Brass & von Cramon, 2002; Braver et al., 2003; Dove et al., 2000; Luks, Simpson, Feiwell, & Miller, 2002; Ruge, Brass, Koch, Rubin, Meiran, von Cramon, 2005). In other words, contrasting long preparation times (i.e. long CSIs) with short preparation times yielded no interaction with the transition (switch) type. Some authors have argued that such a result is incompatible with the idea that preparation allows for reconfiguration of the system, specifically the overcoming of persistent interference from the now irrelevant task set (e.g. Ruge et al., 2005). They argue that if resolution of interference is assumed, this lack of activity is counter to intuition because on switch trials activity should be greater during long CSIs due to the greater requirement of control processes needed to reduce interference. However, this intuition seems to assume any such control processes are not also generated on short CSI trials.

Interestingly, recruitment of the "common" control areas seen in task-switching, such as lateral prefrontal, premotor and posterior parietal cortices, have consistently shown heightened activity for *general* preparation (i.e. for both switch and repeat trials) in task-switching paradigms (Dove et al, 2000; Sohn et al., 2000; Brass and von Cramon, 2002; Gruber et al., 2006). This pattern of results has generally been interpreted as evidence against the notion of switch *specific* endogenous control processes in task-switching situations, despite clear behavioral evidence that preparation reduces switch costs (e.g. Rogers and Monsell, 1995). It should be noted though these claims do not rule out the occurrence of any control processes during switching, rather these mechanisms might be common to both switch and repeat transition trials.

Additionally, researchers have attempted to isolate this general preparatory activity strictly to cue-related processing (Luks et al., 2002; Brass and von Cramon, 2002; Ruge et al., 2005; Barber and Carter, 2005; Gruber et al., 2006 and Slagter et al., 2006), rather than diluted effects of cue plus target processing. However, only the studies by Barber and Carter (2005), which found activity only in a left SPL region, and Slagter et al. (2006), in lateral prefrontal and parietal regions, found activity elicited specifically to cue-driven, preparatory processing for switch greater than repeat trials. These two studies are further detailed below.

While the current study is not focused on preparatory effects of switching per se, and is not designed in a manner to isolate these processes, we are interested in breaking switching into separable components. We next summarize several particularly relevant studies that have attempted to delineate components of switching. However, the time limitations of the fMRI methodology, namely the sluggish response of the BOLD signal, present an interesting problem for trying to separate preparation from stimulus processing with the typical behavioral approach of comparing short versus long CSIs. Although early studies did just this (e.g. Sohn et al., 2000; MacDonald, 2000), they required very long cue-to-stimulus intervals, on the order of several seconds, to reliably separate cue from target BOLD responses. However, behavioral studies of preparation during switching have used CSIs on the order of milliseconds and in fact less than a second or so has shown to be optimal for preparation (e.g. Rogers and Monsell, 1995). This lengthy time delay between the cue and stimulus may well have elicited extraneous or otherwise spurious processing from that seen in behavioral examinations of preparation.

As such, Brass and von Cramon (2002) devised an ingenious method for isolating preparation effects independent of CSI time. The authors employed a cuing paradigm that included the standard cue-interval-target condition, as well as a novel condition in which only a cue, and no target, was presented. With this unique cue-only condition, the authors argued they were able to examine preparation related neural responses unadulterated from any target related neural response. Brass and von Cramon (2002) found a fronto-parietal network, very similar to areas consistently seen in switching studies, for preparation. These areas included a bilateral VLPFC region, near the junction of the precentral and inferior frontal sulci (termed the inferior frontal junction, or IFJ), a more anterior region in MFG, premotor and pre-SMA areas in addition to bilateral IPS and posterior parietal regions. Two of these regions, the IFJ and the pre-SMA, showed strong correlation with behavioral indices of the cuing effect (as measured in this paradigm, cue and target together trials minus trials in which the cue was presented before a target). Moreover, by examining cue-target simultaneous trials with cue-only trials, the authors claimed they were able to separate these preparation related areas from target only areas. Brass and von Cramon (2002) make the claim that the strongest areas from this contrast occurred mostly in premotor and motor cortices, along with the ACC; although this dissociation does not seem to have been completely non-overlapping as posterior parietal areas and the IFG region also showed a heighten response for this contrast. The most critical finding from this study for our purposes, however, is the fact that this preparation activity was common for both for both repeat and switch conditions, consistent with the Dove et al. (2000) finding. However, while a behavioral main effect of cuing was present, this did not interact with switching. This differs from the standard interaction observed between preparation and switch costs, namely a reduction of switch costs with longer CSIs, at least when cuing is assessed in this manner. This lack of a behavioral interaction between preparation and switching may account for the lack of switch specific preparation activity in Brass and von Cramon (2002

In a following study, Brass and von Cramon (2004) also attempted to separate cue-switching from task-switching by employing their so-called “double cue” design with a 4:2 mapping between cues and tasks. As suggested by the name, within each trial, participants would receive an initial cue, followed by a 700 ms interval, then a second cue (which could be the same cue, a different cue but indicating the same task or a different cue indicating the other task) followed by a variable (60 or 700 ms) CTI and finally the target stimulus. These three different second cue types, cue repetition, cue-switch and meaning switch thus correspond to the no-switch, cue-switch and task-switch definitions of Mayr and Kliegl (2003). Stimuli consisted of digits and the tasks were to determine either the magnitude or the parity of the presented number. Additionally, Brass and von Cramon (2004) used single-cue "catch trials" on a proportion of trials, that consisted only of a the first cue and target, but otherwise were like other trial types, in order to "ensure" that participants made use of the first cue in a set. Behavioral results revealed somewhat small, but reliable effects for cue-switching, ~70 ms, and task-switching, ~ 60 ms, at the short CTI. For the imaging analyses, they chose to combine across the CTIs, as their previous study (Brass and von Cramon, 2002) failed to find a switch by CTI interaction. No cue-switch related activity was found in prefrontal cortex, although with a lower threshold they did observe premotor, inferior temporal gyrus and fusiform gyrus areas. Analysis of their task-switch contrast revealed a strong area of activity in an area they earlier termed the inferior frontal junction (IFJ), named because of it's proximity to both the precentral and inferior frontal sulci (Brass & von Cramon, 2002) in the left hemisphere. Additionally, right inferior frontal gyrus (IFG) and right IPS showed task-switch related activity.

In a combined neuroimaging and computational study, Badre and Wagner (2006) attempted to delineate task reconfiguration and interference models of task-switching. Using an explicit cuing paradigm with letter/number stimuli and a variable CSI, Badre and Wagner (2006) found a network of cortical areas similar to those previously reported in lateral PFC (including several distinct regions within in VLPFC), SMA and inferior and superior parietal cortices. A simple connectionist model of task-switching was also constructed and model estimates were compared to regions found from the neuroimaging portion of their study. Their computation model, entitled CAM-TS (control of associative memory during task-switching), contained three simple hierarchical levels: a task level, conceptual (the two concepts within each task, e.g. "odd" and "even") and a response level. Learning within this model occurred via the strengthening of connections between layers that were mutually activated across trials. Theoretically, this is similar to the Logan (e.g. Logan, 2002) conceptualization of learning as discrete "event-files". The negative result of such a learning system is the presence of conflict resulting from the activation of the irrelevant task via associative priming of shared "set" components or features, such as a response key. A critical aspect of their model is a control-like component that biases processing from the task to the concept layers during preparation intervals before task-switches. Results from this model differentiated conflict arising from conceptual level, which was reduced with preparation, from response level interference, which tended to increase with preparation (time/cycles). Critically, Badre and Wagner (2006) showed that these interference effects seen in the model parallel results observed from two regions in the fMRI results. Specifically, a region in what they termed mid-VLPFC showed a decrease in signal change with increasing preparation time (longer CSIs), which closely follows the decrease in activation levels of the conceptual layer of the model with increasing cycles. However, a region in inferior parietal lobe follows the opposite pattern. Activity (percent signal change) in this region actually increased with longer CSIs; the response level layer from the model follows a similar increase with increasing cycles. The author relate this activity in mid-VLPFC to studies of LTM retrieval (semantic and episodic) which have shown similar regions of activity and claim this neural region is involved in essentially the same computations in both task-switching and LTM retrieval situations—the resolution of proactive interference.

The posterior parietal area, they argue, based on previous literature and the trend suggesting a role in response conflict, may be involved in the lower-level processing of conflicting response options.

Slagter et al. (2006) also attempted to disentangle reconfiguration from purely cue-related processing explanations of preparatory effects on switching. By examining the neural response to conditions in which only the cue was presented, the authors argue they were able to isolate processes involved solely in preparation since no target stimulus processing would contaminate the neural response observed in these cases. Tasks involved determining the orientation of either a centrally presented rectangle, based on its color, or based on its spatial location given a unique cue (e.g. "attend left") presented 1500 ms before target onset. Trial conditions thus consisted of cue-repeat, switch-within dimension (e.g. attend left to attend right) and switch-across dimensions (e.g. attend left to attend center). It should be noted that such a paradigm is probably more accurately deemed a cued "attention-shifting" paradigm, rather than the “standard” cued task-switching method largely considered thus far. While previous studies have examined cue-only neural responses, and thus presumably preparatory processing, most of these failed to find regions uniquely involved in switching tasks during preparation (e.g. Luks et al., 2002; Brass and Von Cramon, 2002). Slagter et al. (2006) hoped to differentiate from these studies by also examining so-called "global" aspects of switching, such as the number of features, dimensions and task sets participants were required to switch between. As such, they manipulated the trial types present in a given block such that "repeat blocks" consisted only of cue-repeat trials, "single-switch" blocks containing only cue-repeat and switch-within trials and "mixed blocks" contained all three trial types.

Regions in bilateral motor planning areas (SMA and premotor), bilateral posterior parietal areas (IPS and precuneus) as well as one region in the right fusiform gyrus showed switch related (switch-within greater than cue-repeat) activity to cues presented alone. Further, this difference between switch-within and repeat trials was modulated by block type, as it was smaller in the mixed compared to single-dimension blocks. Moreover, Slagter et al. (2006) showed this effect resulted from an increase in repeat trials across repeat-only, single-dimension and mixed-dimension block types. The authors interpreted this effect as consistent with the claim that changes in "global task" aspects can affect performance in switching situations (as demonstrated by Mayr & Kliegl, 2003). Slagter et al. (2006) offer a number of possible explanations of mechanistic changes in processing that these global differences might elicit. One such explanation is akin to claims that participants adopt a change in strategy when presented with a high percentage of switch trials (Mayr, 2006; Monsell and Mizon, 2006). Overall switch rates in the mixed-block of Slagter et al. (2006) were 75% (50% switch-across and 25% switch-within trials). Recall this strategy hypothesis claims that when confronted with such a high rate of task alternation, participants may simply abandon the just-completed task-set and prepare for a switch in tasks on a majority of trials. While this should be advantageous when an actual switch in tasks occurs, in the case of a task-repeat trial, participants now have to reengage (i.e. reconfigure) this abandoned task set, leading to an inflation of processing resources to repeat trials in these situations. The increase in signal activity on repeat trials across block types seen by Slagter et al. (2006) is highly consistent with this claim as block types increased in not only their "complexity" but also on the percentage of switch trials present in each one (from 0% to 50% to 75% in repeat to single to mixed block types, respectively). Further, they made the claim that the high number of task sets required to switch between in previous studies may account for the previous failures to find switch specific preparatory effects (e.g. Brass and von Cramon, 2002, Luks et al, 2002; Shulman et al, 2002, Ruge et al., 2005).

In yet another studying attempting to isolate components of switching using fMRI, Barber and Carter (2005) attempted not only to separate cue-related from target-related neural processing during task-switching, but also to delineate switch-specific processing from another control process—resolving conflict from prepotent versus non-preponent stimuli. They used a stimulus-response compatibility task, in which participants make responses to simple stimuli (the letters "l" or "r", standing for "left" and "right", respectively) with either compatible left and right responses on a keyboard, or with incompatible (i.e. “non-prepotent") responses (e.g. right keyboard response to the "l" stimulus) based on a cue presented 7.5 seconds before stimulus presentation. The authors found mostly non-overlapping areas for the preparation period: bilateral DLPFC, anterior cingulate and a left anterior frontal areas during preparation for an upcoming non-prepotent, compared to prepotent, stimulus, but only one region involved in preparing for a task-switch, in the medial precuneus (SPL). However, a region in left lateral precuneus (-25 77 43) was activated during the response phase in both the prepotency and switch conditions. Non-overlapping areas during the stimulus phase included medial prefrontal and bilateral premotor areas for prepotency and a right VLPFC and a left inferior parietal lobule (IPL) for switching.

In summary, neuroimaging studies of task-switching have consistently activated a left fronto-parietal network. While early studies did not always find switch specific activity, subsequent studies have isolated regions showing greater activity on switch compared to repetition trials. These switch specific regions tend to occur in the same left dominated network, particularly, in left ventrolateral PFC, lateral premotor and superior parietal regions. Somewhat less consistently, but still oft observed, activations have also been reported in medial frontal regions, such as the anterior cingulate cortex and ventromedial PFC. Early attempts at isolating preparatory components of switching were also met with mixed results, as some studies did not find regions showing a greater response on switch versus repeat trials during preparatory intervals. Even among the early studies that found switch specific preparation activity, this activity did not always include frontal regions. These results have thus been used to argue *against* the idea that control processes are required during switching. However, the failure to find either switch specific or switch specific preparatory activity may have been due to task design (namely very long CSIs) and/or fMRI methodology limitations. Several recent studies employing advanced, rapid event-related fMRI designs have in fact successfully isolated components of task-switching, including PFC regions during preparation.

CHAPTER III

DISSOCIATING CUE-SWITCHING FROM TASK-SWITCHING USING NEUROIMAGING

At this point, we have presented two equally viable models that account for the observed effects in the explicit task-cuing procedure: reconfiguration or retrieval (e.g. Mayr & Kliegl, 2003; Monsell and Mizon, 2006) and cue priming or interference accounts (e.g. Logan & Bundesen, 2003; 2004; Schneider & Logan, 2005; 2006, Arrington & Logan, 2004). Given the implications these disparate results imply for models of task-switching, we attempted to clarify this discrepancy. Specifically, we implemented a fMRI study using the basic 4:2 cue-to-task mapping paradigm originated by Mayr and Kliegl (2003). The two-stage, memory based account of Mayr and Kliegl (2003) and the alternative, "control less" account proposed by Logan and Bundesen (2003) make unique predictions for the patterns of neural activation expected when comparing cue-switch versus task-switch effects. A simple prediction of the two-stage account, for example, is that we should observe separable networks of activation for the task-switch effect compared to the cue-switch effect. Moreover, if the “retrieval” stage truly reflects LTM retrieval of task rules, one would predict neural areas of activation broadly consistent with those found in previous neuroimaging studies of LTM retrieval, such as medial temporal lobes and prefrontal cortex (predominantly left PFC). Similarly, we would predict the “application” stage to activate primarily superior parietal areas in reflection of the attentional changes needed to implement the given task rule once a stimulus is present.

Conversely, the Logen and Bundesen (2003) account would predict very little activation for the task-switch contrast, given the interpretation that no real “task-switching” occurs. This account would also predict a very similar activation pattern between the cue-switch contrast and the neural areas of activation seen in previous research, given they propose that cues are critical in disambiguating the retrieval path to the correct set of response options and their observed behavioral pattern of large effects for cue-switching, but non-significant task-switch effects (Logan & Bundensen, 2003). Moreover, given the priming model of switching posits a single mechanism, such an account would predict a *high* degree of overlap between anatomical regions involved in cue-switching and task-switching. The Logan and Bundensen (2003) model might predict similar regions of activity for cue and task-switching, but that cue-switch and no-switch conditions would show lower activity in these regions, reflecting episodic and semantic priming.

We were interested not only in examining neural networks involved in cue versus task-switching, but also to see if we would observe the areas broadly consistent with those seen in previous fMRI studies of task switching given our rapid, event-related design with a more "realistic" pace between stimuli and that produced switch costs on par with behavioral studies. Many of the earlier studies on task-switching have used extremely long inter-trial intervals on the order of tens of seconds and may compromise or dilute the kind of task switching effects seen in behavioral studies.

Experiment 1

Methods

Participants

Participants were 20 right-handed, native English speakers with normal or corrected to normal vision. The mean age of participants was 24 years old (range of 19-28 years old). Informed consent was obtained in a manner approved by the University of Oregon Institutional Review Board. Participants were compensated monetarily for taking part in the study.

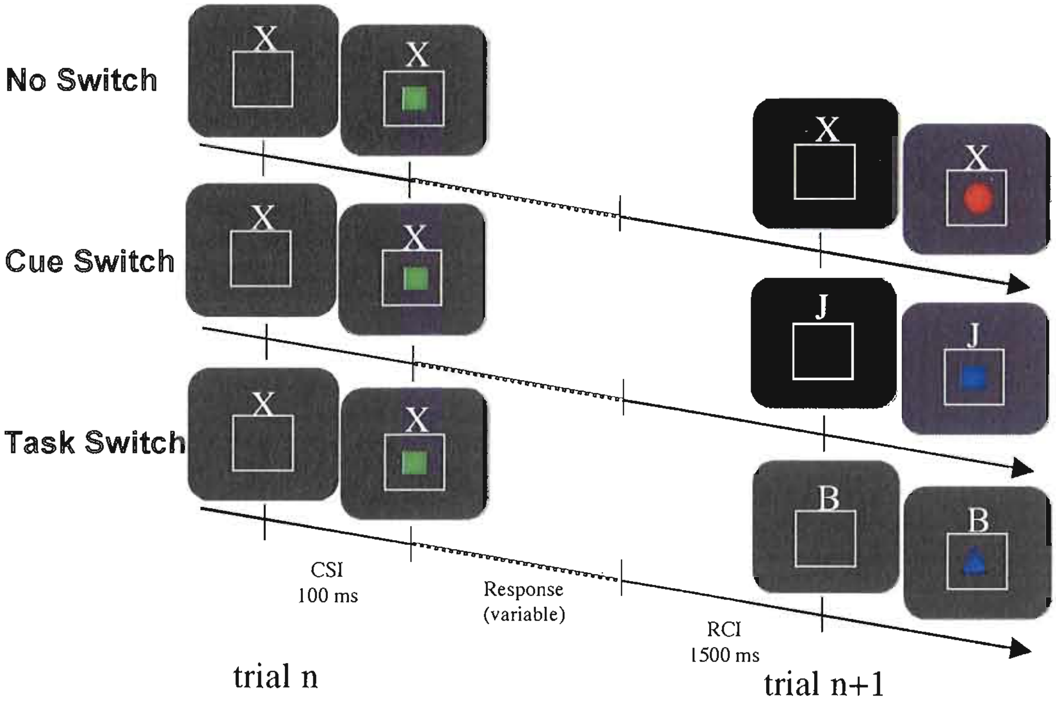
Presentation

The current study employed a random-cuing task-switching design (e.g. Meiran, 1996). This task-switching design required participants to respond to two choice reaction time tasks, responding either to the color (red, green or blue) or the shape (circle, square or triangle) of a stimulus. Stimuli consisted of the nine different permutations of the color/shape combinations possible (e.g. a green triangle).

The visual display on each trial consisted of a centrally located white box against a black background with the colored shapes appearing in the center of the box. Each task was preceded by a single letter cue presented above the box which indicated which of the two tasks was to be performed on the current trial. A 4:2 mapping between letter cues and tasks was used, such that two different letter cues were used to cue each task (Mayr and Kliegl, 2003; Logan and Bundeson, 2003). The letters 'J' and 'X' indicated the color task, while the letters 'B' or 'W' indicated the shape task. See Figure 1.

This allows for the analysis of three main trial types, as discussed above and in Mayr and Kliegl (2003), no-switch, cue-switch and task-switch. A no-switch trial thus is defined as a trial in which the same letter cue is repeated. A cue-switch trials indicates a different cue than the previous trial was presented, but which indicates the same task to be performed on the current trial. A task-switch trial then is one in which both the cue and task change from the previous trial.

Figure 1. Task Design for Experiment 1. Three-choice color discrimination (red, green, blue) and shape discrimination (circle, square, triangle) tasks were used and responses were made with three buttons on a hand-held button box. A 4:2 cues to task design was used, such that each task was cued by two separate letters. The color tasks was cued by the letters 'J' and 'X' while the shape task was cued by the letters 'B' or 'W.' The cue-to-stimulus (CSI) and response-to-cue (RCI) intervals were held constant at 100 and 1500 milliseconds, respectively. Examples of each of the three switch-type conditions of interests (no-switch, cue-switch and task-switch) are shown as illustrated in the trial n+1 panel, as determined by the respective cue and task type from the preceding trial n panel.



Responses were made with a hand-held response box with the left, middle or ring finger of the right hand. The left key was mapped to the “red” or “circle” response, the middle key to the “green” or “square” response and the right key mapped to the “blue” or “triangle” response. This resulted then in a third of the stimuli presented as affording a congruent response (the correct response key would be correct for either task).

Stimuli were presenting using Matlab and Psychophysics Toolbox software (Brainard, 1997) on an Apple Macintosh G4 computer. Stimuli were projected onto a screen at the head end of the bore of the scanner and viewed the screen via a mirror attached to the head coil.

Unlike Mayr and Kliegl (2003), both types of cue-switch transition were allowed per task (i.e. both ‘J’ to ‘X’ and a ‘X’ to ‘J’), however the sequence was generated such that there were equal probabilities of a no-switch (NS), cue-switch (CS) and task-switch (TS) condition type throughout the experiment. The design also implemented a restriction of no more than three switch trials in a row and did not allow for response repetitions (i.e. a trial in which the correct response key was repeated from the previous trial). Response repetitions have been shown to have differing effects for no-switch compared to switch trials (e.g. Rogers and Monsell, 1995). Although examination of these response repetition effects can be informative (e.g. Mayr and Kliegl, 2003), in order to simplify the design and analysis, we choose to avoid this factor for the current experiment.

We employed a rapid event-related fMRI design with the following timing parameters. The letter cue onset was followed by a 100 ms cue-to-stimulus interval (CSI). Time between subsequent trials (cues) was self-paced, such that it was determined by participants' variable response time on each trial, with a time-out maximum of 3,000 ms. This variation helps maximize reconstruction of the hemodynamic response function (HRF) for each condition and participant (Friston, Zarahn, Josephs, Henson, & Dale, 1999). However, to minimize potential "carryover" of the previous task-set, a consistent response-to-cue interval (RCI) of 1500 ms followed each response. To further introduce variability in the average inter-trial interval in hopes of better estimating HRF, 20% of trials were "null" events, such that no cue was presented and instead a white cross ('X') was presented for 3100 msec through the display box. These intervening null events allow for an attenuation of the combined HRF effects of closely spaced trials. Participants were instructed that no task or response was required on these trials but that they should try to maintain their "focus" throughout these trials in order to be prepared for the next trial. Trials following null trials and the first trial in a block were excluded from the analysis, as they are not definable as one of the three critical trial types (NS, CS, TS) given there is not a immediately preceding trial in these cases.

Each participant also partook in a pre-scanning, behavioral practice session in order to familiarize them with the cue-task associations, response mappings and the general procedure of the experiment. The pre-test session consisted of four blocks of single-task trials (two blocks per task) and six mixed-task blocks; all blocks consisted of 48 trials.

Procedure

Participants were tested in eight separate runs; there were a total of 826 trials. Equal numbers of the three critical transition types were presented. Anatomical scans were taken halfway through the experiment (i.e. after run 4).

fMRI Data Acquisition

Imaging data was collected on a 3.0 Tesla Siemens Allegra scanner (Siemens Magnetom Vision, Erlangen, Germany), with standard head-coil, at the Lewis Center for NeuroImaging (LCNI), University of Oregon. Anatomical images were acquired using a MP-RAGE T1-weighted sequence of 167 slices (whole brain) with a thickness of 1 mm (0 gap). Functional data was collected in a whole brain, echo-planar imaging (EPI) sequence consisting of 32 axial slices (slice thickness = 4 mm, 0 gap, TR = 2000 ms, TE = 30 ms, flip angle = 80°, matrix size = 64 x 64, FOV = 200 mm). Thus, each resultant voxel was 3.125 mm x 3.125 mm x 4 mm.

Data analysis was performed using Brain Voyager software (Brain Innovation, Maastricht, Netherlands). Images from each run were first subjected to slice-time and 3-D motion correction and then filtered at a high-pass frequency of 3 cycles per run and linear trends were removed. A 4 mm spatial Gaussian smoothing kernel (FWHM) was then applied to the images. Images were tranformed into Talairach space (Talairach, 1988) and re-sampled into 3 mm isotropic voxels; functional images were then co-registered using one of the middle runs (fourth or fifth).

Analysis Strategy

Our main goal was to determine whether the two putatively independent processes of cue-switching and task-switching could be separated on a neural as well as behavioral level. We employed the following analytical strategy to address this, as well as additional questions. First, each whole-brain individual participant's data was combined and the group data was then submitted to a random-effects, General Linear Model multiple regression analysis. Crossing the task (2) by compatibility (2) by switch type (3) factors resulted in 12 unique predictors. These predictors were convolved to the standard basis set of hemodynamic response functions as used in the BrainVoyager software.

Three critical contrasts were then performed on the group data involving the switch-type factor: 1) the "overall switch" contrast, task-switch versus no-switch trials (TS-NS), 2) the "cue-switch" contrast, cue-switch versus no-switch trials (CS-NS) and 3) the "true task-switch" contrast, task-switch versus cue-switch trials (TS-CS). This contrast will also be referred to simply as the "task-switch" contrast, but it should be noted this is different than the standard switch contrast, TS-NS, used in most task-switching studies. The alpha level for all three contrasts was set to $p < .002$, uncorrected, with a clustering extent threshold of 40 contiguous voxels (1,563 mm^3). The first contrast is intended to create a broad overview of switch-related activity and allows for a comparison of areas found in our study for consistency with previously reported areas of general switch activity. The cue-switch contrast is intended to isolate areas involved in the hypothesized "retrieval" stage (reflecting LTM retrieval and/or rule selection or updating processes). The "true" task-switch contrast is intended to isolate those regions respond uniquely to an actual change in task-set, which might reflect processes involved in switching between attentional dimensions, switching between response options, or resolving conflict on the response level.

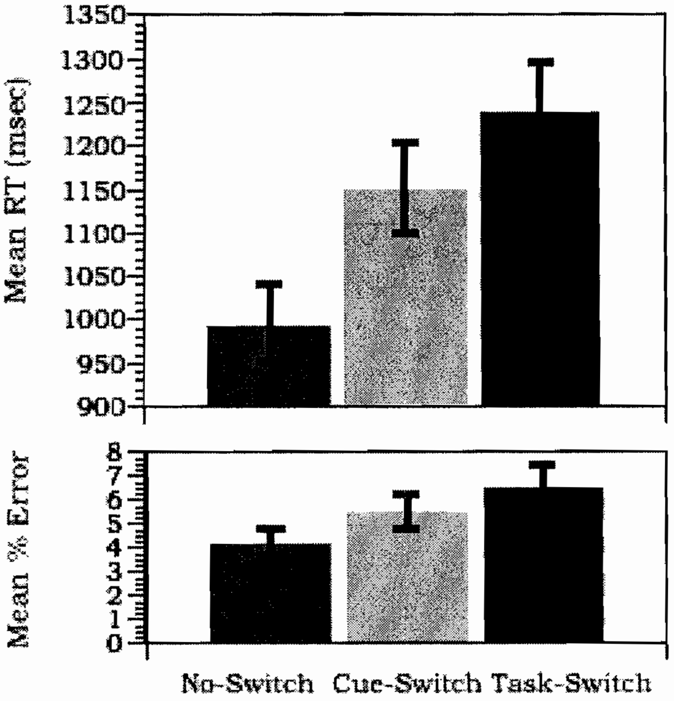
Next, regions of interest (ROI) will be determined based on the results of the cue-switch and task-switch contrasts from the whole-brain analysis. Regions selected will be any that show non-overlapping activity between these two contrasts and that also lie within, or very near, regions also activated in the overall switch contrast. The rationale for this latter constraint that it is possible that a cluster might be activated in the overall analysis that does not reflect switching related processing. For example, an area might respond greater on cue-switch than no-switch trials, but is not also activated more strongly for task-switch compared to no-switch trials and as such is probably not related to switching processes per se.

Event-related averages will be constructed by taking the MR activity from these selected ROIs for the three critical switch-type conditions and averaged over each run, participant and voxel from the selected cluster, from six seconds before to 16 seconds after stimulus (cue) onset. Visual inspection and statistical tests of these event-related averages will serve as confirmatory evidence that the switch-type conditions can be separated in these areas and give us a better indication of the exact neural response of each of these conditions within these regions. Statistical t-tests were conducted on the average percent signal change from a time window of 5-7 seconds (one seconds before and after the average hemodynamic peak) after cue onset comparing cue-switch with no-switch activity (i.e. CS contrast) and comparing task-switch with cue-switch activity (i.e. TS contrast). Correlations between this average MR percent signal change in these areas for these two contrasts and behavioral data was also analyzed.

Behavioral Results

Average reaction times (RT) and percent error scores served as the dependent variables of interest for the behavioral anlaysis. The task transition (switch) type was defined post-hoc based on the preceding trial: no-switch trials repeated both the cue and task type, cue-switch trials repeated the task, but not the cue and "true" task-switch trials, repeated neither the cue nor the task. We first analyzed both the RT and error data with three-way ANOVAs, testing transition type (no-switch, cue-switch, task-switch) by task (color, shape) by congruency (incongruent, congruent). Figure 2 shows the average reaction time (RT) and percent error scores for the three transition types. As expected, we found no-switch trials were the fastest (M = 996 ms, SD = 203 ms), cue-switch trials were intermediate (M = 1153 ms, SD = 232) and task-switch trials the slowest (M = 1241 ms, SD = 241 ms). The accuracy data followed the same general pattern with the fewest errors seen in no-switch trials (M = 3.73 %, SD = 4.61 %), cue-switch trials intermediate (M = 5.16 %, SD = 5.24 %) and task-switch trials incurred the most errors on average (M = 5.48 %, SD = 5.88 %). The main effect of transition type proved highly reliable, both in the RT data, F(2, 38) = 79.24, $\underline{p} < .001$ and

Figure 2. Behavioral Results from Experiment 1. Results shown as a function of transition type. Mean Reaction Times (RTs) are seen in the top panel, mean percent error scores in the bottom panel. Error bars represent standard error scores within each condition.



in the error data, F(2,38) = 4.70, p < .05. Also as expected, the overall congruency effect, incongruent minus congruent trials, was highly reliable in both the RT data (mean difference = 69 ms, SD = 44 ms; F(1,19) = 49.17, p < .001) and the accuracy data (mean difference = 4.33%, SD = 3.51%; F(1,19) = 30.44, p < .001). The color and shape tasks appeared to be similarly difficult as average response times for color trials (M = 1116 ms, SD = 231 ms) were highly similar to shape trials (M = 1124 ms, SD = 219); F(1,19) = .10, p >.10; although color trials elicited slightly less errors (M = 4.44%, SD = 5.00 %) than shape trials ($M = 5.13$ %, $SD = 5.59$ %), this was not a significant difference, $F(1,19) = 1.90$, $p > .10$. Congruency effects interacted with task type, as the congruency effect for shape trials were larger ($M = 109$ ms, $SD = 73$ ms; $M = 5.38$ %, $SD = 4.45$ %) than the congruency effect for color trials ($M = 29$ ms, $SD = 57$; 3.28 %, $SD = 3.87$ %) in the RT and error data: $F(1,19) = 13.84$, $p < .01$ and $F(1,9) = 4.35$ $p = .05$, respectively. Interestingly, the congruency by switch effect was seen in the error data, $F(2,38) = 5.46$, $p < .01$), but not in the RT data, $F(2,38) = .36$, $p > .10$.

In order to examine the effects of interest of transition type, we followed the procedure of Mayr and Kliegl and performed two non-orthogonal contrasts on the data: 1) the cue-switch contrast comparing cue-switch to no-switch trials and 2) the "true" task-switch effect, comparing task-switch trials to cue-switch trials. A large cue-switch effect was seen in RTs ($M = 157$ ms, $SD = 84$ ms) and errors ($M = 1.44$ %, $SD = 2.25$ %), confirmed by the main effect of transition type in the cue-switch contrast for RTs, $F(1,19) = 72.18$, $p < .001$ and errors, $F(1,19) = 8.13$, $p < .05$. A highly reliable congruency effect was again seen (across no-switch and cue-switch trials): $F(1,19) = 30.14$, $p < .001$ and $F(1,19) = 19.33$, $p < .001$, for the RT and accuracy data, respectively. However, the congruency effect was not modulated by the cue-switch contrast in either the RT data, $F(1,19) = .97$, $p > .10$ or the accuracy data, $F(1,19) = .66$, $p > .10$.

A smaller, but highly reliable, task-switch effect was also seen in the RT data, M = 88 ms, SD = 69 ms F(1,19) = 32.09, p <.001. However, the accuracy data failed to show a reliable task-switch effect, F(1,19) = .19, p > .10. Main effects of congruency were again seen when limited to the task-switch effect, F(1,19) = 38.25, p < .001 and F(1,19) = 23.46, p < .001, for RT and accuracy data, respectively. The predicted switch by congruency interaction did prove reliable for the task-switch contrast in the accuracy data, F(1,19) = 9.37, p <.01, but not in the RT data, F(1,19) = .22, p > .10.

Neuroimaging Results: Whole Brain Contrasts

Overall Switch

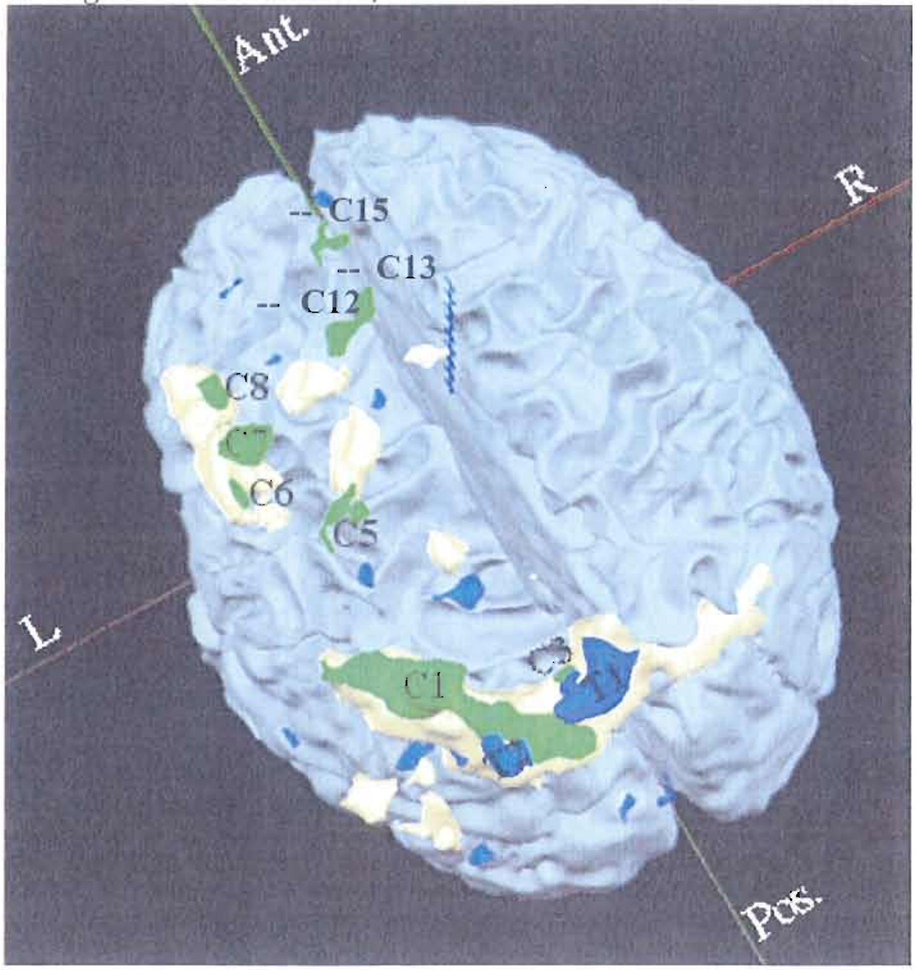
The overall-switch contrast is intended to create a broad overview of switch-related activity. This contrast serves then to compare areas found in our study for consistency with previously reported areas generally involved in switching. Whole-brain analysis was performed comparing task-switch predictors against the no-switch predictors. In general, as seen in previous studies, large areas of primarily left superior parietal lobe (SPL; precuneus, BA 7) and prefrontal cortex (BA 9 & BA 46) were highly activate. Other regions of strong activity were seen in left hemisphere motor-related areas (BA 4 & BA 6) (FEF), visual areas in bilateral fusiform gyrus, posterior cingulate (BA 31) and sub-cortical regions in the midbrain (substantia nigra) and cerebellum. For a complete list of regions, see Table 1. Figure 3 offers a visual display of the frontal and parietal regions activated in the overall switch contrast and Figure 4 shows some of the inferior and cerebellar regions (overall-switch regions shown in tan).

The SPL area of activation encompassed a massive region of voxels including left lateral SPL, a large medial portion and extended somewhat into right SPL. The lateral extent of this region included large swaths of intra-parietal suclus (IPS) as well. The large left frontal region of activity was observed mostly on the Middle Frontal Gyrus (MFG) in prefrontal cortex, although it also included significant portions within premotor and motor cortices anterior on the precentral gyrus.

Table 1. Regions of Activation for the Overall-Switch Contrast. Overall-Switch Contrast = task-switch versus no-switch conditions. MFG = Middle Frontal Gyrus. SFG = Superior Frontal Gyrus. Ant. = Anterior. Pos = Posterior. BA = Brodmann Area.

Label	Area of Peak Activation	BA	Extent (mm^3)	Talairach x	Talairach y	Talairach z
	Parietal Lobe Regions					
A.	L/M/R Superior Parietal Lobule (SPL)	7	645,703	-19	-65	41
B.	M SPL Precuneus	31	11,172	0	-68	22
	Frontal Lobe Regions					
C.	L MFG - Lateral PFC	9/46	122,813	-45	17	30
D.	L MFG - pos. Premotor	6	28,164	-27	-8	61
E.	L MFG - ant. Premotor	6	17,930	-27	11	55
F.	L MFG - inf/lat Premotor	6	4,453	-44	1	48
G.	M SFG - medial Premotor	6	2,539	-2	6	51
H.	L Motor - Precentral Gyrus	4	2,266	-45	-7	45
I.	L Inferior Frontal Gyrus (IFG)	9	1,680	-43	-3	24
	Inferior Regions					
J.	L Fusiform Gyrus	37	8,281	-50	-55	-16
K.	L Fusiform Gyrus	37	3,242	-38	-56	-13
L.	M Occipital Lobe (Lingual Gyrus)	19	2,852	2	-58	0
	Sub-Cortical Regions					
M.	Midbrain - Substantia Nigra		9,336	-12	-19	-5
N.	L Cerebellum - Pos. Lobe (Declive)		18,477	-40	-66	-19
O.	R Cerebellum - Pos. Lobe (Declive)		16,641	36	-68	-22
P.	M Cerebellum - Ant. Lobe (Nodule)		7,461	1	-50	-30
Q.	R Cerebellum - Pos. Lobe (Uvula)		2,695	28	-78	-24
R.	R Cerebellum - Pos. Lobe (Tonsil)		1,836	40	-59	-31

Figure 3. 3D Rendering of Brain Activations from Experiment 1. Portions of the activations from the Overall Switch (TS-NS; shown in tan), Cue Switch (CS-NS; shown in green) and the Task Switch contrast (TS-CS; shown in blue) are plotted in 3D space. Regions represent group data from the whole-brain analyses projected on a surface rendering of Talairach space from one participant, with a transparent view of the left hemisphere. Labels correspond to Cue Switch and Task Switch clusters identified in Table 2 and Table 3, respectively. L = Left , R = Right. Ant. = Anterior, Pos. = Posterior.



Cue-Switch Contrast

We then turned our attention to separating cue changes from task changes. The cue-switch contrast, again, compared cue-switch (CS) predictors to no-switch (NS) predictors. Table 2 lists the regions, including the Talairach coordinates from the center of peak activation, significantly activated above our threshold for the cue-switch contrast. Cue-switch regions are identified by label, starting with the letter "C" (for cue-switch contrast) in Table 2. The major left frontal and parietal regions are also seen in Figure 3 (in green).

The largest region of activity was again found in left superior parietal lobule (precuneus, BA 7; C1) with a extent of 130,391 mm^3, although this region was more left lateralized than in the overall switch contrast. A separate, much smaller region was seen more medially in left SPL (C3) as well as small region in right SPL (C2). Two left frontal, motor related regions were observed, one appearing in motor cortex proper (BA 4; C5) and one more anterior region presumably in premotor cortext (BA 6; C6). Two large left prefrontal regions along MFG were also activated: a more anterior and ventral region in BA 46 (C8), hereafter also labeled VLPFC, and a more posterior and slightly dorsal region in BA 9 (C7), hereafter also referred to as Inferior Frontal Junction (IFJ), after Brass and von Cramon (2002). Two regions were found along the cingulate gyrus, one, smaller region, along the anterior cingulate (BA 24; C9) and another in posterior cingulate cortext (BA 31; C4). Further analysis of these regions indicated they were uniquely involved in cue-switch related processing (i.e. cue-switch activity was greater than no-switch activity, but task-switch activity was not greater than no-switch activity). One other small anterior region, was activated near the left insula (BA 13; C10). The only inferior regions showing significant activation was seen in the right anterior lobe of the cerebellum, near the culmen (C11).

Additionally, several regions showed "deactivations" such that no-switch activity was greater than cue-switch activity in these clusters. Two of these regions were along the dorsal extent of anterior cingulate cortex (BA 24; –C12 and –C13), one in right middle frontal gyrus (BA8, –C14) and one in medial frontal gyrus (BA 9; –C15). Examination of event-related averages revealed a similar pattern in all of these regions: decreases in all three switch conditions below baseline, followed by the quicker rise of no-switch conditions, in relation to cue-switch and task-switch conditions, back to and above baseline. All regions showed a significant effect of no-switch greater than cue-switch trials, but none showed a significant difference between cue-switch and task-switch trials.

Table 2. Regions of Activation for the Cue-Switch Contrast. Cue-Switch Contrast = Cue-switch versus No-switch conditions. BA = Brodmann Area. Labels indicate the position of the region (if visible) in Figure 2. Labels preceded with a "-" sign indicate those areas that showed greater no-switch than cue-switch activity Areas in italics indicate areas that underwent further investigation in Region of Interest analyses; event-related averages for these regions are shown in Figure 3.

				Talairach		
Label	Area of Peak Activation	BA	Extent (mm^3)	x	y	z
	Posterior Regions					
C1	*L Superior Parietal Lobe (Precuneus)*	7	130,391	-33	-59	43
C2	R Superior Parietal Lobe (Precuneus)	7	2,188	8	-71	41
C3	L Superior Parietal Lobe (Precuneus)	7	1,758	-11	-65	45
C4	R cingulate	31	13,438	25	-46	22
	Anterior Regions					
C5	*L Motor*	4	4,297	-36	-16	60
C6	*L Premotor*	6	2,422	-49	1	45
C7	*L Middle Frontal Gyrus (IFJ)*	9	8,398	-41	12	30
C8	*L Middle Frontal Gyrus (VLPFC)*	45/46	4,727	-40	27	22
C9	R cingulate	24	2,539	14	0	39
C10	L Insula	13	2,031	-27	-10	24
	Inferior Regions					
C11	R Cerebellum - Ant. Lobe (Culmen)		1,797	17	-45	-15
	Deactivations (ns > cs)					
-C12	dorsal Anterior Cingulate Cortex	24	7,695	-7	30	-2
-C13	dorsal Anterior Cingulate Cortex	24	6,094	-2	31	8
-C14	R Superior Frontal Gyrus	8	2,656	15	38	41
-C15	L Medial Frontal Gyrus	9	2,227	-3	45	15

Task-Switch Contrast

As with the behavioral data, we also looked for regions that responded more during task-switch compared to cue-switch trials, i.e. regions showing a "true" task-switch effect. Table 3 lists regions found above threshold for this contrast and the two largest regions can be seen in Figure 3 (in blue). These two regions were again seen in superior parietal lobule, however with one occurring medially (T1) and more or less non-overlapping with the large left lateral region seen in the cue-

Table 3. Regions of Activation for the Task-Switch Contrast. Task-Switch Contrast = task-switch versus cue-switch conditions. BA = Brodmann Area. Label indicates the position of the region (if visible) in Figure 2. Areas in italics indicate areas that underwent further investigation in a Region of Interest analysis; event-related averages for these regions are shown in Figure 4.

				Talairach		
Label	Area of Peak Activation	BA	Extent (mm^3)	x	y	z
	Parietal Lobe Regions					
T1	*M Superior Parietal Lobe (Precuneus)*	7	43,516	-6	-70	44
T2	*L Lateral Superior Parietal (Precuneus)*	19	9,375	-29	-72	37
	Inferior Regions					
T3	R Fusiform Gyrus	18	2,617	19	-79	-16
T4	M occipital (Cuneus)	18	1,914	-2	-92	20
	Sub-Cortical Regions					
T5	R Cerebellum - Ant. Lobe (Culmen)		4,297	40	-49	-22
T6	L Cerebellum - Pos. Lobe (Tonsil)		2,305	-36	-47	-33
T7	*M Cerebellum - Ant. Lobe (Nodule)*		2,148	-1	-50	-29
T8	L Cerebellum - Pos. Lobe (Tuber)		1,836	-35	-73	-27

switch contrast (C1). The other superior parietal area found in the task-switch contrast (T2), occurs more laterally, just posterior to the large SPL/IPS region (C1) seen in the cue-switch contrast.

In addition to the posterior parietal regions, two regions in occipital cortex showed significant activation levels: a region along the right fusiform gyrus and a medial region within the cuneus. Several sub-cortical regions were also observed within the cerebellum. These included a left, medial and right region all approximately the same position along the superior-inferior (z axis) and anterior-posterior (y axis) planes (T6, T7 and T5 in Table 3, respectively). One additional cerebellar region was seen more caudally in the posterior lobe (Tuber) of the cerebellum. These regions, except for the medial occipital (T4) can be seen in Figure 4.

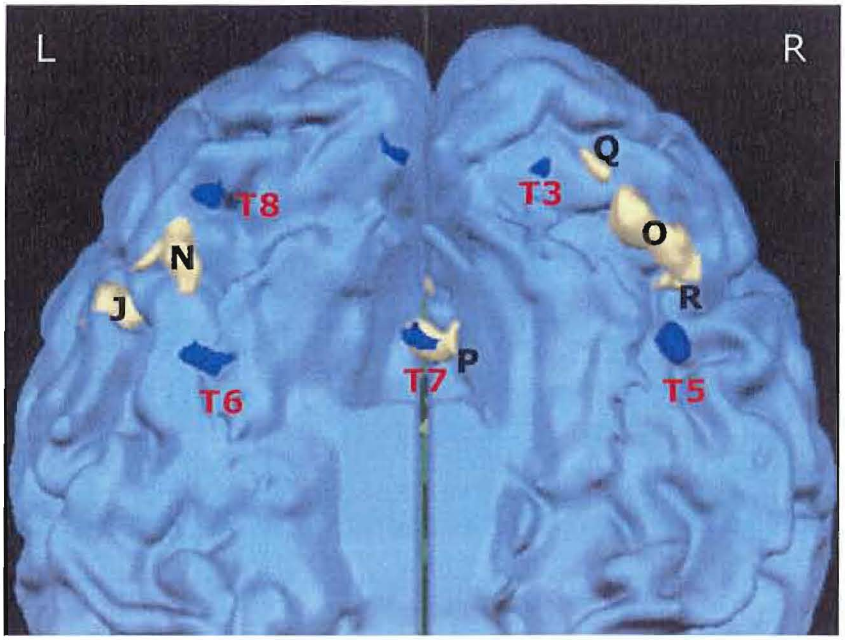


Figure 4. 3D Rendering of Inferior and Posterior Regions of Activation for Experiment 1. Overall switch contrast (TS-NS) is shown in tan; Task-Switch contrast (TS-CS) is shown in blue. Group activations are projected on a 3D cortical surface rendering from one participant transformed into Talairach space (cerebellum not shown). Refer to Tables 1 and 3, respectively, for coordinates of the Overall-Switch and Task-Switch regions shown.

Neuroimaging Results: Region of Interest Analyses

Cue-Switch Regions

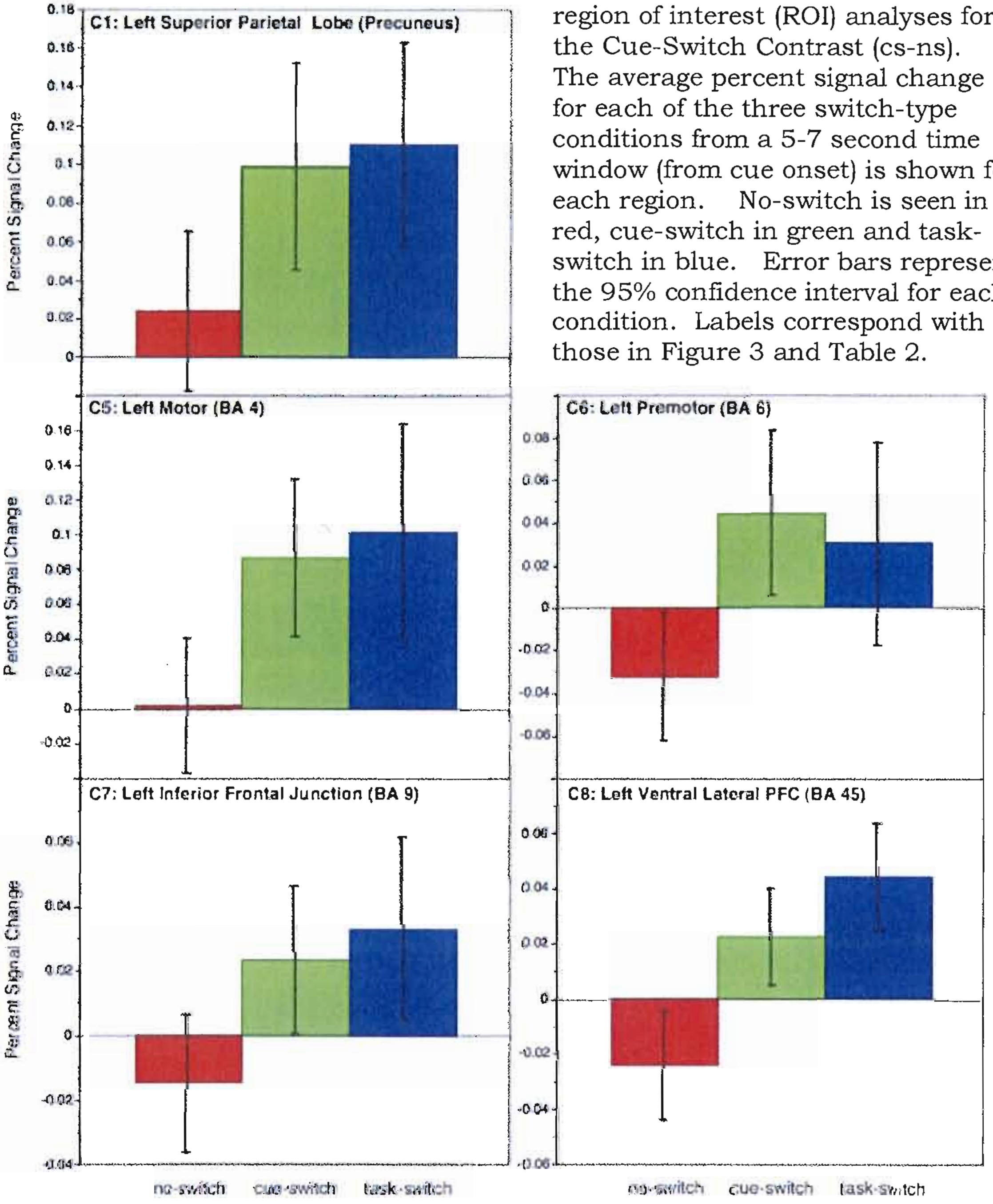
The whole brain contrast analysis gives us a good overview of the regions significantly activated during task-switching in general, as well as allow us to specify regions of interests from the cue-switch and task-switch contrasts. However, as our primary goal remains to separate putative cue-switching from task-switching processes, we need to take a deeper look at the activity patterns present in these regions. While the whole brain contrasts help us narrow down specific areas of interest, it does not necessarily inform us if these regions are truly involved in cue-switching or true task-switching —at least in terms of how we have defined cue-switch related processing. That is, can we find areas that are activated strongly during *both* task-switch and cue-switch conditions compared to no-switch conditions? The cue-switch analysis, for example, will generate areas of activation that respond higher to cue-switch than no-switch conditions, but the overall pattern could theoretically occur in a more graded response; in other words, task-switch might also be greater than cue-switch conditions in these regions (TS > CS > NS). While this pattern would of course still be of interest, it would not necessarily fit our strict "retrieval" prediction of cue-switching. Cue-switch processing, as we have hypothesized, would produce regions that respond roughly equal to both cue-switch and task-switch conditions, since in either is a change in retrieval pathway, but with little to no no-switch activity.

A constraint employed for determining a region for further ROI analysis was that it lay within, or very near, areas activated in the overall switch contrast. If two components of task-switching are truly separable, then we should be able to find cue-switch processing areas within the areas activated by the overall switch contrast. The areas used from the cue-switch contrast are listed in italics in Table 2 and the event-related averages from these regions can be seen in Figure 5. The average percent signal change from the specified time window (5-7 seconds post cue-onset) from each of these regions was also subjected to the cue-switch and task-switch contrasts and is reported for each of these regions below.

We found responses of the following regions consistent with our predicted cue-switch response in several of the ROIs taken from the whole-brain cue-switch contrast. The large left superior parietal region (C1), showed a large difference between CS and NS, $t(19) = 3.11$, $p = .006$, but no difference between TS and CS, $t(19) = .76$, $p > .10$. A similar pattern was seen in the two left precentral gyrus regions: motor cortex (C5) and premotor (C6) both showed strong CS greater than NS effects, $t(19) = 3.09$, $p < .01$ and $t(19) = 2.81$, $p < .05$, but no difference between TS and CS, $t(19) = .62$, $p > .10$ and $t(19) = -.44$, $p > .10$, respectively. The left posterior VLPFC region, i.e. IFJ (C7), area also showed the predicted cue-switch response, with CS activity much larger than NS, $t(19) = 3.12$, $p < .01$ but TS statistically equal to CS activity, $t(19) = .83$, $p > .10$. The other left, more anterior, VLPFC region (C8) also showed a large CS versus NS effect, $t(19) = 4.11$, $p < .01$, but a more graded response overall as the TS minus CS difference just missed significance, $t(19) =$

2.09, $p = .05$. Although not shown in Figure 5, we also examined the event-related averages from the two smaller superior parietal regions. The more medial left SPL region (C3) actually showed neither a cue-switch, $t(19) = 1.78$, $p = .09$ nor a task-switch effect, $t(19) = 1.63$, $p = .12$ for the specified time window examined, while the right SPL region (C2) showed a more graded response, with both CS greater than NS, $t(19) = 2.12$, $p < .05$ and TS greater than CS, $t(19) = 2.90$, $p < .01$, activity.

Figure 5. Event-Related Averages from the Cue-Switch Contrast. Select region of interest (ROI) analyses for the Cue-Switch Contrast (cs-ns). The average percent signal change for each of the three switch-type conditions from a 5-7 second time window (from cue onset) is shown for each region. No-switch is seen in red, cue-switch in green and task-switch in blue. Error bars represent the 95% confidence interval for each condition. Labels correspond with those in Figure 3 and Table 2.

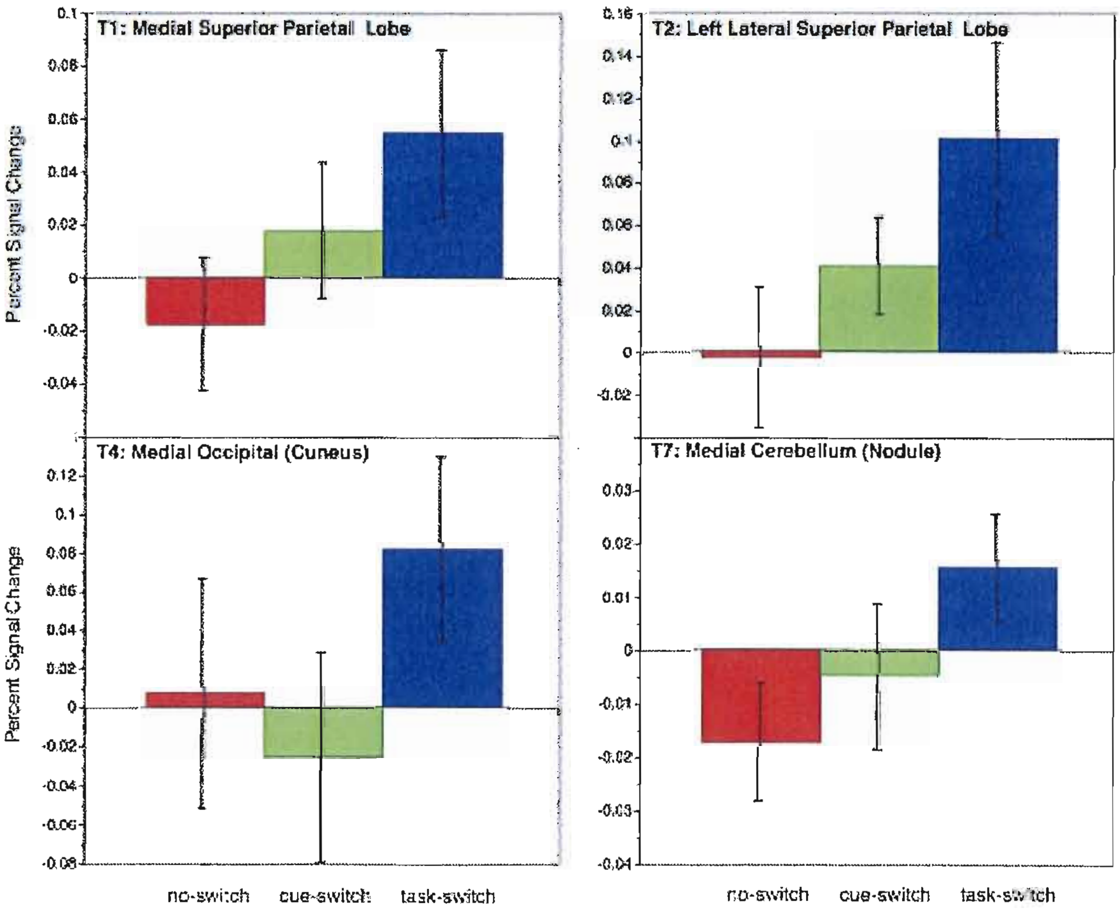


Task-Switch Regions

Event-related averages and corresponding correlational analyses with the behavioral task-switch effects (TS-NS) were also calculated. According to our predictions, areas showing "true" task-switching effects would be those that show a high activity for TS conditions and low activity for both CS and NS conditions, with no significant difference between CS and NS. Regions activated from the whole-brain task-switch contrast that also fell within areas activated by the overall task contrast can be seen in italics in Table 3. The event-related averages from these three regions can be seen in Figure 6.

The largest of these regions was the medial SPL cluster (T1), which showed the predicted "true" task-switch effect of a large difference between TS and CS, t(19) = 3.21, p < .01, but no significant difference between CS and NS, t(19) = 2.00, p > .05. Another medial posterior region, the medial occipital cuneus (T4) also showed the predicted pattern with TS much greater than CS, t(19) = 3.01, p < .01 but no difference between CS and NS, t(19) = -.81, p > .10. Of the several cerebellar regions activated from the whole brain task-switch contrast, only one fell within a region also activated from the overall switch contrast, an areas within the medial portion of the anterior lobe of the nodule of the cerebellum (T7); see Figure 3. This sub-cortical regions showed a strong TS greater than CS effect, t(19) = 3.21, p < .01, but no difference between CS and NS, t(19) = .057, p > .10. The other left, laterally located SPL region (T2), however, showed a graded response as the contrast between TS and CS was highly significant, t(19) = 3.40, p < .01 as was the CS versus NS contrast, t(19) = 2.40, p < .05.

Figure 6. Event-Related Averages from the Task-Switch Contrast. Select region of interest (ROI) analyses for the Task-Switch Contrast (ts-cs). The average percent signal change for each of the three switch-type conditions from a 5-7 second time window (from cue onset) is shown for each region. No-switch is seen in red, cue-switch in green and task-switch in blue. Error bars represent the 95% confidence interval for each condition. Labels correspond with those in Figure 3 and Table 3.



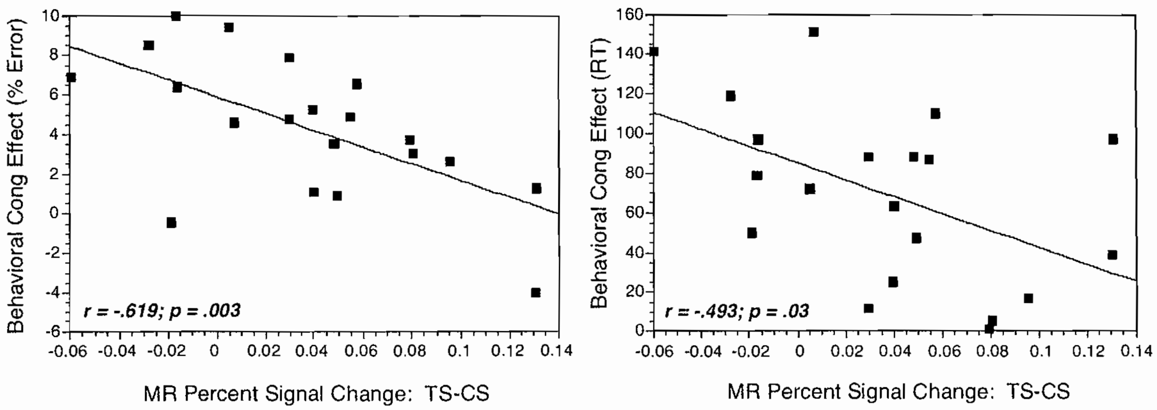
Behavioral and Neurophysiological Correlations

For all the ROIs areas, we also performed several correlational analyses of the MR percent signal change data from each region with behavioral measures of performance. While we first looked at potential correlations between behavioral cue-switch and task-switch effects (both RT and Percent Error scores) and MR cue-switch and task-switch differences, respectively, no significant correlations were seen in any of these regions. However, given that "true" task-switch areas were proposed to be involved specifically with an "application" stage given stimulus onset, we hypothesized that these areas might be particular sensitive to congruency effects. Congruency effects, recall, have been suggested to be tied directly to the residual component of task-switching, and might reflect interference from the automatic activation of the now irrelevant (i.e previous) task set. We performed correlational analyses then between the behavioral measures of the congruency effect (i.e. incongruent minus congruent conditions) for both RT and Percent Error scores with the MR percent signal change difference between TS and CS (task-switch effect) from the “true” task-switch regions of interest defined above.

Moderate to strong correlations were seen in three of these regions, as can be seen in Figure 7. The medial SPL region (T1) showed significant negative correlations between both the behavioral accuracy and behavioral RT congruency effects with the task-switch minus cue-switch (TS effect) percent signal change difference, Pearson's correlation coefficient r = -.619, p = .003 and r = -.493, p =.03, respectively. The medial occipital (cuneus, T4) showed a similar negative correlation between behavioral accuracy congruency effects and the MR task-switch effects, Pearson's r = -.603, p = .005. Likewise, the medial nodule cerebellum region (T7) also showed a significant negative correlation between the behavioral percent error congruency effect and the TS-CS percent signal change from this region, Pearson's r = -.451, p < .05.

To ensure this was not simply a general phenomenon with congruency, we also looked for significant correlations in the cue-switch ROIs, between the MR CS-NS difference and the RT and accuracy congruency effects. No significant correlations were seen and Pearson's r coefficients were all below .30.

T1: Medial Superior Parietal Lobe



T4: Medial Occipital Lobe (Cuneus)

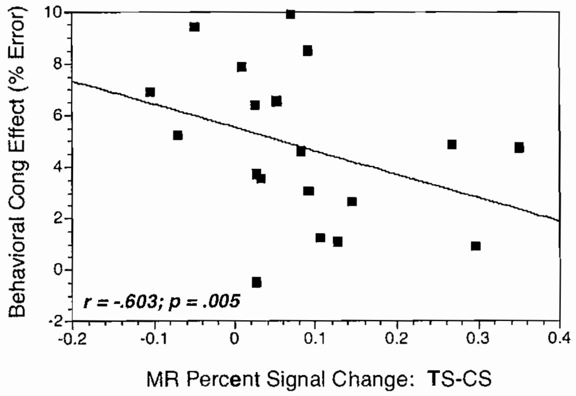
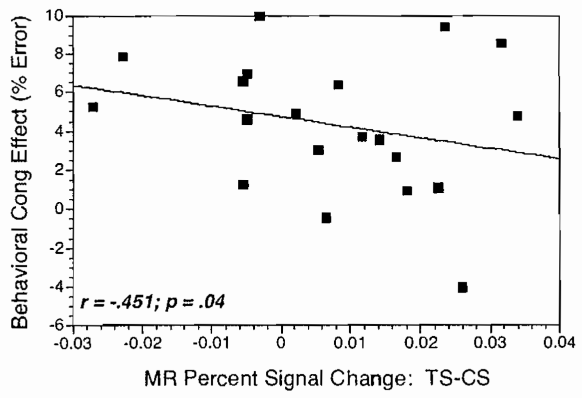


Figure 7. Behavioral Congruency Effect and MR Task-Switch Contrast Correlations. Correlations between the percent signal change difference between task-switch and cue-switch (i.e. Task-Switch Contrast) conditions and behavioral measures of the congruency effect (incongruent – congruent trials) for regions T1 (top), T4 (middle) and T7 (bottom). Pearson's correlation coefficients and p-values are shown within each graph in italics. The behavioral measures reported here are accuracy (Percent Error) and Reaction Time (RT).

T7: Medial Cerebellum (Nodule)



Discussion

We attempted to achieve four main objectives with this experiment: 1) replicate primary areas seen in previous studies of task-switching 2) find areas involved preferentially in "true" task-switching 3) determine whether areas involved in “true” task-switching overlap with areas involved in cue-switching and 4) determine the degree to which these results support the two-stage ("retrieval" and "application") theory of task-switching put forth by Mayr and Kliegl (2003).

The first goal we attempted to answer with this study was the degree to which neural areas implicated in previous imaging experiments on task-switching would also be seen with the novel 4:2 cues to task mapping. Replication of the same basic brain networks seen in earlier studies of task-switching might, on one hand, seem a safe prediction. However, any possible number of differences could arise from the introduction of two cues per task that could significantly alter the observed brain response. For example, a greater working memory load might be required by participants to successfully maneuver in the more complex task structure our design presents. The results from the overall switch contrast (TS-NS) allow us to address how well we were able to replicate previously observed regions implicated in task-switching; again, this contrast is the “standard” measure of switching used and the most appropriate then for answering this question. Our overall switch contrast did in fact yield results in line with many of the previous neuroimaging studies of switching: chiefly in left superior parietal lobe, left premotor and motor cortices and left prefrontal cortex. Successful replication of the neural loci involved in switching with the 4:2 cues-to-task paradigm is critical for several reasons. For one, we have now established that the same general neural areas are involved in the standard cuing switching paradigm and the 4:2 cues-to-task version. These areas then are presumably involved in similar computational processes in both paradigms.

Summarizing the results from the cue-switch contrast, we found activated regions primarily within the left fronto-parietal network observed in previous switching studies. The most prominent of these regions was a very large, robust region in left lateral SPL (C1). Additional areas activating in cue-switching were a number of frontal regions, including motor (C5) and premotor (C6), probably lying within the frontal eye fields (FEFs), and two large lateral prefrontal regions (C7 & C8). All of these regions, except for the anterior VLPFC (C8) region, demonstrated the predicted pattern of large responses from cue-switch and task-switch trials, while little to no response in no-switch trials. This more or less equal response of cue-switch and task-switch trials (again, except arguably the anterior VLPFC region) suggests these cortical areas are involved in similar processing requirements during both cue-switch and task-switch trials. Computations that may be common with a change in cue and a change in task likely include, but are not limited to: retrieval of task rules (S-R associations) or goals from LTM, loading and/or maintaining these goals/rules in working memory, encoding and interpretation of the cues and preparing appropriating motor plans based on these S-R associations. Theoretically, this pattern of results is consistent with a contribution of these regions to the conceptual first-stage (retrieval/preparation) of task-switching. The finding of this left frontal-parietal network as seen in previous studies in our cue-switch contrast suggests previous studies of task-switching, which also activated this network, were in fact activating this "retrieval/reconfiguration" component of switching. Those studies that did not find frontal areas specific to switching used long intervals between the cue and target, thereby presumably allowing ample time for preparation and thereby potentially nullify detection of any preparation related neural components.

We also observed several smaller regions, primarily in anterior and posterior cingulate gyrus, involved preferentially in cue-switching. That is, cue-switch activity was larger than no-switch *and* task-switch activity. While the cue-switch signal change in these areas was not particularly large, it is an intriguing effect. These regions clearly do not fit the predicted "retrieval" component pattern of activity, since task-switch responses are not also elicited. While highly speculative, one possible explanation of this activity is that it represents a sort of "conflict response" due to a change in cue, but no change in task. In other words, these areas may be attempting to clarify the appropriate behavior (change or stay on the same task?) given a change in cue. This purposed function might be related to the purposed strategic changes hypothesized to occur in participants depending on the particular task parameters (like switching probability; e.g. Mayr, 2006). One way to test this idea then would be to observe whether fMRI activity in these regions is modulated by manipulations of switching probabilities. Additionally, if this activity represents a general "confusion" about the need to switch tasks or not given two cues per task, we might expect this activity to be greater during earlier portions versus later portions of the experiment, where task performance is more practiced.

We have also yet to address the number of "deactivation" (ns greater than cs) regions seen in the cue-switch contrast. Again, these regions, located in medial frontal regions, anterior cingulate cortex and medial PFC, showed sustained no-switch responses compared to cue-switch and task-switch. More specifically, the no-switch responses tended to drop below baseline along with cue and task-switch conditions early in their response function, but then showed a more rapid rise than the other conditions. One straightforward interpretation of this pattern, especially given the ACC and medial PFC loci of these regions, is that these regions monitor for task or rule repetitions and when detected, they cause a “reactivation” of the just used task rule, allowing for quick responses in the case of a task repetition. While these regions are likely not involved in the actual implementation of these rules, they may be responsible for signaling other task-specific regions that repeat of rule is allowed.

As predicted, we were able to find several regions involved preferentially in "true" task-switching. Most notably, medial and posterior regions in superior parietal (T1) and occipital (T4) cortices, as well as medial cerebellum (T7) were seen. Examination of the event-related averages within these areas revealed large responses to task-switch conditions, with little to no response from cue-switch or no-switch conditions. Finding such regions that respond solely to task-switching supports the notion that changing tasks requires unique processing that is not necessary when simply changing cues; this in turn also supports the idea of the existence of independent components comprising switching. Further, the medial parietal, medial occipital and cerebellar location of these regions is consistent with the putative "application" stage of switching. Although we have thus far remained mostly agnostic as to the type of computational processing this so-called applications stage of processing entails, we shall address this in more detail below. For now, it is important to note the establishment of unique, and more or less non-overlapping areas, for true task-switching. Although the number of regions found in the task-switch contrast were few, there is no a priori reason to believe that large or numerous areas of cortex need be involved in "true" task-switching, especially as theorized by Mayr and Kliegl (2003) as primarily responsible for application of task-rules to given stimuli. Although the other large left, lateral superior parietal region (T2) also showed a strong response to the task-switch contrast, deeper examination leaves us hesitant to also classify this as a "true" task-switching area, or an area preferentially involved in the "application" stage of switching. While the task-switch response was clearly the strongest from this region, the ROI analysis of this region revealed a more graded response with a robust response seen not only between task-switch and cue-switch trials, but also between cue-switch and no-switch trials.

Additional evidence that supports the idea these medial and posterior areas might be involved in stimulus specific processing, comes from the correlational results between behavioral congruency effects and task-switch contrast imaging effects from these regions. All three of these areas showed negative correlations between the congruency and task-switch variables, that is, greater MR signal change difference between TS and CS tended to result in smaller behavioral congruency effects in these participants. This suggests that these regions might be specifically involved in reducing conflict in incongruent conditions, presumably a process that can only be accomplished once the stimulus is present (i.e. without preparation). As aforementioned, congruency effects in switching situations may emergence from the relatively automatic activation of irrelevant stimulus-response associations. This is consistent then with the idea that these task-switch regions might be involved in low-level, stimulus or response based processing. These observed correlations with congruency were unique to these two "true" task-switching regions (medial SPL and nodule of the cerebellum) and not in any of the cue-switching regions, evidence consistent with the role of these areas in the "application" stage of switching.

Not only were we able to detect brain regions responsive to both cue-switching and task-switching, these regions activated by these two contrasts were found to be more or less non-overlapping. Cue-switching activated a primarily left frontal-left lateral SPL network, while the task-switch contrast produced mostly medial, posterior areas. In fact, an additional whole-brain conjunction analysis between the cue-switch and task-switch contrasts was performed to explore the question of neural overlap between these two theoretically distinct computational processes (i.e. CS-NS and TS-CS) and revealed only one region that survived the threshold – but not in parietal cortex or even the cerebellum, but in the left thalamus (Talairach coordinates: -21, 3, -2; extent = 4,297 mm^3).

However, one might still argue that the two largest regions from the cue-switch and task-switch contrast both occur in proximal SPL regions, C1 and T1, respectively. Given the proximity of these regions, one could argue, even if non-overlapping, these regions may be involved in similar computational demands and should not be considered independent of each other. Additionally, the second largest task-switch region (T2) is also seen in left lateral SPL and essentially abuts part of the large left lateral cue-switch (C1) area. While there is some merit to this argument, the results from the ROI analyses of these regions provides a strong argument for a functional independence of these areas (at least T1 compared to C1). Again, C1 shows a strong response for both cue-switch and task-switch conditions while T1shows a sole response for task-switch trials. Moreover, T1's strong correlation with behavioral congruency effects, while C1 lacks such a correlation, further suggest a functional difference between the two regions. However, the more lateral T2 region, which shows a pattern somewhere in between these two and physically sits between the two regions, may act as an intermediary between the two areas. It could be involved functionally in both preparation/retrieval and application components of switching, or it could be a communication conduit between parietal cue-switch and task-switch locations. In summary, the physical difference between cue-switch and task-switch regions, including a total lack of frontal areas involved in task-switching, combined with an apparent functional difference, provides evidence for independent components of task-switching. Again, this is not to say there are not some areas that may be involved in both processes (or sub-processes) or communicate between regions involved solely in one or the other component, but the evidence presented strongly argues against a completely overlapping system.

Contributions of These Regions to Switching

Before we address the final goal of the study, assessing the two-stage model of task-switching, we speculate on what computational processes might be occurring within each of the major regions found in our study during switching. This speculation is based primarily on previous neuroimaging studies that activated similar regions with relevant tasks. For example, the left lateral prefrontal regions (VLPFC), "C7" and "C8" observed in the cue-switch contrast are consistent with previous task-switching studies showing greater left VLPFC activity on switch versus no-switch trials (e.g. Dove et al, 2000; Dreher and Berman, 2002; Badre & Wagner, 2006). However, what computations might lateral PFC regions contribute, specifically, to task-switching performance?

Outside of the task-switching literature, lateral PFC regions have oft been implicated as critical to the maintenance and manipulation of information in working memory (Smith & Jonides, 1999; Curtis & D'Esposito, 2003). Manipulation of information within working memory might include processes such as: updating and or selecting the contents of WM, inhibition of previously relevant material in WM or sequencing different chunks in WM. We cannot make strong claims about whether or not any of these sub-processes of working memory manipulation are necessarily occurring in our task-switching paradigm. However, it follows theoretically that manipulation of material in working memory is a likely candidate for the type of computation occurring in lateral PFC during switching (or during cue-switch and task-switch trials in our case). This is a critical point, that this proposed manipulation of material within WM is unique to switch trials (in our case, a cue- or task-switch). This is opposed to any general WM processes, for example mere maintenance of information, which might occur during all trials types—as evidenced by the lack of a response for NS trials from these lateral PFC regions in our data. This result differs from some of the previous studies on task-switching which do not find switch specific frontal areas. Although, as previously mentioned, this failure to find frontal areas involved specifically in switching may be due to extended preparation times in these studies. Sufficient preparation time would allow participants to update necessary information (task-rules/goals/S-R associations) in working memory and presumably the frontal regions reflecting this process would not be seen in contrasts between switch and no-switch with long preparation intervals.

Further, a breadth of regions in left prefrontal regions have oft been attributed to other mnemonic functions, in particular, retrieval of task relevant information from LTM. As previously discussed, LTM retrieval has been argued to be a major determinant of switch costs (e.g. Mayr and Kliegl, 2000) and cue-switch costs have been argued to reflect this process (Mayr & Kliegl, 2003). Similar left VLPFC regions have been previously implicated in LTM retrieval studies (e.g. Ranganath, Johnson, D'Esposito, 1999). Left VLPFC seems particularly involved in the retrieval of semantic associations (Gabrieli, Poldrack, & Desmond, 1998; Fiez, 1997; Poldrack, Wagner, Prull, Desmond, Glover, & Gabrieli, 1999). More specifically, activity in left VLPFC regions has been show to be related to overcoming interference from competing representations in LTM retrieval tasks (Badre, Poldrack, Pare-Blagoev, Insler, & Wagner, 2005; Dobbins & Wagner, 2005), which may be restricted specifically to mid-VLPFC (Badre & Wagner, 2006), analogous to our more anterior VLPFC region ("C8").

The more posterior of our left PFC regions, ("C7"), lies within a region that has been activated in a number of previous task-switching studies and has been dubbed inferior frontal junction "IFJ", due to its anatomical location near the intersection of the precentral sulcus and the inferior frontal sulcus (Brass and von Cramon, 2002, 2004; Derrfuss, Brass, Neumann, & von Cramon, 2005). In the Brass and von Cramon studies (2002; 2004), this area was activated during the preparation of task rules and was correlated with behavioral cuing scores (Brass and von Cramon, 2002). Further, the IFJ showed up as a common cluster of activation in a meta-analysis of task-switching, set-shifting (such as in the Wisconsin Card Sorting Task; "WCST"), Stroop task and S-R reversal tasks (Derrfuss et al., 2005). Additionally, Brass and von Cramon (2004) argued that activation in this area is not related simply to encoding the cue. These combined results point to a critical role of the IJF in the updating of task representations (Brass and von Cramon, 2002; 2004, Derrfuss et al., 2005). This is also highly consistent with the argument made for a very similar left VLPFC region's role as retrieving and maintaining abstract rules (Bunge, Kahn, Wallis, Miller, &Wagner, 2003; Crone, Wendelken, Donohue, & Bunge, 2006).

All of these possibilities—working memory updating, rule representation, conflict resolution and LTM retrieval—fit our theorized notion of the cue-switch component's role during task selection. While we can not definitively exclude any of these possibilities, the results from the Badre and Wagner (2006) study shed some additional light on the source of switch costs and the utility of these lateral frontal regions during task-switching. Namely, their "mid-VLPFC" region, an area that uniquely showed a reduction in activity with increased CSI that mirrored activity from the "concept" layer of their model, lies in a corresponding location to the more anterior of our two left lateral PFC regions ("C8"). They also showed a large region of activity in an IFJ-like region, although activity here was not modulated by CSI. They argue then that left mid-VLPFC region exerts control in the context of task-switching by overcoming conflict from competing task-sets, consistent with perceived notions of left inferior PFC role in resolving proactive interference (see Jonides & Nee, 2006 for a review of PI in WM tasks).

The role of the large left lateral SPL/IPS area (C1) is less clear, but several possibilities exist. Intraparietal sulcus is commonly activated in studies investigating attention, both of the spatial and non-spatial variety (Wojciulik & Kanwisher, 1999; Kanwisher, & Wojciulik, 2000). Lateral superior parietal areas have also been implicated in stimulus-response (S-R) associations. Such activity has been suggested to involve the actual mapping of a stimulus onto a response (i.e., "response selection"); for example, Jiang and Kanwisher (2003) found the bilateral IPS (as well as frontal eye fields) to be a common site of response selection, across several paradigms and modalities. Although the exact locus of this parietal region may differ slightly depending on whether the task material is spatial or non-spatial, such posterior parietal regions are a common area activated in response selection manipulations (Schumacher, Elston, & D'Esposito, 2003; Bunge, Hazeltine, Scanlon, Rosen, & Gabrieli, 2002).

Regarding the "true" task-switch areas, the cerebellar activity may at first glance appear a bit puzzling. The function of the cerebellum in motor coordination is well known (Ito, 1984). More recent work, however, suggests cerebellar processing may not be limited strictly to motor control. The cerebellum has been implicated on a wide range of tasks, including, but not limited to: non-motor related associative learning (Drepper, Timmann, Kolb and Diener (1999), attention switching (Courchesne, et al., 1994; Wager, Jonides, Smith, & Nichols, 2005), conflict resolution (Schweizer, Oriet, Merian, Alexander, Cusimano, & Stuss, 2007) or other "executive" like processing, given its preferential connections with prefrontal cortex (Middelton and Strick, 2001). This putative role in attentional shifting is highly consistent with activation from our task-switch contrast, which presumably require shifts attention from one perceptual dimension and cerebellar activity has been linked specifically to switching between visual features in a study by Le, Pardo and Hu (1998).

However, as Bischoff-Grethe, Ivry and Grafton (2002) point out, such studies often confound the actual shift of attention with changes in S-R mappings. Using a procedure intended to disentangle attention shifting from these changes in S-R mapping, termed "response reassignment" by the authors, they in fact found bilateral cerebellum activity unique to the response reassignment conditions, but not to conditions solely involving shifting attention (Bischoff-Grethe et al., 2002). The Schweizer et al. (2007) study provides additional evidence that control functions of the cerebellum may be tied specifically to stimulus-response associations, possibly particularly in resolving conflict between competing S-R associations. They found that patients with localized cerebellar lesions demonstrated larger congruency effects compared to controls. Switching further modulated this effect, as congruency effects were larger for switch compared to repeat trials in the patient group, but not in the control group (Schweizer et al., 2007).[5] Moreover, this did not appear to be a general deficit in task difficulty in the patient group as no group differences were seen in overall switch costs. Given this result in conjunction with our correlational data relating the brain activity from the task-switch contrast to behavioral congruency effects, it seems likely that the cerebellum plays a significant function in resolving conflict between task sets and S-R associations.

Interpretation of the large medial SPL (T1) area's role in “true” task-switching parallels the interpretation of cerebellar activity. Medial posterior parietal regions have been implicated in both studies of

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[5] However this was true only in the error data as this contrast did not reach significance in the RT data.

attention shifting and response switching. For example, a highly homologous cluster to our observed "T1" area was seen in medial precuneus, extending into left IPS, during shifts of attention from one visual feature to another (Liu, Slotnick, Serences, & Yantis, 2003). Similar, albeit slightly superior and inferior, medial precuneus regions have also been implicated in shifts of spatial and object-based attention compared to maintenance of attentional focus, suggesting that medial SPL areas may be involved in *general* shifts of attention, independent of the exact type of attention employed (Serences, Liu, & Yantis, 2005). Consistent with this idea, Wager et al. (2005) looked for common areas of activation between "object" switching and "attribute" shifting within the context of a task-switching like paradigm. They argue that most studies of task-switching confound the switching of the locus of attention from one visual dimension to another (what they call "object" switching) with switching the operation to be performed, in other words changing the task rule (what they call "attribute" switching). One common areas of switching activity found in their study was within medial parietal lobe; additionally, this area was more strongly activated by "object" versus "attribute" switches (Wager et al., 2005).

However, as previously discussed, there lies the possibility that attention switching activity, as tested experimentally, may also reflect switching of motor responses. A fMRI study by Rushworth, Paus and

Sipila (2001) supports this idea that attention shifting and response shifting occur in dissociable areas within posterior parietal cortex. Clusters of activity occurred slightly more anteriorly and laterally in IPS for visual attention shifts compared to more medial and posterior areas involved in response switches. However, it should also be noted this was a between-subjects comparison and differences could have arisen solely on anatomical variability or normalization differences between participants. Also consistent with this idea of medial SPL function in response mappings, or reversal of previous S-R mappings, a meta-analysis of imaging studies involved in interference resolution found a peak cluster highly similar in location to our "T1" area (Nee, Wager, & Jonides, 2007).

Regarding the more posterior parietal cluster activated in the task-switch contrast (T2), it is difficult to make strong claims, based on previous literature, that processing in this parietal region is qualitatively different that the IPS region (C1) observed in the cue-switching contrast. However, it is possible that anterior and posterior regions of IPS contribute distinct processes during switching. Posterior IPS may be particularly critical for switching between perceptual dimensions, consistent with putative processing in the "application" stage of task-switching, which can only occur once the stimulus is presented. Le, Pardo and Hu (1998) found a region of posterior SPL, very similar to our observed posterior SPL (T2) area, when contrasting attention shifting from sustained attention.

Assessment of the Two-Component Model of Task-Switching

In summary, it should be noted that these regions, particularly posterior parietal and lateral prefrontal cortical areas have been activated in a multitude of neuroimaging studies. As such, a full assessment of the numerous cognitive, motor and affective tasks that have elicited activity in our ROIs is well beyond the scope of this discussion. However, our intention was to illustrate a number of relevant results that coincide with the likely contributions of these areas to task-switching. Further, this investigation of possible processing demands of each of these regions allow a qualitative assessment of the "model" of task-switching put forth by Mayr and Kliegl (2003). Namely, as aforementioned, they propose a two-component conceptualization of switching consisting of a "retrieval" stage and an "application" stage, with each mapping more or less onto the cue-switch and task-switch contrast, respectively.

Again, this first stage, thought to be reflected in the cue-switch contrast, potentially involves LTM retrieval, updating of task rules within working memory and overcoming interference from previous task-sets. The imaging results from the cue-switch contrast mesh well with Mayr and Kliegl's (2003) speculation, as the strongest and largest areas responding to this contrast were in left lateral PFC and left lateral superior parietal lobe, areas repeatedly observed in memory studies. Lateral PFC, particularly VLPFC, as observed in our study, have also oft been implicated in LTM retrieval studies as well as overcoming proactive interference—both consistent with reconfiguration. It is difficult to speculate much beyond this, although the results from the Badre and Wagner (2006) study suggest that mid-VLPFC might be uniquely involved in control processes needed to overcome interference. The more posterior PFC region (IFJ) likely is involved in the other major proposed process during reconfiguration of updating the currently relevant task goal or task rules. Retrieval and updating of task rules may occur even on no-switch trials and may explain why this region is sometimes also activated during preparation intervals for repeat trials. Presumably though, updating is a necessary process on switch trials, whereas on repeat trials it is only occasional recruited, in instances where the current task-set is lost (e.g. due to distraction). The lateral IPS/SPL activity seen in the cue-switch contrast is also consistent with working memory functions, but SPL activity is also sometimes observed in LTM retrieval tasks (Fletcher, Shallice, & Dolan, 1998).

The application stage, in contrast to the reconfiguration stage, was thought to involve those processes that can only be, as the name implies, "applied" once a target stimulus is perceptually presented (Mayr

& Kliegl, 2003). Again this conceptualization is highly consistent with the results from the task-switch contrast, as regions associated with non-spatial shifts of attention between visual features and/or between response options were observed. Given our bilvalent stimuli, presumably shifting attention from the formerly relevant to the currently relevant dimension (e.g. color to shape) is a necessary step for task-switch, but not cue-switch, trials. This might be particularly true of the posterior IPS region seen in the task-switch contrast. A related process presumably required for task-switch, but not cue-switch, trials is the resolving of interference present when a response is required to the current stimulus that is different (i.e. incongruent) than the response to this stimulus in a previous context (i.e. task-set). The process of decoupling a no longer relevant stimulus-response association and/or the activation of the currently relevant stimulus-response association is likely reflected in our medial posterior and cerebellar regions from the task-switch contrast. These areas presumably work to resolve these incongruencies, as larger differences in the percent signal change between task-switch and cue-switch resulted in lower behavioral congruency effects on average, as evidenced by the negative correlations reported in these medial regions. In summary then, our results provide strong support for the proposed retrieval and applications stages of task-switching.

While we favor an interpretation of the present results that supports the two-component account of cue-switching versus task-switching, it is by no means an indisputable conclusion. For example, while our cue-switch and task-switch contrasts are *mostly* non-overlapping, there are a number of areas in which these “separable” components are in close proximity. Namely, left lateral superior parietal area includes both cue-switch and task-switch swaths of activity. While even the fairly liberal threshold used in our analysis results in largely non-overlapping cue-switch and task-switch areas, lowering this threshold further obviously results in much larger regions of overlap. Moreover, there are a few regions showing graded responses between task-switch, cue-switch and no-switch (i.e. ts greater than cs, cs greater than ns). Specifically, the lateral posterior parietal area seen in the task-switch contrast (T2) shows such a pattern, as does the anterior VLPFC region (C8) seen in the cue-switch contrast. Although this VLPFC region does not show a statistical difference between task-switch and cue-switch, visual inspection of the responses here clearly follow a graded response.

These facets of the results, the graded responses and higher overlap with lower thresholds, could be argued as being incompatible with a two-component account. In fact, instead of characterizing this graded response pattern as showing task-switch *greater* than cue-switch, it may be more accurate to refer to the pattern as *reduced* cue-switch compared to task-switch activity. Such a characterization is thus more consistent with the associative priming model (e.g. Schneider and Logan, 2005).

However, before conceding to a singular priming account of our data, note that only two of all the ROIs we analyzed showed clear graded responses. Further, the whole-brain analyses, with the above caveats, still reveal a more or less non-overlapping cue-switch and task-switch pattern. Additionally, alternative interpretations to the priming account of these graded responses, particularly the VLPFC region, are possible. One such possibility we liken to the potential strategic computations that occur during switching, as postulated by Mayr (2006) and Monsell and Mizon (2006). Recall that Mayr (2006) presented evidence suggesting task-switches are particularly sensitive to the conditional probability of switching given a cue change. Relating this to our observed anterior VLPFC region, activity here may initially begin to ramp up with presentation of a new cue, in anticipation of a task-change, but relax once cue encoding processes, that indicate a change in task is not required, have completed. Further, an interpretation of this region as reflecting purely priming processes is inconsistent with Badre and Wagner's (2006) interpretation of activity in a highly similar region as reflecting control processes that resolve interference, based on their computational and neuroimaging results

Conclusion

Thus far we have addressed and provided support for the goals of this study as previously outlined. Namely, our observed left fronto-parietal network of activation is consistent with activity found during switching in neuroimaging studies using more "conventional" task-switching paradigms. This overlap provides construct validity that the 4:2 cues-to-tasks method is in fact assessing the same switching processes, in so far as this can be reflected by common neural regions of activity, as other task-switching paradigms. Additionally, consistent with behavioral differences between task-switches and cue-switches, we found regions (mostly medial posterior and cerebellar) that responded preferentially to "true" task-switching. This result supports the idea that task-switching, at least in the context of cuing designs, does not simply reduce to cue-switching; this in turn supports the idea that task-sets are a critical determinant of selection. Moreover, regions involved in true task-switching were delineated from regions involved in cue-switching. Qualitative examination of the likely type of cognitive processing occurring in each of these regions lends support for two-component models of task-switching (e.g. the "reconfiguration" and "application" stages proposed by Mayr & Kliegl, 2003). A recent event-related potential study by Jost, Mayr, and Rosler (2008) also closely parallels our results, as it also provides evidence of a neurophysiological dissociation between cue-switching and task-switching. Specifically, Jost et al. (2008) observed an early, cue-switch difference appearing relatively early (following cue onset) in anterior sites, while a later, task-switch difference was seen in more posterior sites. However, our results can not *conclusively* rule out priming accounts, or at least contributions from priming like mechanisms, or switching. However, the results are consistent with the idea that retrieval between task-sets is a necessary processing step during switching, an idea further considered in Chapter V.

CHAPTER IV

TASK SELECTION COST ASYMMETRY WITHOUT TASK-SWITCHING: EVIDENCE FOR ASSOCIATIVE RETRIEVAL MECHANISMS IN TASK-SWITCHING

Recall from Chapter I a particularly intriguing result from the task-switching literature, the so-called "switch cost asymmetry" effect. Again, this phenomenon, first described by Allport, Styles and Hsieh (1994), occurs when participants switch back and forth between two tasks differing in relative dominance, such as Stroop word naming versus color naming. In such situations, switching from the less dominant to the more dominant task takes longer than vice versa. In other words, it seems more difficult to establish an easy task than to establish a difficult task. The paradoxical nature of this effect makes it an important challenge for models of executive control.

So far, the dominant account of the switch cost asymmetry is in terms of trial-to-trial carryover of relative levels of activation for the dominant versus the non-dominant task within a connectionist type model (e.g., Gilbert & Shallice, 2002; Yeung & Monsell, 2003). We refer to this class of models as "carryover" accounts of task-switching. For example, in Gilbert and Shallice's computational model, selection between two tasks occurs through the relative activation of two "task demand nodes" that exert top-down control on lower level task-specific nodes. Dominant task pathways (e.g., Stroop word reading) are characterized by stronger associations than non-dominant task pathways (e.g., Stroop color naming). Thus, to select the dominant task, little additional activation of the corresponding task node (and little suppression of the non-dominant task node) is needed. According to Gilbert and Shallice (2002) the cost asymmetry then arises because:

> "... a larger value is added to the net input of the color task demand unit on color trials than is added to the net input of the word task demand unit on word trials. Thus, on switch trials, reconfiguration of the task demand units for the intended task is slower for the word-reading task than the color-naming task, hence the paradoxical asymmetry in switch costs" (p. 317).[6]

The carryover account is parsimonious and intuitively appealing. It basically reduces the problem of switching between tasks to a problem of a network requiring more time (on switch trials) or less time (on no-switch trials) before settling into a state that allows successful response

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[6] This is actually not a fully complete account for how the asymmetry arises in this model. The additional aspect to consider is that for the color task, but not for the word task, a relatively large task-demand input is required even on no-switch trials. Thus, there is a very large difference for word-demand units between no-switch and switch trials, whereas the relative difference for color demand units is much smaller.

selection. In fact, Gilbert and Shallice (2002) suggest that given the success of their model, assumptions about "extra" processes that might be relevant for task selection, but not for selecting between responses, are unnecessary.

As such, carryover accounts make a straightforward prediction. Given that the reason for the cost asymmetry lies in the carryover of activation between consecutive trials, task-switch transitions are a necessary condition for obtaining a cost asymmetry. In other words, carryover accounts could not explain cost asymmetries that occur in the absence of an actual switch in task.

However, cost asymmetries in the absence of switch transitions can also be explained by a class of models that differentiates between task maintenance in working memory (across no-switch transitions) and retrieval of task rules from LTM (usually, but not limited to switch transitions) as two distinct sets of processes (e.g., Allport & Wylie, 2000; Mayr & Kliegl, 2000, 2003; Hazy, Frank, & O'Reilly, 2006). According to such LTM-retrieval views of selection, asymmetric costs could arise from interference of LTM traces of previous selection instances whenever a task-set needs to be retrieved from LTM, even when this does not occur in the context of a task-switch transition. Further elaboration on how the cost asymmetry can arise as a result of LTM interference will be discussed in later sections. At this point the critical aspect is that by the

LTM view, switch transitions would be a sufficient, but not a necessary condition for obtaining a cost asymmetry.

Interestingly, it has been known for some time that substantial performance costs arise not only at switch transitions, but also when ongoing performance is interrupted by a short pause (Gopher, Armony, & Greenshpan, 2000). Furthermore, according to a thus far largely ignored result by Allport and Wylie (2000), such "restart" costs show similar asymmetries as actual switch costs. The authors explicitly interpreted this result as inconsistent with the idea that "persistent activation or inhibition of processing pathways" (p. 49) is responsible for switch costs and the cost asymmetry.

Experiments 2 and 3

Our goal was to replicate (Experiments 2 and 3) and expand (Experiments 4a and 4b) the findings by Allport and Wylie (2000). In Experiments 2 and 3, we used a variant of the alternating runs paradigm (Rogers & Monsell, 1995). We adapted this paradigm to create situations in which participants were likely to re-retrieve task sets from LTM even when the task did not change from the previous trial (see Figure 8 and the Methods section for detailed explanations).

Specifically, we speculated that with long delays between successive trials (i.e., the interval between the preceding trial response and the next stimulus; i.e. RSI) there should be a larger probability of losing the current task set from working memory than for short delays. Thus, we predicted a selection cost asymmetry not only after task-switch transitions, but also after long-RSI no-switch transitions. Note, that we expect that a long RSI increases the probability that re-retrieval of task sets is required on task-repetition trials, but this does not imply that retrieval never occurs after short RSIs. Thus, the critical prediction is that of a cost asymmetry for the task-repetition transitions, but it is less important that the cost asymmetry be reliably modulated by the short/long RSI factor. In Experiments 2 and 3 we used two different sets of tasks with established dominance relationships: stimulus-response compatible versus stimulus-response incompatible mappings (i.e., S-R Compatibility) and Stroop word naming versus Stroop color naming (i.e., Stroop task).

Methods

Participants

Thirty-six students of the University of Oregon participated in Experiment 2 (S-R Compatibility) in exchange for course credits or payment of $7; 30 students participated in Experiment 3 (Stroop).

General Design

We used an alternating runs paradigm in which participants selected between two different tasks in two runs of four trials (i.e. AAAABBBB). See Figure 8 for a schematic representation of how tasks were presented in Experiment 2 (note that only the boxes and the stimuli were actually shown to participants; task presentation in Experiment 3 was analogous). Stimuli were presented one at a time, rotating clockwise through the eight boxes displayed on the screen sequentially. The same-task runs were further broken down into pairs of two same task trials (i.e., AA-AA-BB-BB). This design allowed for two types of between-pair transitions: task-change transitions (i.e. AA-BB and BB-AA) and task-repetition transitions (i.e. AA-AA and BB-BB). The response to stimulus intervals (RSI) between two within-pair trials was very short (50 ms) and held constant. However, the RSI between pairs of trials varied randomly between short (500 ms) and long (5000 ms). With this design, we capitalize on the fact that participants have a strong tendency to group a sequence of tasks into smaller chunks (e.g., Lien & Ruthruff, 2004). Therefore, we expected then that participants would often need to re-retrieve the current task from LTM, even when the relevant task does not change. The measurement of "selection cost" we used then was the difference between the first and the second position within a pair, irrespective of transition type. We expected this need to re-retrieve the

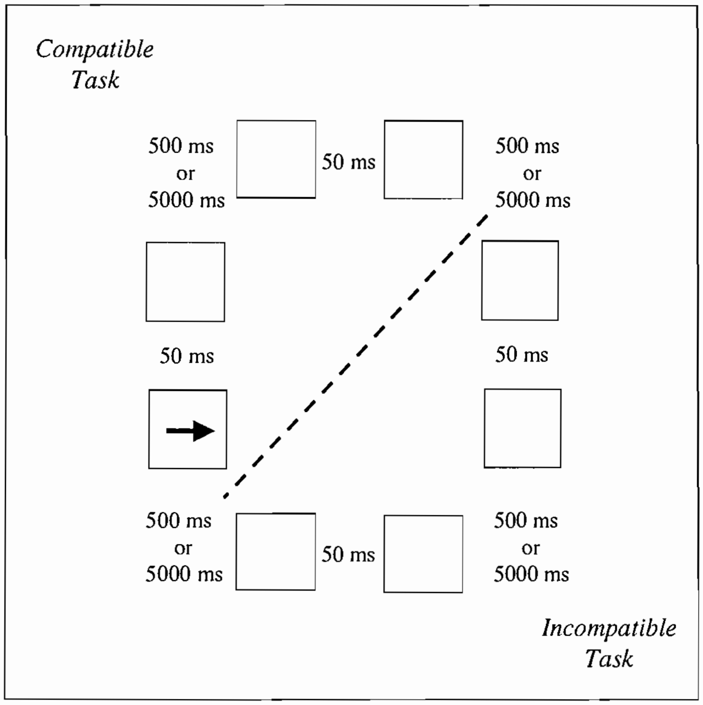


Figure 8. Task Design for Experiments 2 and 3. Stimuli were presented one at a time in one of the eight boxes, rotating clockwise through the AA-AA-BB-BB task sequence. Tasks were defined spatially, with the compatible task to be performed in the upper-left half of the display and the incompatible task in the lower-right half of the display; the dashed line represents the task boundary. Within-pair RSIs were short (50 ms), while RSIs between pairs of trials varied between short (500 ms) and long (5000 ms). These between-pair RSIs (shown at the corners in the figure) allowed for the different task transition types (task change and task repetition). The actual display shown to participants only included the task stimuli for a given trial and the eight boxes (i.e. it did not include the task cues, dashed line or RSI label). The design was identical for Experiment 3 except that within-pair RSIs were 500 ms (to accommodate for the vocal response method) and the stimuli presented in each box were Stroop color words, with the two tasks being word naming and color naming.

task to be particularly true for the long (5000 ms) RSI, given the higher probability of losing the relevant set from working memory after longer delays.

Stimuli, Tasks, and Procedure

Stimuli in Experiment 2 were two arrows, one pointing to the left and one pointing to the right. Responses were made with the left and right arrow keys of the keyboard. In the dominant task condition, participants responded in a compatible manner (i.e. left key for left arrows) and in the non-dominant task condition participants responded in an incompatible manner (i.e. left key for right arrows). Participants began with a block of 96 practice trials, alternating between the dominant and non-dominant tasks as described above. Participants then completed nine more blocks for a total of 864 trials (excluding practice).

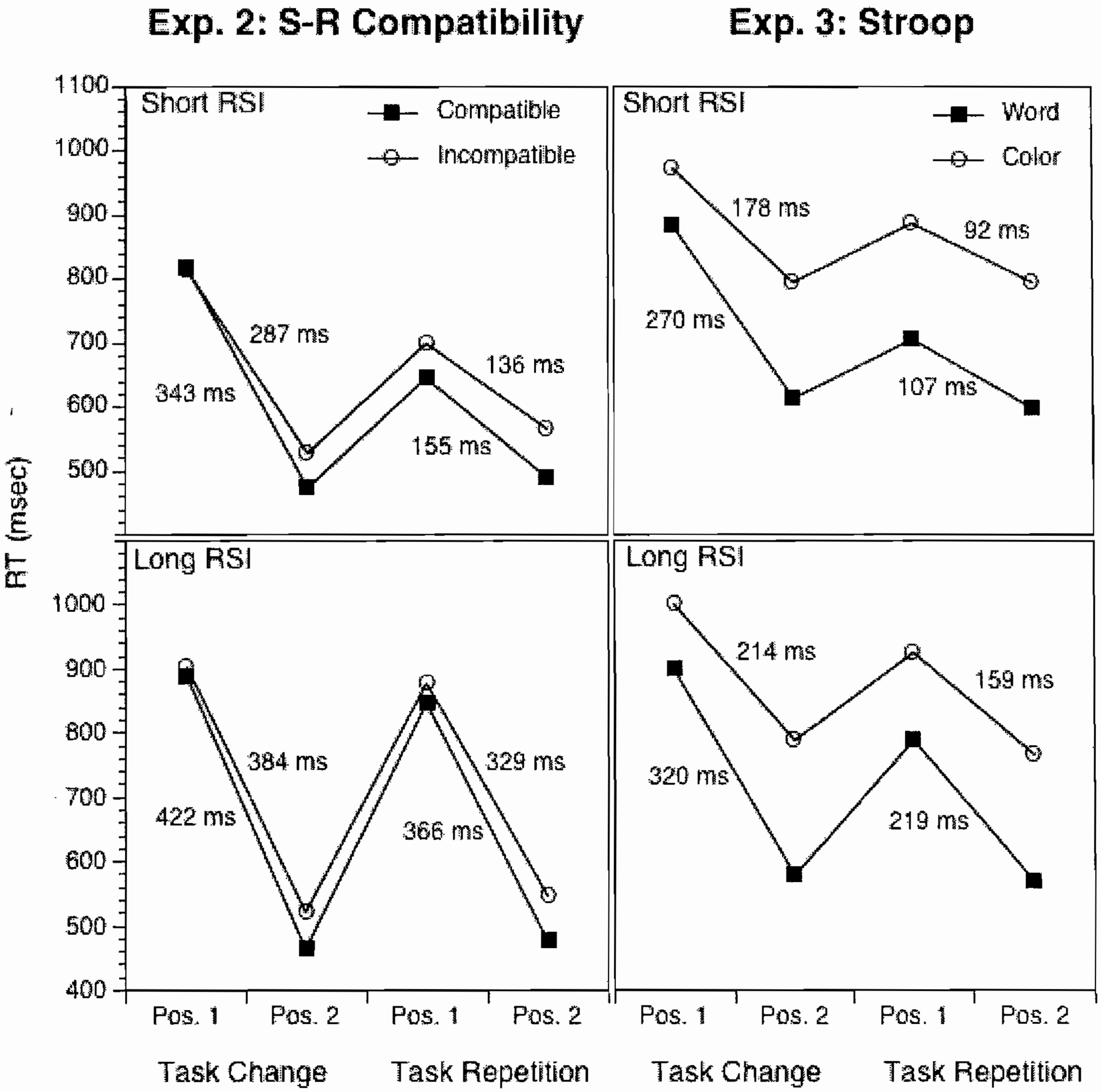
Stimuli in Experiment 3 were the words "red", "green", "blue" and "yellow" displayed in the colors red, green, blue or yellow. Only incongruent stimuli were used (i.e. the color and the name of the word were always inconsistent) resulting in 12 unique stimuli. Participants made vocal responses to the stimuli based on the experimental condition—dominant responses required producing the name of the word (word naming), while non-dominant responses required saying the color of the word (color naming). An experimenter was present to record errors and monitor performance. The experiment began with two 48-trial blocks of single task practice (with the order task presentation counterbalanced across participants), and then proceeded with two "mixed" practice blocks (i.e. alternating between the two tasks) of 48 and 72 trials, respectively. After practice, eight 72-trial mixed blocks were performed. Within-pair RSI was kept constant at 500 ms (the longer within-pair RSI here compared to Experiment 2 was necessary to allow registration of vocal responses).

Results and Discussion

Response times (RT) served as the primary dependent variable; values excluded from analysis were those faster than 200 ms, the longest .5% of trials (above 2500 ms and 1772 ms, respectively for Experiment 2 and 3), error trials and trials immediately following errors, as well as trials in which the microphone was not properly triggered (in Experiment 3). Response repetition trials were also excluded in Experiment 3. Response repetitions usually produce different effects for task repetitions (benefits) versus switches (costs). Specifically, stimulus/response repetitions on task-repetition transition trials may allow bypassing the usual selection stage and thus render subtle effects more difficult to detect. It should be noted that when in an analysis in which we did not eliminate response repetitions, the critical pattern of results is weakened, however, remains reliable. However, response repetitions were not excluded in Experiment 2 given that repetition effects were very small in this experiment and that with only two different stimuli, this would have resulted in the loss of about half of the data.

Table 4 shows the complete RT and percent error results. Figure 9 presents the RT results as a function of task, position and RSI for Experiment 2 and 3. As can be seen, there were large selection costs for both types of between-pair transitions, but these costs were somewhat smaller for the task-repetition transitions than for the task-change transitions. As expected, the selection-cost asymmetry, that is the interaction between the task and the position factor was reliable overall in both experiments, Experiment 2: $F(1,35) = 11.29$, $p < .01$, Experiment 3: $F(1,29) = 36.20$, $p < .001$. This cost asymmetry was larger for task-change transitions in Experiment 3 as the interaction with transition type was highly reliable, $F(1,29) = 14.65$, $p < .01$; however this interaction did not meet the reliability criterion in Experiment 2, $F(1,35) = 1.81$, $p = .19$.

Figure 9. Reaction Time Results for Experiments 2 and 3. Mean RT (ms) shown as a function of task, position, task transition type and RSI for the S-R Compatibility (Experiment 2; left panel) and Stroop tasks (Experiment 3; right panel). Short = between-pair RSI of 500 ms; Long = between-pair RSI of 5000 ms. Values shown next to each line indicate "selection costs" (i.e., the difference between position 1 and position 2 within a trial pair) for the respective RSI by task by transition type condition.



To test our predictions, it is critical to examine the asymmetry separately for each transition type: For task-change transitions the asymmetry was highly reliable, Experiment 2: $F(1,35) = 13.28$, $p < .01$; Experiment 3: $F(1,29) = 32.72$, $p < .001$. However, as predicted, even for task-repetition transitions a reliable asymmetry was obtained, Experiment 2: $F(1,35) = 4.40$, $p < .05$; Experiment 3: $F(1,29) = 16.23$, $p < .001$. The critical task by position interaction for task-repetition transitions was reliably modulated by RSI in Experiment 3: $F(1,29) = 8.83$, $p < .01$, but not in Experiment 2, $F(1,35) = .70$, $p = .41$. When testing the task by position interaction separately for both the long and short RSI (for task-repetitions), the asymmetry proved reliable for the long RSI in Experiment 2 and 2: $F(1,35) = 4.15$, $p < .05$ and $F(1,29) = 21.9$, $p < .001$, respectively. However, the asymmetry failed the reliability criterion for the short RSI (for task-repetitions) in Experiment 2: $F(1,35) = 1.73$, $p = .20$, and in Experiment 3: $F(1,29) = 1.88$, $p = .18$.

As can be seen from Table 4, the error data from Experiment 2 generally followed the RT pattern, even though the critical asymmetry effects did not always meet the reliability criterion. Error effects from Experiment 3 were a bit more complex. In particular, a close look at the error pattern for the task-repetition transitions suggests some evidence for a speed-accuracy tradeoff modulated by RSI. Numerically, the expected asymmetry pattern in terms of position 1 versus position 2 selection costs was found for the short RSI, but a reversed pattern (i.e. color naming costs larger than word naming selection costs) was found for the long RSI. Neither of these effects was reliable, nor was the interaction between RSI, task and position. Nevertheless, to ensure that the RT effects were not compromised by a tradeoff with accuracy, we looked at the RT asymmetry effects in the critical condition (task-repetition, long RSI) for just those participants (n = 18) who showed the "standard" asymmetry pattern in their error scores and found that they did observe a reliable RT asymmetry in the correct direction, F (1,17) = 17.73, p < .01. Thus, combined with the results from Experiment 2, where there was no indication of a speed-accuracy tradeoff, we can be relatively confident that the RT asymmetry for task-repetitions is a real phenomenon.

Table 4. Descriptive Statistics for Experiments 2 and 3. Note: Short = between-pair RSI of 500 ms; Long = between-pair RSI of 5000 ms. Pos. 1, Pos. 2 = position 1 and position 2, i.e., the first and second trial within a pair.

Experiment 2:			*Compatible*				*Incompatible*			
S-R Compatiblity			Pos. 1		Pos. 2		Pos. 1		Pos. 2	
			M	SD	M	SD	M	SD	M	SD
Task Repetition	Short	RT (ms)	644	144	489	73	700	144	564	110
		Error (%)	0.68	1.51	0.39	1.29	0.83	1.54	1.65	2.43
	Long	RT (ms)	844	171	478	69	876	160	547	95
		Error (%)	1.00	1.99	0.34	0.86	0.70	1.58	0.56	1.22
Task Change	Short	RT (ms)	816	200	473	70	813	164	526	87
		Error (%)	6.38	4.32	0.37	0.96	4.46	3.67	0.61	1.61
	Long	RT (ms)	886	186	464	80	904	164	520	84
		Error (%)	4.05	4.28	0.14	0.61	2.12	2.55	0.51	1.29

Experiment 3:			*Word*				*Color*			
Stroop			Pos. 1		Pos. 2		Pos. 1		Pos. 2	
			M	SD	M	SD	M	SD	M	SD
Task Repetition	Short	RT (ms)	704	76	597	102	887	102	795	118
		Error (%)	1.70	2.51	2.77	4.75	2.47	3.51	5.14	6.07
	Long	RT (ms)	788	96	569	81	924	97	765	106
		Error (%)	1.28	2.47	3.28	4.83	2.89	4.60	2.80	4.59
Task Change	Short	RT (ms)	884	94	614	116	971	96	793	118
		Error (%)	6.02	6.41	2.19	3.82	2.85	4.09	4.69	6.22
	Long	RT (ms)	898	113	578	99	1002	106	788	107
		Error (%)	4.46	4.97	3.21	4.86	3.07	4.62	2.41	4.13

Experiments 4a and 4b

In Experiment 4a, we attempted to provide a still stronger test of the LTM-retrieval view of asymmetric costs. According to this account, the greater difficulty with selecting the dominant task arises from LTM interference. If this is correct, the effect of such LTM influences should be detectable beyond the type of rapid back-and-forth task-switching situations used in Experiments 2 and 3. Specifically, we predicted that dominant task RTs would be increased in single task blocks when these are intermixed with non-dominant single task blocks. Again, this effect should be particularly strong for long RSIs where frequent occasions of a "loss of set" and subsequent acts of re-retrieving the task can be expected. Thus, in this context, the cost asymmetry should become apparent as a larger increase of RTs for the dominant than for the non-dominant task as a function of an increase in RSI.

We also contrasted dominant and non-dominant single task performance in a between-subject design (Experiment 4b) that was otherwise completely analogous to Experiment 4a. It is possible that the type of asymmetry in long RSI, task-repetition trials that we have seen in Experiments 2 and 3 is an unspecific phenomenon that has nothing to do with competition between tasks. For example, people might habitually prepare for short RSIs, so that long RSIs produce an expectancy violation (e.g., Gottsdanker, 1979), to which in turn, easy tasks might be more sensitive than difficult tasks. If the cost asymmetry is actually tied to competition between tasks, eliminating such competition with the between-subject design should lead to identical RSI effects for dominant and non-dominant tasks.

Methods

Participants

Sixteen participants were included in the within-subjects Experiment 4a, 32 participants were included in the between-subjects Experiment 4b.

General Design

Experiment 4a was identical to Experiment 3 including all aspects of the stimuli, the display, and the RSI manipulation, except that participants only performed a single task (word naming or color naming) during each block. Participants alternated between 72-trial, word and color naming blocks in an ABBAABBA sequence, counterbalanced across participants by which task was presented first. Prior to actual testing, participants were given one 72 trial practice block each of color and word naming.

Experiment 4b was identical to Experiment 4a except that the task condition was manipulated between-subjects such that a given participant only performed one of the tasks (color naming or word naming). Practice involved two blocks of 72 trials of a given task.

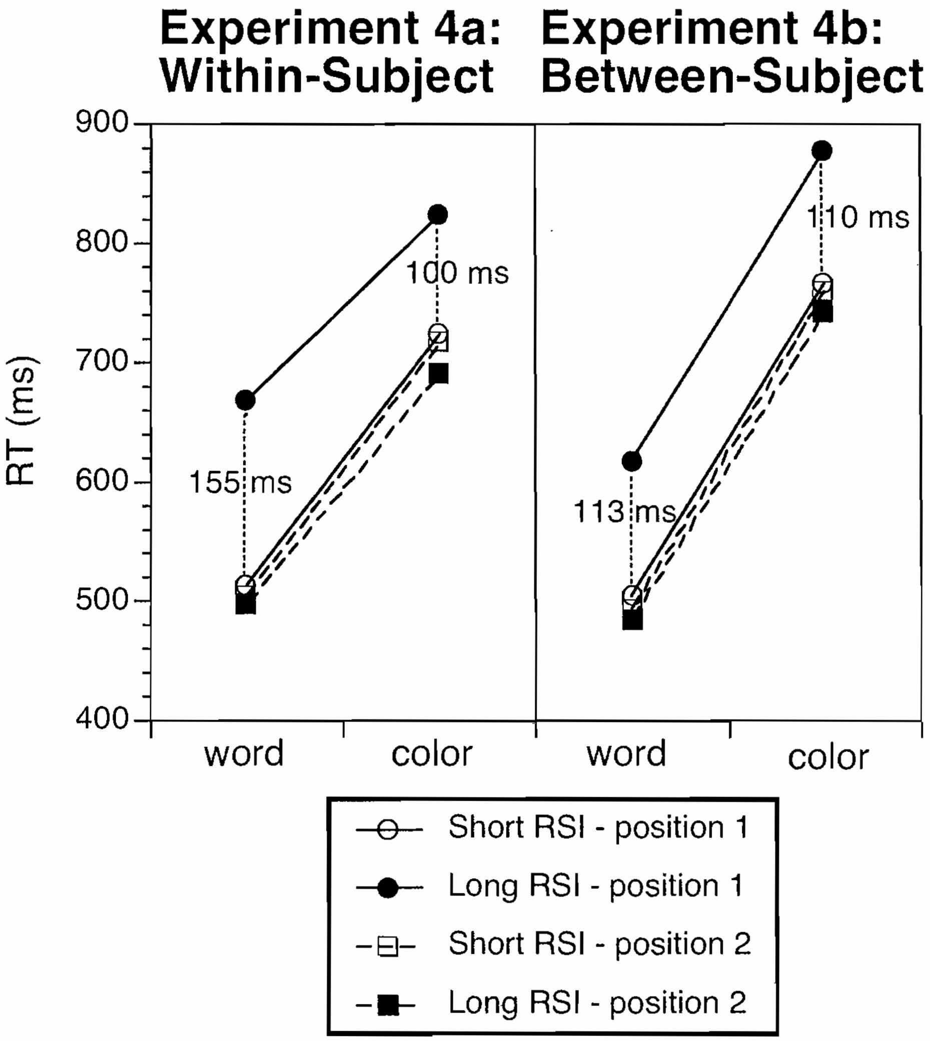
Results

The criteria used for excluding trials were identical to Experiment 3. Figure 10 shows RTs as a function of task, position and RSI within a task pair for both the within-subject (Experiment 4a) and the between-subject (Experiment 4b) experiments. We had predicted that when between-task competition is high (Experiment 4a) and there is a high likelihood of losing the task set from working memory (i.e., position 1 after long RSIs) RTs for the dominant word task should be prolonged compared to the color task. As evident in the left panel of Figure 10, this was the case. The critical interaction between task, position and RSI was highly reliable, F(1,16) = 10.76, p < .01 for Experiment 4a. Specifically, the RT increase as a function of RSI was considerably larger for the word than for the color task on position 1 trials (M = 155ms, SD = 72 ms and M = 100 ms, SD = 62 ms, respectively).

Experiment 4b matched Experiment 4a in all respects, only that the task factor was manipulated between subjects, thus eliminating direct competition between the dominant and the non-dominant task.

Consistent with the assumption that the cost asymmetry is not an unspecific phenomenon, but rather driven by competition between tasks, the RSI effect was highly similar for the two tasks here (position 1 word = 113 ms, SD = 59 ms, position 1 color = 109 ms, SD = 65 and there was no hint of a reliable interaction between task, RSI and position, F(1,26) = .04, p = .84. It should be noted that this analysis includes the full set of data for Experiment 4b. It could be argued that it is more appropriate to analyze only the first half of the data for this experiment, given that each participant performed the same number of total trials as participants in Experiment 4a, thereby resulting in twice the number of trials for each task. However, when analyzed this way, the overall pattern of results stays the same. The critical interaction between the task, RSI and position is again far from reliable, *F*(1,26) = .29, *p* = .60. Overall, error rates were very low and did not counteract the critical pattern of RT results (see Table 5).

Figure 10. Reaction Time Results for Experiments 4a and 4b. Mean RT (ms) for the within-subject (Experiment 4a, left panel) and the between-subject (Experiment 4b; right panel) manipulation of task. Shown as a function of RSI, position and task. Short = between-pair RSI of 500 ms; Long = between-pair RSI of 5000 ms.



We also directly contrasted the asymmetry for the position 1 selection costs (i.e., long RSI vs. short RSI) between Experiments 4a and 4b, using a procedure suggested by Erlenbacher (1977) for comparing effects from within vs. between subject designs. The asymmetry for the selection costs was reliably larger in the within than in the between-subject design, F(1, 20.58) = 4.60, $p < .05$, confirming that between-task competition is in fact critical for the emergence of asymmetric costs.

Table 5. Mean Percent Errors for Experiments 4a and 4b. Note: Short = between-pair RSI of 500 ms; Long = between-pair RSI of 5000 ms. Pos. 1, Pos. 2 = position 1 and position 2, i.e., the first and second trial within a pair.

		Word				*Color*			
		Pos. 1		Pos. 2		Pos. 1		Pos. 2	
		M	SD	M	SD	M	SD	M	SD
Exp. 4a (Within-sub.)	Short	0.00	0.00	0.00	0.00	1.98	1.68	1.87	2.23
	Long	0.10	0.37	0.10	0.38	0.42	0.69	1.15	1.30
Exp. 4b (Between-sub.)	Short	0.22	0.59	0.14	0.36	1.08	1.20	1.46	1.31
	Long	0.00	0.00	0.07	0.25	0.51	0.88	1.45	0.99

General Discussion

Taken together, the three experiments reported here provided clear evidence that a switch in task is a sufficient, but not a necessary condition to obtain a selection cost asymmetry (see also Allport & Wylie, 2000). A cost asymmetry was obtained both on trials in which the task changed and on trials in which the task repeated, when there was a long delay between trials. We had hypothesized that long delays increase the likelihood of losing the previous trial set and therefore enforce retrieval of task-set information from LTM, just as would otherwise occur during a switch in task (e.g., Mayr & Kliegl, 2000). The idea that cost asymmetries result from LTM influences is particularly strengthened by the fact that an asymmetry was obtained in Experiment 4a, even though the two tasks were separated into distinct blocks, thus ruling out any role of short-term priming effects.

The current demonstration of a selection cost asymmetry, even in the absence of an actual task-switch, is theoretically important because it cannot be explained by carryover accounts of task-switch costs (see also Allport & Wylie, 2000). By these accounts, an actual switch in tasks is a necessary condition for an asymmetry. We do not, however, want to claim that such models could not be amended to produce the observed asymmetries. For example, Gilbert and Shallice (2002) speculate (in a somewhat different context) about the consequences of allowing long-term strengthening of associations between stimulus/response and task-set nodes, rather than resetting them from trial to trial. However, the required amendments would clearly move the continuous-activation accounts closer to the LTM-retrieval account proposed here.

So far, we have alluded to the LTM-retrieval view of task selection only in a very general manner. How exactly would this account explain the cost asymmetry? One possibility we currently favor is the following: Assume that each task-selection instance, whether after a switch or a loss of the currently relevant task set over time, requires retrieval of the relevant task information from LTM. In addition, each trial also provides a learning opportunity that, with some probability, adds traces encoding specific features about that selection instance to LTM (Logan, 1988, 1990; Mayr & Bryck, 2005). Past work has already shown that automatic retrieval of such memory traces, which include a representation of the task-set previously used, provide at least a partial explanation for switch costs (Waszak, Hommel, & Allport, 2003). However, an additional assumption is necessary to explain the selection-cost asymmetry: The probability of encoding a memory trace needs to increase as a function of attentional control exerted during the selection instance. Assuming that more attentional control is necessary for non-dominant than for dominant tasks, more traces representing non-dominant task instances would be laid down in LTM than for dominant task instances. As a result, during attempts to retrieve task-set information from LTM (e.g., on switch or restart trials) there is a greater degree of interference through non-dominant task traces than through dominant-task traces.

There is some evidence in the memory literature that encoding efficiency is a direct function of how much attention is devoted to the to-be-encoded information (e.g., Craik, Govoni, Naveh-Benjamin, & Anderson, 1996). In future work, it will be important to provide additional, more direct evidence for the critical claim that greater interference during encoding, such as via a dominant competitor task, actually leads to the encoding of more memory traces for the non-dominant than for the dominant task.

Irrespective of how this particular theoretical account of asymmetric costs holds up in future work, the critical finding of this study is that we could confirm and extend reports by Allport and Wylie (2000) that switch transitions are not a necessary condition for asymmetric costs. As a result, the intuitively appealing idea that switch costs and switch cost asymmetries arise from trial-to-trial carryover effects may have to be reconsidered.

CHAPTER V

CONCLUSIONS AND FUTURE DIRECTIONS

How people perform in multi-task situations can provide important information about the architecture of cognitive control. Thus far, we have summarized critical finding from task-switching literature thought to tap fundamental aspect of control. Findings have been characterized as highlighting either "control-like" or "control-less" features of switching. Results from Experiment provide both functional and anatomical evidence for a non-overlapping, two-component system. One component showed a highly left lateralized prefrontal and superior parietal network, consistent with controlled retrieval mechanism necessary for efficient switching. Further, this finding is consistent with previous literature detailing this as a controlled retrieval mechanism (Mayr & Kliegl, 2003). The other component was seen in more medial and posterior regions of parietal and occipital cortices, as well as medial cerebellar regions. This pattern was consistent with a proposed automatic "application" stage of switching, likely involved in either the shifting of attention to relevant stimulus features and/or the reassignment of response features. Further, Experiments 2–4 characterized the switch cost asymmetry effect as arising from the automatic retrieval of long-term memory traces. These results, taken in concert, are suggestive of both endogenous control (retrieval) and low-level automatic processes as critical determinants of switching.

In a review of the task-switching literature, Monsell (2003) outlines findings that are easily explainable by the control-like accounts, but not by the (presumably control-less) associative priming accounts and vice versa. For example, control based accounts of the preparation effect abound. Likely, because the notion of an endogenous executive process, that can be preplanned in order to set up the cognitive system for action, is intuitive. However, there are situations in which a preparation interval improves overall performance, but does not reduce switch relative to repeat trial RTs (Sohn & Carlson, 1998; Dreisbach, Haider & Kluwe, 2002). Similarly, residual switch costs are also not easily explained by control only mechanisms, although, De Jong (2000) provides evidence that residual costs may arise from inadequate preparation on some trials, a finding which could be deemed compatible with control accounts.

Conversely, it is difficult to apply purely associative interference accounts in order to explain all phenomena of switching. The just mentioned preparation effect is one such example. It is not intuitive why more time between cues and tasks should reduce switch costs, if they are due simply to repetition priming of no-switch trials. Additionally, switch costs have been observed, at least in residual costs, even with unambiguous (univalent) stimuli, where there is no reason to expect interference between task-sets (e.g. Rogers and Monsell, 1995). Moreover, even for certain classes of ambiguous (bivalent) stimuli and tasks, such as making prosaccades and antisaccades, switch costs are not observed as would be expected by low-level associative interference accounts (Hunt & Klein, 2002).

Can we not reconcile these two accounts though? We have already argued in favor of a two-component model of switching based on the disparate findings present in the literature, as well as the results from the present studies, regarding the role of control in switching. To be fair, many authors acknowledge the existent of both control and low-level mechanisms and do not necessarily argue these to be mutually exclusive mechanisms. In fact, two-component models of task-switching have received considerable support (e.g., Rogers & Monsell, 1995; Rubinstein et al., 2001; Mayr & Kliegl, 2003). Even authors that have emphasized one component over the other tend not to be completely exclusionary towards the deemphasized account. For example, Allport and Wylie (2000) acknowledge the likelihood of control processes, likely to determine the current goal, in addition to task-set inertia explanations of residual switch costs. However, there are some strong arguments made in favor of single-component accounts of switching (e.g. Logan and Bundenson, 2003; Altmann & Gray, 2002). Integration and interpretation of the present results, however, clearly supports a two-component account of task-switching.

The LTM Retrieval Model Revisited

More specifically then just framing our results in terms of a simple two-component, we argue that the LTM retrieval view of task-switching, developed by Mayr and colleagues (Mayr & Kliegl, 2000, 2003; Mayr, 2003), best accounts for our results and in turn our results provide further support in favor of the model. Recall some basics features of this model. First of all, a limited working memory focus is hypothesized to be the critical determinant of selection. That it, to hold a task-set in working memory is equivalent to selecting it for action. This single-task constraint of working memory, at least in the context of multi-task performance, is thus an all-or-none mechanism, requiring the removal of the previously activated task-set in the case of a task-switch (Mayr & Kliegl, 2000; Rubinstein et al., 2001; Mayr, 2003). Converse to this argument, congruency effects in switching have been argued for as support for the idea that two or more task-sets can be held active simultaneously in WM, or at least partially active (e.g. Meiran, 2000). However, Mayr (2003) argues that it may be difficult to hold two incompatible task-sets concurrently— much as it is impossible to hold two differing perspectives of an ambiguous figure in perception at the same time (Chambers & Reisberg, 1985). Maintaining only one of several competing task-sets on-line at any given time may additionally be an efficient way of reducing between task competition (Rubinstein et al., 2001). Further, this constraint requiring a coherent representation is not with out precedent in the broader control literature (see for example, the "global workspace model" of Dehaene, Kerszberg, & Changeux, 1998).

Rather than multiple active representations, it is argued that this limited focus WM system makes rapid connections with "long-term memory retrieval structures" (Mayr, 2003) that hold practiced or established constellations or routines. In this way, high demands on working memory can be lessened by selection of these practiced "routines" (e.g. S-R rules) that are stored in long-term memory but easily and quickly accessible. The consequence of all this is that a switch in task necessitates the need to retrieve (or re-retrieve) the appropriate task-set from LTM. Thus, in the context of task-switching, it follows that sufficient preparation time allows for the controlled retrieval of task rules from LTM. Empirical evidence supports this claim and has been used to support LTM retrieval accounts of switching, as aforementioned (Mayr & Kliegl, 2000; Rubinstein et al., 2001; Badre & Wagner, 2006).

Additional evidence in favor of a memorial account of task-switching comes from the model and data from Badre and Wagner (2006). Recall they presented a simple computational model consisting of task (e.g. "color"), concept (e.g. "red") and response layers (e.g. "left"). Experience strengthens connections between layers co-activated during task performance. Thus, on a task-switch, greater priming from the now irrelevant connections results in a proactive-like interference effect that slows task-switches compared to repeat trials (i.e. switch costs). Bias from the task level onto the relevant concept layers reduces conflict and as such declines with increasing CSI, in other words, parallels the preparation effect. Interestingly, because the relevant concept layers (e.g. "red" and "green") come to dominate, more conflict is present in the response layer with increasing CSI. This is due to the feed forward activation from the two relevant concepts nodes, which equate activations between the two response nodes over time, such as during long CSIs (whereas presumably the response used in the preceding trial would have a stronger, persisting activation with short intervals).

Strikingly, these two differing CSI by conflict patterns were paralleled in fMRI activity by an decrease in left mid-VLPFC (concept) and increase in left posterior parietal (response) with increasing CSI. These left mid-VLPFC and posterior regions found in Badre and Wagner (2006) are highly congruous with regions found in our fMRI study, left VLPFC

("C8") and left SPL ("C1") respectively. Moreover, the interpretations and conceptualization of switching made in the Badre and Wagner (2006) paper is also highly similar to the LTM retrieval argument of switching. For example, another feature of the Badre and Wagner (2006) model is that switching can occur even without bias input from the task layer ("control"). However, in such conditions, conflict remains high and there is no observed reduction in activity with increasing CSI. Moreover, this control process is likened to the control process of selecting between competing representations in a LTM retrieval task. This is analogous then to the two-component model we suggest, consisting of a control-like retrieval of relevant task rules as well as the influence of automatically retrieved competing memory traces that can interfere with selection of the current task.

A mnemonic view of task-switching, and control in general, is appealing. First of all, it provides parsimony. Framing task-switching in terms of structures and functions of memory simplifies our understanding of how switching is accomplished and avoids the introduction of novel, "switch specific" processes to the already complex framework of cognition. As such, we can apply the extant knowledge of LTM to further explore and characterize phenomenon associated with task selection. In fact, the LTM retrieval view has been shown as fully capable of explaining the range of task-switch findings, unlike purely control or purely associative models; see Mayr (2003) for how the LTM retrieval model accounts for such findings as preparation, congruency, residual costs, global costs and inhibition effects.

Further, purported control processes in task-switching share descriptive as well as anatomical overlap with those control processes purported in LTM literature. Consider, for example, the summary of Buckner (2003, p. 4000) on the role of VLPFC areas in control processes active during LTM retrieval: "prevailing interpretation of these results is that... [VLPFC areas] participate when a novel or weakly associated representation must be momentarily constructed to solve a task goal, at the exclusion of other possible, but context-inappropriate, representations." Such an interpretation should sound familiar, as it is highly similar to prevalent models of control processes during task-switching— where task rules can be substituted for novel or weakly associated representations (given most task-switching studies work with novel tasks) that serve to solve task goals, namely speeded responses to stimuli based on context, i.e. "current task", in the face of competing representations (i.e. now irrelevant task sets).

Future Directions

Thus far, we have characterized switching as a two-component LTM process; however, the degree to which these two mechanisms might interact is not fully known. It may make sense to think of these two purported components as reflecting two heads of the same beast. Namely the more or less controlled retrieval of task rules from long-term memory and the automatic retrieval of task configurations, while each has separable influences on switching, they are both in essence mnemonic functions. It is known that memory cues can induce either automatic or intentional retrieval, for example. Future exploration of whether the two-components posed here map discretely onto the controlled versus automatic distinction is of high interest. One way to potentially examine this would be to employ a process dissociation procedure (e.g. Jacoby, 1991) with the 4:2 cues-to-task cuing procedure. Divided attention tasks have been used before (Jacoby et al., 1993) as a method of manipulating control aspects, as presumably a controlled process would interact with a shared stage of processing in a divided attention task, but automatic mechanisms should be relatively unharmed by such a manipulation. Another avenue for addressing this controlled versus automatic question might be manipulations involving the amount of training of each of these components. One would assume that training would affect the controlled cue-switch component, as strengthening of cue-task pathways should benefit from practice. Conversely, given the presumed automatic nature of the task-switch component, training would be expected to have less of an effect on the task-switch component. Training effects on the intentional component would in fact be consistent with the reduction of the cue-switch effects across blocks in Experiment 1 of Mayr and Kliegl (2003).

One potential avenue of further study would be to explore the degree to which a 4:2 cuing paradigm might induce additional processing demands not necessary in the standard 1:1 cuing paradigm. For instance, additional "cue encoding" processes may be required in the 4:2 version to simply allow the system to verify whether a change in cue also indicates a change in task or not. Such fast cue encoding processes may be particularly useful in situations where assessing the conditional probability of a task change, given a cue change, is beneficial to performance (e.g. Mayr, 2006).

Conversely, providing two cues per task may actually improve performance, as two cues per task may provide a sort of compound retrieval cue to the appropriate response pathway. On the other hand, offering two cues per task may actually hinder performance, compared to the standard one cue per task situations. Such a possibility might result if each cue forms a unique representation with its given task, as opposed to the idea that each cue provides an additional pointer into the same task representation. Thus, in the unique representation case, a cue-switch transition would itself require a type of switch between separate representations. These two opposing conceptualizations of "double cue" performance could be easily tested. For example, additional conditions could be implemented in the 4:2 cuing paradigm in which *both* cue types appear simultaneously before target presentation, following a typical single cue trial type. This double cue condition could involve a full (no-switch), partial (cue-switch) or no (task-switch) overlap with the cue from the previous single cue trial. Thus, if two cues per task provide additional pathways into the same task representation, we would expect double cue presentation to facilitate performance relative to single cue presentation trials. However, the opposite pattern of results might be predicted if each cue forms a unique association with a given task.

Another interesting possibility, which we have alluded to but have as yet not specifically addressed, is the possibility that the (true) task-switching component we have seen, both behaviorally and anatomically, is a reflection of the automatic retrieval of memory traces, such as proposed in our studies of the asymmetry effect. Mayr and Kliegl (2003), recall, found that the "true" task-switch component was insensitive to CSI manipulations and characterized it as an automatic process. In our discussion of the neuroimaging results, we postulate a number of possible functions of the medial parietal, occipital and cerebellar regions seen in the task-switch contrast. While these proposed functions, attention shifting and/or response representation, are certainly still tenable in a more or less "pure" from, it is also possible that these regions specifically reflect representations of these memory traces, or event-files. For example, the medial occipital region may reflect specific visual features, the cerebellar areas the response components and the medial parietal may reflect either additional perceptual features, or it could reflect the necessary deployment of attention for formation of these traces (Logan, 2002). Additionally, our correlations of task-switch MR activity with the behavioral congruency effect are also highly consistent with this proposal. Mayr (2003) has suggested that congruency effects arise due to priming from the retrieval of response codes from LTM, akin to the idea that these memory traces are automatically retrieved when the presentation of similar context (e.g. tasks, stimuli, rules). See Mayr and Kliegl's Experiment 3 (2003) for evidence of a "task-congruency" effect, even when the intentional LTM retrieval component should not be a factor in switching.

If this speculation that the "true" task-switching component reflects memory traces is correct, than an interesting question is whether the activity observed in our fMRI study for the task-switch contrast in indicative of the *encoding* or the *retrieval* of these traces. Use of fMRI in a paradigm, like our modified alternating runs paradigm with interruptions used in Experiments 2-4, might help resolve this question. First we would need to simply replicate activity in these medial regions.

Moreover, if activity here reflects the encoding of memory traces, we would expect greater activity in these regions when performing the non-dominant compared to dominant task overall. However, if instead these areas reflect the automatic retrieval of traces, and if stronger traces are more easily retrieved, then we would expect greater activity in these regions when either switching to, or selecting the more dominant task after a long delay. Greater activity in these areas in either case would lend credence to this claim that these regions reflect memory trace representations.

Applications

One potential pedagogical application of interest is suggested by the asymmetry findings. Recall that a critical determinant to the successful formation of these traces is attention to a stimulus, or a given feature of stimulus (Logan, 2002) and we further hypothesized that the *strength* of a trace is directly related to the amount of attention employed during formation of the trace. Our interpretation of asymmetric switch costs was due to the greater interference of retrieved memory traces associated with the non-dominant task, relative to the interfering effects of dominant traces, during non-dominant performance. In other words, non-dominant traces are "stronger" and thus retrieved more readily during dominant task performance than dominant traces are retrieved during non-dominant performance. It is assumed then that conditions requiring higher attentional control demands (e.g. color-naming Stroop task) produce stronger, or more readily available memory traces.

This suggests then that highly demanding situations requiring, in terms of the amount of attentional control required, might actually provide better learning situations than less demanding conditions. If such an effect held up with further testing, this general principle of bettering learning in more difficult contexts, it could be applied to educational settings. Namely, learning situations requiring more executive or attentional control may well lead to better memory traces. More abundant or more efficient traces then would presumably lead to better memory performance when this material later needs to be recalled, such as on a test, given the postulated automatic retrieval of this traces when similar situations or contexts are present. Thus, one proposal of interest to examine in classroom settings would be to present to-be-learned material under conditions requiring high demands of control. Exactly what types of high demand would lead to the best traces, thus best memory performance is of course yet to be determined experimentally. This general idea is also consistent with the proposal that high difficulty material is retained and recalled better than low difficulty material (e.g. Schmidt & Bjork, 1992).

In conclusion, if switching phenomena can be accurately accounted for by LTM mechanisms, a skeptical question might be then, why should we really "care" then about task-switching if it is can be explained purely in mnemonic terms? Remember though that both switching and selection from LTM have been hypothesized to require a control process in order to resolve interference between competing memory structures. A hallmark of human behavior is the ability to stay on target and select the intended action in the face of distracting external stimuli. This ability presumably requires a coherent, stable task-set that is highly resistant to interference. Examination of the mechanics of this processes, whether from the context of memory or task-switching studies, will help illuminate how selection is accomplished.

Deficits in both the ability to maintain a coherent, stable representation, as well as the flexibility to form new plans of action are common in patients with frontal lobe damage. "Utilization" behavior, for example, is the response to an object based on its affordance, despite the current context. A classic example of this phenomenon is documented by a patient that, when entering the bedroom, would start putting on his pajamas, despite it being the middle of the day (Lhermitte, 1983). Such durability in behavior must be tempered with the ability to demonstrate flexible behavior in the face of changing internal goals or external demands. A classic failure to do such is seen in frontal patients' tendency to show "perseverative behavior," the continued repetition of a behavior, particularly if this behavior is no longer relevant in the current context. This is perhaps most famously documented in perseverative errors in the Wisconsin Card Sorting Task (e.g. Milner, 1963). The importance of these control processes is certainly not trivial then, as these abilities appear to be a core component of human cognition.

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