Attentional Control Mechanisms and the Measurement of Switch Costs:

Switching *TO* or Switching *FROM*?

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ABSTRACT

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When people are required to switch from performing one task to another, response times are typically slower than when they are required to repeat the same task twice in succession. This switch cost remains even when the need to switch is predictable or advanced preparation is possible. The mechanisms underlying such switch costs were the focus of this research. Rogers and Monsell (1995), using the "alternating runs" paradigm which they devised, provided evidence favoring the idea that switch costs are due to mental preparation for the task being switched *to*, that is, to the task set reconfiguation required by the upcoming task. Wylie & Allport (2000, Experiment 1), using the alternating runs paradigm embedded in a special three stage research design, provided evidence favoring the idea that switch costs are due to the carry over of inhibition present in the task being switched away *from*, that is, to a form of task set inertia stemming from the trial just completed. These two sets of researchers drew different conclusions as to what underlies switch costs; it is possible, however, that their different outcomes were due to the fact that they used very different stimuli and tasks. In particular, Rogers and

Monsell's task set reconfiguration result was obtained when the two tasks involved were very similar to one another in terms of overall difficulty and how automatically they could be executed. On the other hand, Allport and Wylie's task set inertia result was obtained when the two tasks involved were asymmetrical in terms of overall difficulty, and when one task could be executed more automatically than the other. The present research investigated whether such differences underlie these different outcomes. Experiment 1 used the three stage research design advocated by Allport and Wylie for differentiating whether switch costs are due to what one is switching *from* versus switching *to*, but with stimuli and tasks of the type used by Rogers and Monsell. Unlike what Allport and Wylie would have predicted, the results supported Rogers and Monsell's task set reconfiguration hypothesis (what matters is what one is switching *to*). Experiment 2 repeated the previous experiment with one task being made more difficult than the other by involving an episodic rather than a semantic judgment. Again, support was found for the task set reconfiguration hypothesis. Experiment 3 again repeated the main design of the first experiment, but one task involved more automatic processing than the other. This time, support was found for the task set inertia hypothesis (what matters is what one is switching *from*). The results are discussed in terms of how the complex processing attentional and memory demands of switching between tasks can determine whether task set reconfiguration or carryover of inhibition plays a significant role in determining switch costs.

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INTRODUCTION

Each stimulus encountered in our environment is associated with a range of responses which may or may not be performed depending on one's current intentions. Furthermore, we need to skillfully navigate amongst the thousands of stimuli which compete for our attention, and focus on goal-relevant information while actively ignoring distractors. Thus when performing complex activities, such as driving a car, attentional control over which action is to be performed at any given moment needs to be tightly exercised. For example, if you are stopped at an intersection and the traffic light turns green, the most likely response you are to execute under these circumstances is to press on the gas pedal and proceed along your route. However, if at the same moment, a pedestrian runs across your path to catch the bus, you need to switch your attention towards the pedestrian, inhibit your first response, and stop the car if you want to avoid causing serious injury. This example of a simple routine activity illustrates the crucial role attention plays in adaptive behavior. A question that has interested researchers in cognitive psychology over the last few decades concerns the types of mechanisms that underlie the flexible and adaptive skill of attentional control. While the selection of an appropriate response is determined in part by a number of variables (the context within which the stimulus is embedded, learning experience, current short-term and long-term goals, skill, motivation, to name a few), the role of attention is ubiquitous to all human activity that involves skilled, goal-directed behavior.

Nevertheless, while attention has been recognized as a necessary component of complex skill, the concept itself is multi-faceted, and has generated different lines of research investigating skills such as sustained attention, perceptual selection, dual-task performance, and controlled/automatic processing (discussed in Baddeley, 1997). Recently, there has been a surge of interest in the role that attention plays in the coordination of action.

As pointed out by a number of researchers in the field of attention, (Allport, Styles & Hsieh, 1994; Baddeley & Hitch, 1994; Gopher, 1996), we have developed a broad knowledge base about basic processes underlying individual tasks such as word identification, semantic categorization, sentence comprehension, memory, etc. Yet, little is known about the nature of the executive control processes that enable the smooth operation and coordination of the various cognitive activities that allow the pursuit and unfolding of directed, willful, and meaningful behavior. The research presented in this thesis represents an attempt at understanding how basic task processes interact with the control mechanisms that underlie coordinated action.

The importance of developing an articulated model which describes the functional architecture of attentional control is not only important for information processing theory, but also has practical implications for research and applications in neuropsychology. Indeed, assessment tools used in neuropsychology to diagnose neurological impairments following brain injury or disease rely on tasks which presumably tap into specific processes carried out by different regions of the brain. The inferences derived from subjects' performance on these tasks enable clinicians to formulate hypotheses as to the nature and extent of neurological impairment. For example, there exists a battery of tasks which have been used to diagnose frontal lobe deficits, a brain region commonly associated with executive functions underlying the control of action. Such tasks (e.g., the Wisconsin Card Sorting Test or the Tower of Hanoi) presumably tap into executive control functions and allow clinicians and researchers alike to draw inferences about executive functioning. Typical functions believed to be controlled by this region are: a) shifting between tasks or mental sets, b) updating and monitoring of working memory representations, and c) inhibition of dominant or prepotent responses (e.g., Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000).

However, the issue of task impurity (i.e., tasks measuring processes other than the intended target(s)) has somewhat muddled the conclusions derived from studies attempting to draw a functional architecture of executive functions. In fact, research highlighting the heterogeneity of deficits in patients with frontal lobe pathologies, and the low correlation found between different executive tasks in individual differences studies suggest a fractionation of frontal lobe functions is both possible and necessary (Allport et al, 1994; Baddeley, 1996; Logan, 1985; Monsell, 1996; Monsell, Yeung, & Azuma, 2000; Myake et al, 2000, Shallice, 1994; Shallice & Burgess, 1991; Stuss, Shallice, & Alexander, 1995). Thus while the issue of basic task processes is secondary to that of executive control mechanisms, these results emphasize the importance of understanding how components of single- and multi-step tasks interact with attentional control mechanisms. As Logan (2000) stated in his introduction to a journal issue dedicated to the study of attention and performance, "theories of executive processing must develop hand in hand with theories of subordinate processing" (p.211).

Theories of Attentional Control of Action

Several models attempting to explain the role of attention in the control of action have been proposed in the last two decades, some more influential than others. Implicit in most models are the concepts of automatic and controlled processing, and their role in the willful control of behavior. While it is beyond the scope of this thesis to review each and every one in depth, special attention is devoted to Norman and Shallice's (1986) "attention to action" (ATA) model (for a review of this model and that of others such as SOAR and CAP, see Shallice, 1994). The ATA model represents a clearly articulated proposition that incorporates the automatic/controlled processing distinction within its functional architecture. It has been linked to Baddeley's influential model of working memory and its concept of a central executive (discussed in Baddeley & Hitch, 1994).

The Norman and Shallice Model

The model proposed by Norman and Shallice (1986; Shallice, 1994) is a multiple-layer, hierarchical organization containing different control levels. At the lowest level are psychological processing structures controlled by action or thought schemas which contain information specifying the procedures for carrying out specific action sequences. Schemas are selected for action whenever their activation value exceeds their thresholds (which may be variable across time and conditions, and are specific to each schema). Activation occurs in part when schema trigger conditions meet those stored in a trigger data-base. Source schemas are believed to feed activation to component schemas allowing for the timely sequencing of complex behaviors. Recency and frequency of use are believed to lower schema threshold values such that habitual, highly practiced, and recently performed actions will tend to be triggered into action whenever environmental conditions are met. In order to resolve potential competition amongst simultaneously activated schemas, two levels of control are postulated: contention scheduling and supervisory attention system (SAS) control.

Contention-scheduling resolves schema selection competition by means of lateral inhibition, following a horizontal thread structure. This mechanism allows for the resolution of competition for common processing resources amongst schemas, and is used for common, well-learned, routine actions. It is considered a more or less automatic form of control, occurring below the level of conscious awareness. Inhibition between any two schemas is determined in part by the sharing of common processing structures. But the model is not specific as to what determines when two tasks will use common processing structures. The schema whose fit is closest to current goals wins the competition by inhibiting rival schemas. Importantly however, it is assumed that as tasks become more automatic, "the schemas controlling them become more specialized in their use of processing structures, reducing potential structural interference and minimizing the need for mutual inhibition among schemas" (Norman & Shallice, 1986, p. 6). This principle is important insofar as it makes a processing distinction between tasks and the schemas representing them. It addresses a concern expressed by Logan (2000) and Monsell et al., (2000) about the need to develop an understanding of basic task components in interaction with the processes controlling them.

Not all situations lend themselves to this type of automatic selection or we would be condemned to strict environmental control. In situations necessitating novel sequences of behavior, trouble-shooting, planning and decision-making, overcoming habitual tendencies, performing dangerous or complex skills, Norman and Shallice's model proposes that a higher level of control, the SAS, comes into play. Thus the SAS intervenes when the outcome of contention scheduling leads to an impasse or when voluntary action is required. The SAS acts vertically upon schema activation values and biases the contention scheduling outcome by adding activation or inhibition to particular schemas in order to conform to the conditions posed by a given situation or intention. Thus, the SAS does not participate directly in schema selection but acts to bias the outcome of contention scheduling. It is assumed that the SAS has access to information from the environment as well as a person's goals and intentions. Once this type of attentional activation is terminated, the schema activation values return to their previous levels.

The model "accounts for the ability of some action sequences to run themselves off automatically, without conscious control or attentional resouces, yet to be modulated by deliberate conscious control when necessary" (Norman & Shallice, 1986, p.3). It further specifies that if resources are consumed by other processes or schemas, this will affect an individual schema's operation and activation value (which may or may not continue to be above the schema's threshold, and therefore control current behavior). In this respect, the model incorporates the notion of limited attentional resources and their critical role in the operation of controlled and automatic skills.

Norman and Shallice's model has been useful in explaining the neurological impairments typically observed in frontal lobe patients (reviewed in Shallice & Burgess, 1991; Monsell, 1996). Damage to the frontal lobes has been related to a range of behaviors that reflect breakdown in executive control: perseveration, failures of voluntary initiation, capture errors, distractability, poor planning, sequencing, and goal-maintenance. All of these deficits can be linked to attributes presumably carried out by the SAS. Executive control failure can also occur in the absence of pathology as when one intends to do one thing but does another instead: dialing a friend's old phone number instead of the new one, getting off at the wrong bus stop, taking the route home instead of going to work, filing an article instead of giving it to the intended person, etc.. These 'slips of actions' (described in Norman 1981; Reason, 1984) reflect a temporary failure in executive control, and bear a close resemblance to some of the behaviors seen in frontal lobe patients.

Norman and Shallice's model thus accounts for a wide range of behaviors observed both in normal and clinical populations. The principles and assumptions embedded within its architecture also serve the dual purpose of addressing the question of executive control mechanisms and how specific task processes within the context of a limited capacity processing system interact within this system. More importantly, it can serve as a useful template against which to evaluate the empirical evidence collected so far in the cognitive literature as well as the data gathered in this thesis. This evidence is reviewed next.

Empirical Investigations of Attentional Control

In order to study the cognitive processes that enable attentional control over action, investigators have devised paradigms that require subjects to perform different tasks in alternation. By measuring the time required for subjects to switch between tasks, it has been possible to measure the contribution of cognitive processes that underlie attentional control over performance, and to manipulate different variables that might influence the outcome of this process.

Early Evidence

While research on attentional control has become more active in the last decade, early evidence dates back to 1927 with the pioneering study of Jersild. In his study, Jersild had subjects perform arithmetic operations in pure and alternating blocks, a procedure we shall refer to as the successive task procedure. In the pure condition, subjects either had to subtract three from or add six to each number presented in a list. In the alternating condition, subjects alternated on every second trial between the adding and subtracting operations as they went down the list. By comparing the average time taken to perform the operations in the pure condition to that of the alternating condition, Jersild found that switching tasks incurred a cost as reflected by the longer RTs found in the alternating condition. Furthermore, this cost interacted with the complexity of the operations required. When subjects had to add or subtract two-digit numbers, the switch cost was even greater, thus suggesting that operation complexity posed a greater challenge on the attentional demands required for task switching. Interestingly, when subjects were required to shift between non-overlapping categories such as performing an arithmetic operation (adding 3's) and naming the antonym of a word, there were no costs of shifting suggesting that when the stimuli unambiguously trigger the upcoming task, there is no need for an extra control process.

Spector and Biederman (1976) replicated Jersild's results with non-overlapping tasks. They also extended Jersild's study, and examined the role of visual cues in modulating the magnitude of the switch costs. As in Jersild, they instructed subjects to perform arithmetic operations in pure and alternating conditions, but in addition manipulated the presence or absence of visual cues indicating which operation had to be performed (adding a + or - sign beside the numbers in the list). They found that including a visual cue beside the numbers in the lists substantially reduced (although did not eliminate) the cost of switching operations.

Theoretical Positions Regarding Task-Switching Costs

Together, these early investigations suggest that switching one's attention from one task to another somehow calls upon special brain control mechanisms, and that a number of variables may modulate the influence of this internal process. While research on this topic was relatively scarce for a long period of time, the last decade or so has witnessed a proliferation of studies each attempting to identify and circumscribe the conditions under which switch costs are observed. Importantly, while the switch cost effect is generally robust, the nature of the process responsible for it has been the subject of considerable controversy, leading to diverging points of view regarding the mechanisms involved. Special emphasis in this thesis is given to two major theoretical positions put forward by Allport and colleagues (Allport et al., 1994; Allport & Wylie, 1999, 2000; Wylie & Allport, 2000) and by Monsell and colleagues (Rogers & Monsell, 1995; Monsell, 1996; Monsell, Yeung, & Azuma, 2000) as they motivated the experiments developed for this thesis.

The Task-Set Reconfiguration Hypothesis

One major position on the nature of switch costs is that proposed by Rogers and Monsell (1995). They argue that switching to a different task involves a task-set reconfiguration process whereby the connections between different processing modules are reconfigured to enable the appropriate stimulus-response (S-R) mappings required by the novel task. A task-set within this context is defined as a schema which contains information ("relevant stimulus attributes, response modes and values, classification schemes, S-R mappings, response criteria", etc.) about how to perform a particular task given the right internal or external trigger conditions. In other words, a task-set specifies the instructions for performing a particular task and contains a whole set of S-R associations relating to a particular task (Rogers & Monsell, 1995; Monsell et al., 2000; etc). On task-switching trials, the task-set reconfiguration process is believed to delay performance relative to repeat trials where task-sets have already been configured to enable the task-relevant S-R mappings.

The task-set reconfiguration hypothesis (hereafter referred to as the Reconfiguration hypothesis) is believed to involve both an endogenous control component which can be initiated in anticipation of a task-switch, and an exogenous control component which is triggered into action by the presentation of the new task relevant stimulus. Stimulus-triggered activation of different S-R mappings at this level (caused by the presence of irrelevant task-stimuli) may cause competing task-sets to interfere with performance and increase RT. This position is consistent with the SAS and contention-scheduling mechanisms proposed by Norman and Shallice's ATA model, and can be considered to fall under the umbrella of theories advocating the involvement of endogenous executive control mechanisms.

The Task-Set Inertia Hypothesis

A contrasting position regarding the origin of switch costs was proposed by Allport and colleagues (Allport et al., 1994; Allport & Wylie, 1999, 2000; Wylie & Allport, 2000). Rather than considering switch costs as reflecting the involvement of a stage-like reconfiguration process, they propose instead that switch costs reflect the passive influence of processes activated on trials preceding a task-switch. This position, termed the task-set inertia hypothesis (hereafter referred to as the Inertia hypothesis), attributes the costs of switching tasks to the time it takes for the system to overcome positive priming of recently activated task-sets and inhibition of previously irrelevant but currently relevant task-sets. In other words, when switching from Task A to Task B, subjects need to overcome positive priming from task A, and lift the inhibition previously applied to Task B. The interference stemming from pre-switch trials is assumed to decline gradually over time and may take up to a few minutes to completely dissipate.

Wylie and Allport (2000) recently modified the Inertia account, but the general principles remain essentially the same. In this new account, named the retrieval hypothesis, they suggest that subjects learn S-R links. During current task performance, competing links learned during previous task performance are re-evoked and interfere with current task performance. For example, in performing task A, subjects learn to associate Task A stimuli to Task A responses, and Task B stimuli to a null response. When they then switch to Task B, Task A stimuli (when present) re-evoke the previous S-R association and interfere with current Task B performance. Furthermore, it is believed that the strength of associations can be modified on every trial thus accounting for the gradiant nature of interference effects over time. While this account differs from the Inertia hypothesis in its details, it more or less captures the same basic principles, namely, that switch costs reflect the influence of processes active on trials preceding a task-switch. More importantly, in its strong version, it does not ascribe any major role to top-down control other than initiating the change of task-sets, but emphasizes the passive influence of carry-over effects from previous trials in determining the magnitude of switch costs.

Empirical Evidence Regarding the Origin of Switch Costs

Each of these positions have been supported by evidence collected by their respective proponents and extended in studies conducted by other researchers. The original studies which gave rise to these theoretical positions are reviewed next.

Early Evidence Supporting the Task-Set Inertia Hypothesis

Allport et al. (1994) originally developed their Inertia hypothesis following a series of exploratory experiments designed to identify various control components responsible for task switching. All of their experiments used the successive task procedure modeled after Jersild's with the exception that in their Experiment 5, individual RTs rather than list completion times were measured.

Task Difficulty

Allport et al. (1994) initially tested Norman and Shallice's assumption about the limited capacity of the central executive by manipulating the cognitive load of the tasks being switched between. To this end, they manipulated various aspects of task dimensions between which subjects had to switch, some being more difficult than others: stimulus features, response modes, semantic categories, and cognitive operations.

For example, in the first two experiments, subjects were presented with displays of 1 to 9 identical digits. The value of the digits was always incongruent with the number of digits in the display. In one condition, subjects had to switch between stimulus dimensions (group size or value), keeping the type of judgment to be made constant (e.g., even or odd). In another condition, the stimulus dimension was kept constant across switches, but subjects alternated between judging whether the display was even or odd or more or less than a specified value. In yet another condition, subjects switched between stimulus dimensions and types of judgments to be made. Finally, in Experiment 3, they manipulated task domains by having subjects switch between the digit Stroop task (described above) and the standard Stroop-color task. Switches were required across task domains, or between the dominant or non-dominant S-R mappings within each task.

To obtain a measure of switch costs, they compared subjects' performance in pure and alternating blocks. They reasoned that switches between more difficult tasks by virtue of their larger cognitive load on the central executive should yield larger switch costs. While the more difficult tasks yielded longer RTs, Allport et al. found switch costs of equivalent magnitude regardless of the difficulty levels presented by task switches.This they interpreted as violating Norman and Shallice's assumption about a limited capacity central executive. These results have been replicated in other studies manipulating task difficulty levels (Mayr & Keele, 2000; Rubinstein, Meyer, & Evans, 2001)

Pre-Switch Experience

Interestingly, Allport et al. (1994) found that even when subjects switched between non-overlapping tasks (alternating between a digit task and a color-naming task), their performance evidenced a switch cost . These results contrast with those of Jersild (1927) and Spector and Biederman (1976) who found no evidence of switch costs when subjects alternated between non-overlapping tasks. This led them to hypothesize that perhaps the fact that the stimuli had been associated with other tasks in previous conditions (e.g., performing a digit judgment in one condition and a numerosity judgment in another), caused more than one S-R mapping to develop over time. As such, these conflicting mappings may have interfered with performance, and caused switch costs to increase when prior experience with a stimulus was associated with a different response.

To test these ideas, they ran an experiment (Experiment 4) where subjects initially performed two tasks - reading a color word or naming the value of the digits within a display - in pure and alternating blocks. Following this, subjects were presented with the same stimulus types but now had to focus on the color of the word fonts and the group size of the display, thereby having to manage different S-R mappings to otherwise identical stimuli. In a third phase, they were instructed to perform the same tasks presented initially, thus returning to the original S-R mappings.

Allport et al. reasoned that if switch costs reflect the interference of previous S-R mappings, then the switch costs across trials within phases 2 and 3 should gradually decrease as the new associations gained in strength over the old ones. Results supported these predictions. In phase 1, switch costs virtually disappeared after the first few runs.

replicating Jersild's and Spector and Biederman's results. Thus, in the absence of previous experience with conflicting S-R mappings, switching between non-overlapping tasks incurred no costs to performance. In phase 2 and 3, there was a decrement of switch costs across trials as the new S-R mappings gained in strength, and the influence of the preceding ones faded away.

Task Asymmetry

In a further attempt to test their Inertia hypothesis, Allport et al. (1994, Experiment 5) manipulated the response-stimulus intervals (RSIs) using neutral and Stroop color-naming and word-reading tasks, hereafter referred to as Color and Word respectively. As mentioned earlier, individual RTs were measured in order to provide a more precise measure of switch costs. They reasoned that if switch costs reflect the time for a stage-like control process to operate, then providing preparation intervals exceeding the maximum switch cost should eliminate switch costs completely. RSIs of 20ms, 550ms, and 1100ms were introduced in blocks of trials involving the pure and alternating task conditions.

Several features of their results provided unexpected evidence. First, switch costs were found to be asymmetrical, and appeared to be confined to the Word task. The Color task evidenced no switch costs during any of the RSI intervals. Second, while the switch costs observed on Word trials evidenced a slight reduction across RSIs, a reliable switch cost nevertheless remained at RSIs of 1100ms. These results occurred in a context where performance on the Color task was slower than on the Word task, and Stroop interference effects were restricted to the Color task (as is found in classic Stroop studies; for a review, see MacLeod, 1991). To Allport et al. the evidence was incompatible with the notion of a stage-like control process for a number of reasons: first, if switch costs reflect the duration of an executive process, then why would switch costs be present on Word trials but absent on Color trials. Second, given that the RSI of 1100ms exceeded the alleged duration of this process, switch costs should have been eliminated at this interval.

Instead, Allport et al. proposed the following account for their results. The failure of preparation intervals in the order of 1100ms to fully eliminate Word switch costs is compatible with the notion that proactive interference effects typically extend beyond this interval. Thus, under these time considerations, the Inertia hypothesis would predict that interference from previous S-R mappings would continue to slow down performance on switch trials, thus accounting for the switch costs they found on Word trials at RSIs of 1100ms.

To account for the asymmetry of switch costs found between the Word and Color tasks, Allport et al. proposed the following explanation. In the presence of conflicting S-R mappings, suppression of the irrelevant and activation of the relevant S-R mapping will be more important when the task involves the non-dominant task-set. This is because the dominant S-R mapping tends to be evoked more strongly as classic Stroop interference effects demonstrate[1]. As a result, switching to the dominant task-set will incur stronger interference effects from the non-dominant task-set than the reverse situation. Thus,

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[1] The data collected in their experiment confirmed this notion: as reported above, Stroop interference effects were found on the Color task but were absent on the dominant Word task.

when subjects switched to the dominant Word task, they had to overcome more 'inertia' from having performed the Color task before they could activate the relevant S-R mappings, hence the larger switch costs found. The absence of switch costs on Color trials was interpreted as evidence that the activation and suppression of S-R mappings preceding the switch to Word was still operative by the time they switched back to the Color trials since the dominant Word task required no activation-suppression of the Color S-R associations.

Summary

To summarize, the Inertia hypothesis put forward by Allport and colleagues made several predictions that found support in the experiments reviewed above. In essence, the Inertia hypothesis predicted that switch costs would be found whenever the task subjects were switching from included features that afforded the task being switched to. More specifically, it predicted that the interference arising from the suppression-activation of irrelevant and relevant S-R mappings on pre-switch trials[2] would delay performance on switch trials. Consistent with this position, task difficulty had no effect on switch costs because the stimulus features responsible for the difficulty manipulation were held constant across switches. On the other hand, differential experience with a particular task established either through prior learning or through experimental manipulations caused particular S-R mappings to accrue in dominance and interfered with switch performance.

[2] The later version of the Inertia hypothesis, the retrieval hypothesis, would attribute the interference as arising from the retrieval of competing S-R links learned on pre-switch trials.

provided of course that the stimuli afforded both tasks. Asymmetrical switch costs were found when prior learning led one task to be dominant over the other. Allport et al. interpreted the data reviewed above as being incompatible with the notion that switch costs are determined by the control demands of the task subjects are switching to. Instead, they argued, they reflect interference effects arising from pre-switch performance.

Early Evidence Supporting the Task-Set Reconfiguration Hypothesis

Rogers and Monsell (1995) conducted a series of 6 experiments in an attempt to isolate the endogenous and exogenous components they assumed were responsible for task-set reconfiguration. To this end, they developed the alternative runs paradigm which requires subjects to make predictable switches between tasks on every second trial, thus integrating repeat and switch trials within a same block in an AABB-type design. They introduced this paradigm in response to concerns they held over Jersild's original successive task procedure. Switch cost estimates derived from comparing performance between pure and alternating blocks, they argued, were potentially tainted by differences related to arousal, effort, response criterion, and working memory demands posed by having to hold one versus two tasks in memory.

Their study was designed to address two major questions. The first one concerned the effect of providing various preparation intervals on switch costs. They hypothesized that if task-set control includes an endogenous component, then providing advance preparation in the form of increasing RSIs should benefit performance on switch trials. The second question they addressed concerned the task-cuing effects of competing stimulus attributes on performance. Exogenous control they reasoned, would manifest itself in the presence of task-irrelevant stimulus attributes cuing competing S-R associations. To test for these possibilities, they manipulated RSIs and independently varied stimulus attributes associated with each task. The stimuli they used for each task thus included a target and a foil. The foil was either a neutral foil (not associated with either task), or a competing foil (associated with the other task) whose response was either congruent with the target or incongruent. The tasks they chose required subjects to decide whether a letter was a vowel or a consonant or whether a number was even or odd.

Preparation

The main findings of their study can be summarized as follows. Increasing RSIs from 150ms to 600ms reduced switch costs by approximately one third. Further increments (up to 1100ms) produced no benefits on performance, leaving a residual switch cost. Thus it would appear that while subjects were able to take advantage of preparation time, part of the task-set reconfiguration could not be completed endogenously. The RSI effect, however, occurred only when RSIs were blocked and predictable. When RSIs were varied randomly across trials, switch costs remained invariant. They interpreted this to mean that the RSI effect was the result of an active reconfiguration process, not merely the outcome of passive decay, else why should it occur only when the interval was held constant (and predictable) across trials within a block.

Crosstalk and Task-Cuing

The presence of crosstalk stimuli (i.e., including a competing foil with the target) led to slower performance on both switch and repeat trials, but affected switch trials to a greater degree, a finding they referred to as the 'exogenous cuing effect'. Consistent with the Reconfiguration hypothesis, competing stimulus features appear to have cued the competing task-set, thus making it harder to switch to the other task as evidenced by longer RTs. Relative to neutral trials, there was also a tendency for congruent trials to benefit and for incongruent trials to slow down performance, a finding they referred to as the crosstalk effect. These task cuing and crosstalk effects led Rogers and Monsell to argue that the presence of competing foils cues the whole task-set. And when subjects shift task-sets, they need to somehow suppress the currently-irrelevant S-R mappings associated with the competing task-set.

Importantly, the task cuing and cross talk effects did not interact with RSIs and were found consistently throughout all the intervals, suggesting to Rogers and Monsell that they were associated with the residual switch cost. Furthermore, residual switch costs were found in the absence of crosstalk (when none of the stimuli included competing task attributes). As such, the residual switch cost could not be attributed with 'the need to suppress crosstalk'. Instead, Rogers and Monsell argued that the residual switch cost represented the exogenous control component of task-set reconfiguration. That is, reconfiguration must await the appearance of the next stimulus in order to be completed.

Post-Switch Trial Runs

Finally, Rogers and Monsell found that when runs on the same task were increased from 2 to 4 trials following an AAAABBBB design, the switch cost was confined solely to the first trial. In other words, no further improvement was observed following the first post-switch trial. These results they argued were incompatible with the notion that the residual switch cost represents gradual dissipation of proactive interference from the competing task as Allport et al. (1994) proposed (but see Salthouse, Fristoe, McGuthry, & Hambrick, 1998).

Summary

The data reviewed above shows that by affording longer intervals between a response and the appearance of the stimulus for the next task, part of the task-set reconfiguration process can be accomplished endogenously, in anticipation of the task shift. However, residual shift costs remain which cannot be attributed to gradual dissipation of proactive interference as switch costs appear to be confined to the switch trial itself; further trials within a run showed no decrement in RT. Task cuing and crosstalk effects on the other hand suggest that the residual component is associated with an exogenous control component.

Interim Summary

Both Rogers and Monsell and Allport and colleagues found evidence supporting their theoretical positions. However, their results are difficult to compare since both groups of researchers used paradigms that were meant to answer different questions. Nevertheless, both groups found that increasing preparation intervals reduced switch costs (although in Allport et al.'s study, these reductions were confined to the Word task and much smaller in magnitude), providing evidence for the existence of an endogenous control process. Importantly, both found a substantial residual cost that persisted after intervals of around 500-600 msec. In subsequent publications, Allport and colleagues (Allport & Wylie, '1999, 2000, Wylie and Allport, 2000) clarified their position with regards to the existence of endogenous control processes:

> One clarification of the TSI hypothesis is needed. Allport et al. proposed that their task-alternation costs resulted from the involuntary persistence of a prior, competing, or conflicting, task-set. However, this hypothesis emphatically does not presuppose that the persisting task-set activation must remain, necessarily, unaffected by any other, subsequent processes, other than passive decay. It is most unlikely that any neuro-cognitive activation/inhibition functions should remain encapsulated from other ongoing processes in this way... Allport et al. explicitly proposed that disengagement from the prior task-set can be triggered by task-relevant stimuli for the upcoming task, in conjunction with an instruction (or intention) to shift tasks … On the other hand, the question of how far, or under what conditions, the reconfiguration of S-R mappings is *complete* after a single switch trial, is an empirical question ... Undoubtedly, additional control processes are brought to bear on the pre-existing task-set, on a 'switch' trial. If not, the previous task would continue to be executed ... How this occurs; what forms of task-relevant cuing can facilitate or impede it; how the appropriate condition-action rules--mediating an externally and/or internally cued shift of

stimulus-to-task mappings--are represented in procedural working memory; and how such rules are initially compiled or acquired; these are all fundamental questions for a theory of task control. They constitute a major agenda for future research. In this paper, however, we are primarily concerned with the *nature of the resulting control states* (emphasis added), and their consequences once they have been engaged. (Allport & Wylie, 1999, p. 279-280).

Thus it would seem that the point of contention here is not so much about the intervention of endogenous control processes per se. Allport and Wylie, in their 1999 paper, state that "in one respect at least, Allport et al. (1994) were clearly, empirically mistaken. Finding no compelling evidence in their data for active preparation of the upcoming task, or 'task-set reconfiguration', in advance of the imperative stimulus for a switch trial, they were tempted to infer that such anticipatory task-preparation might simply not be observable task-switching paradigms of this kind ... Since then, a number of other authors have provided clear evidence of anticipatory task-preparation, using task-switching paradigms with variable preparation intervals" (Allport & Wylie, 1999, p. 279-280). Indeed, there has been ample evidence that switch costs can be reduced or increased by manipulating variables that afford preparation in anticipation of a task shift: Affording longer preparation intervals by manipulating either RSI or the interval prior to and after the presentation of a task-cue (Goshke, 2000; Kramer, Hahn, & Gopher, 1999; Mayr & Keele, 2000; Mayr & Kliegl, 2000; Meiran, 1996, 2000, 2001; Meiran, Chorev, & Sapir, 2000; Rogers & Monsell, 1995), providing cues or instructions informing subjects in advance of the task shift (Gopher, Armony, & Greenshpan, (2000); Goshke, 2000; Mayr & Kliegl, 2000; Meiran, 1996; 2000; Meiran et al., 2000; Rubinstein et al., 2001), preventing subjects from preparing for the upcoming trial (Goshke, 2000), or manipulating expectancy prior to the task shift (Ruthruff, Remington, & Johnston, 2001) have all been shown to affect switch costs. Thus, while there seems to be a consensus with regards to the role of endogenous control processes in engaging a new task-set, the point of contention concerns the interpretation of residual switch costs.

The Residual Switch Cost

According to Allport and colleagues, residual switch costs represent the 'resulting control states' after endogenous control mechanisms have enabled the task shift. Interference from preceding task-sets, they argue, are the 'principal determinants' of residual shift costs. On the other hand, Rogers and Monsell (1995) claim that residual switch costs represent an exogenously triggered control process that must wait for the appearance of the next stimulus to complete task-set reconfiguration. Any viable theoretical model, they argue, needs to explain why crosstalk and task-cuing effects are immune to preparation intervals (Monsell et al., 2000). Other authors have offered alternative explanations for the residual switch cost. These are reviewed next.

Incomplete Preparation:

De Jong (2000) proposed that residual switch costs represent incomplete preparation or occasional failures to prepare for the upcoming task due to a lack of motivation, failure to appreciate the advantage of preparation, or because it requires effort. By mixing repeat trials performed at long RSIs (fully prepared trials) with switch trials at short RSIs (unprepared trials), De Jong demonstrated that the distribution of switch RTs at long RSIs represents a good fit of these mixed distributions. The data collected in De Jong (2000, and in De Jong, Emans, Eenshuistra, & Wagenmakers, forthcoming, cited in De Jong 2000) supports this mixture model. Furthermore, their model motivated an experiment where residual switch costs completely disappeared under conditions favoring optimal preparation (De Jong et al., forthcoming, cited in De Jong, 2000). Nieuwenhuis & Monsell (2002) reanalysed Rogers and Monsell's Experiment 3 (1995) data, and found that the mixture model fit their data well. Nevertheless, their model failed to fully account for data they collected in a replication of the experiment where they manipulated the incentives for optimal preparation. That is, while they succeeded in reducing basic RTs , the effect of increasing RSIs only reduced switch costs by half. Thus, while De Jong's model may account for part of the residual switch cost, it fails to completely explain the data.

A different but consistent position regarding the effects of incomplete preparation was proposed by Mayr and Kliegl (2000). In their view, task switching involves the retrieval of S-R associations from long-term memory. Given the high-interference nature of the experimental context, residual switch costs reflect occasional failures to retrieve task-set retrieval rules from LTM. On occasions where subjects' retrieval attempts fail, they must wait for the appearance of the stimulus to retrieve the appropriate response. Hence, while these retrieval failures may not necessarily lead to erroneous responses, they nevertheless occasionally slow down performance overall on switch trials, hence the residual switch costs. Note that this view is also compatible with that of Rogers and Monsell's task-cuing explanation, albeit for different reasons.

Response-Set Reconfiguration

Meiran (2000a) objected to the view that residual switch costs represent a state of incomplete preparation. Instead, he proposed that task switching involves different task facets that are reconfigured independently of one another at different points in time during the RSI interval (see also Meiran et al., 2000, Meiran, 2000b). Meiran argued that switch costs occur because stimuli, responses, and possibly other task facets afford more than one task, and need to be independently reconfigured to enable accurate performance on switch trials. He assumed that part of the switch cost which decreases with longer preparation intervals is associated with stimulus-set reconfiguration while residual costs are associated with response-set reconfiguration. Accordingly, he demonstrated (Meiran, 2000a, Experiment 1) that when the stimuli are bivalent but the responses are univalent (thus eliminating the need to reconfigure response-sets), long preparation intervals succeeded in abolishing the switch cost completely. Meiran also found evidence of interference from previous task-sets on switch costs. However, unlike Allport and colleagues, this interference was associated with the stimulus-set reconfiguration and not to the residual cost.

Backward Inhibition

A different approach was adopted by Mayr and Keele (2000) who hypothesized that backward inhibition of to-be-abandoned task-sets may be responsible for the residual switch costs observed in paradigms where subjects continuously shift back and forth between two task-sets. They reasoned that backward inhibition may serve the purpose of preventing perseveration errors. To test this hypothesis, they had subjects shift between three tasks, and compared shift performance on tasks that were repeated two trials earlier to those where no such repetitions occurred (i.e., comparing the third trial of an ABA run to that of a CBA run). The baseline measure involved trials where no shifts or repetitions of lag-2 trials were involved (i.e., the third trial of an BAA run). This allowed them to compare pure shift costs against those involving an inhibition component. They found that RTs were larger when a lag-2 repetition was involved. Moreover, they demonstrated that pure shift costs (those devoid of lag-2 repetitions) were almost eliminated at long preparation intervals, leading them to conclude that the residual shift costs observed in experiments where subjects keep shifting between two task-sets may in part reflect backward inhibition. When the need for backward inhibition is eliminated, residual switch costs disappear at long intervals. Importantly, they demonstrated that this inhibition effect is due to a low-level control mechanism that operates on the switch trial itself. Thus, unlike Allport and colleagues, they attributed the inhibition effect to a process occurring during disengagement from a task-set to prevent re-activation of irrelevant responses.

Arbuthnott and Frank (2000) replicated these effects using semantic categorization tasks therefore confirming the generalizability of Mayr and Keele's findings to other type of stimuli. Moreover, they used vocal responses which enabled them to discriminate between errors due to a failure to engage the appropriate task-set (wrong-task errors) and errors due to selecting the inappropriate task-set response (task decision errors). They found that wrong-task errors were mainly associated with the portion of switch cost associated with the backward-inhibition process. Importantly, they argued that this task-alternation cost (ABA) could not be due to passive interference occuring on the previous trial since no cost was observed in the pure shift cost condition (CBA).

Conclusions

Clearly, these results highlight the fact that no simple explanation will resolve the issue. The studies reviewed above demonstrate that task-sets involve many components all of which or some of which may need to be reconfigured during a task shift. As Meiran's results suggest, switch costs may be multi-componential and specific to the processes engaged by the tasks used in different paradigms. As such, explorations into task-switching across different paradigms may be uncovering different but complementary components involved in task control. As Monsell et al. (2000) also argue, given that task-sets by definition involve a variety of task parameters, it is likely that switch costs reflect the resetting of multiple components: "'Task-set' must be a complex of numerous 'settings': which locus to attend to, which attribute of the stimulus to attend to, which response mode and values to get ready, what classification of the relevant stimulus attribute to perform, how to map those classes to response values, with what degree of caution to set one's criterion for response, etc." (p. 252). In this thesis, we entertain the idea that perhaps the particular tasks between which subjects are required to shift call upon different sets of control processes depending on the basic processes each task entails. Alternatively, the same set of control processes may produce different effects depending on the basic task processes they are called upon to operate.

A Closer Look at Allport and Colleagues' Findings

In this respect, it is interesting to note that most of the evidence collected by Allport and colleagues to support their Inertia hypothesis and later their Retrieval hypothesis was based almost entirely on the use of the Stroop-color task. This task incorporates 'control' challenges of its own (Ward, Roberts, & Phillips, 2001), and indeed has long been considered the epitome of the automatic-controlled processing distinction (e.g., MacLeod, 1991; MacLeod & MacDonald, 2000). The fact that the task incorporates dominant and non-dominant S-R mappings may be a critical factor in explaining the pattern of results obtained by Allport and colleagues. We shall return to this issue in a later section, but before, a summary of subsequent work by Allport and colleagues is presented below.

The 'Before and After' Paradigm

After their 1994 publication describing exploratory investigations into the origins of shift costs, Allport and colleagues extended their work using a variety of paradigms that capitalised on the divergent S-R mappings of the Stroop-color task. Their work led them to question the assumption that repeat trials represent an appropriate baseline against which to measure switch costs. In one group of studies, they employed what they termed the 'before and after' paradigm (Allport & Wylie, 1999, 2000). In this procedure, subjects are required to perform pure blocks of neutral and Stroop Word trials prior to and after having performed blocks of Stroop Color trials. Blocks included anywhere from 10 to 30 trials. In this manner, it is possible to examine the effects of prior exposure to divergent Color S-R mappings on subsequent Word performance. Note that except for the first trial within a block, there were no task shifts involved.

Using different variants of this paradigm, the authors (Allport & Wylie, 1999, 2000) found that relative to pre-Color exposure blocks (or to a control group which never performed the Color task), there were substantial interference effects on Word RTs. The recency and frequency of prior exposure to divergent S-R mappings determined the magnitude of interference. The interference was strongest on the first trial of a pure block. Importantly, the interference persisted on further trials within a run and was asymptotic (e.g., Allport & Wylie, Experiment 3, 1999). The fact that interference continued on repeat trials, and was proportional to the amount of experience subjects had with divergent S-R mappings, led them to claim that these trials cannot be used as a baseline measure against which to compute switch costs. In addition, the asymptotic performance found in the presence of continued interference also cast doubt on Rogers and Monsell's original conclusion that these data represent a state of completed reconfiguration.

The authors also found evidence of a restart effect: when subjects did not switch tasks but rather just paused between blocks of the Word task, RTs to the first trial were slower. Allport and Wylie (1999, 2000) argued that these restart and first trial interference effects represent a large portion of the residual switch cost. In their arguments, they made a distinction between goal setting and performance readiness which represents "the time needed for the system to 'settle' to a unique response" (Allport & Wylie, 1999b, p. 66). Thus, in their view, these interference effects represent long-term priming from the prior performance of tasks with divergent S-R mappings. "We find it helpful to think of attention and "control" issues in terms of the integrated competition (IC) hypothesis. as put forward by Duncan and colleagues ... goal activation. determines (constrains) which task is performed. The processing time ... needed to settle to a unique response. on the other hand will depend on the amount of conflict within the network. Associations. connection weights. formed in the execution of a prior. competing task. we suggest. can contribute massively to such conflict." (Allport & Wylie. 1999b, p. 67).

Together. the evidence collected by Allport and colleagues with the 'before and after' paradigm seems to provide strong support for their theory. The prolonged interference effects found on Word repeat trials following a task shift presents problems for any theory positing the existence of an extra control process of the kind proposed by Rogers and Monsell (1995). Nevertheless. this finding can be accomodated by such a theory given that performance was asymptotic following the task shift in the post-Color Word blocks. Indeed. it seems surprising that RTs on repeat trials within a run did not show decrements as any theory of interference would predict. There were perhaps not enough trials to witness such decay in the procedure they used. Yet in other studies using fewer runs (albeit with a different paradigm) (Wylie & Allport. 2000. Experiments 2 and 3) such decrements were observed. Thus the issue in this regard cannot be settled with this kind of data.

Task Asymmetry Revisited

Perhaps the most damaging evidence to theories emphasizing a stage-like reconfiguration process over the influence of pre-shift performance is the finding that it is more difficult to switch to a task affording the dominant S-R mappings. Recall that

Allport et al. (1994) found that switching to the dominant Word task incurred larger switch costs than switching to the non-dominant Color task. They explained their findings by suggesting that the stronger inhibition applied to the Word task during Color performance carried over to the Word trials. As a consequence, it took longer for the system to lift this inhibition and activate the Word response. Such inhibition was unnecessary on Word trials by virtue of their more dominant S-R mappings. Thus shifting to the Color task after having performed the Word task incurred very little or no shift costs. Similar findings have been reported by other researchers in studies exploiting the relative dominance of tasks (Loasby, 1998, cited in Allport & Wylie, 1999; Meuter & Allport, 1999; Yeung, 1997, cited in Allport & Wylie, 1999). That it should be more difficult to switch to the 'easier' task presents serious problems to theories postulating that it is the control demands of the engaged task that determine the magnitude of switch costs.

On the other hand, the need to inhibit the dominant response to stimuli when the task requires the non-dominant response may be assumed to introduce additional control demands that confound the pattern of results observed. Several assumptions contained in Norman and Shallice's ATA model address this issue. In the model, it is assumed that inhibition between any two schemas at the level of contention scheduling is determined in part by the sharing of common processing structures. This would be the case in situations involving divergent S-R mappings as is the case in the Stroop-color task. It is further assumed that when tasks become highly practiced, the schemas controlling them are less vulnerable to interference from other schemas which use the same processing structures.

In this respect, we may speculate that the Stroop Word task represents this type of automatic processing that is immune to interference from other schemas, in particular the schema associated with the Color task. The model further proposes that less automatic schemas which make use of the same processing structures as other competing schemas will either need to undergo contention scheduling or the biasing intervention of the SAS to become activated. Furthermore, in situations involving the overcoming of habitual tendencies (as we might expect when subjects are asked to name the color of incongruent color words after having had to perform the Word task), intervention of the SAS is needed to help the schema win the contention scheduling competition. If we assume that the Color task represents this second type of control situation, we find ourselves in a position where performance on Stroop Color trials may necessitate additional control operations over and above those required by a task shift. This implies that additional intervention from the SAS may be necessary on repeat Stroop Color trials. Therefore, when computing a measure of switch costs by subtracting repeat RTs from switch RTs, little or no differences may be found. This would be consistent with the absent switch costs found on Color trials in Allport et al. (1994, Experiment 5).

An additional assumption contained within Norman and Shallice's model addresses the issue of switch costs they found on the Word task: when other schemas or processes consume working memory resources, this may lower a particular schema's activation value and make it harder for it to reach threshold. Applied to the Stroop situation within a task shifting paradigm, these assumptions suggest the following scenario: performing the Stroop Color task places additional demands on working memory resources. As a consequence, less than the optimal amount may be available to perform the Word task, therefore requiring additional activation to raise the schema's activation value above threshold: hence, the larger switch costs they found on the Word task relative to the Color task. This scenario rests of course upon the assumption that both task-sets are represented within working memory. It is not an unreasonable assumption to make and certainly Allport and colleagues, in their writings, seem to have embraced it . Furthermore, its role in task shifting and in overcoming Stroop interference has been demonstrated in a number of individual differences studies (e.g., Engle, Tuholski, Laughlin, & Conway, 1999; Kramer, Hahn, & Gopher, 1999; Kray, & Lindenberger, 2000; Long, & Prat, 2002).

While the above account is highly speculative[3], it nevertheless raises the possibility that Allport and colleague's findings are due to confounding factors embedded in the use of tasks involving asymmetrical (dominant and non-dominant) S-R mappings. Clearly, we need to establish the generality of their findings with other types of tasks and stimuli. Whether the same pattern of results would obtain with tasks employing

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[3] The present scenario was developed to account for the absence of switch costs found on Color performance and the larger switch costs found on Word performance in Allport et al.'s study (1994, Experiment 5). It does not directly address the persisting interference effects observed on pure Word blocks following performance on pure Stroop Color blocks (Allport & Wylie, 1999). Additional assumptions would be needed to account for these effects. A discussion of these is not included here as the purpose of the exercise was to direct the attention of the reader to potential problems involved in the use of asymmetrical S-R mappings in these task-switching paradigms.

symmetrical S-R mappings or other types of stimuli remains an empirical question which we set out to explore in the experiments presented in this thesis.

PARADIGM AND OVERVIEW OF THE EXPERIMENTS

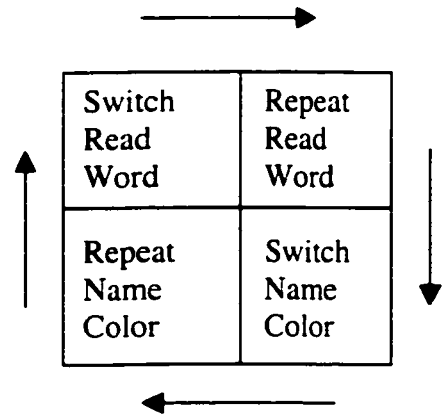
The three experiments reported in this thesis were conducted to investigate further the control mechanisms that underlie switch costs. The experimental approach developed by Wylie and Allport (2000, Experiment 1) was chosen for its ability to isolate the source of switch costs. Because this approach is central to the design employed in this thesis, the basic rationale is explained in detail below.

Wylie and Allport argued that the alternating runs paradigm as used in Rogers and Monsell's (1995) did not permit a determination of whether the switch costs observed arose from processing taking place on previous trials (trials being switched *from*) or on current trials (trials being switched *to*). They proposed that proactive interference arising from previous trial processing may be equally responsible for the switch costs Rogers and Monsell (1995) observed in their study.

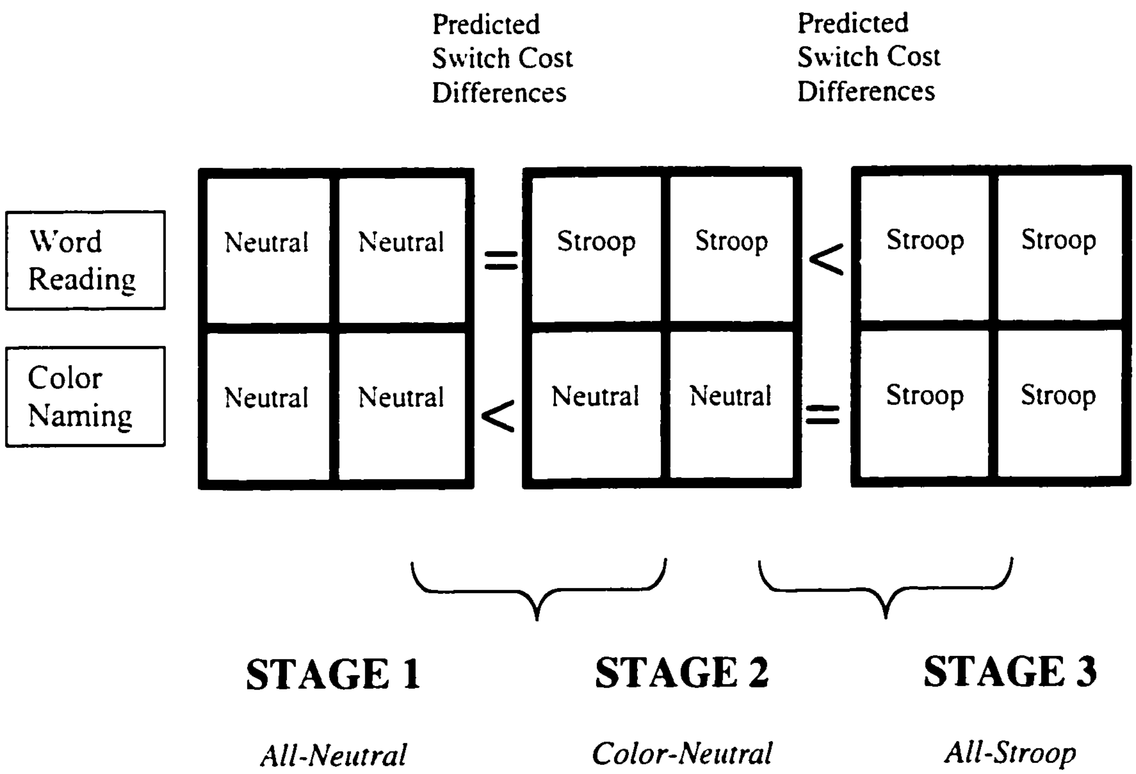
In order to tease out the influence of previous processing from current task processing on switch costs, they used the alternating runs paradigm, and independently manipulated the valence of stimuli in tasks being switched *to* and tasks being switched *from*. The tasks they employed were the Stroop Color and Word tasks. Subjects were required to alternate between Color and Word switch and repeat trials in three conditions. In a first stage, all the stimuli were neutral (univalent) with respect to the competing task. Thus each task was unambiguously cued by its respective stimuli. In a second stage, the word stimuli became Stroop (bivalent) while the Color stimuli remained neutral. Finally, in a third stage, all the stimuli were Stroop, meaning that they afforded or cued both the Color and Word tasks.

The different conditions are illustrated in Figure 1. Consider how Word changes from being neutral in the first stage to being Stroop in the second and third stages. On the other hand, Color remains neutral in Stages 1 and 2, and becomes Stroop in Stage 3.

Wylie and Allport (2000) predicted that if switch costs are determined by the control demands of tasks being switched *from*, then the difference in switch costs for any one task between stages should be determined by whether or not the stimuli of the competing task were the same or different across any two stages. For example, consider the Word task in Stages 1 and 2. Switch costs on Word should be the same between these stages since the task subjects are switching *from* (Color) is neutral in both cases, and does not necessitate inhibition of the competing Word task. These predictions are reversed when we consider Stages 2 and 3. That is, a greater switch cost to Word is predicted in Stage 3 relative to Stage 2. Again consider the control demands of the task subjects are switching *from*. Here the Color stimuli change from being neutral in Stage 2 to being Stroop in Stage 3. This means that in performing the Color task in Stage 3, subjects must inhibit their tendency to read the word (the competing task). This inhibition in turn must be lifted when subjects switch back to the Word task. Therefore switching *from* Color to Word incurs a greater switch cost in Stage 3 relative to Stage 2.



(a)



(b)

Figure 1. (a) Sequence of trials within the alternating run blocks within each stage. Each block consists of switch and repeat trials alternating between each task in a clockwise direction as indicated by the arrows; (b) Predicted switch costs differences for each task between Stages 1 and 2 and Stages 2 and 3 in Wylie and Allport's (2000, Experiment 1) design.

The reverse pattern is predicted when performance on Color is considered[4]. Given that the valence of the task subjects are switching *from* (Word) changes from neutral in Stage 1 to Stroop in Stage 2, the Inertia hypothesis predicts greater switch costs in Stage 2. No difference in switch costs to Color is predicted between Stages 2 and 3 given that Word is Stroop in both stages.

Now consider predictions borne out of the Reconfiguration hypothesis favored by Rogers and Monsell (1995). Here greater switch costs are predicted when the task being switched *to* involves competitor-cuing (determined in this case by task valence). Accordingly, given that Word changes from being neutral in Stage 1 to being Stroop in Stage 2, a greater switch cost to the Word task is predicted in Stage 2. On the other hand, no difference is predicted between Stages 2 and 3 because Word is Stroop in both cases, thus representing equivalent control demands. With Color, the Reconfiguration hypothesis predicts no difference in switch costs between Stages 1 and 2, and a greater switch cost in Stage 3 relative to Stage 2. This occurs because Color (the task being switched *to*) is neutral in Stages 1 and 2, and Stroop in Stage 3.

As can be seen from the above description, this type of design allows one to test contrasting views on the origin of switch costs. It affords the further advantage of incorporating the alternative runs paradigm used by Rogers and Monsell (1995), thus making it easier to compare the two theories. The data that Wylie and Allport (2000, Experiment 1) collected under these conditions clearly supported the Inertia hypothesis

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[4] Although the design of Wylie and Allport's experiment was meant primarily to study Word performance, it nevertheless allows predictions to be made on Color.

(see Figure 2). That is, the magnitude of switch costs on Word and Color tasks between stages followed changes in the valence of the competing task, and this, irrespective of changes in the valence the task being switched *to*.

Consider the data from the Word task. Wylie and Allport found that switch costs between Stages 1 and 2 did not differ while those found in Stage 3 were greater than those of Stage 2. The authors argued that this pattern mirrored the change in valence status of the competing Color task across the three stages (neutral-neutral-Stroop), and thus argued in favor of the Inertia hypothesis. Now consider the data from the Color task. Wylie and Allport' results showed that it was the change in valence of the competing Word task across stages (neutral-Stroop-Stroop) that determined the magnitude of change in Color switch costs. Accordingly, Color switch costs were greater in Stage 2 when the competing Word task became Stroop. No differences were found between Stages 2 and 3, presumably because the competing Word task was the same (i.e., Stroop) in both cases. Thus, when the experimental design permits a dissociation of previous task processing from that of current task processing the evidence favors the Inertia hypothesis over the Reconfiguration view put forward by Rogers and Monsell (1995).

A closer look at Wylie and Allport's data however, suggests that the use of the highly asymmetrical Stroop Word and Color tasks may have introduced working memory confounds. That is, in addition to changes in the magnitude of switch costs across stages, there were block effects between Stages 2 and 3 which reflected a general slowing down in performance that affected both repeat and switch trials alike. If we assume that these stage effects reflect a higher load on working memory, then it becomes difficult to

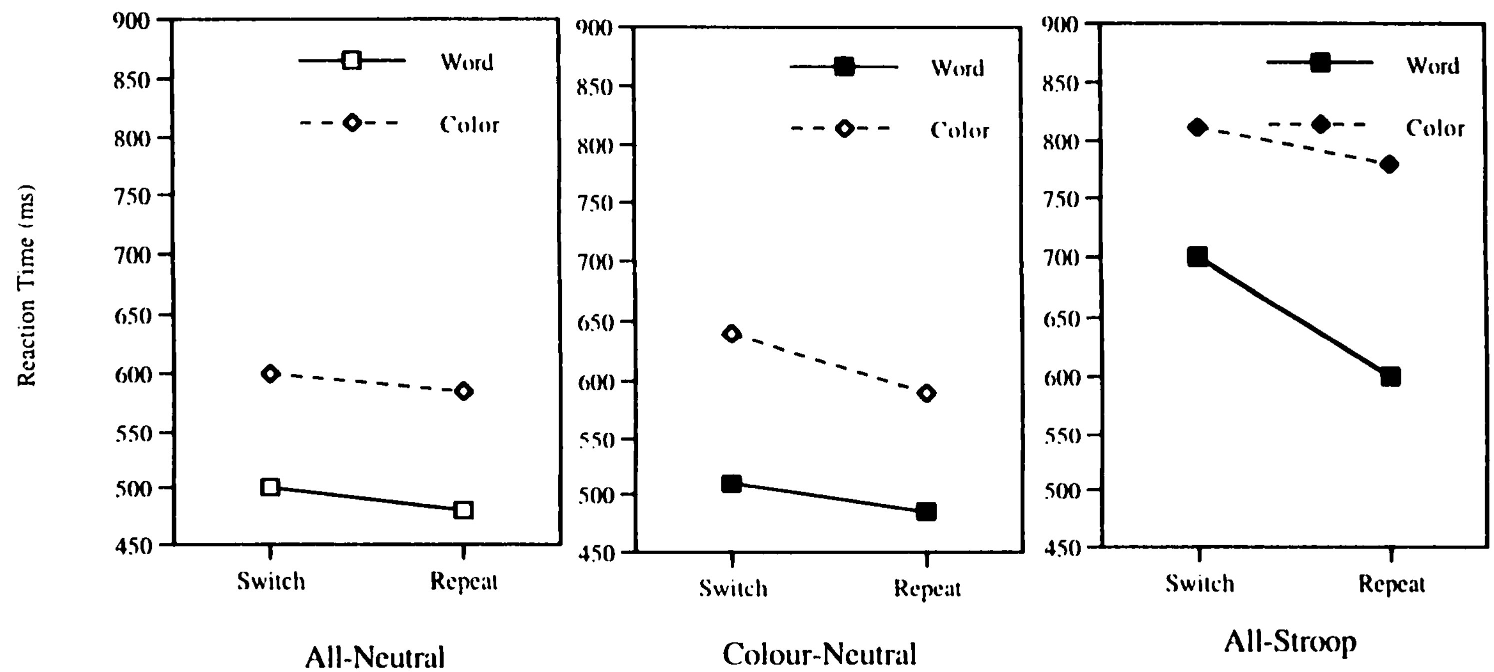

Figure 2. Reproduction of Wylie and Allport's (2000) pattern of findings on word-reading and color-naming performance across the three stages. Mean RTs are plotted for word-reading and color-naming switch and repeat trials within the alternating runs of each stage (filled symbols represent Stroop stimuli whereas empty symbols represent neutral stimuli).

unambiguously interpret the pattern of changes on switch costs because each task makes different demands on working memory. Does the introduction of Stroop stimuli on the Color task affect working memory resources to a greater extent than the introduction of Stroop stimuli on the Word task? And is it important whether one or both tasks involve Stroop stimuli?

It may be that under a low working memory load (Stages 1 and 2 where the competing Color task was neutral but the Word task was Stroop), the highly practised Word task was not affected by the added difficulty presented by Stroop stimuli. Indeed, the lack of interference from Stroop stimuli on Word has been well documented in the literature (for a review, see MacLeod, 1991). So the lack of Stroop interference found in Stage 2 is hardly surprising, and has been shown to occur whether subjects are performing in a switching context or merely reading Stroop color words. On the other hand, introducing Stroop stimuli in the competing Color task in Stage 3, may have taxed working memory resources to such a degree that even the relatively easy Stroop Word task became more challenging; hence, the larger RT and the larger switch cost on Word in Stage 3. A useful analogy in this regard is that of driving. Having a conversation while driving a car in easy traffic conditions is relatively effortless and "costless" , but as soon as driving conditions become hazardous, the relatively "automatic" skill requires more attentional resources. Although this analogy reflects concurrent task processing, it applies to the current experimental situation if we assume that holding both tasks in a state of readiness within procedural working memory bears similarities to dual task performance.

The point that is being made here is that when the tasks subjects are switching between are asymmetrical, there may be an interaction with available working memory resources that is specific to each task. The dimensions over which the tasks are asymmetrical (e.g., degree of automaticity in the case of the Color and Word tasks) may also introduce confounds related to the presence of differential control operations[5].

Given that available working memory resources may interact with task demands in the determination of performance (as the presence of stage effects would suggest), it seems reasonable to question whether these influences are equivalent when the tasks are asymmetrical. Unless we remove or control for this factor, it is difficult to draw any firm conclusions about what the data mean with regards to the Inertia hypothesis. The experiments conducted in this thesis therefore represent an attempt to disentangle these issues by using the same paradigm as that of Wylie and Allport's, but manipulating task symmetry as well as types of tasks employed.

Task Switching Paradigm

In keeping with Wylie and Allport (2000, Experiment 1), the experiments in this thesis were modeled after Rogers and Monsell's alternating runs paradigm . Subjects were required to switch between two tasks (generically termed tasks A and B for purposes of this section) on every second trial. Each task required subjects to respond to target-foil stimulus pairs that belonged to one of two response categories. The target was either paired with a neutral foil (the combination of which is named hereafter as a univalent

[5] Note here that task asymmetry is reflected by RT differences. This index does not provide any information as to which cognitive factor is responsible for the difference.

stimulus) or with a competing foil (the combination of which is named hereafter as a bivalent stimulus). Each target-foil pair appeared in one of four quadrants presented at the center of a computer monitor. Subjects indicated their response by pressing one of two buttons. The location of the stimulus pair within the four quadrants cued the subject as to which task to perform. Two adjacent quadrants were assigned to each task. Trials rotated in a clockwise fashion through the four quadrants alternating between task switches and task repetitions.

The experiment proceeded in three discrete consecutive stages designed to separate the effects of interference from the disengaged task from the control demands of the engaged task.

Prior to the experimental phase, subjects were trained in alternating pure blocks of trials to help establish stimulus-response associations for each task. Each trial in this phase consisted of single univalent stimuli (target paired with a neutral foil) presented in a square at the center of the monitor.

As in Wylie and Allport (2000, Experiment 1), various combinations of task valence were chosen in each of the three experimental stages to separate influences on switch costs caused by current task demands (task being switched *to)* from those of previous task demands (task being switched *from)*. In the first stage, both tasks A and B involved univalent stimuli. This implies that the stimuli used for each task unambiguously cued the target task. In the second stage, Task A involved bivalent stimuli while Task B involved univalent stimuli. Note here that Task A afforded both the current and the competing task while Task B was neutral with respect to the competing task. And finally, in a third stage, both tasks A and B involved bivalent stimuli and thus each afforded both the current and the competing tasks.

Four critical contrasts are of interest in this design: performance on Task A between Stages 1 and 2 and between Stages 2 and 3, and performance on Task B between Stages 1 and 2 and between Stages 2 and 3. Taken together, these contrasts permit a test of the Inertia hypothesis against that of the Reconfiguration hypothesis.

Overview of the Experiments

Given that the theoretical position put forward by Allport and colleagues (Allport et al., 1994; Allport & Wylie, 1999, 2000; Wylie & Allport, 2000,) rests primarily on evidence collected with the Stroop-color task, it seemed important to verify the generalizability of their findings to other tasks and stimuli.

Experiment 1: Effects of Task Symmetry.

Experiment 1 explored the possibility that Wylie and Allport's results arose because of the asymmetry that existed between the tasks they chose, namely, reading and naming the color of neutral and Stroop stimuli. This may have introduced a potential working memory confound that could have influenced the pattern of results observed. Accordingly, letter (vowel or consonant judgments) and digit (even or odd judgments) tasks, symmetrical in terms of relative difficulty, were created for Experiment 1. (In terms of the overall design, the letter task corresponded to Task A, and the digit task, to Task B). This symmetry manipulation accomplished the joint purpose of testing their model with stimuli used in Rogers and Monsell's studies while removing aspects of task asymmetry that may have introduced working memory confounds into Wylie and Allport's studies.

Experiment 2: Effects of Task Asymmetry - Semantic vs. Episodic

Data from the first experiment indicated that when task asymmetry was removed, the resulting pattern was more consistent with Rogers and Monsell's Reconfiguration hypothesis. In order to determine whether task symmetry was a critical factor in the pattern of results observed in Experiment 1, the second experiment examined whether introducing a task asymmetry using the same type of stimuli as that employed in Experiment 1 would replicate the pattern of results obtained by Wylie and Allport (2000, Experiment 1). Accordingly, Task B now involved an episodic component to increase processing difficulty relative to task A. This manipulation translated into slower RTs for Task B which became the non-dominant task relative to task A. The type of stimuli employed otherwise remained the same as in Experiment 1.

Experiment 3: Effects of Task Asymmetry - Controlled vs. Automatic

Whereas the task asymmetry in Experiment 2 varied along a semantic-episodic processing distinction, a different task asymmetry was built into Experiment 3. This manipulation was introduced following a failure to replicate Wylie and Allport's pattern of results in Experiment 2 despite the inclusion of a task asymmetry. In Experiment 3, each task was semantic in nature but one task, Task B, was more difficult to perform than the other (as reflected in slower RTs). In this respect, the tasks more closely resembled the Color and Word tasks used by Wylie and Allport insofar as we assumed that they differed in the degree of automaticity with which they were carried out. We entertained the possibility that the critical factor underlying the emergence of interference effects with Stroop-color stimuli was related to asymmetry with regards to the degree of automaticity that each task entailed.

EXPERIMENT 1

Experiment 1 was designed to test the possibility that Wylie and Allport's (2000. Experiment 1) results were due. in part. to the built-in asymmetry present in the Stroop-color task. Working memory confounds caused by the different demands posed by the Color and Word tasks may have biased the differences observed across the three conditions in Wylie and Allport. Moreover. given that the Color task involves different control demands relative to the Word task. the pattern of results observed may have been confounded by this factor. In order to remove these potentially confounding factors. we used the letter and digit tasks used by Rogers and Monsell (1995) (see also. Poulsen & Segalowitz. 2000) which have proved to present symmetrical degrees of difficulty as far as reaction time is concerned. In terms of Wylie and Allport's experimental design. the letter task corresponded to Task A and the digit task. to Task B.

The inclusion of the letter and digit tasks within the paradigm used by Wylie and Allport also permitted a test of their theory with other types of stimuli. In principle. given that the pattern of variation in stimulus valence across the three conditions in the present experiment was identical to that produced in Wylie and Allport with Stroop-color stimuli. the Inertia hypothesis. if valid. should predict the same pattern of results. On the other hand. if working memory demands and control factors inherent to basic task processing confounded the results. we might expect to see a pattern of results more consistent with the Reconfiguration hypothesis now that these factors are controlled for. That is. the change in switch cost magnitude could be determined by the control demands of the task being switched *to*. An additional advantage to using the letter and digit tasks employed by Rogers and Monsell (1995) was to permit a direct comparison of switch costs on selected equivalent trials: comparing results in the all-univalent condition of Experiment 1 to those obtained in their no-crosstalk condition, and results in the all-bivalent condition to those in their cross-talk condition.

Method

Subjects

Sixteen subjects (M = 28 years old) participated. Subjects were paid 6$ for participating or received partial credit for course fulfillment.

Materials

Two stimulus lists were prepared for the letter and the digit tasks. Stimuli consisted of character pairs made up of a target and a foil. The target for the letter task was selected from a sub-set of consonants (G, K, M or R) and vowels (A, E, I, U). For the digit task, the subsets consisted of even (2, 4, 6, 8) and odd (3, 5, 7, 9) digits. Foils were selected from a collection of symbols (#, +, &, %) that were neutral with respect to each task.

Training Stimuli

For the training phase, we created a list of 8 blocks of 24 digit and 8 blocks of 24 letter stimuli, for a total of 384 stimulus items. Trials alternated between letter and digit blocks. The targets and foils were randomly selected with replacement from their respective pools and randomly assigned the left or right position within the pair. Each target was paired with a neutral foil, making the stimuli univalent.

Experimental Stimuli

Three stimulus sequence templates (specifying stimulus options, order, counterbalancing, etc.) corresponding to one of the three experimental stages were used to create lists of 192 experimental stimuli. The templates were further divided into four blocks of 12 warm up trials and 36 experimental trials. The template of the first block was used to select stimuli for the practice block as well as the first experimental block. Each template designated specific stimulus attributes that were later used to randomly select targets and foils from their respective samples (resulting in a pseudo-random sampling procedure). Each template specified an equal number of letter and digit targets which were paired with alternating sequences of switch and repeat trials. Target and foil position within the pair as well as well response category (left or right key-press) were counterbalanced across trials. Also, whether the current trial required the same or different left-right response as the previous trial was counterbalanced across other sub-conditions.

In Stage 1, all of the letter and digit targets were paired with neutral foils. In Stage 2, the digits were paired with neutral foils and the letters were paired with competing digit foils. In Stage 3, both the letter and digit targets were paired with competing foils. In stages that involved bivalent stimuli (letter-digit combinations), response congruency between target and foil was counterbalanced across trials. The various conditions are illustrated in Figure 3. No more than four consecutive left or right button presses, congruent or incongruent trials, and left or right target positions were allowed to occur.

The templates were then used to create eight unique experimental lists per stage for purposes of quadrant and response counterbalancing assignments described later in the

(a)

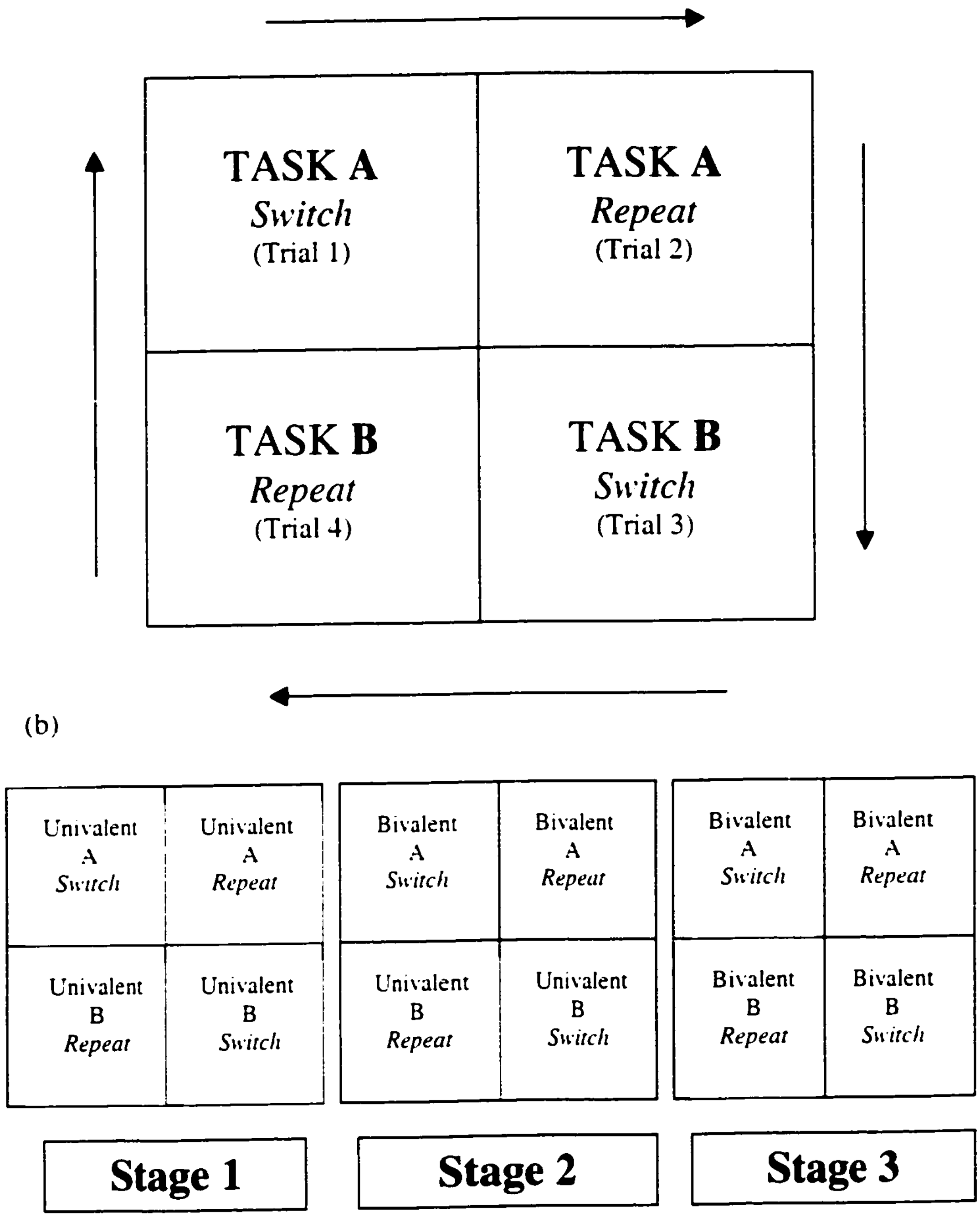

Figure 3. (a) Illustration of clockwise alternation of switch and repeat trials on Tasks A and B in alternating runs paradigm; (b) Wylie & Allport's (2000) Experiment 1 design : subjects proceed through three discrete consecutive stages comprised of blocks of switch and repeat trials modeled after the alternating runs paradigm described above : task valence (univalent-bivalent) is manipulated across stages.

procedure. No two consecutive identical targets or foils were allowed to be selected within a sequence. The selection process resulted in each exemplar target and foil being represented an approximately equal number of times across the lists. The first 48 trials of each template were used to create the practice block preceding each experimental stage.

The stimuli were presented on a Power MacIntosh 4400/200 attached to a 14-inch monitor set to 640 X 480 pixel resolution. Stimuli were shown in uppercase 24-point Palatino font. Hypercard version 2.3 software was used to program stimulus presentation and collection of reaction time (RT) and error data. An XCMD subroutine was used to measure RTs with about 5 ms resolution, and to toggle trials with the onset of each screen frame. Responses were made on a number key pad with number 4 and 6 keys labeled with left and right arrows respectively.

Procedure

Subjects signed a consent form which informed them as to the nature of the study and the general procedures used. The experimenter then explained to them that the experiment was divided into two parts: Part I, and Part II which was further divided into three stages. They were informed that they would receive written instructions prior to each part, but they were kept naive as to the purpose of the training phase and the three experimental stages. The experiment took about one hour to complete.

During both the training and the experimental phase, subjects classified letters into vowel/consonant and digits into even/odd categories. The stimulus remained on the screen for 5000 ms or until the subject responded. If participants made an error, they heard a "boing" sound. The response stimulus interval (RSI) was approximately 318 ms. This interval is shorter than the RSI normally associated with the residual switch cost. However, it served the dual purpose of maximizing the probability of observing interference effects while allowing for effects due to endogenous reconfiguration to emerge. Participants obtained an extra 1500 ms following erroneous responses to help them recover and prepare for the next trial. Information at the bottom of the screen throughout the experiment reminded subjects about the response key assignments for each task.

For half the subjects, the even digit responses were assigned to the left key, while the other half received a right key assignment. Consonant judgments were assigned a left key response and vowels a right key response. Subjects were instructed to respond as quickly as possible without sacrificing accuracy. They were strongly encouraged to keep their errors below four. To motivate them to maintain a strict response criterion, a point system was used during both the training and experimental phases. Subjects were given feedback and recorded their performance on a response form after each block of trials. Each correct response earned them 1 point while each error cost them 3 points. They obtained a bonus of 5 points if their performance was faster on a current block than it was on a preceding block, and another bonus of 5 to keep their errors below four.

Training Phase

The training phase was divided into 8 blocks of letter trials and 8 blocks of digit trials. Subjects alternated between performing blocks of digit trials and blocks of letter trials. Each block started with a signal "Press any key to begin". Seated approximately 60 cm from the monitor, subjects saw a target and foil in a rectangle (measuring 8 cm by 4.5

cm) appear at the centre of the screen and responded with the appropriate key press. Participants proceeded between each block at their own pace.

Experimental Phase

In this phase, subjects were told that they would perform the same tasks as previously, but that the stimuli would be presented in a different format. They were instructed that the stimuli would now appear in one of four quadrants presented at the center of the monitor, and that they were to perform the digit and letter task as before. Two adjacent quadrants were assigned the letter task and the other two, the digit task. Trials always began with the letter task. The stimuli appeared one at a time, in a clockwise manner resulting in the alternation of predictable switch and repeat trials. This setup made it possible for the letter task to begin in one of four quadrant positions. Crossing quadrant positions with the two response-key assignments for the digit task thus resulted in eight counterbalanced sets. This procedure controlled for potentially confounding eye movement and position factors.

Each experimental stage included one practice block and four test blocks of 48 trials each, for a total of 192 trials. After completing Stage 1, subjects were informed that Stage 2 involved the same tasks but that the letter stimuli would now be paired with a digit instead of a neutral symbol. They were otherwise instructed that everything else would remain the same and to continue as they did before. Once they completed this stage, they were given further instructions informing them that in Stage 3, both the letter and digit stimuli would be paired with competing foils. The complete experimental design is illustrated in Figure 4.

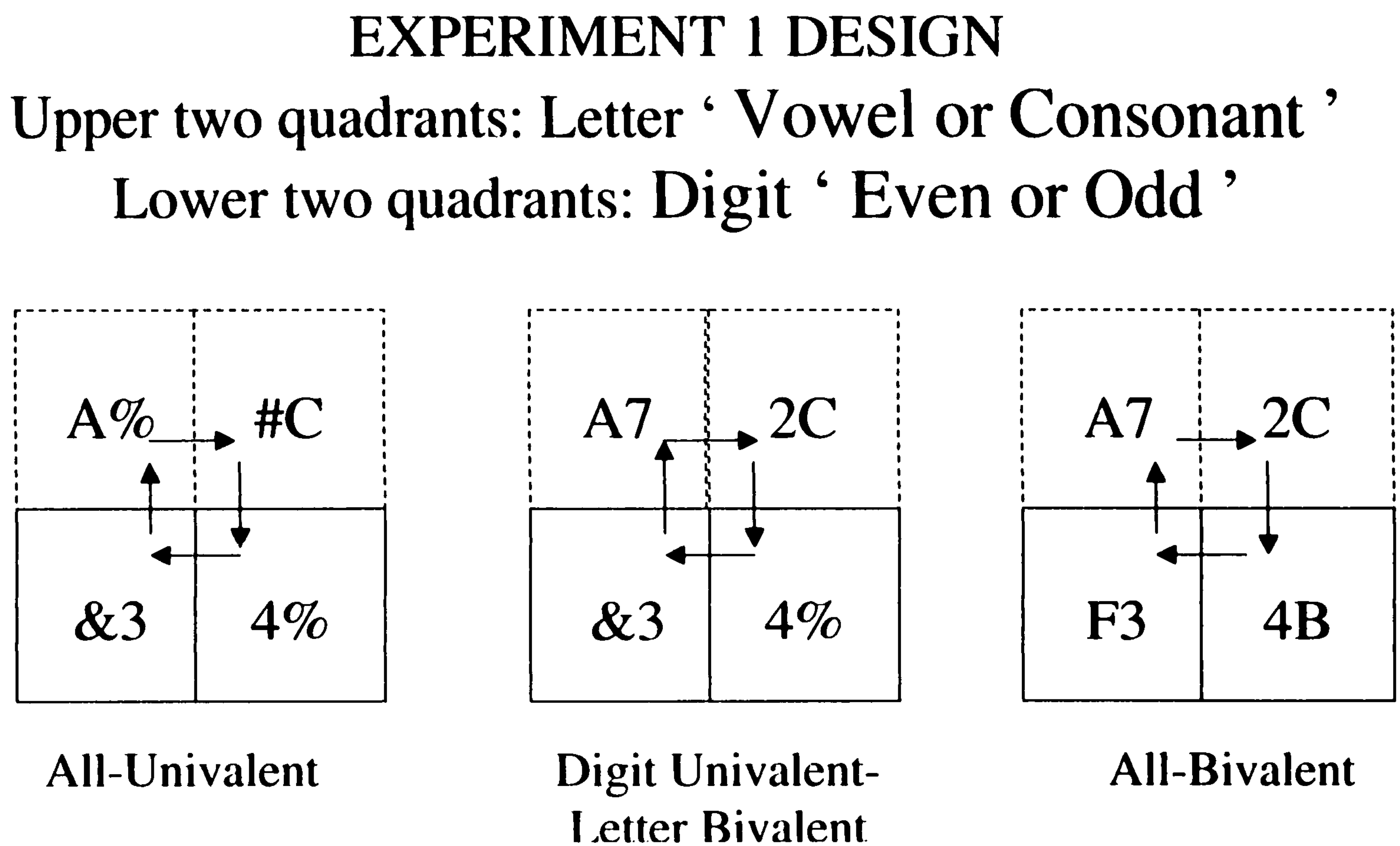

Figure 4. Example of letter and digit trials within each stage of Experiment 1. In the first stage all stimuli were univalent; in the second stage, the digit stimuli were univalent, and the letter stimuli, bivalent; in the third stage, both letter and digit stimuli were bivalent. Subjects' task was to classify the letters as 'vowels or consonants' and digits as 'even or odd' by pressing a left or right key.

Results

Mean RTs were calculated for each subject. A total of twelve design cells resulted from the combination of the following three variables: Task (digit or letter), Switch (switch or repeat), and Stage (1, 2, or 3). RTs that were associated with errors (M = 2%) as well as trials following errors were removed from the analyses resulting in the mean removal of 4% of the 432 experimental trials for each subject. The slowest 10% RT data were then replaced with the next highest value for each design cell for each subject following a winsorizing procedure.

Repeated-measures ANOVAs were used in all the analyses. Group mean RTs for each cell are presented in Appendix B. Results representing performance on switch and repeat trials across each stage of the experiment are illustrated in Figure 5. The following sections present detailed analyses of the main effects and interactions for each stage.

Within-Stage Comparisons

Repeated-measures ANOVAs were conducted in each stage using Task (letter vs digit) and Switch (repeat vs switch) as factors. These analyses provided information about task symmetry and switch costs. In the present study, the letter task was meant to be the counterpart of Wylie and Allport's Word task, while the digit task, the counterpart of their Color task.

Stage 1: All Univalent

Results from Stage 1 showed no main effect of Task, indicating equivalent performance on each task. Mean RT on the digit task was 651 ms, and on the letter task, 670 ms, F (1, 15) = 1.85, MSE = 3269, p > .05. These data confirm that tasks were

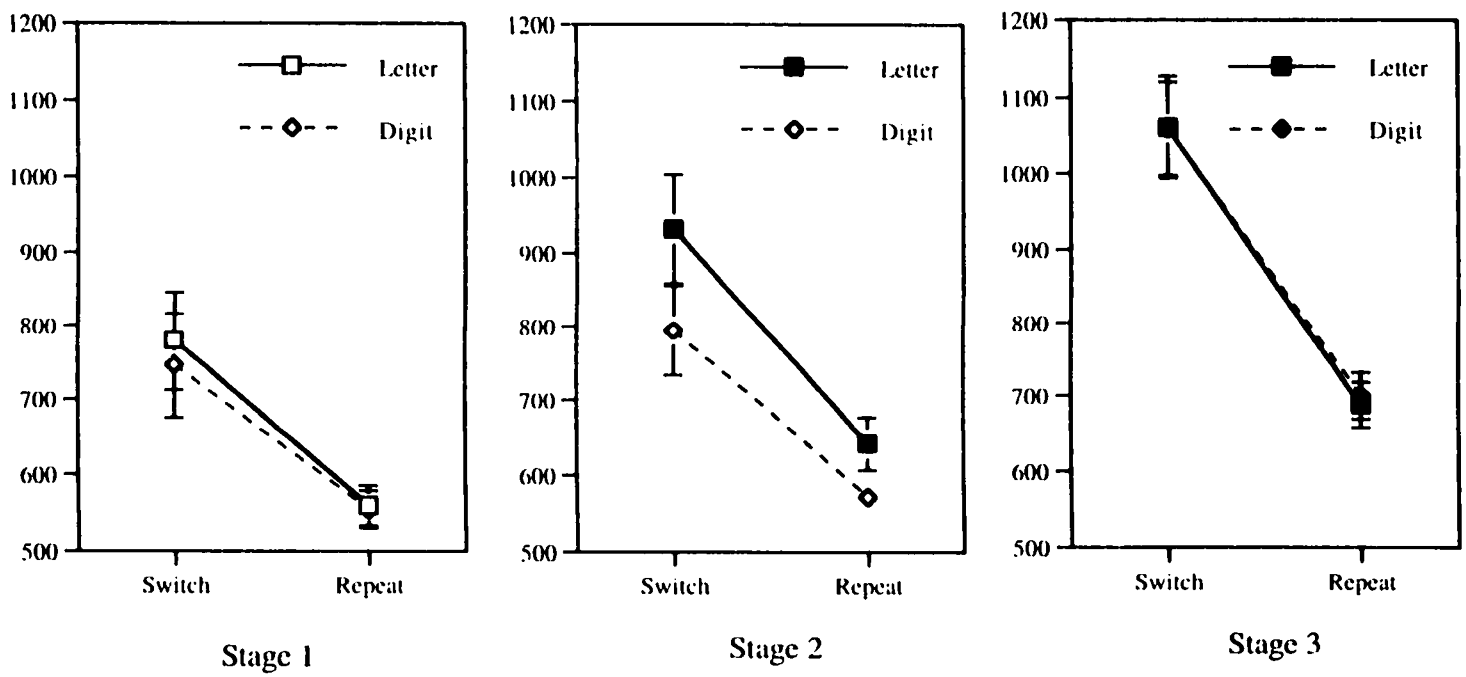

Figure 5. Mean RTs for switch and repeat letter and digit trials across the three stages of Experiment 1 (univalent trials are represented by empty symbols and bivalent trials, by filled symbols). Error bars represent between-subjects standard errors.

symmetrical with respect to RT. There was, however, a main effect of Switch, with repeat trials averaging 558 ms , and switch trials, 763 ms, $F(1, 15) = 12.59$, $MSE = 53{,}564$, $p = .003$. The interaction of Task and Switch was not significant, $F(1,15) = 1.40$, $MSE = 2439$, $p > .05$. This suggests task symmetry on both repeat and switch trials. The mean switch cost for letter trials (M cost = 220 ms) was statistically equivalent to that of digit trials (M cost = 191 ms).

Stage 2: Digit Univalent / Letter Bivalent

A similar analysis was conducted on the data from Stage 2. In this stage, the main effect of Task was significant, $F(1,15) = 10.97$, $MSE = 15{,}816$, $p = .005$. The digit task which involved univalent stimuli averaged faster RTs than the now bivalent letter task ($M = 683$ ms and $M = 787$ ms respectively), suggesting that the increased challenge presented by the letter task slowed down RTs. Again there was an effect of switch. Repeat trials ($M = 607$ ms) were significantly faster than switch trials (M = 863 ms), $F(1, 15) = 30.85$, $MSE = 34{,}135$, $p < .0005$. The interaction, however, was not significant, $F(1,15) = 3.05$, $MSE = 5{,}850$, $p > .05$, suggesting that switch costs were not significantly different across both tasks (letter M cost = 290 ms, digit M cost = 223 ms).

Stage 3: All Bivalent

In the third stage, both tasks involved bivalent stimuli that cued the current task as well as the competing task. In this case, the task asymmetry found in Stage 2 disappeared and the main effect of Task was not significant, $F(1,15) = .06$, $MSE = 5{,}899$, $p > .05$. The mean RT performance on the digit was 879 ms while on the letter task it was 875 ms. Again there was a main effect of Switch, $F(1,15) = 44.42$, $MSE = 48.355$, $p < .0005$, with repeat trials averaging 694 ms and switch trials, 1060 ms. The interaction was not significant, $F(1,15) = .28$, $MSE = 2.587$, $p > .05$. As shown in Figure 5, the switch cost for letter trials (*M* cost = 373 ms) was equivalent to that of digit trials (*M* cost = 360 ms)

Between-Stage Comparisons

Two separate repeated-measures ANOVAs comparing performance across stages were conducted for each task using Stage (1 vs 2, and 2 vs 3) and Switch (repeat vs switch) as factors. They were meant to examine the influence of changes in the valence of current and competing tasks across stages on switch costs for each task. Switch cost indices for each critical comparison were computed by subtracting RT on repeat trials from RT on switch trials. Where indicated, two post hoc *t*-tests (for each task) using Bonferroni-adjusted alpha levels were conducted to identify the source responsible for interaction effects.

Letter Task (Task A)

The purpose of this analysis was to compare switch performance on letter trials across Stages 1 and 2, and across Stages 2 and 3. Recall that the letter task followed a sequence of univalent-bivalent-bivalent across the three stages, while the digit task followed a sequence of univalent-univalent-bivalent (see Figure 4).

Stage 1 vs. 2.

According to Wylie and Allport's previous results with the Stroop-color task, the switch cost on letter RTs should have remained the same between Stages 1 and 2, even though the letter task was bivalent and thus more challenging in Stage 2. This is because the digit task was univalent in both stages, and therefore did not involve inhibition of the letter task. On the other hand, Rogers and Monsell would predict a greater switch cost on letter trials in Stage 2 given the increased challenge presented by the presence of bivalent letter stimuli in Stage 2.

Results generally supported Rogers and Monsell's position. There was a main effect of Stage, $F(1,15) = 16.89$, $MSE = 13{,}013$, $p = .001$, and a main effect of Switch, $F(1,15) = 24.20$, $MSE = 42{,}977$, $p < .0005$. Subjects took longer to respond to switch trials ($M = 856$ ms) than to repeat trials ($M = 601$ ms). Letter RTs were slower in Stage 2 ($M = 787$ ms) than in Stage 1 ($M = 670$ ms). More importantly, the interaction between Stage and Switch was close to significance, $F(1,15) = 4.11$, $MSE = 4{,}780$, $p = .061$.

As seen in Figure 5, letter switch costs appear larger in Stage 2 than they were in Stage 1. Thus, even though the competing task, the digit task, was univalent in both stages, the data suggested a trend towards an increased switch cost on letter trials in Stage 2. In other words, despite the fact that participants did not need to inhibit the letter task while performing the digit task, there appeared to be an increased cost incurred by switching to the letter task in Stage 2.

Post hoc *t*-tests revealed that both repeat and switch trials evidenced an increase in RT from Stage 1 to Stage 2 (see Figure 5). Repeat RTs averaged 560 ms in

Stage 1 and 642 ms in Stage 2, t (15) = 3.55, p = .003; switch RTs averaged 780 ms and 932 ms respectively, t (15) = 3.70, p = .002. Thus, the increased challenge presented by the presence of bivalent stimuli in the letter task in Stage 2 not only increased switch costs, but seems to have slowed down letter RTs overall.

Stage 2 vs. 3.

In this analysis, letter RTs were compared across Stages 2 and 3 with a repeated-measures ANOVA, again using Stage (Stage 2 vs Stage 3) and Switch (repeat vs switch) as factors. Letter trials were bivalent in both these stages but the competing task, the digit task, involved univalent stimuli in Stage 2 and bivalent stimuli in Stage 3. According to Wylie and Allport, the need to inhibit the letter task while performing the bivalent digit task in Stage 3 should have caused the letter switch cost in Stage 3 to increase relative to Stage 2. On the other hand, Rogers and Monsell would predict no difference given that equivalent challenges are presented in both stages with respect to the bivalent letter task.

Results again seemed to favor Rogers and Monsell's position. There was a main effect of Stage, F (1,15) = 5.62, MSE = 21,687, p = .032, and a main effect of Switch, F (1,15) = 46.04, MSE = 38,199, p < .0005. Subjects appeared to be faster in Stage 2 than in Stage 3, with letter RTs averaging 787 ms and 875 ms respectively. Subjects were also faster to respond on repeat trials (M = 665 ms), than on switch trials (M =997 ms). More importantly, the interaction was not significant, F (1, 15) = 2.57, MSE = 10,741, p > .05, (see Figure 5). Thus, where Allport and Wylie would predict an interaction (given that the valence of the task being switched *from* was different), none was present in this experiment. This pattern is more consistent with Rogers and Monsell's position which would predict no difference in switch costs between Stages 2 and 3 given that letter trials presented equivalent challenges (both involved bivalent stimuli).

Digit Task (Task B)

The purpose of these analyses was to compare switch costs on digit trials between Stages 1 and 2 and Stages 2 and 3. Recall that letter trials were univalent in Stage 1 and bivalent in Stages 2 and 3 while digit trials were univalent in Stages 1 and 2, and bivalent in Stage 3 (see Figure 4).

Stage 1 vs 2.

A repeated-measure ANOVA was conducted using Stage (Stage 1 vs Stage 2) and Switch (repeat vs switch) as factors. While the valence of the digit task remained the same across the two stages (univalent), the status of the letter task changed from univalent to bivalent. If the magnitude of switch costs is determined by the task being switched *from*, then one should observe increased switch costs to the digit task in Stage 2. On the other hand, if it is the control demands of the task being switched *to* that is critical, then no difference is predicted.

The only significant effect was that of Switch, $F\ (1,15) = 16.13$, $MSE = 42{,}458$, $p = .001$. Subjects responded more quickly on repeat trials ($M = 563$ ms) than on switch trials ($M = 770$ ms). Overall, digit latencies in Stage 1 ($M = 651$ ms) did not significantly differ from those in Stage 2 ($M = 683$ ms), $F\ (1,15) = 1.98$, $MSE = 8{,}549$, $p > .05$. Nor was the interaction of Task and Stage significant ($F\ (1,15) = .73$, $MSE = 5,\ 774$, $p > .05$). As can be seen in Figure 5 , switch costs in Stage 1 were equivalent to those in Stage 2.

Thus, contrary to the Inertia hypothesis, the presence of bivalent stimuli in the letter task in Stage 2 did not significantly affect the switch cost on the digit task relative to Stage 1.

Stage 2 vs. 3.

In this analysis, digit switch and repeat latencies were examined across Stages 2 and 3 with a repeated-measures ANOVA again using Stage and Switch as factors. There was a main effect of Stage, $F(1,15) = 84.86$, $MSE = 7,266$, $p < .0005$. Subjects were slower overall in Stage 3 ($M = 879$ ms) than in Stage 2 ($M = 683$ ms). There was also a main effect of Switch with repeat trials averaging 636 ms, and switch trials, 927 ms, $F(1,15) = 38.92$, $MSE = 34,916$, $p < .0005$. More importantly, the interaction was significant, $F(1,15) = 10.55$, $MSE = 7,071$, $p = .005$. As can be seen in Figure 5, the switch cost on digit trials in Stage 2 was smaller than in Stage 3. This pattern supports Rogers and Monsell's position that it is the challenge presented by the task being switched *to* that is critical to the magnitude of switch costs observed. Thus when the valence status of the digit task changed from univalent in Stage 2 to bivalent in Stage 3, greater switch costs were observed in Stage 3.

Post hoc t-tests revealed that both repeat and switch trials evidenced an increase in RT from Stage 2 to Stage 3. Repeat RTs averaged 572 ms in Stage 2 and 700 ms in Stage 3, $t(15) = 6.02$, $p < .0005$; switch RTs averaged 795 ms and 1059 ms respectively, $t(15) = 7.23$, $p < .0005$. Thus, in addition to the increased digit switch cost reflected by the Stage by Switch interaction, there was evidence of an overall performance slow down on both switch and repeat trials alike in Stage 3.

Discussion

The main purpose of Experiment 1 was to test Wylie and Allport's (2000) Inertia hypothesis against Rogers and Monsell's (1995) Reconfiguration hypothesis. To this end, the same design and procedure as that employed by Wylie and Allport (2000, Experiment 1) was used since it allowed to contrast predictions borne out of each model.

In order to remove a potential working memory confound related to the use of asymmetrical tasks, symmetrical letter and digit tasks were employed . The choice of the latter was also motivated by a need to test the Inertia hypothesis with tasks and stimuli different from the widely used Stroop-color task. To help contrast the results of this experiment with those of Wylie and Allport (2000, Experiment 1), it is useful to remember that in terms of the overall design, the letter task corresponds to their Word task (Task A), while the digit task corresponds to their Color task (Task B).

Within-Stage Analyses

Before considering the critical contrasts, it is important to consider analyses concerned with overall switch effects and the presence or absence of task symmetry within each stage. Results show a robust switch effect as evidenced both in the within- and between-block analyses. The data also confirm that the tasks were symmetrical in Stage 1 and 3 at least as far as RT is concerned. When we consider the analyses within each stage, the only time that there was a significant task effect was in Stage 2 where tasks varied on stimulus valence: the bivalent letter task took longer to perform than the univalent digit task. On the other hand, when both tasks were univalent (as in Stage 1) or bivalent (as in Stage 3), task performance was equivalent as evidenced by the absence of a task effect. The lack of interaction between Task and Switch in Stage 2 suggests that although the letter task was slowed down overall, the switch costs for each task were equivalent. In fact, none of the within-block analyses revealed a Task by Switch interaction. This suggests that the inclusion of bivalent stimuli affected repeat and switch trials in a similar fashion.

Between-Stage Analyses

Critical contrasts concern the analyses for each task across Stages 1 and 2, and Stages 2 and 3. Unlike Wylie and Allport's findings, when the magnitude of switch costs for each task was compared between stages, the pattern of results clearly supported Rogers and Monsell's model of a stage-like executive control mechanism.

Letter Trials (Task A)

Consider the letter data first. Whereas Wylie and Allport found switch costs differences with the Word task (akin to the letter task in this experiment) between Stages 1 and 2, and equivalent switch costs between Stages 2 and 3, the present data showed the exact opposite pattern. In fact, results showed that switch costs varied as a function of valence changes in the trials being switched *to*. There was a trend towards increased letter switch cost in Stage 2 relative to Stage 1, consistent with the idea that including a competing foil in the task being switched *to* causes switch costs to increase. This occurred in a context where the competing digit task was univalent in both stages, and as such did not require suppression of the letter task. These data are consistent with Rogers and Monsell's (1995) data who found that the inclusion of cross-talk stimuli (as was the case in this experiment with the inclusion of bivalent stimuli within Stage 2) increased both main RTs and switch costs. That is, they found greater switch costs on trials involving bivalent stimuli[6].

And, contrary to Wylie and Allport's findings, no differences in switch costs were observed between Stages 2 and 3. Thus the fact that the competing digit task required inhibition of the letter task in Stage 3 does not seem to have increased letter switch costs. This pattern is more consistent with the idea that it is the control demands presented by the current task that determines the magnitude of switch costs.

Digit Trials (Task B)

Performance on digit trials across stages was also determined by changes in the valence of current trials as opposed to that of previous trials. There were no differences in switch costs observed between Stages 1 and 2 while increased switch costs were found in Stage 3 relative to Stage 2. Again this pattern, rather than following changes in the valence of the competing task, followed changes in the valence of the current digit task. The results are consistent with Rogers and Monsell's task cuing effects on main RTs and switch costs. Relative to Stage 2, when the digit stimuli included competing letter attributes in Stage 3, there was a main stage effect and an increased switch cost. These results are in direct contrast to Wylie and Allport's data, and seem to refute the Inertia hypothesis: on their Color task (comparable to the present digit task in terms of the overall design), switch costs differed between Stages 1 and 2, and were the equivalent between Stages 2 and 3.

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[6] The reader should be aware, however, that these analyses refer to the crosstalk condition and were conducted on RTs collapsed across tasks.

General Considerations

Together, the findings from the letter and digit analyses seem to support the notion that switch costs vary as a function of the demands of the task being switched *to*, irrespective of previous task processing conditions, at least in the case where neither task is dominant. As such, they are consistent with Rogers and Monsell's notion that the control demands of switch trials themselves determine the costs to performance. Of course, it is entirely possible that contention scheduling is responsible for the increased switch costs observed on bivalent trials. The present design was not meant to address this issue. Nevertheless, consistent with Rogers and Monsell's task cuing effects found in the presence of crosstalk, including a competing stimulus attribute on switch trials in the present experiment slowed down subjects' ability to activate the task-set over and above general slowing down effects.

In fact, when we contrasted our data to Rogers and Monsell's (1995) Experiment 1 data, we found RTs of comparable magnitudes (see Figure 6). Collapsed across tasks, switch costs in the all-univalent stage of the present experiment averaged 205 ms whereas those of Rogers and Monsell's in the no crosstalk condition (involving neutral stimuli only) averaged 161ms. When considering data from the all-bivalent stage, switch costs averaged 366 ms whereas Rogers and Monsell's with crosstalk stimuli averaged 328ms. Considering the expected fluctuations one would anticipate given the differences inherent to the different paradigms employed in the respective studies, these data are remarkably analogous.

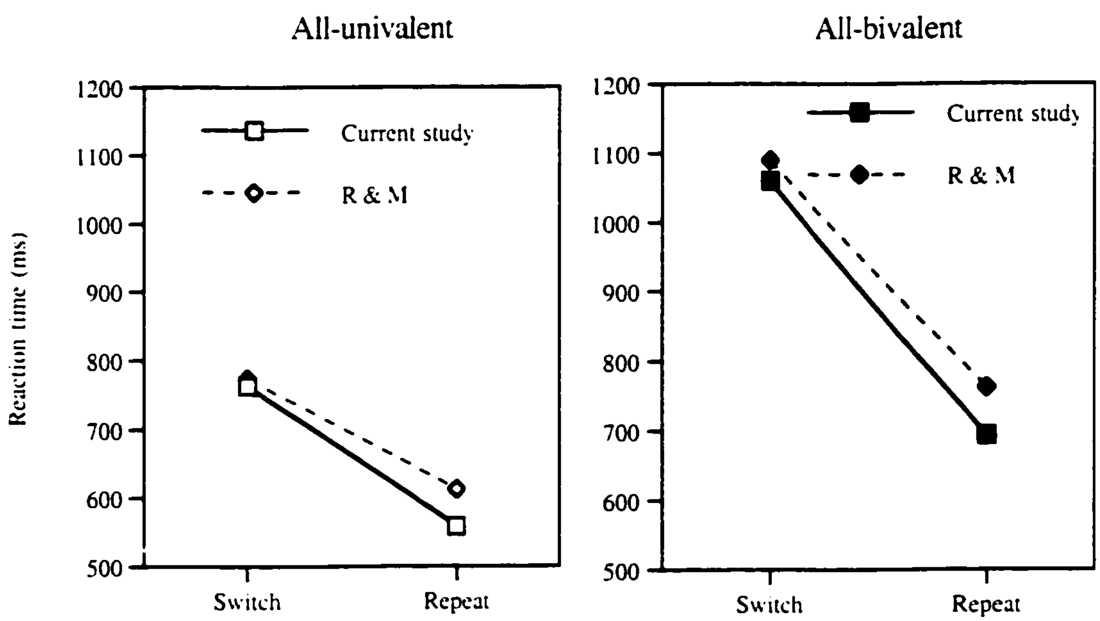

Figure 6. The graph on the left side shows data from Stage 1 (all-univalent), Experiment 1 of the present study and the no-crosstalk condition of Rogers and Monsell's (1995) Experiment 1; the graph on the right side shows data from Stage 3 (all-bivalent), Experiment 1 of the present study and combined data from congruent and incongruent trials in the crosstalk condition in Rogers and Monsell's Experiment 1 (bivalent trials are represented by filled symbols).

Another finding merits our attention. Whereas there was a main effect of Stage for the letter task between Stages 1 and 2 (indicating that both repeat and switch RTs were slower when the letter stimuli were bivalent), no such effect was found for the digit task. This is compatible with the fact that the digit repeat and switch stimuli were univalent in both stages and therefore represented equivalent task demands. Given that the letter task consumed more working memory resources, however, one might have expected the digit performance to be slowed down. Certainly, the data found in Rogers and Monsell's (1995) Experiment 1 would suggest this: when they analysed performance on neutral trials in the context of the no crosstalk condition and compared it to performance on neutral trials in the crosstalk condition (which included 2/3 crosstalk stimuli), they not only found that RTs were slower in the crosstalk condition, but switch costs were larger in that condition. In the case of the present study, however, the bivalent letter stimuli represented only one half of the trials. In addition, the bivalent status of trials clearly distinguished which task was to be performed: the digit trials were always neutral, whereas the letter trials, always bivalent. As such working memory resources may not have been taxed enough to slow down performance on digit trials.

More interesting is the pattern of results obtained between Stages 2 and 3. Recall that in this case, the letter stimuli were bivalent in both stages while the digit stimuli gained bivalent status only in Stage 3. Despite the fact that the letter task in and of itself represented the same demands, there was a main effect of Stage, indicating that letter RTs were slower overall in Stage 3. There was also a main effect of Stage for the digit task which, in this case, is consistent with the fact that both switch and repeat trials now involved bivalent stimuli. The combined result was that both digit and letter tasks once again exhibited symmetrical RTs (as they did in Stage 1).

Together these data suggest a greater change in RT than one would expect from the changing demands for each task. That is, if task demands (as reflected by task valence) had been the sole determinant of changes in RTs, then one would have expected basic RTs in the digit task to increase to the level of the letter task in Stage 2. And in principle, the letter RTs should have remained the same in both stages given equivalent valences (i.e., letter RTs should not have evidenced a Stage effect). Certainly, this was the case for the digit task between Stages 1 and 2 where equivalent stimulus valence across both stages led to equivalent RTs on both switch and repeat trials. Thus, had these considerations been the sole determinant of changes in performance, we might have expected letter RTs in Stage 3 to be the same as in Stage 2, and digit RTs to increase to the level of Stage 2 letter RTs. Instead, when comparing Stage 3 to Stage 2 performance, it appears that both tasks evidenced an increase in RT. This would suggest that the change of performance on the digit task between Stages 2 and 3 was more than proportional to the change warranted by the change in valence. Moreover, it would suggest that the changing task demands of the digit task influenced performance on the letter task even though its valence did not vary across Stages 2 and 3.

Together, these results seem to point to the possibility that tasks with their varying degrees of difficulty, not only can place different demands on working memory, but that these demands interact with individual task performance. It could be argued that when the digit task became bivalent, this affected subjects' ability to carry out the letter task with the same ease they experienced in Stage 2. This increased working memory load in turn affected their performance on the digit task which was now competing for less working memory resources than it would have, had the letter task been univalent for example.

These data lend credibility to the argument that switch performance cannot be studied without giving consideration to working memory issues.

It could be argued that controlling for the potential working memory confound by using symmetrical tasks eliminated a portion of switch differences between stages that could be attributable to this factor. Interestingly, when the stimuli on both tasks regained equivalent valence status in Stage 3 (albeit different from that of Stage 1), performance was again completely symmetrical on both switch and repeat trials. These results contrast with those of Wylie and Allport who found a Task by Switch interaction in Stage 3. It would seem then that unlike Wylie and Allport's Color and Word tasks, the processing demands required by the present symmetrical tasks interacted with working memory resources in an equivalent fashion. While this factor represents one possible explanation for why we did not obtain a pattern of results consistent with Wylie and Allport's, further exploration of this hypothesis tested in Experiments 2 and 3 suggested that the story is more complicated. As will soon be shown, it appears that the type of tasks used is critical to the pattern of switch cost differences obtained.

EXPERIMENT 2

Results from Experiment 1 showed that when tasks are symmetrical with regards to RT, switch costs are determined by the control demands of the engaged task. In other words, by the task one has switched *to*, and not by the task one has switched *from*. In order to ascertain that these effects were due to the removal of the asymmetry factor, we proceeded to re-introduce a task asymmetry using the same type of stimuli used in Experiment 1. Accordingly, we manipulated task difficulty by adding an episodic retrieval demand to the digit task. That is, subjects' task was to determine whether a digit belonged to numbers forming two pre-specified 2-digit primes (29, 47) or squares (36, 81). This resulted in the arbitrary allocation of prime-forming digits to one response category and square-forming digits to another response category. For example, if subjects saw the digit '3', they had to decide if it occurred in the squares "36, 81" or the primes "29, 47". For reasons unrelated to the present study, the letter task was also slightly modified: instead of judging whether letters were consonants or vowels, subjects now determined whether they belonged to the early or late part of the alphabet. We expected that the additional retrieval demands posed on the digit task would slow down performance relative to the letter task, thereby creating an asymmetry in RT performance.

Method

Subjects

Twenty-four subjects (*M* = 24 years old) participated. Subjects were paid 6$ for their participation or received partial credit for course fulfillment.

Materials

Two stimulus lists were prepared for Task A, the letter task, and Task B, the digit task. As in Experiment 1, stimuli consisted of character pairs made up of a target and a foil. Targets for the letter task were selected from a sub-set of letters occurring early in the alphabet (A, B, C, E) or late (U, X, Y, Z). Targets for the digit task consisted of a single digit that belonged either to two prime numbers (29, 47) or two squares (36, 81). Foils consisted of any one of the following symbols: #, +, &, and %.

Training and Experimental Stimuli

The method for creating the lists of training and experimental stimuli was identical to that used in Experiment 1. Only the most important features are presented here. For more details, the reader is referred to the method section of Experiment 1.

For the training phase, a list of 384 univalent stimuli consisting of 16 blocks of digit and letter trials was created. The blocks alternated between 24 digit and 24 letter trials that were each paired with a neutral foil. For the experimental phase, 3 lists of 192 experimental stimuli were created, one for each stage, following the same rules and counterbalancing procedures detailed in Experiment 1. Stage 1 stimuli consisted of univalent letter and digit trials; Stage 2 stimuli consisted of univalent digit trials and bivalent letter trials; finally Stage 3 stimuli consisted of bivalent letter and digit trials. A sample of trials for each stage is illustrated in Figure 7.

Procedure

The same procedure as that used in Experiment 1 was used. Subjects proceeded through a training and an experimental phase which was further divided into three stages.

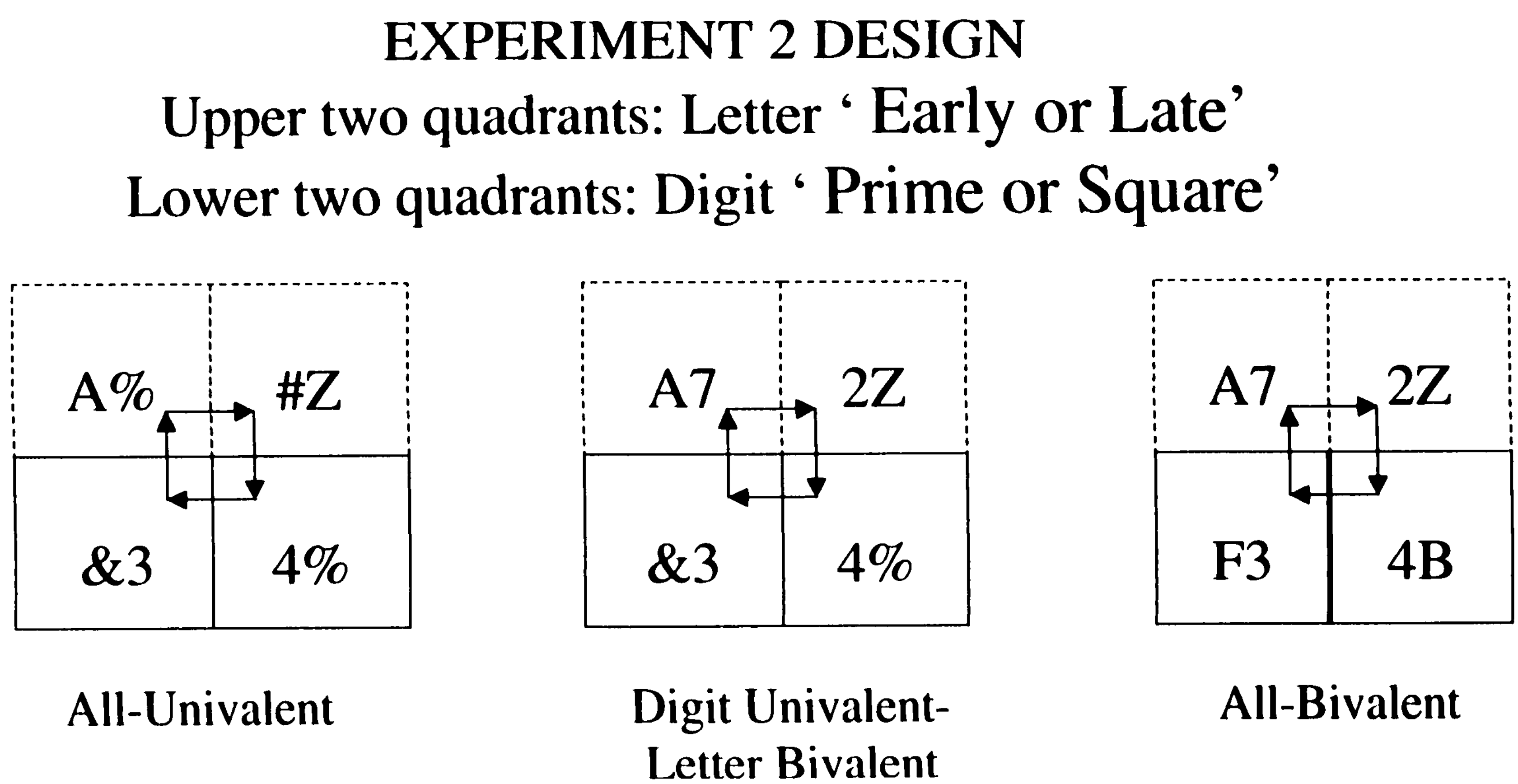

Figure 7. Example of letter and digit trials within each stage of Experiment 2. In the first stage all stimuli were univalent; in the second stage, the digit stimuli were univalent, and the letter stimuli, bivalent; in the third stage, both letter and digit stimuli were bivalent. Subjects' task was to classify the letters as occuring ‘early’ or ‘late’ in the alphabet, and digits as being one of the digits forming the prime numbers ‘29 or 47’ or the square numbers ‘36 or 81’ using a left or right key response.

The training phase contained 384 trials and each stage of the experimental phase consisted of 1 block of 48 practice trials followed by 4 blocks of 12 warm-up and 36 experimental trials. Details about the physical set-up, feedback procedure, stimulus presentation times are provided in the procedure section of Experiment 1.

Results

Essentially the same data preparation and analytic procedures that were used in Experiment 1 were applied on the data from Experiment 2. Mean RTs in each of the twelve design cells involving the combination of Task, Switch, and Stage were calculated for each subject. The data from each cell were winsorized, resulting in the replacement of the slowest 10% data points by the next highest value. On average, errors were committed on 2% of the 432 experimental trials. Trials following errors (M = 2%) as well as error trials themselves were excluded from the analyses resulting in the mean removal of 4%.

Repeated-measures ANOVAs were used in all the analyses. Estimates of switch costs were calculated by subtracting repeat RTs from switch RTs. Group mean RTs for each cell are presented in Appendix B. Results representing performance on switch and repeat trials across each stage of the experiment are illustrated in Figure 8. The following sections present detailed analyses of the main effects and interactions for each stage.

Within-Stage Analyses

To verify the presence of task asymmetry within each stage as well as the presence of switch costs, the data was examined within each stage using Task (letter vs digit) and Switch (repeat vs switch) as factors. In the present study, the dominant letter

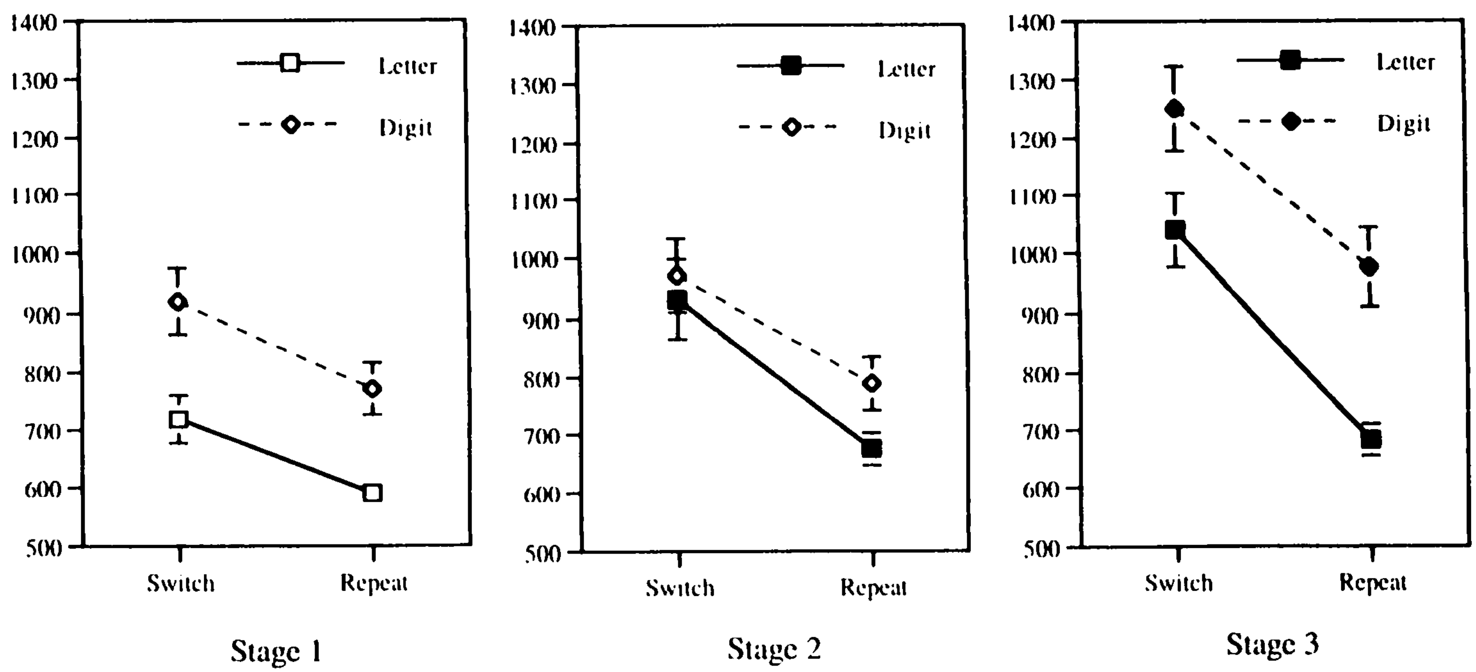

Figure 8. Mean RTs (ms) for switch and repeat letter and digit trials across the three stages of Experiment 2 (univalent trials are represented by empty symbols while bivalent trials are represented by filled symbols). Error bars represent between-subjects standard errors.

task was meant to be the counterpart of Wylie and Allport's dominant Word task, while the digit task, the counterpart of their Color task.

Stage 1: All Univalent

Results confirmed that the manipulation intended to make one task more difficult (i.e., slower) than the other was successful, as shown by a main effect of Task, $F(1,23) = 29.80$, $MSE = 29{,}543$, $p < .0005$. Subjects responded to letter trials ($M = 654$ ms) faster than they did to digit trials ($M = 846$ ms), resulting in a mean difference of 192 ms. There was also a main effect of Switch, $F(1,23) = 31.92$, $MSE = 14{,}445$, $p < .0005$. Repeat trials ($M = 681$ ms) were faster than switch trials ($M = 819$ ms). The interaction was not significant ($F(1,23) = .41$, $MSE = 5{,}329$, $p > .05$), suggesting equivalent switch costs on letter (M cost = 129 ms) and digit (M cost = 148 ms) trials (see Figure 8).

Stage 2: Letter Bivalent / Digit Univalent

Analyses showed that the main effect of Task was almost significant ($F(1,23) = 4.05$, $MSE = 35{,}137$, $p = .056$). Letter RTs appeared faster on average ($M = 803$ ms) than digit RTs ($M = 880$ ms). The difference, however, was substantially smaller than in Stage 1 (283 ms in Stage 1 vs. 77 ms in Stage 2). As subsequent analyses described in the between-blocks section will later show, performance on the letter task was slowed down by the inclusion of bivalent stimuli in Stage 2 while that of the digit task remained stable. As expected, there was however a main effect of Switch, $F(1,23) = 45.06$, $MSE = 25{,}776$, $p < .0005$, with repeat trials averaging 732 ms, and switch trials, 952 ms. The interaction almost reached significance, $F(1,23) = 3.23$, $MSE = 10{,}203$, $p = .085$. As seen in Figure 8, the switch cost appeared larger in the dominant letter task (M cost = 257 ms) than in the digit task (*M* cost = 183 ms). resulting in a mean difference of 44 ms. These results contrast with those of Wylie and Allport who found that it was the non-dominant Color task which exhibited larger switch costs.

Stage 3: All Bivalent

Analyses of the data from Stage 3 showed a main effect of Task. $F(1,23) = 18.74$. $MSE = 81.918$. $p = .001$. Here. performance on letter trials (*M* = 861 ms) was again faster than performance on digit trials (*M* = 1114 ms). yielding a mean difference of 253 ms. Again there was a main effect of Switch. $F(1.23) = 62.08$. $MSE = 38.690$. $p < .0005$. with repeat trials averaging faster RTs (*M* = 830 ms) than switch trials (*M* = 1.146 ms). The interaction almost reached significance. $F(1.23) = 3.22$. $MSE = 13{,}034$. $p = .086$. As can be seen in Figure 8. switch costs found on the dominant letter task (*M* cost = 358 ms) again appeared larger than those found on the non-dominant digit task (*M* cost = 275 ms). These results compare to those of Wylie and Allport who found larger switch costs on the dominant Word task.

Between-Stage Comparisons

Performance on each task was compared between Stages 1 and 2. and Stages 2 and 3 to examine the effects of stimulus valence changes on the magnitude of switch costs across each stage. This resulted in four critical analyses using Stage (either Stages 1 vs 2 or Stages 2 vs 3) and Switch (repeat vs switch) as factors. Where indicated. two post hoc *t*-tests (for each task) using Bonferroni-adjusted alpha levels were conducted to identify the source responsible for interaction effects.

Letter Task (Task A)

The purpose of these analyses was to compare switch costs on letter trials between Stages 1 and 2 and Stages 2 and 3. Recall that letter trials were univalent in Stage 1 and bivalent in Stage 2 and 3 while digit trials were univalent in both Stages 1 and 2 and bivalent in Stage 3 (see Figure 7).

Stages 1 and 2.

Results showed a main effect of Stage, $F\,(1,23) = 35.33$, $MSE = 15{,}029$, $p < .0005$; and a main effect of Switch, $F\,(1,23) = 33.12$, $MSE = 27{,}005$, $p < .0005$. Responses on repeat trials ($M = 632$ ms) were faster than on switch trials ($M = 825$ ms). And subjects were faster in Stage 1 ($M = 654$ ms) than in Stage 2 ($M = 803$ ms). More importantly, there was a significant interaction between Stage and Switch, $F\,(1,23) = 8.92$, $MSE = 11{,}018$, $p = .007$. As seen on Figure 8, the letter switch cost in Stage 2 (M cost = 257 ms) was larger than in Stage 1 (M cost = 129 ms).

Post hoc *t*-tests revealed that both repeat and switch trials evidenced an increase in RT from Stage 1 to Stage 2. Repeat RTs averaged 590 ms in Stage 1 and 674 ms in Stage 2, $t\,(23) = 6.52$, $p < .0005$; switch RTs averaged 719 ms and 932 ms respectively, $t\,(23) = 4.75$, $p < .0005$. Thus, not only did switch costs increase from Stage 1 to Stage 2, but overall performance was slowed down by the inclusion of bivalent stimuli in Stage 2.

These results are in direct contrast to those of Wylie and Allport who found equivalent main RTs and switch costs on the dominant Word task between both stages. Given that the letter task was the dominant task in the present study (in terms of relative task difficulty), a pattern of RTs comparable to those obtained by Wylie and Allport with the dominant Color task had been expected. That is, equivalent letter RTs across stages 1 and 2 should have obtained given that no inhibition of the letter task was involved when performing the digit task in either stage. Instead, the effect of an increased letter switch cost in Stage 2 is more consistent with Rogers and Monsell's position that the challenge represented by the engaged task is critical to the magnitude of switch costs observed. These results are surprising in light of the fact that the built-in task asymmetry was hypothesised to be responsible for the pattern of results Wylie and Allport found. This point will be further addressed in the discussion.

Stages 2 and 3.

Analyses of letter performance between Stages 2 and 3 yielded a highly significant switch effect, $F(1,23) = 46.61$, $MSE = 48,726$, $p < .0005$, resulting in faster repeat times ($M = 710$ ms) compared to switch times ($M = 986$ ms). There was also a main effect of Stage, $F(1,23) = 5.95$, $MSE = 13,673$, $p = .023$. It seems that letter RTs were even slower in Stage 3 ($M = 861$ ms) than they were in Stage 2 ($M = 803$ ms). However, these findings are qualified by a significant Stage by Switch interaction, $F(1,23) = 6.72$, $MSE = 9,137$, $p = .016$. The slower performance in Stage 3 was associated with changes on switch trials but not repeat trials.

Post hoc t-tests revealed that while performance on switch trials was slower in Stage 3 (M switch = 1040 ms) than it was in Stage 2 (M switch = 932 ms), $t(23) = 2.70$, $p = .013$, performance on repeat trials in Stage 3 (M repeat = 682 ms) was statistically equivalent to that of Stage 2 (M repeat = 674 ms), $t(23) = .46$, *ns*. Thus it would seem that the larger letter switch cost found in Stage 3 (M cost = 324 ms) relative to Stage 2 (M

cost = 257 ms) was due to a selective increase in switch times per se. Unlike the pattern of results obtained between Stages 1 and 2, this effect is inconsistent with Rogers and Monsell's model. Instead, it is more compatible with the Inertia hypothesis which predicts greater switch costs in Stage 3 given the presence of bivalent stimuli in the competing digit task.

Digit Task (Task B)

The purpose of these analyses was to compare switch costs on digit trials between Stages 1 and 2 and Stages 2 and 3. Recall that letter trials were univalent in Stage 1 and bivalent in Stages 2 and 3 while digit trials were univalent in Stages 1 and 2 and bivalent in Stage 3 (see Figure 7).

Stages 1 vs. 2.

In the case of digits with regards to Stages 1 and 2, there are two contrasting predictions that can be made. Whereas the Inertia hypothesis would predict increased switch costs in Stage 2, the Reconfiguration hypothesis predicts no such difference given that the valence of the digit stimuli was the same in both stages. Results seemed to favor the latter. The only significant effect was that of switch , $F(1,23) = 56.08$, $MSE = 11{,}727$, $p < .0005$. Performance on repeat trials ($M = 780$ ms) was faster than on switch trials ($M = 946$ ms). Neither the effect of Stage ($F(1,23) = 1.21$, $MSE = 23{,}126$, $p > .05$) nor the interaction between Stage and Switch ($F(1,23) = 1.21$, $MSE = 6{,}003$, $p > .05$) were significant. Thus, switch costs were statistically equivalent in Stages 1 and 2, averaging 148 ms and 183 ms respectively. This result means that performance on digit trials was essentially the same in Stages 1 and 2. A result again which is inconsistent with the idea that processing on previous trials (the inhibition of the digit task while performing the bivalent letter task in Stage 2) carries over to the next trial.

Stage 2 vs. 3.

Here, the predictions from the contrasting views are reversed. While the Inertia hypothesis predicts no difference in switch costs between Stages 2 and 3 (the competing task was bivalent in both stages), the Reconfiguration hypothesis predicts increased switch costs in Stage 3 (the valence of the current task changed from univalent to bivalent). Results again seemed to favour the latter view. Analyses revealed a main effect of Stage, $F(1,23) = 77.06$, $MSE = 17,077$, $p < .0005$, and a main effect of Switch, $F(1,23) = 55.15$, $MSE = 22,766$, $p < .0005$. Performance was overall faster in Stage 2 (M = 880 ms) than in Stage 3 (M = 1114 ms), and repeat times (M = 883 ms) were faster than switch times (M = 1111 ms). More importantly, there was a significant interaction between Stage and Switch, $F(1,23) = 7.12$, $MSE = 7,073$, $p = .014$. Digit switch costs were smaller in Stage 2 (M cost = 183 ms) than in Stage 3 (M cost = 275 ms).

Post hoc t-tests revealed that both switch and repeat trials evidenced a change in RT. Mean repeat times increased from 789 ms in Stage 2 to 977 ms in Stage 3, $t(23) = 5.29$, $p < .0005$. Mean switch times increased from 971 ms to 1251 ms, $t(23) = 10.26$, $p < .0005$.Thus, not only were subjects slowed down overall by the addition of stimulus bivalence in Stage 3, but they experienced more difficulty switching to the bivalent digit task in Stage 3 as reflected by the increased switch costs.

Discussion

The main goal of Experiment 2 was to examine whether the pattern of switch costs obtained by Wylie and Allport (2000) would be replicated when tasks were asymmetrical. To this end, we used a letter and digit task as in Experiment 1, but introduced an episodic component to the digit task with the intent to slow down performance, and thus make the tasks asymmetrical with regards to speed of responding. The decision to use letter and digit stimuli was also motivated by a wish to minimize differences between the two experiments in order to increase our ability to attribute any effects observed to the task manipulation itself. Results from the within-block and between-block analyses presented mixed evidence which on the whole favored the Reconfiguration hypothesis. These are reviewed in turn.

Within-Stage Analyses

A robust switch effect was found on both tasks across all three stages. Results also confirmed that the manipulation designed to slow down performance on the digit task with respect to the letter task was successful. Analyses showed that in Stages 1 and 3, performance on letter trials was faster than on digit trials. With the exception of Stage 2 results, these findings parallel those of Wylie and Allport who found a task effect in all three stages with the dominant Word task showing considerably faster RTs than the non-dominant Color task.

However, the patterns of interaction between Task and Switch within stages in the present experiment presented mixed evidence with regards to the Inertia hypothesis. Wylie and Allport found symmetrical switch costs in Stage 1, (their All-neutral condition), suggesting to them that in the absence of competing task attributes, switch costs were unaffected by interference from the competing task. In Stage 2 (their Color-neutral condition), the non-dominant Color task exhibited slightly larger switch costs than Word whereas in Stage 3, this pattern reversed, with Word exhibiting the larger switch costs. These patterns were compatible with their Inertia hypothesis insofar as they mirrored the activation-suppression processing taking place in the competing task. In the present experiment symmetrical switch costs were found in Stage 1 whereas the dominant letter task showed a trend towards larger switch costs in *both* Stages 2 and 3. Thus while data from Stages 1 and 3 is compatible with that of Wylie and Allport's, that of Stage 2 is not. This suggests that the inclusion of bivalent stimuli in the letter task in Stage 2 (while maintaining the univalent status of the digit task) was responsible for the performance slow down. Moreover, the result is inconsistent with the notion that the effect was due interference from the competing task since in this case, the competing digit task was univalent. Thus, while Wylie and Allport interpreted the increased switch costs on Color in Stage 2 to mean that the Stroop Word task was interfering with performance on the neutral Color task, the present data presented evidence inconsistent with this interpretation[7].

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[7] A closer look at Wylie and Allport's data shows that the switch cost difference between Color and Word was small, and not reflected in analyses of interactions. Moreover, the Color switch cost was compared against a switch cost that was absent on the Word trials of Stage 2. This contrasts with data from Stage 1, where Word and Color trials both evidenced a switch cost. Given that the Word switch cost disappeared in Stage 2, it becomes difficult to interpret the larger naming switch cost difference they found in Stage 2.

Between-Stage Analyses

As far as the more critical contrasts between blocks are concerned, the presence of task asymmetry did not replicate the pattern of results found with the Stroop-color tasks used by Wylie and Allport. In fact, if we consider the between-block analyses, three out of the four critical comparisons supported Rogers and Monsell's position. These are considered in turn.

Letter Trials (Task A)

With regards to the dominant letter task, analyses show that the switch cost in Stage 2 was greater than in Stage 1. This finding contrasts with Wylie and Allport's Word data and is instead compatible with the Reconfiguration hypothesis. Recall that the letter task proceeded from univalent status in Stage 1 to bivalent status in Stages 2 and 3. Within the present experiment, it seems that adding bivalent status to the letter task in Stage 2, not only caused an increase in letter RTs (as evidenced by the Stage effect) but also caused switch costs to increase. Thus, the added burden of dealing with bivalent stimuli appears to have made it more difficult to switch to the letter task in Stage 2. Again, the Inertia hypothesis predicted no such difference given that the competing digit task was neutral in both stages. The data, however, are compatible with Rogers and Monsell's task cuing effects (larger switch costs when the stimuli include a competing attribute), and replicate the pattern obtained in Experiment 1 of the present study.

Another important difference between the two studies, however, concerns the general slowing down of letter RTs in Stage 2 relative to Stage 1. As in Experiment 1 of the present study, subjects not only evidenced increased switch costs when the letter stimuli became bivalent, but their overall performance on both switch and repeat trials was slower in Stage 2. Wylie and Allport found no such decrement with their Word data: performance on Word was equivalent across both stages, even though incongruent Stroop stimuli were included in Stage 2. As mentioned before, this lack of a Stroop interference effect on Word has been largely documented in the literature, and has been construed as an indication of the automatic nature of the Word task. Within the experimental switching context, however, Wylie and Allport interpreted it as evidence of a lack of interference from the competing neutral Color trials. Competitor cuing of Color on Word in the color-neutral condition they argued, could have resulted in increased interference. "However, if any competitor-cuing took place, it was not evident in the RTs associated with the Word task." (p. 17). While this explanation may hold true at least as far as Stroop-color stimuli are concerned, the present data did not support this view.

However, analyses revealed an increased switch cost on letter trials in Stage 3, and as such support the pattern of results obtained by Wylie and Allport. Here the letter task was bivalent in both Stages 2 and 3 while the digit task changed from being univalent in Stage 2 to being bivalent in Stage 3. Results showed that switch costs were larger in Stage 3. Given that the trials being switched *to* were bivalent in both stages, and thus represented equivalent task demands, it is difficult to attribute this finding to the control demands of the engaged task. Instead, this finding is more compatible with the view that interference from the bivalent digit task carried over to the letter task as reflected by the switch cost increase. While together these results offer mixed evidence as far as both task shifting control models are concerned, it is important to consider data from the digit trials before drawing any formal conclusions.

Digit Trials (Task B)

Together, data from the non-dominant digit task is consistent with the view of an executive reconfiguration process controlling task shifting. That is, switch costs seemed to have changed as a function of current task demands as opposed to previous ones. There were no switch cost differences between Stages 1 and 2 when the digit task being switched *to* was univalent. And there was evidence of a greater switch cost in Stage 3 associated with the inclusion of bivalent digit stimuli. These changes failed to match the change in valence of the competing letter task.

As in Experiment 1, there was no evidence of a Stage effect between Stages 1 and 2 where subjects responded to identical digit trials. Digit RTs, however, were considerably slowed down by the inclusion of bivalent stimuli in Stage 3 as evidenced by the main effect of Task. Thus not only were switch costs affected, but overall RTs were affected as well.

General Considerations

Working Memory Issues

The bulk of results from Experiment 2 seems to favor the Reconfiguration hypothesis. In three out of the four between-block analyses, changes in switch costs were associated with changes in current task demands. It seems then that building a task asymmetry did not succeed in replicating the pattern of results obtained by Wylie and Allport. The only anomalous finding is that of the larger letter switch cost in Stage 3.

Here the evidence was consistent with the proactive interference view. Whether these results can be attributed to an increased working memory load caused by the addition of bivalent stimuli in the non-dominant digit task remains an open question which we will defer answering until we review results from Experiment 3.

Wylie and Allport did not formally address the Stage effects they found in their study. Instead, they treated them more as collateral findings. They indirectly discussed the issue while raising the potential problem of confounds within the alternating runs paradigm. They interpreted the Stage effect obtained on both Color and Word performance as meaning that considerable interference from the competing task was affecting processing on both switch and repeat trials alike. This led them to question the assumption that repeat trials reflect complete task-set reconfiguration (i.e., fully reconfigured baseline). But we may argue that if this were the case, a Stage effect on Color performance should have obtained in Stage 2 (their Color-neutral condition) where interference from Stroop Word performance was carried-over to Color performance. Instead, they only found a slightly larger switch cost on Color RTs.

The question as to what these Stage effects reflect thus remains open, and the meaning of what baseline RTs (repeat trials) really convey is open to speculation. They could reflect carry-over interference[8] from disengaged tasks, or a working memory resource problem interacting with task demands, or both. If we summarize results from

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[8] Certainly, there is evidence in the literature supporting the view that interference from pre-switch performance can influence switch costs (Mayr & Kliegl, 2000).

both Experiments 1 and 2 (as far the between-block analyses are concerned), the following pattern emerged for both tasks: when processing on current tasks proceeded across stages from univalent to univalent, no Stage effect obtained; bivalent to bivalent, a Stage effect effect obtained only in Experiment 1; in Experiment 2, there was an increased switch cost on letter trials but no general slow down in performance; and univalent to bivalent, both a Stage effect and an increased switch cost obtained irrespective of which stage this occurred in. The increased switch cost evidenced on letter trials in Stage 3 of this experiment certainly does not rule out an interference explanation. But it may also reflect beginning evidence that when the tasks are asymmetrical, the different processing demands for each task interact with limited working memory resources. In Stage 3, working memory resources were being increasingly solicited by the now bivalent non-dominant digit task. It may be that once a certain threshold of difficulty is reached, other tasks which otherwise would be performed at a given level, now compete for increasingly fewer working memory resources. This may in turn have affected the ability to carry out the shift to the already demanding bivalent letter task.

Wylie and Allport also considered explanations to the effect that differences between stages could be due to the number of cues subjects had available to perform the Word and Color tasks. In the first two stages, both the location of the stimuli within the quadrants as well as the stimuli themselves provided cues as to which task to perform. In the third stage, subjects needed to rely on location exclusively if they were to perform the tasks accurately. This is because the stimuli themselves cued both tasks, and as such did not provide any information as to which task should be performed. Wylie and Allport considered this possibility as a potential explanation for the pattern of results they obtained, but they argued that this hypothesis was unlikely given the Color switch costs differences found between the All-neutral (Stage 1) and Color-neutral (Stage 2) conditions. Here subjects had available to them both location and stimulus cues. Yet, Color switch costs were different between each stage. The same argument applies to Word performance between Stages 2 and 3 (the color-neutral and all-Stroop conditions). The word stimuli in both stages were incongruent, and therefore provided the same number of cues, yet switch costs were greater in Stage 3, their all-Stroop condition.

This explanation, however, fails to consider that availability of task cues may have a general effect with respect to demands made on working memory resources. We must remember that task switching takes place within a general context: the more cues are available, the easier it is to decide what to do, hence the more resources available to carry out other aspects of the task. The fact that tasks vary in terms of the number of cues they make available is probably one of the factors that contributes to general working memory demands. The present experiment was meant to disentangle those issues by manipulating task demands to create the type of working memory confounds that could have been responsible for Wylie and Allport's results. This attempt was only minimally successful. With one exception, most of the evidence in this experiment favors Rogers and Monsell's position.

LTM Retrieval Demands

An additional issue concerning the symmetry of switch costs we found in Stage 1 despite the presence of a task asymmetry needs to be addressed here. Mayr and Kliegl

(2000) found that switching to a task involving an episodic component produced larger switch costs than switching to a task requiring semantic judgments to be made. They further established that this effect was not due to the higher difficulty level of the episodic task. They interpreted these results within a model postulating that task shifting entails the retrieval of task-set rules from long-term memory (LTM) (see also Rubinstein et al., 2001). Task-set rules involving an episodic component place higher retrieval demands from LTM than tasks involving a semantic component. Mayr and Kliegl's results at first glance would appear incompatible with those of the present experiment given we also manipulated LTM retrieval demands: where they found increased switch costs associated with the episodic task relative to the semantic task, we found equivalent ones. However, if we consider other results they reported in the same study, these differences can be reconciled. In a further experiment, Mayr and Kliegl found that when subjects were provided with retrieval cues giving them advance information concerning the retrieval rules, switch performance between the semantic and episodic tasks became equivalent. In the present experiment, subjects were provided with information at the bottom of the screen reminding them about response key assignments for each task throughout the experiment. Insofar as this information acted as retrieval cues, then we may consider that the episodic retrieval demand effect was greatly reduced in a manner similar to that found in Mayr and Kliegl's experiment. The retrieval demand factor may thus be considered to have merely increased task difficulty level, a factor which has been shown to affect basic performance but not switch cost magnitude (Allport et al., 1994;

Kray & Lindenberger . 2000; Mayr & Kliegl, 2000; Monsell, 2000; Rubinstein et al., 2001; Salthouse et al, 1998).

Given that task difficulty level merely affected main processing as reflected by the absence of an interaction between Task and Switch within Stage 1, it seems safer to assume that the increased switch cost observed on the dominant letter task in Stage 2 was due to the inclusion of competing stimulus attributes.

The Issue of Task Dominance

It would appear then that the asymmetry we built into the tasks for Experiment 2 was insufficient to replicate and explain Wylie and Allport's results. Throughout our disccusion, we have used the concept of task dominance quite liberally, and included in our definition any pair of tasks that were unequal in terms of RT. This appeared sufficient to accomodate our working memory hypothesis. It became evident, however, that some particularity inherent in the asymmetry found with the Stroop-color task must be responsible for the pattern of results found by Wylie and Allport, else why should we not find it given we applied the same experimental paradigm and used asymmetrical tasks? It would seem then that the factor over which tasks vary may be critical in the determination of switch cost patterns.

Where Wylie and Allport's Word and Color tasks can be considered to involve semantically-based processing varying in degree of automaticity, the letter and digit tasks used in this experiment were designed to vary in terms of LTM retrieval demands[9]: semantic and episodic. It is possible then that the type of processing which forms the basis of the asymmetry plays an important role in the determination of task switching mechanisms. These issues are considered in Experiment 3.

[9] Although, as mentioned earlier, this manipulation was only partly successful. It may be that by providing retrieval cues at the bottom of the screen throughout the experiment, we substantially reduced the episodic component of the digit task, and merely increased task difficulty levels.

EXPERIMENT 3

The goal of this third experiment was to further test Wylie and Allport's Inertia model with two tasks that both required semantic processing while at the same time being asymmetrical with regards to degree of automaticity. The objective was to build an asymmetry that more closely matched the one found with the Stroop-color task while at the same time using tasks involving symbols in order to provide a continuity with the tasks used in Experiments 1 and 2, as well as those used by Rogers and Monsell. To this end, we employed a letter-name identity task and a location task. The former required judging whether the identity of two letters (presented in upper and lower case fonts) was the same or different, while the latter required a left versus right side judgment about the location of the stimulus within its quadrant. The stimuli for the location task were made up of either of non-alphabetic characters or letters, enabling us to combine location and letter-identity factors to create stimuli in the bivalent conditions (see below).

We reasoned that making location judgments would involve a direct mapping between the stimulus identification stage and the response stage, whereas an additional stage would be required in the letter-name identity task: subjects would first have to identify the letters and then decide whether they were the same or different before making a response. Although we did not obtain an independent measure of automaticity, we expected the location task to be both faster and more automatic than the letter-name identity task.

Method

Subjects

Sixteen subjects (M = 24 years old) participated. Subjects were paid 6$ for participating or received partial credit for course fulfilment.

Materials

Stimuli consisted of character pairs made up of two letters or two non alpha numeric symbols. The letter-pairs were selected from the following pool of same or different letter pairs respectively: Bb, Dd, Gg, Pp and Bp, Db, Gd, Pg. The letters were presented in upper and lower case to prevent physical similarity from assisting subjects' decisions. In a similar vein, letters were chosen to rhyme with one another to prevent decisions based on phonemic characteristics. The pool of non-alphanumeric stimuli consisted of eight symbol pairings chosen from among the set {#, &, *, %}. Each symbol was paired four times with another symbol, twice for stimuli to be used in the left location, and twice for the right location resulting in the following sets for the left and right locations respectively: %*, *#, #&, &%, and *&, #%, &#, *%.

In order to create the sets of stimuli used for the univalent and bivalent conditions, we crossed location (left/right or center - where center was considered neutral with respect to the left-right location task) with type of stimuli (letter or non-alphanumeric characters - where the latter was considered neutral with respect to the letter task). Thus, univalent stimuli for the location task consisted of non-alphanumeric character pairs presented to the left or right side of their target quadrant whereas for the letter task, the stimuli consisted of letter-pairs presented at the center of their target quadrant. For the bivalent conditions, all the stimuli consisted of letter-pairs presented either to the left or right side of their respective quadrants. Depending on which quadrant the subjects were on, they either had to focus on the location of the letter-pairs or on their identity.

Training Stimuli

For the training phase, we created a list of 8 blocks of 24 letter-pairs and 8 blocks of 24 non-alphanumeric stimuli, for a total of 384 stimulus items. The stimuli were randomly selected with replacement from their respective pools. Each non-alphanumeric character pair was associated with a left or right location specifying four different heights within the rectangle. The letter-pairs were presented within the center of the rectangle.

Experimental Stimuli

The same three stimulus templates of Experiments 1 and 2 were used to create the lists of 192 stimuli employed in each of the three experimental stages. Only critical aspects are presented here (for more details, refer to the procedure section of Experiment 1).

The stimulus template used for Stage 1 was designed to make letter stimuli always appear in the center of the quadrant and for location stimuli (non-alphanumeric characters) to be presented on four different heights within the left or right side of the quadrant. In Stage 2, the template was designed for letter stimuli to be again presented within the center of the quadrant whereas the location stimuli was to consist of letter-pairs presented within the left or right side of the quadrant. In Stage 3, the template was used to create stimuli for both the letter and location tasks that consisted of letter-pairs presented on four different heights within the left or right side of their respective quadrants (see Figure 9 for an illustration of the stimuli used in the three stages).

Procedure

Aside from the task-specific instructions. subjects followed the same basic procedure as in Experiments 1 and 2 with respect to the training and experimental stages. Subjects proceeded through a training and an experimental phase which was further divided into three stages. The training phase contained 384 trials and each stage of the experimental phase consisted of 1 block of 48 practice trials followed by 4 blocks of 12 warm-up and 36 experimental trials.

For the location task. they were instructed to decide whether the target was presented on the left of right side within the quadrant irrespective of stimulus height. For the letter-name identity task they were instructed to decide whether the letters presented within the quadrant bore the same or a different identity.

For half the subjects. the same letter-pair responses were assigned to the left key. while the other half received a right key assignment. Left location targets were assigned a left key response and right location targets. a right key response. Instructions with regards to accuracy and speed of responding. feedback, point-system rewards, RSI. time the stimulus remained on the screen. etc. were the same as in Experiments 1 and 2.

Trials always began with the letter-name identity task (this task will be further referred to as the letter task). After completing Stage 1, which presented univalent letter and location trials. subjects were informed that Stage 2 involved the same tasks. but that the location stimuli would now involve letter-pairs presented on the left or right side

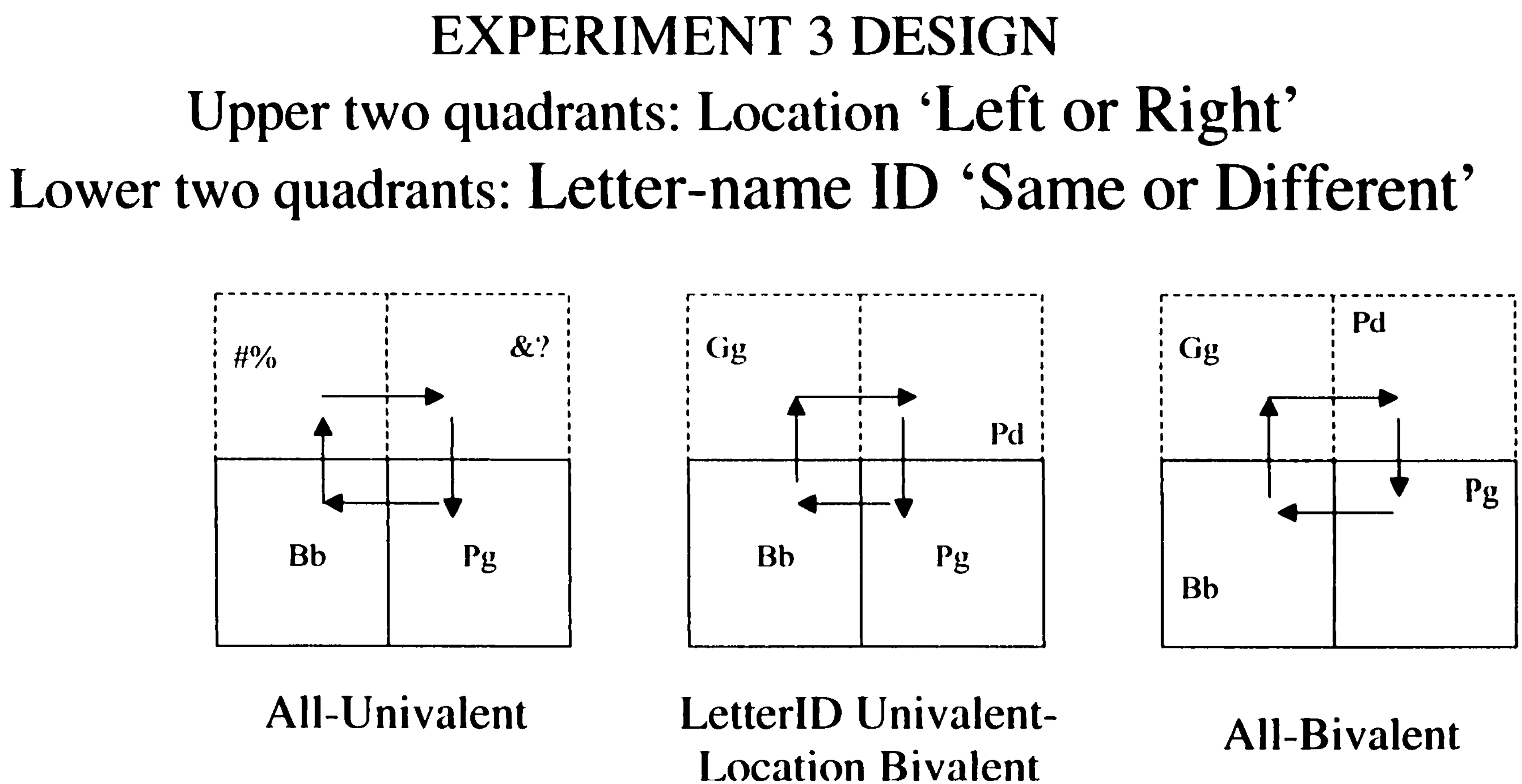

Figure 9. Example of location and letter trials within each stage of experiment 3. In the first stage all stimuli were univalent; in the second stage, the letter stimuli were univalent, and the location stimuli, bivalent; in the third stage, both location and letter stimuli were bivalent. Subjects' task was to classify the location stimuli as occuring within the left or right sides of their respective quadrants, and to decide whether the identity of letter-pairs was the same or different, using a left or right key response.

within their respective quadrants. They were instructed to ignore the identity of the letter-pairs and to continue performing the location task as they did previously. Once they completed this stage, they were informed that the last stage would consist entirely of letter-pairs presented on the left or right side within their respective quadrants. Depending on which quadrants the targets appeared in, they were instructed to continue performing the letter and location tasks as they did in Stages 1 and 2. Throughout the experiment, instructions for the different tasks and their response-key assignments appeared at the bottom of the screen.

Results

As with Experiments 1 and 2, a winsorizing procedure was applied to subjects' mean RTs for each of the twelve design cells resulting from the combination of Task, Switch, and Stage. The same sets of repeated-measures ANOVAs that were chosen for Experiments 1 and 2 were applied to the data. On average, subjects committed errors on 2% of the 432 experimental trials. Taking into consideration the removal of trials following errors ($M = 2\%$), four percent of the trials were excluded from the analyses resulting in a mean loss of seventeen data points for each subject. Results representing performance on switch and repeat trials across each stage of the experiment are illustrated in Figure 10. The following sections present detailed analyses of the main effects and interactions for each stage.

Within-Stage Analyses

Performance within each stage was examined. To this end, repeated-measures ANOVAs were conducted using Task (location vs letter) and Switch (switch vs repeat) as

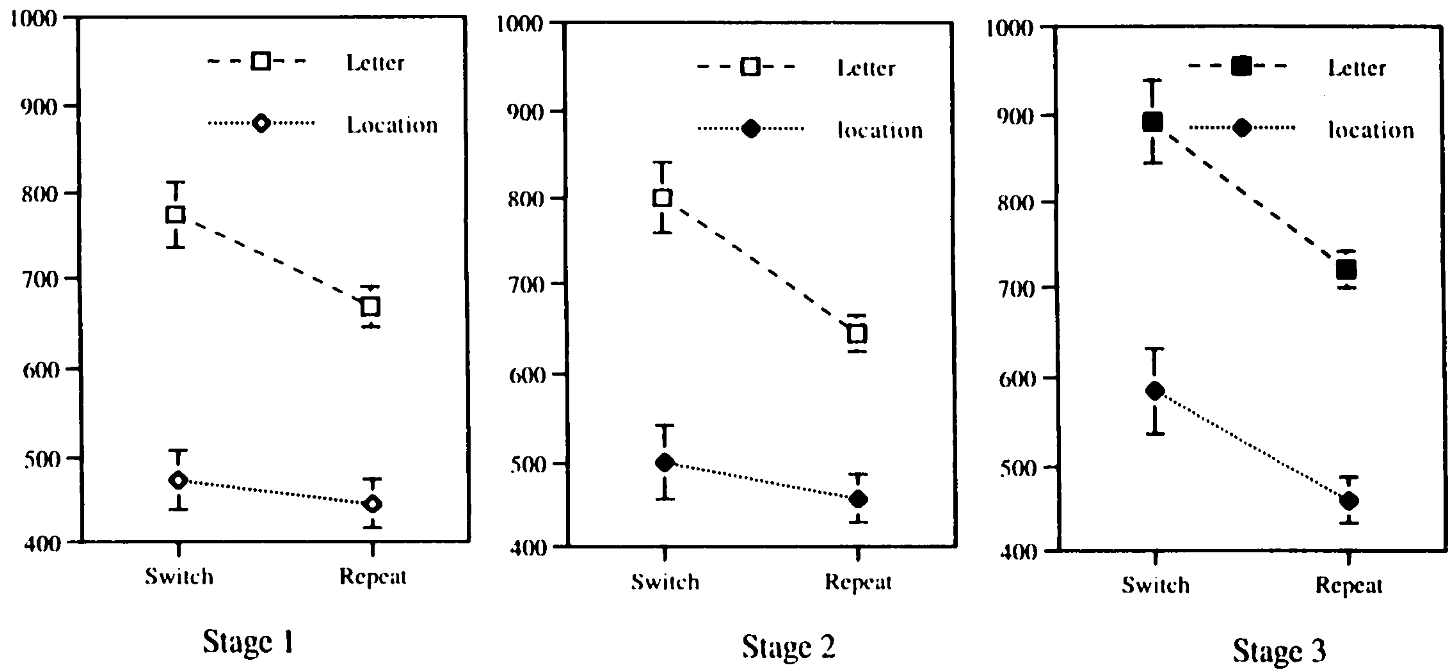

Figure 10. Mean RTs for switch and repeat letter and location trials across the three stages of Experiment 3 (empty symbols represent univalent trials, and filled symbols, bivalent trials). Error bars represent between-subjects standard errors.

factors. The presence of a task asymmetry favoring the location task as the fastest of the two tasks was expected. Where indicated, post hoc *t*-tests using Bonferroni-adjusted alpha levels were conducted to verify the presence of a switch cost on each task.

Stage 1: All-Univalent

The main effect of Task was highly significant, $F(1,15) = 123.65$, $MSE = 8.792$, $p < .0005$. Performance on location trials ($M = 461$ ms) was much faster than on letter trials ($M = 722$ ms), a mean difference of 261 ms. These results therefore confirm the presence of a task asymmetry. There was also a main effect of Switch, $F(1,15) = 8.50$, $MSE = 8.339$, $p = .011$. Switch RTs averaged 625 ms while repeat RTs averaged 558 ms. The interaction was also significant, $F(1,15) = 25.17$, $MSE = 933$, $p < .0005$. As shown in Figure 10, the switch cost on letter trials (M cost = 105 ms) was larger than the switch cost on location trials (M cost = 28 ms).

Inspection of Figure 10 however suggests that the switch cost on location trials might not have been significant. Post hoc *t*-tests were conducted to verify the presence of a significant switch cost on each task. Results showed that only the switch cost involving letter trials was significant, $t(15) = 3.78$, $p = .002$ (M repeat = 669 ms, and M switch = 774 ms). The switch cost involving location trials was not significant, $t(15) = 1.43$, *ns* (M repeat = 447 ms, and M switch = 475 ms). It would appear therefore that performing the location task was both fast and efficient as far as the cost of shifting to the location task is concerned.

Stage 2: Letter Univalent / Location Bivalent

Stage 2 performance replicated the pattern of results found in Stage 1. There was again a significant effect of task, $F(1,15) = 133.34$, $MSE = 7{,}046$, $p < .0005$. Performance was faster on location trials ($M = 480$ ms) than it was on letter trials ($M = 722$ ms), resulting in a mean difference of 242 ms. There was also a significant switch effect, $F(1,15) = 21.53$, $MSE = 7{,}293$, $p < .0005$, with repeat RTs ($M = 552$ ms) being faster than switch RTs ($M = 651$ ms). The interaction was significant: $F(1,15) = 10.79$, $MSE = 4{,}752$, $p = .005$. As can be seen in Figure 10, the switch cost on the letter task (M cost = 156 ms) was larger than that found on the location task (M cost = 42 ms).

Again, *post hoc* t-tests were conducted to verify the presence of a significant switch cost on each task. Results revealed that the difference between letter repeat (M = 645ms) and letter switch ($M = 800$ ms) trials was significant: $t(15) = 4.77$, $p < .0005$. For location trials, the difference between repeat ($M = 459$ ms) and switch ($M = 501$ ms) trials was not significant, $t(15) = 2.02$, *ns*. Thus, the pattern of results as a whole mirrored that observed in Stage 1.

Stage 3: All-Bivalent

Results from Stage 3 revealed a main effect of Task: $F(1,15) = 108.82$, $MSE = 11753$, $p < .0005$. Performance on location trials averaged 523 ms while that on letter trials averaged 806 ms, a mean difference of 283 ms. Again there was a significant switch effect, $F(1,15) = 26.07$, $MSE = 13{,}511$, $p < .0005$. Repeat RTs (M= 590 ms) were faster than switch RTs (*M* = 739 ms). The interaction, however, did not reach significance, *F* (1,15) = 2.10, *MSE* = 4,333, $p > .05$. As shown in Figure 10, the location switch cost (*M* cost = 125 ms) was statistically equivalent to that found on the letter trials (*M* cost = 172 ms).

Between-Stage Comparisons

As for Experiments 1 and 2, the goal of these analyses was to compare the pattern of switch costs for each task between Stages 1 and 2, and between Stages 2 and 3. Repeated-measures ANOVAs were conducted using Stage (1 vs 2, and 2 vs 3) and Switch (repeat vs switch) as factors in each contrast. Recall that the location task was univalent in Stage 1 and bivalent in Stages 2 and 3, while the letter identity task was univalent in Stages 1 and 2, and bivalent in Stage 3 (see Figure 9). Where indicated, two post hoc *t*-tests using Bonferroni-adjusted alpha levels were conducted to identify the source responsible for interaction effects.

Location Trials (Task A)

Stage 1 vs. 2.

Subjects took on average 461 ms to perform the location task in Stage 1 and 480 ms in Stage 2. This difference was not significant, *F* (1,15) = 1.39, *MSE* = 4,209, $p > .05$. There was a marginal effect of Switch, *F* (1,15) = 3.74, *MSE* = 5,353, $p = .072$, with switch trials averaging 488 ms and repeat trials, 452 ms. More importantly, the interaction between Stage and Switch was not significant, *F* (1,15) = .62, *MSE* = 1,293, $p > .05$. Thus, despite the fact that the location task became bivalent in Stage 2, no significant difference in the magnitude of switch costs emerged (see Figure 10). This finding is consistent with the Inertia hypothesis which in this case predicts no switch cost difference between Stages 1 and 2 given that the task subjects were switching *from* was univalent in both stages.

Stage 2 vs 3.

Analyses revealed a significant switch cost, $F(1,15) = 14.28$, $MSE = 7.812$, $p = .002$. Switch times averaged 543 ms while repeat times averaged 460 ms, a mean difference of 83 ms. The effect of Stage was also significant, $F(1,15) = 11.07$, $MSE = 2.680$, $p = .005$. On average subjects were faster in Stage 2 ($M = 480$ ms) than in Stage 3 ($M = 523$ ms). However, this main effect is qualified by the significant interaction found between Stage and Switch, $F(1,15) = 17.97$, $MSE = 1.499$, $p = .001$.

As illustrated in Figure 10 , the switch cost in Stage 3 was much larger than that in Stage 2. Post hoc *t*-tests showed that only switch trials differed from Stage 2 to Stage 3. Switch RTs in Stage 2 (M switch = 501 ms) were faster than those observed in Stage 3 (M switch = 585 ms), $t(15) = 4.13$, $p = .001$. Repeat RTs in Stage 2 (M repeat = 459 ms) and Stage 3 (M repeat = 461 ms) were not significantly different from one another, $t(15) = .20$, *ns*.

Thus it would seem that in the case where subjects were switching from the non-dominant letter identity task to the dominant location task, the stimulus valence of the previous trial was critical in the determination of switch cost changes across stages.

Letter Trials (Task B)

Stage 1 vs. 2.

Analyses revealed a main effect of Switch, $F(1,15) = 21.58$, $MSE = 12{,}585$, $p < .0005$, and a significant Stage by Switch interaction, $F(1,15) = 4.95$, $MSE = 2{,}085$, $p = .042$. The stage effect was not significant, $F(1,15) = .00$, $MSE = 2{,}656$, $p > .05$. On average, performance in Stage 1 ($M = 722$ ms) was statistically equivalent to that of Stage 2 ($M = 722$ ms), and subjects were generally faster on repeat trials ($M = 657$ ms) than on switch trials ($M = 787$ ms). Of interest is the fact that the switch cost was larger in Stage 2 (M cost = 156 ms) than in Stage 1 (M cost = 105 ms)(see Figure 10). These results are consistent with predictions borne out of the Wylie and Allport model.

However, inspection of Figure 10 suggests that the larger switch cost found in Stage 2 could be attributed to faster repeat trials. Two post hoc t-tests were conducted to verify this possibility. Results showed that switch RTs in Stage 1 ($M = 774$ ms) and Stage 2 ($M = 800$ ms) did not significantly differ from each other, $t(15) = 1.20$, *ns*. On the other hand, the difference between Stage 1 and Stage 2 repeat RTs was almost significant, $t = 2.30$, $p = .036$. Thus, Stage 1 repeat RTs ($M = 669$ ms) were in fact larger than Stage 2's ($M = 645$ ms).

While these results support the Inertia hypothesis, the fact that the larger switch cost in Stage 2 was based on faster repeat trials could be problematic. To explore a possible cause for this finding, the data from Stage 1 and Stage 2 were separated into two blocks (resulting in 72 observations for each block). This procedure was implemented to check for practice effects. Two separate repeated-measures ANOVAs using Block (Part 1 vs Part 2) and Switch (switch vs. repeat) on the data from Stage 1, and from Stage 2 were conducted.

As expected, results from Stage 1 showed a significant effect of Switch, $F(1,15) = 14.46$, $MSE = 12{,}331$, $p = .002$. More importantly, there was a significant effect of Block, $F(1,15) = 10.93$, $MSE = 2{,}191$, $p = .005$. The interaction was not significant, $F(1,15) = .60$, $MSE = 1{,}455$, $p > .05$, suggesting that this speed up effect occurred on both switch and repeat trials alike. As shown in Figure 11, RTs in the first part of Stage 1 (*M* switch = 790 ms; *M* repeat = 692 ms) were slower than in the second part (*M* switch = 759; *M* repeat = 646 ms).

In Stage 2, the only significant effect was that of Switch, $F(1,15) = 22.74$, $MSE = 16{,}983$, $p < .0005$. Neither the Block, nor the Block by Switch interaction were significant, all Fs < 1. As shown on Figure 12, RTs in the first part of Stage 2 (*M* switch = 803 ms; *M* repeat = 649 ms) were equivalent to those of the second part (*M* switch = 798 ms; *M* repeat = 641 ms) suggesting that performance had stabilized by the time subjects reached Stage 2.

Together these results suggest that performance in Stage 1 continued to improve until it reached asymptote levels in Stage 2. Yet, in spite of these practice effects, a greater switch cost emerged in Stage 2 where performance had become relatively stable. In order to tease out these practice effects from the analyses, a repeated-measures ANOVA using data from the second block in each stage was conducted, again using Stage and Switch as factors. While some of the power was lost due to the smaller number of observations per cell per subject, results showed some interesting patterns that help

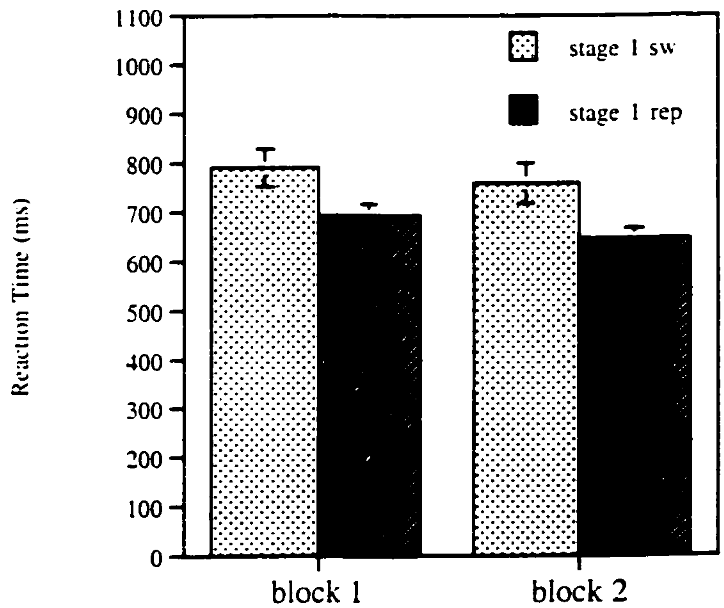

Figure 11. Mean RT for letter switch and repeat trials in the first and second part of Stage 1, Experiment 3. Error bars represent between-subjects standard errors.

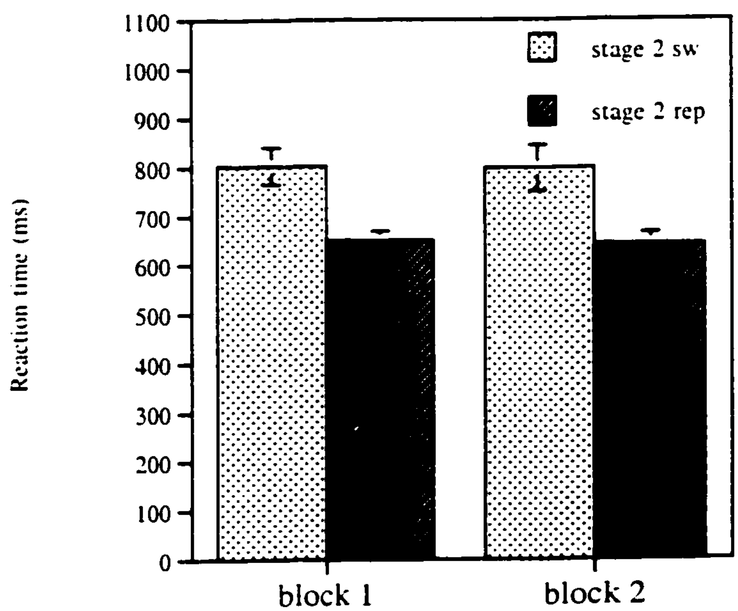

Figure 12. Mean RT for letter switch and repeat trials in the first and second part of Stage 2. Experiment 3. Error bars represent between-subjects standard errors.

interpret the Stage by Switch interaction reported above (and the smaller repeat RTs found in Stage 2): as expected, the effect of switch was again significant, $F(1,15) = 18.62$, $MSE = 15{,}657$, $p = .001$; and the effect of Stage, not significant, $F(1,15) = .961$, $MSE = 4{,}772$, $p > .05$. The interaction between Stage and Switch almost reached significance, $F(1,15) = 4.33$, $MSE = 1{,}796$, $p = .055$. Inspection of Figure 13 clearly suggests that the increased switch cost found in Stage 2 was not related to faster repeat trials. Repeat trials averaged 646 ms in Stage 1 and 641 ms in Stage 2, while switch trials averaged 759 ms and 798 ms respectively.

Stage 2 vs. 3.

Analyses revealed a different pattern for Stages 2 and 3 that was again compatible with Wylie and Allport's model. There was a significant effect of Stage, $F(1,15) = 26.18$, $MSE = 4{,}259$, $p < .0005$. Subjects were faster in Stage 2 ($M = 722$ ms) than they were in Stage 3 ($M = 806$ ms). There was also a significant effect of Switch, $F(1,15) = 24.28$, $MSE = 17{,}715$, $p < .0005$, with switch times averaging 846 ms, and repeat times, 682 ms. The interaction between Stage and Switch was not significant, $F(1,15) = .39$, $MSE = 2{,}864$, $p > .05$. Thus, while subjects took longer to respond to the bivalent letter trials in Stage 3, the cost of switching to these trials remained the same as it was in Stage 2, when the letter stimuli were univalent (see Figure 10).

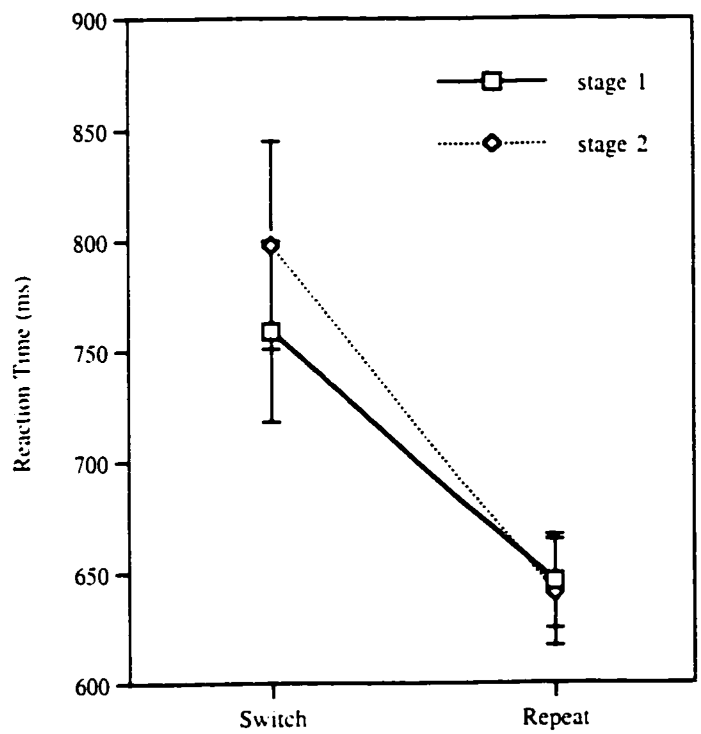

Figure 13. Mean RT for letter switch and repeat trials in the second part of Stages 1 and 2 of Experiment 3. Error bars represent between-subjects standard errors.

Discussion

The objective of this third experiment was to further test Wylie and Allport's Inertia model with asymmetrical tasks that more closely matched the type of asymmetry found with the Stroop-color task. Results from Experiment 2 suggested that the dimension over which tasks vary may be critical in the unfolding of switch cost patterns. We thus attempted to choose tasks that varied not only on speed of performance but on degree of automaticity as well, while keeping LTM retrieval demands similar in kind (i.e., semantically-based in both cases). In keeping with these objectives, we developed two tasks that required subjects to make judgments about the identity of letter-pairs or the location of target stimuli.

Contrary to results observed in Experiments 1 and 2, we found a pattern of switch costs across stages that replicated Wylie and Allport's (2000, Experiment 1) findings. That is, switch costs on both the letter and location tasks varied, across stages, as a function of valence changes in the task subjects were switching *from*, consistent with the Inertia hypothesis put forward by Allport and colleagues. Thus when the valence of the competing task changed from univalent to bivalent, switch costs to the engaged task increased, irrespective of its own valence status. Results for each task are reviewed in detail next.

Within-Stage Comparisons

Performance on the location task was faster in each of the three stages, confirming the presence of a task asymmetry at least as far as speed of responding is concerned. The pattern of switch cost differences between the location and the letter task in each of the three stages, however, was slightly different from that observed in Wylie and Allport's experiment. In Stage 1, we found a switch cost on letter trials only. Location performance failed to show evidence of a switch cost. In Stage 2, there was again no evidence of a switch cost on the location task while the letter task incurred a switch cost. In Stage 3, a switch cost of equivalent magnitude obtained on both tasks. In Wylie and Allport's experiment, a switch cost of equivalent magnitude was observed on Word and Color in Stage 1 whereas in Stage 2, only non-dominant Color trials evidenced a switch cost. In Stage 3, both tasks showed a switch cost but the cost was larger on dominant Word trials.

Several possibilities may explain the discrepancy found between the results of the two experiments. While two of these are presented below, the reader should keep in mind that these discrepancies are minor with regards to the main hypotheses. Indeed, the within-block analyses only provide information about relative differences that exist between tasks. Given that the tasks used in each experiment come with their own unique sets of processing demands, we may expect different patterns to emerge between them. This argument is especially relevant to results obtained in Stage 1 where stimuli were univalent, and thus uniquely cued their respective task-sets. Thus, in and of themselves, these analyses are secondary in terms of the main hypotheses, and the differential predictions made by each theoretical model tested in this thesis. The more revealing analyses concern the performance comparisons on the same task across stages. Nevertheless, the observations obtained within each stage can be useful insofar as they provide us with information concerning relative task performance.

One of the possibilities that may be considered with regards to Stage 1 results is related to differences in the amount of overlap that was inadvertently built-in within each task. Wylie and Allport invoked this possibility to explain the presence of switch costs on both Color and Word performance in their all-neutral condition. Given that the stimuli they used were meant to uniquely cue their own task-set, the presence of switch costs was unexpected. They argued that the black color fonts used to present the neutral Word trials, and the colored x's used to present the neutral Color trials could nevertheless have cued the competing task by virtue of this minor overlap with the competing task. In a similar vein, we might argue that in the present experiment, the stimuli used in the letter task overlapped with the location task given they were presented in a nameable location (center). On the other hand, the stimuli used for the location task in the univalent stage could be considered to have much less overlap given they had no nameable letter identity (two different non-alphanumeric characters): Hence, the larger switch costs we found on letter trials in this stage, and the absence of switch costs on location trials.

Importantly however, these results are inconclusive with regards to the locus of the effect. Overlap could be considered to affect the control mechanisms underlying cue-inhibition costs as proposed by Rogers and Monsell or proactive interference from the competing task as proposed by Wylie and Allport. However, for the latter to hold true, one would have expected the switch cost on location trials to be larger than that to letter trials in Stage 1. Given that letter trials presented a nameable location and therefore would have required the inhibition of the location task-set, the proactive interference view would predict subsequent interference with performance on location trials, and consequently, larger switch costs on location trials. We found the opposite result: there was a switch cost on letter trials while none was observed on location trials.

A more likely possibility is that each task entails its own set of processing demands which interact with control mechanisms when a shift of task-set is required. When the tasks are symmetrical, it becomes possible to interpret within-block analyses because we can presume that tasks make the same demands on control mechanisms provided of course that they are equivalent in terms of processing demands. On the other hand, when there is a large discrepancy between the processing demands involved in each task, it becomes difficult to determine the origin of the larger switch cost. In Stage 2 of the present experiment for example, we found larger switch costs on the univalent non-dominant letter trials. This could have been caused by the change in competing location trials which by the time subjects reached Stage 2 had gained bivalent status, and thus required inhibition of the letter task-set (consistent with Wylie and Allport's position). But then, for this position to be correct, we should have obtained the reverse pattern in Stage 3. That is, given that both tasks were bivalent, a larger switch cost should have obtained on the dominant location task, consistent with predictions borne out of the proactive interference hypothesis. Instead, we found equivalent switch costs on both tasks. Thus in this respect, this experiment failed to replicate the larger switch cost Wylie and Allport found on the dominant Word task. If, however, shifting mechanisms involve the activation of task rules as proposed by Rubinstein et al. (2001) then it becomes difficult to interpret these results since each pair of tasks is unique and comes with its own particular set of processing rules which may or may not interact with shifting mechanisms. In this respect, the between-stage analyses are more revealing since they permit the comparison of the same pair of tasks across different conditions.

Nevertheless the within-stage analyses indicate the following: 1) the manipulation designed to build an asymmetry between the location and letter tasks was successful: subjects were much faster on location trials in all three stages; 2) it would appear that the control mechanisms involved in shifting to the location task were more efficient in Stages 1 and 2 (indeed, shifting to location trials in Stage 1 was so efficient that no cost was observed) than those controlling the shift to letter trials; and 3) unlike Wylie and Allport who obtained a larger shift cost on the dominant word task in their all-Stroop condition (Stage 3), we obtained equivalent shift costs on location and letter trials in Stage 3. Thus while the pattern of switch costs between stages (as discussed below) replicated those of Wylie and Allport's, we failed to replicate the finding that it is more difficult to switch to the dominant task. It seems then that it is not necessary to obtain this asymmetry of switch costs within stages to observe the influence changing the valence of the competing task on current task performance (we shall address this issue in the general discussion).

Between-Stage Comparisons

The critical analyses comparing switch cost differences between Stages 1 and 2 and between Stages 2 and 3 on location and letter performance revealed that the switch cost difference was determined by the task subjects were switching *from*, and not the control demands of the task they were switching *to*. The results were thus entirely consistent with those of Wylie and Allport (2000, Experiment 1).

Location Trials (Task A)

Performance on the location task showed that the change in switch cost magnitude across stages mirrored changes in the valence of the competing letter task consistent with the proactive interference view. Results showed that when the valence of the competing letter task remained the same in Stages 1 and 2, the switch cost on location trials remained the same, even though they were bivalent in Stage 2 and thus presented a larger challenge. And unlike results observed in Experiments 1 and 2, there was no main effect of Stage: subjects were equally fast in both stages. On the other hand, despite the fact that location trials were bivalent in both Stages 2 and 3, increased switch costs were observed in Stage 3, where the competing letter task had by then gained bivalent status. Unlike Wylie and Allport however, we observed no general slowing down effects between Stages 2 and 3 despite the observation of a larger switch cost. Thus it would seem that performance on the location task was overall equivalent across the three stages.

Letter Trials (Task B)

Letter performance followed a similar pattern. That is, changes in switch cost magnitude across stages followed changes in the valence status of the competing location task. Thus, when the location task became bivalent in Stage 2, the letter switch cost increased relative to Stage 1, even though the letter task was univalent in both stages. Despite this increase in switch cost, subjects were not slowed down overall as there was no effect of stage. On the other hand, no switch cost difference emerged between Stages 2 and 3 (even though letter trials became bivalent in Stage 3) as the competing location task was bivalent in both these stages. However, consistent with Wylie and Allport's findings and those of Experiments 1 and 2 of the present study, subjects evidenced a Stage effect and were somewhat slower in performing the letter task in Stage 3.

General Considerations

Generalizability of Findings

Together, the findings from Experiment 3 replicate the pattern of results reported by Wylie and Allport (2000, Experiment 1). It would seem then that the type of asymmetry that exists between any two tasks is critical to obtaining results supporting the Inertia hypothesis. The reason as to why we should obtain this pattern with certain pairs of tasks but not others raises several possibilities which will be more fully explored in the general discussion. For now, we may conclude that because we were able to obtain dramatically different patterns of performance using different pairs of tasks under the same paradigm, that neither Wylie and Allport's position nor Rogers and Monsell's are quite sufficient to explain the origins of switch costs. As Monsell et al. (2000) argued, switching between tasks requires the changing of various component settings. "What is involved in changing each component may also change radically with the pairs of tasks considered" (p.252).

Certainly, the absence of a Stage effect observed on location performance with bivalent stimuli in Stage 2 is consistent with findings (see McLeod, 1991 for a review) that show a lack of interference from incongruent Color attributes on Word stimuli. Location performance in this experiment showed a similar lack of interference (that is, it was unaffected by the presence of competing stimulus attributes), lending further support to the notion that this task involved a high level of automaticity[10]. Whether this has informative value with regards to the issues at hand remains an open question which will be explored in the general discussion.

Working Memory Issues

It is interesting to note that not only did we replicate the pattern of switch costs Wylie and Allport found across stages, but the pattern of performance on the dominant task (task A) in Stages 1 and 2 was quite different from that observed in Experiments 1 and 2 of the present thesis. Whereas in the first two experiments, performance on Task A (the letter tasks) showed a general slowing down effect with the inclusion of bivalent stimuli in Stage 2, no such decrement was observed on the dominant location task in Experiment 3. Thus, just like performance on the dominant Word trials in Wylie and Allport's experiment, location performance was not affected by presence of competing stimulus attributes in Stage 2. Monsell et al (2000) argue that block effects may reflect long-term carry-over interference of the sort proposed by Allport and colleagues as they found subjects to be generally slower on repeat trials within alternating run blocks relative to pure blocks. What the results of this experiment suggest, however, is that some tasks may be more impervious to these types of influences than others.

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[10] However, we cannot really state that location performance was more automatic than letter performance since there was no condition involving univalent location and bivalent letter trials in this experiment that would permit the evaluation of this hypothesis. Therefore, what these results do indicate is that, similar to performance on incongruent Word stimuli, bivalent location performance did not show interference from competing attributes.

Only when subjects had to switch between bivalent location and letter tasks in Stage 3 did we observe a general decrement in performance, and then only on the non-dominant letter task. In terms of general speed of responding, performance on the location task was the same across the three stages. This pattern differs from that reported by Wylie and Allport who found much slower performance on both Word and Color tasks in Stage 3 (see Figure 2). While we had entertained the hypothesis that these Stage effects reflected a higher working memory load which in turn could have caused the pattern of results reported by Wylie and Allport. the results of the present experiments are inconsistent with this view. That is. despite the fact that general performance on location trials was equivalent across stages. we still obtained a pattern of switch costs consistent with the Inertia position. The implications of this is that if working memory plays a role in the pattern of shift costs obtained. Stage effects as manifested in RT measures cannot be used to index this role.

GENERAL DISCUSSION

The goal of the experiments presented in this thesis was to extend Wylie and Allport's (2000, Experiment 1) paradigm to other pairs of task to test their Inertia theory and the generalizability of their findings. On the assumption that their results may have been due to specific factors related to the asymmetry existing between the Stroop Word and Color tasks, we set out to use other task pairs that were either symmetrical (Experiment 1) or asymmetrical (Experiments 2 and 3). We wanted to contrast predictions borne out of the Inertia hypothesis supported by Allport and colleagues to those of the Reconfiguration hypothesis supported by Rogers and Monsell (1995). In keeping with this goal, we incorporated tasks that more closely resembled the letter and digit tasks used by Rogers and Monsell (1995) while at the same time borrowing the paradigm adopted by Wylie and Allport (2000, Experiment 1).

The results we obtained present a mixed picture which provides partial support for each theoretical position. It appears that the pattern of switch costs obtained for any given pair of tasks is highly dependent on the particular pairs of tasks employed. To assist the reader in the discussion that will follow the reader is referred to Tables 1 and 2 which present a summary of the findings we obtained in the three experiments of the present study, and the pattern of results obtained by Wylie and Allport (2000, Experiment 1).

As seen in Table 1, when subjects had to switch between symmetrical letter and digit tasks (Experiment 1), switch costs across stages varied as a function of the control demands of the currently engaged task. When an episodic component was added to the

Table 1

Summary of results relative to between-stage analyses (Stage (2) X Switch (2)) for experiments 1, 2, and 3, and Wylie & Allport's (2000) Expt. 1.

	STAGE 1-2	STAGE 2-3
EXPERIMENT 1		
Task A (Letter)	. ***Larger switch cost in stage 2*** *(p = .061)* Longer latencies in stage 2 Main effect of switch	. Equal switch costs Longer latencies in stage 3 Main effect of switch
Task B (Digit)	. Equal switch costs Equal latencies Main effect of switch	. ***Larger switch cost in stage 3*** Longer latencies in stage 3 Main effect of switch
EXPERIMENT 2		
Task A (Letter)	. ***Larger switch cost in stage 2*** Longer latencies in stage 2 Main effect of switch	. ***Larger switch cost in stage 3*** Longer latencies in stage 3 Main effect of switch
Task B (Digit)	. Equal switch costs Equal latencies Main effect of switch	. ***Larger switch cost in stage 3*** Longer latencies in stage 3 Main effect of switch
EXPERIMENT 3		
Task A (Location)	. Equal switch costs Equal latencies Main effect of switch (p = .072)	. ***Larger switch cost in stage 3*** Equal latencies Main effect of switch
Task B (Letter)	. ***Larger switch cost in stage 2*** * Equal latencies Main effect of switch	. Equal switch costs Longer latencies in stage 3 Main effect of switch
WYLIE & ALLPORT		
Task A (Word)	. Equal switch costs Equal latencies Main effect of switch	. ***Larger switch cost in stage 3*** Longer latencies in stage 3 Main effect of switch
Task B (Colour)	. ***Larger switch cost in stage 2*** Equal latencies Main effect of switch	. Equal switch costs Longer latencies in stage 3 Main effect of switch

Note. * The p level for the interaction was .055 after practice effects were removed digit task in Experiment 2, thus creating a task asymmetry in terms of RT, three out of the four critical analyses examining switch cost differences between stages replicated the results of Experiment 1. That is, for the letter task between Stages 1 and 2, and for the digit task between Stages 1 and 2, and Stages 2 and 3, it was the change in valence of the engaged task (from univalent to bivalent) that caused switch costs to increase across stages. We found one exception to this pattern. Despite the fact that the letter task was bivalent in both Stages 2 and 3, we observed a larger switch cost in Stage 3. This result was more consistent with the changes that took place in the competing digit task which was univalent in Stage 2 and bivalent in Stage 3. Nevertheless, the introduction of a task asymmetry, overall, failed to replicate the pattern of findings that would support Wylie and Allport's position.

Given that the type of asymmetry that characterized the tasks in Experiment 2 was built along a semantic-episodic dimension, we further explored Wylie and Allport's position in Experiment 3 by using tasks that we assumed differed in the degree to which they were automatic. This seemed more consistent with the type of processing distinction that characterized the Word and Color Stroop tasks used by Wylie and Allport (2000). The results we obtained with this procedure were consistent with the pattern of switch costs observed by Wylie and Allport (see Table 1). That is, switch costs across stages for both tasks varied according to the demands taking place on the task preceding a task shift. Thus, for the dominant location task, we observed an increase in switch costs in Stage 3, whereas performance was stable across Stages 1 and 2. This pattern was consistent with the type of processing that took place on the non-dominant letter trials preceding the task shift. Similarly, for the non-dominant letter task, the pattern of shift cost changes across stages corresponded to changes that took place in the competing dominant location task: switch costs increased in Stage 2, and remained stable across Stages 2 and 3 . This was consistent with the change in stimulus valence of the competing location task.

Thus, the results of the experiments presented in this thesis indicate that whatever mechanisms enable attention shifting in alternating task performance, their expression, at least as far as RT is concerned, depends on which pair of tasks is employed. The reasons as to why this should be so are manifold. While the procedures used in the present study were not meant to address this question directly, we shall explore some potential explanations.

But before doing so, another finding merits closer inspection. While the critical analyses concerned performance on each task across stages, we nevertheless compared performance between tasks within each stage (see Table 2). In Experiment 1, the switch costs between tasks was the same in each of the three stages. In Experiments 2 and 3, the switch cost differences between tasks in each of the 3 stages did not seem to follow any logical pattern with regards to the Inertia and Reconfiguration hypotheses. Our best guess at the moment is that inherent task characteristics determined the pattern of switch cost differences.

To summarize, the findings reviewed thus far indicate that: 1) when symmetrical tasks are used, the pattern of shift costs across stages varies as a function of the control

Table 2

Summary of results relative to within-stage analyses (task (2) X switch (2)) for experiments 1, 2, and 3 and Wylie & Allport's (2000) study.

	STAGE 1	STAGE 2	STAGE 3
EXPERIMENT 1 (A=B)	Equal switch costs ***Equal latencies tasks A&B*** Main effect of switch	Equal switch costs Slower task A performance Main effect of switch	***Equal switch costs*** Equal latencies task A&B Main effect of switch
EXPERIMENT 2 (A<B)	Equal switch costs ***Faster task A performance*** Main effect of switch	Larger switch cost on task A ($p = .085$) Faster task A performance Main effect of switch	***Larger switch cost on task A*** ($p = .086$) Faster task A performance Main effect of switch
EXPERIMENT 3 (A<B)	Switch cost on task B only ***Faster task A performance*** No main effect of switch	Switch cost on task B only Faster task A performance Main effect of switch	***Equal switch costs*** Faster task A performance Main effect of switch
WYLIE & ALLPORT (A<B)	Equal switch costs ***Faster task A performance*** Main effect of switch	Switch cost on task B only Faster task A performance No main effect of switch	***Larger switch cost on task A*** Faster task A performance Main effect of switch

demands of the engaged task; and 2) when asymmetrical tasks are used, the pattern of shift costs across stages is variable, and may reflect interference from disengaged tasks and/or the control demands of the engaged task; and 3) the relative shift costs in the case of asymmetrical tasks are independent of the pattern of shift costs observed across stages. The question that these findings raise is why should shifting performance be sensitive in some cases to the influence of prior processing, while in others, it seems to reflect the control demands of current processing. Two major possibilities present themselves. The first one concerns the possibility that different attentional control operations are involved depending on the type of task mechanisms that need to be mobilized. Depending on which types of tasks subjects have to switch between, shift costs may reflect interference accruing from previous trials or the control demands of current trials. The second possibility is that the same type of control mechanisms are involved, but the outcome is determined by their interaction with basic task processes. The outcome in terms of which control process seems more influential will depend on the relative dominance that exists between tasks, and the basic task processes involved (including the way they interact with each other). The position defended in this thesis and which we will attempt to develop below is biased towards this latter possibility.

Is it More Difficult to Switch to the Dominant Task?

Given that task dominance is central to Allport and colleagues' argumentation, a closer look at this concept is warranted. The use of asymmetrical tasks in task-shifting studies has led to the counter-intuitive finding that it is more difficult to switch to the dominant task (Allport et al., 1994; Meuter & Allport, 1999; Monsell et al., 2000; Wylie

& Allport, 2000). Wylie and Allport (2000) replicated this finding in their Experiment 1. That is, the cost of switching to the dominant Word task in Stage 3 was larger than the cost of switching to the non-dominant Color task. Allport and colleagues interpreted this result as strong support for their Inertia proposition. Why else would it be more costly to shift to an "easier" task were it not for the fact that stronger inhibition had to be applied to the dominant task to enable performance of the preceding non-dominant task? In Wylie and Allport's conceptualization this pattern of activation suppression (i.e., activating the Color task-set and inhibiting the Word task-set) interfered with subjects' ability to re-activate the dominant task-set on a shift trial, thus creating a larger shift cost.

This effect however, may not be as robust as has been believed until now. First, the results of the present experiments did not invariably replicate it. Looking at Stage 3 data (where both tasks were bivalent and thus afforded both the current and the competing tasks) we found the following: While both Experiments 2 and 3 used a dominant and non-dominant task, the cost of shifting to the dominant task was larger in Experiment 2, consistent with Allport and Wylie's findings, but equivalent to that of shifting to the non-dominant task in Experiment 3[11] (see Table 2).

What is peculiar about these findings is that it was the results of Experiment 3 that supported Wylie and Allport's predictions with regards to the more critical between-

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[11] An equivalent shift cost between tasks A and B was also observed in Stage 3 of Experiment 1. This finding was consistent with the symmetry that existed between the tasks, and is not directly relevant to the issue discussed here.

stage comparisons. And yet, in this experiment we failed to demonstrate the effect that it is more difficult to switch to the dominant task . On the other hand, in Experiment 2, we replicated the dominance effect but failed to show a pattern of shift costs across stages that was consistent with the Inertia hypothesis. It appears then that the two types of findings are independent from one another. In other words, using a paradigm which allows one to observe the effects of changing the valence of tasks across stages can lead to evidence favoring the Inertia hypothesis (as observed in Experiment 3), and yet fail to demonstrate a 'larger shift cost to the dominant task' effect. The reverse is also true. In Experiment 2, the between-stage analyses failed (with one exception) to support the Inertia hypothesis, but the between-task analyses in Stage 3 were consistent with it: switching to the dominant letter task incurred larger switch costs than shifting to the non-dominant digit task.

Given that the between-stage analyses afford a comparison of performance on the *same* task across different conditions, they may be considered to be more informative with regards to the Inertia hypothesis than analyses which compare switch cost performance on different tasks. The problem with comparing performance on two different tasks is that there is no baseline against which to evaluate and interpret switch cost differences. Given that tasks come with their own sets of processing demands or conditions, it is difficult to determine whether switch cost differences between tasks are caused by factors related to control mechanisms or processes specific to the activation of individual task-sets, or a combination of both. Comparing switch costs on the *same* task across different conditions, it would seem to us, allows a much tighter control over what factor may be responsible for the shift cost.

Nevertheless, interesting patterns emerge when switch costs are compared between tasks that are unequal in strength. Monsell et al. (2000) investigated various types of task asymmetries in the context of a task shifting paradigm. What they found is that larger switch costs to the dominant task-set obtained only with certain pairs of tasks while the majority of the tasks they studied yielded the opposite pattern (i.e., larger switch costs to the more difficult, non-dominant task). One finding that was particularly impressive with regards to the issue of task dominance (Yeung & Monsell, in preparation, cited in Monsell et al., 2000) is that by handicapping the Word task (delaying the onset of the word string relative to the color patch) they were able to reverse the direction of switch cost differences: it became more difficult to switch to the Color task. Interestingly however, the pattern of dominance obtained in pure blocks (comparing pure Stroop blocks to neutral blocks) still favored the Word task.

In another series of experiments they compared the switch cost on a dominant digit naming task to that of three different non-dominant tasks: 1) key pressing, even-odd classification, 2) vocal, even-odd classification, or 3) vocal, tens-complement (e.g., saying 4 in response to 6). They found that it was more difficult to switch to the non-dominant task when subjects alternated between the digit naming task and the even-odd classification tasks. However, the reverse occurred when subjects alternated between the digit and the tens-complement naming tasks. Here it was more difficult to switch to the dominant digit-naming task.

It would seem then that the relationship between tasks is critical in determining which task will incur the larger switch cost (MacLeod, & MacDonald, 2000). This conclusion is made even stronger by the fact that the same dominant task (digit-naming) was compared to that of three different non-dominant tasks. Certainly, the effect that it is "easier to switch to the dominant task" has not been consistently observed (e.g., Gopher, Armony, and Greenspan, 2000; Poulsen & Segalowitz, 2000 ; Rubinstein et al., 2001). One observation that Monsell et al. highlighted in their attempt to interpret these findings is the larger discrepancy in task strength that distinguished the digit naming and the tens complement task-pair: looking at repeat trials only, performance differed by about 122 ms in favor of the dominant digit-naming task. On the other hand, performance on the first and second task-pairs combining the digit naming task with the even-odd naming and key-pressing classification tasks differed by 83 ms and 96 ms respectively.

Task Dominance Revisited

In looking at our own data, we also found that a large discrepancy in task strength characterized the tasks used in Experiment 3 relative to those used in Experiment 2. Using Stage 1 repeat trials as a baseline measure, the mean RT difference between the two tasks in Experiment 3 was 223 ms, and 182 ms in Experiment 2 (see Figures 15 and 24). Thus it would seem that in Experiment 3, where we found evidence favoring the Inertia hypothesis (as far as between-stage analyses were concerned), the difference in speed of performance between the dominant and non-dominant tasks was relatively larger than that found in Experiment 2.

We decided to follow up on this idea of relative task strength, and examine the pattern of task dominance using a different approach from the one we started with. Initially, we had decided to look at basic RT differences between two tasks. The task with the fastest RT was considered the dominant task. It was this criterion that served to establish task dominance in the experiments presented in this thesis. However, it is possible that this measure was too crude to reveal any real differences in task strength that would be critical in the outcome of switch cost patterns. Following Monsell et al., we thus decided to borrow from the concept of interference developed in the Stroop literature to examine the pattern of task dominance within the experiments of the present study.

Within the Stroop literature, one way to operationalize task dominance has been to compare RTs to incongruent stimuli with those of neutral stimuli. The task exhibiting less interference from the presence of competing stimuli has been considered dominant. A classic finding with regards to the Stroop effect is that naming the color of incongruent word stimuli relative to neutral color patches takes longer. The reverse situation, that is reading color words printed in incongruent color fonts relative to neutral (black) fonts, under most conditions yields no differences. There has been controversy regarding the locus of the effect, but a consensus is now forming that attributes the effect to the relative strength of S-R associations (e.g. MacLeod & MacDonald, 2000). Recently, Monsell, Taylor, & Murphy, 2001 demonstrated that competition at the level of the word-reading and color-naming task-sets is also an important determinant of interference. While these issues are important in their own right, for purposes of the present discussion, it is sufficient to say that the task exhibiting less interference is considered to be the more dominant task.

Using this index of interference, Monsell et al. (2000) found that on repeat trials, the tasks exhibited a pattern of interference that was consistent with the dominance pattern conferred by simple mean RT differences. On the other hand, they observed that when interference indices were derived from switch trials, the tasks became "transiently more equal in strength" (p.257). This finding is interesting insofar as it suggests that on switch trials, some additional process must be operating which the repeat RT data does not allow one to distinguish.

In keeping with this approach, we decided to look at task dominance in a way that more closely parallels the traditional Stroop approach. While we did not have available pure trial blocks from which to extract interference measures, we derived interference indices by comparing performance on bivalent Stage 3 trials to univalent Stage 1 trials. This would compare with the subtraction of neutral RTs from incongruent RTs in traditional Stroop studies. Planned *t*-tests were then conducted to compare interference indices of each task within each experiment. As was the case with Monsell et al. (2001), we did separate analyses on data obtained on repeat trials and on switch trials.

Repeat Interference Indices

Results from indices obtained on repeat trials are shown in Figure 14. In Experiment 1, significant interference from competing foils in Stage 3 slowed down processing time relative to Stage 1 in both tasks. The difference between each task however was not significant, $t(15) = .73$, *ns*. These results parallel RT data obtained in

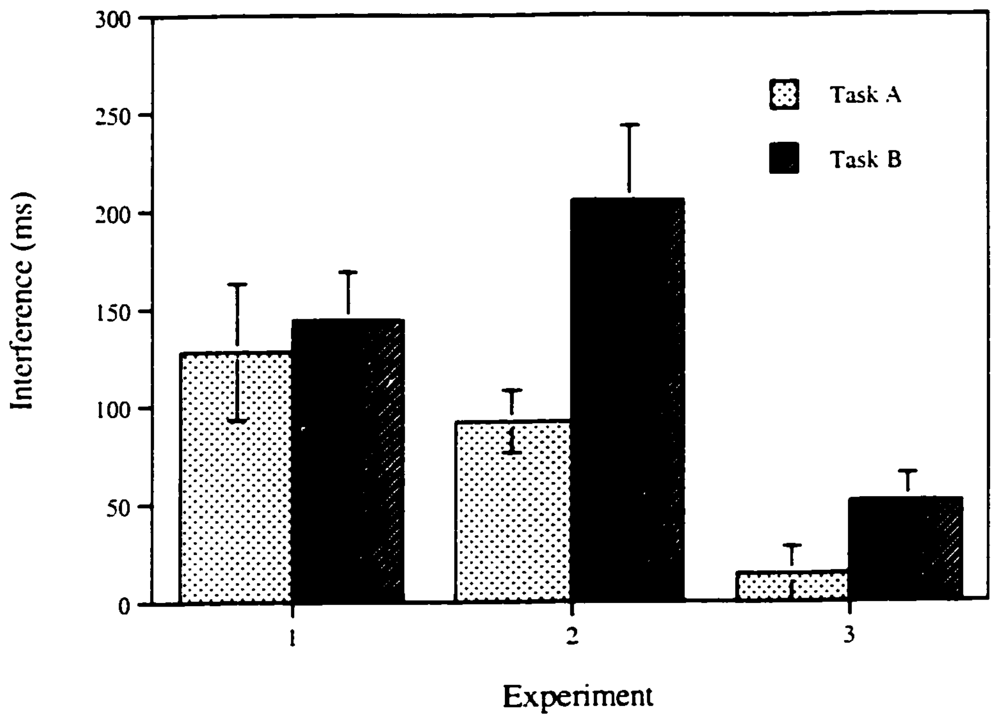

Figure 14. Interference indices (ms) measured on repeat trials for Tasks A and B across the three experiments (Task A corresonds to the letter task in Experiments 1 and 2 and to the location task in Experiment 3; whereas Task B corresponds to the digit task in Experiments 1 and 2, and the letter-name identity task in Experiment 3). Interference measures were derived from subtracting repeat univalent trials in Stage 1 from repeat bivalent trials in Stage 3. Error bars represent between-subjects standard errors.

Stage 1 repeat trials, and give further support to our assumption of a task symmetry in this experiment. In Experiment 2, results showed that the digit task exhibited more interference than the letter task, $t\ (15) = 2.90, p = .008$, supporting the Stage 1 RT data which conferred dominance to the letter task. Results from Experiment 3 showed a slightly different pattern. As in Experiment 2, the difference between the interference indices was significant ($t\ (15) = 2.58, p = .021$), and confirmed the assumed dominance of the location task. However, as shown on Figure 14, the dominant task, the location task was not slowed down by presence of competing stimuli. That is, the location task exhibited no interference from the presence of competing letter attributes. On the other hand, the letter identity task sustained significant interference from the presence of competing location attributes.

The results of these interference analyses confirm as a whole the assumptions we held concerning the direction of task dominance in the three experiments. In addition however, they provided another piece of information that we did not obtain using our original RT measure of task dominance. That is, the dominant location task in Experiment 3 appeared immune from interference effects and, as such, "behaved" in a manner very similar to the automatic Word task in Stroop studies. A similar lack of interference on the location task was reported by Palef and Olson (1975). This "immunity" to interference from competing stimulus attributes lends further credibility to the hypothesis that it is perhaps the distinction regarding the involvement of automatic processes that confers the patterns of findings reported by Allport and colleagues and in Experiment 3 of the present thesis.

A question that these findings raise however is how does this affect the attentional control mechanisms that enable the activation of the engaged task-set on switch trials. It may be that when one of the tasks is automatic *and* beyond a certain threshold of dominance relative to the other task, the task-set becomes automatically activated in the presence of task-related stimuli, irrespective of whether it is currently the appropriate task to activate or not[12]. This would result in the need to actively inhibit the inappropriate dominant task-set in order to allow the smooth operation of the relevant task-set.

Switch Interference Indices

Results concerning RT interference indices obtained on switch trials are shown in Figure 15. Planned *t*-test comparisons confirmed Monsell et al.'s findings: On switch trials, all of the task-pairs in Experiments 1, 2, and 3 exhibited symmetrical interference (none of the *t*-tests led to significant results (Experiment 1: t (15) = 1.37, *ns*; Experiment 2: t (23) = .183, *ns*; Experiment 3: t (15) = .216, *ns*). These data therefore suggest, as Monsell et al. pointed out, that on switch trials both task-sets become more equal in strength as subjects are preparing to de-activate the previous one in favor of the upcoming

[12] A point of caution concerning the "automaticity" interpretation typically conferred to the Stroop effect should be given. Besner and Stolz (1999) demonstrated that it is not because word-reading interferes with color-naming that word-reading is necessarily "automatic". Rather, the authors demonstrated that contextual control determines the activation of the word-reading pathway. On the other hand, Catena, Fuentes, and Tudela (2002) showed that even in the absence of Stroop interference effects, it is possible to demonstrate that words are automatically processed in that they can negatively prime subsequent color-naming trials. Thus, the use of interference indices to indicate the automaticity of the irrelevant stimulus feature is not as straightforward as has been typically believed.

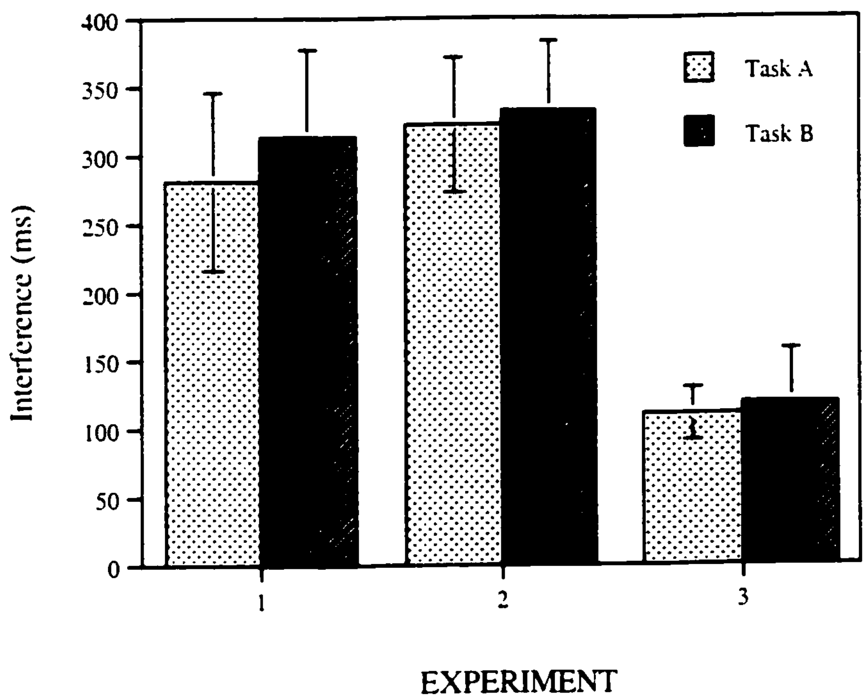

Figure 15. Interference indices (ms) measured on switch trials for Tasks A and B (Task A corresponds to the letter task in Experiments 1 and 2, and to the location task in Experiment 3; Task B corresponds to the digit task in Experiments 1 and 2, and to the letter-name identity task in Experiment 3). Interference measures were derived from subtracting univalent switch RTs in Stage 1 from bivalent switch RTs in Stage 3. Error bars represent between-subjects standard errors.

one. While it would not be feasible to obtain interference indices from these trials to estimate task dominance, the result suggesting that task dominance disappeared altogether on switch trials is interesting in and of itself. This finding certainly merits further investigation.

The Reverse Stroop effect

Wylie and Allport (2000, Experiment 1) found that performing the Word task in the context of shifting with the Color task caused a 'reverse Stroop effect'. That is, comparing performance in Stage 3 to that of Stage 1, they found that Word performance was significantly slowed down by the presence of incongruent color attributes: A finding they referred to as the 'reverse Stroop effect'. In pure blocks, such interference from Color on Word is usually absent (for a review, see McLeod, 1991). They interpreted this finding as additional support for their Inertia theory: interference accruing from inhibiting the Word task-set on Color trials caused Word performance on Stroop trials to slow down. However, as seen above, we found no such interference on the dominant location task of Experiment 3 despite the fact that the results of this experiment supported their Inertia theory. In fact we interpreted this lack of interference to indicate the 'automaticity' of the location task. Why the discrepancy? Our best guess at the moment is that the location task was so automatic that it was even more immune to interference from the presence of competing stimuli than the Word task.

Integrating Task-Switching Mechanisms with Individual Task Processes

The results reviewed so far point to the possibility that individual task processes interact with executive control mechanisms. A promising model in this regard has been developed by Rubinstein, Meyer and Evans (2001). Their model posits discrete processing stages that afford separate contributions for executive control mechanisms and basic task processes. The latter involve stimulus-identification, response selection and movement production stages while the former includes two distinct stages: a goal shifting stage and a rule activation stage. Goal shifting involves inserting and deleting goals from declarative memory, and can occur in advance of a task shift in which case it would be endogenous; or after a stimulus has been identified, in which case it would reflect a type of exogenous control. Rule activation on the other hand is assumed to be triggered exogenously, and to occur after the stimulus has been identified and before the response selection stage. The rule activation stage serves to load current task rules into procedural memory and disable the rules that served to select the prior task's response. It is during this stage that interference and crosstalk effects are assumed to occur.

The model makes several assumptions the most important of which are the strict successiveness of component stages, the additivity of component stage durations to overall RTs, and the selective influence of factors which can affect single or multiple stages. Multiple factors can also act on a single stage. When factors affect different stages, their effects on switch costs and main RTs are assumed to be additive. For example, task cuing and rule complexity are assumed to selectively influence different executive control stages (goal shifting and rule activation). Their contributions to switch costs is therefore predicted to be additive. When the same factor affects both executive control and task processes, its effect is assumed to interact with switch costs. For example, rule complexity is assumed to affect both rule activation and response selection stages. The model therefore predicts main effects (i.e., changes in switch and repeat trials alike) and an interaction with switch costs. Finally, a factor that would selectively affect a task processing stage would affect main RTs only and leave switch costs unchanged.

Rubinstein et al. (2001) found evidence to support their model in a series of experiments that manipulated rule complexity, task cuing, and stimulus discriminability using card sorting and arithmetic problem-solving tasks. For example, in their Experiment 1, Rubinstein et al. had subjects sort geometric figures according to shape, numerosity, size, or shading in alternating and pure blocks. The dimensions over which subjects had to sort the cards allowed the authors to manipulate rule complexity and stimulus discriminability. As predicted, they found main effects of rule complexity and stimulus discriminability on RTs, presumably because these factors affect task processes. However, switch costs were larger for the high rule complexity task than for the low, consistent with the assumption that rule complexity influences the executive rule activation stage.

While Rubinstein et al.'s model is in need of further empirical validation and refinement, it has received independent corroboration in a number of studies positing different executive control components (Gopher, 1996; Kramer, Hahn, and Gopher, 1999; Meiran, 1996; Meiran, 2000a, Meiran et al., 2000; Rogers & Monsell, 1995). The attractiveness of the model lies in its ability to combine individual task processes and executive control mechanisms within a single unitary framework. Furthermore, it has the capacity to accommodate a number of findings reported in the task-switching literature with respect to manipulating variables such as RSI, task cuing, task difficulty levels, stimulus valence, etc. It also offers a tentative explanation for the stage effects we obtained in our experiments with certain tasks and stage combinations. That is, for experiments 1 and 2, we obtained stage effects only when the tasks proceeded from being univalent to being bivalent (see also Rogers & Monsell, 1995). According to Rubinstein's et al.'s model, adding competing stimulus attributes to targets affects the rule activation stage. If we make the further assumption that this occurs as a result of increased rule complexity, then according to the model, the response selection stage should be affected as well (since this factor affects both these stages); hence, the general increase in RT. Thus, the effect would not be caused by an increased working memory load as we initially believed, but by a higher challenge posed simultaneously on executive control and task processes.

The question that remains, is why should we not consistently observe these same effects with the tasks used in Experiment 3. According to Rubinstein et al. (2001), tasks which involve a high degree of automaticity call for additional assumptions and processing considerations. They hypothesize that highly familiar tasks may be "permanently 'active' in procedural long-term memory"[13], and bypass the need for the rule activation stage. In the case of the Stroop-color task, where processing on Word is more "automatic" but that on Color is more "controlled", the smaller switch cost effect found on Color is explained because the contribution of executive processes is masked by stimulus processes. The latter are assumed to proceed in parallel with the automatic activation of

[13] For a treatment of related issues concerning long-term working memory, see Ericsson and Kintsch (1995).

the competing Word stimulus processes in a type of race, the result of which causes executive control RTs to be obscured. No such race occurs on Word trials since Color does not compete with word-reading in the same manner.

While the model does not directly provide an explanation for the pattern of results obtained in Experiment 3, it does serve to illustrate the crucial need to incorporate an automatic-controlled processing distinction into our understanding of task switching mechanisms in interaction with basic task processes.

Two more findings bear on this issue. First, in a study where subjects had to switch between Color-Stroop and Digit-Stroop tasks in pure and alternating blocks, Ward, Roberts, and Phillips (2001) demonstrated that switch and Stroop costs represent two independent constructs. That is, while they found that switch costs for different pairs of tasks correlated with each other, switch costs did not correlate with Stroop interference, nor did the different Stroop interference indices for the different tasks correlate with one another. These results suggest that two different control mechanisms deal with the attentional demands posed by the switch and Stroop situations. Correlational analyses conducted on the present experiments' data confirmed these findings (see Table 3). That is, while the switch costs to tasks A and B significantly correlated with one another in each experiment, the majority did not correlate with the interference costs. The only exception to the latter finding was in Experiment 3 with task A. Here the interference and switch cost indices correlated. In light of the fact that this task was presumed to involve more automatic processing, we might conclude that this finding reflects the highly automatized nature of the task in both control situations. Thus,

Table 3

Correlation Coefficients Between Switch and Interference Indices in Experiments 1 (n = 16), 2 (n = 24), and 3 (n=16)

	Experiment 1		Experiment 2		Experiment 3	
Switch A & B	.913	***	.463	*	.846	***
Interference A & B	.769	**	.142	*ns*	.457	+
Switch A & Interf. A	.010	*ns*	-.121	*ns*	.579	*
Switch B & Interf. B	-.325	*ns*	-.163	*ns*	.218	*ns*

Note. + = $p < .10$; * = $p < .05$; ** = $p < .01$; *** = $p < .0005$. Task A corresponds to the letter task in Experiments 1 and 2, and to the location task in Experiment 3; Task B corresponds to the digit task in Experiments 1 and 2, and to the letter task in Experiment 3.

the correlational analyses conducted on the experiments of the present thesis are consistent with the notion of functional independence of control components.

Second, Long and Prat (2002) demonstrated that one of the mechanisms that is involved in controlling Stroop interference is related to subjects' ability to inhibit the irrelevant response. This ability is directly tied to an individual's working memory capacity: High span subjects in Long and Prat's study showed less Stroop interference than low span subjects, but only when this strategy was induced by including a high proportion of Stroop trials within a block.

These results further support Rubinstein et al.'s contention regarding the functional independence of executive control components. Furthermore, they draw our attention to the fact that we need to better understand the nature of the control processes that are applied to resolve competition between relevant and irrelevant stimulus features, and their possible interaction with working memory resources. It may be that for certain types of Stroop-like stimuli, the competition is such that the inhibitory mechanism applied to suppress the irrelevant feature does carry over to the other task on switch trials.

Methodological Issues

Several issues related to the experimental design employed in the present experiments need to be addressed. The first one concerns our choice of RSI. In our experiments, we used an RSI known to implicate endogenous control processes. We reasoned that it would maximize the probability of observing strong interference effects. This prevents us from drawing any conclusions with regards to residual switch costs.

However, the fact that we failed to obtain interference effects in Experiments 1 and to some extent in Experiment 2, but then did so in Experiment 3 indicates that this factor is not critical to the Reconfiguration/Inertia issue. There would seem little point then to use longer RSIs given we failed to observe interference effects at shorter intervals.

A second issue concerns the number of training trials subjects were given prior to the experimental phase. Given that performance continued to improve in the first stage of the letter trials in Experiment 3, this would indicate a need to increase the training phase to ensure asymptotic performance in the first stage of the experiment.

Another issue which could help us draw firmer conclusions about the results obtained in Experiment 3 concerns the need to obtain an independent measure of automaticity. If automaticity is really at the root of the pattern of findings we obtained in this experiment, our conclusions would be made stronger if we could independently confirm this assumption. That could be accomplished by looking at interference indices obtained on pure univalent and bivalent blocks of trials, or by using tasks that have been widely known to be automatic.

Another index that could be used is the coefficient of variability (CV) which has been shown to provide information about the involvement of automatic and control processes. More specifically, Segalowitz and Segalowitz (1993) developed a theoretical and empirical model that allows one to measure changes in the contribution of automatic and strategic control processes to skilled performance by using the coefficient of variability (CV). The CV represents the SD divided by mean RT. The basic rationale underlying the use of this measure is that as tasks become more automatic, there is a qualitative restructuring of component processes (dropping "noisier" and more variable control processes) that results not only in faster RT but in more stable performance. While speed-up effects frequently observed with practice are accompanied by proportional reductions in SD, they do not necessarily reflect a form of qualitative restructuring.

Instead, Segalowitz and Segalowitz (1993) proposed that by using the CV, we obtain a measure that indicates "the variability *for a given level of response latency*" (p. 373). Although the use of this measure is relatively new, it has nevertheless received empirical support from studies examining changes in the development of skilled performance and automaticity (Segalowitz & Segalowitz, 1993; Segalowitz, Segalowitz & Wood, 1998). More importantly, it received further validation in a task-shifting study conducted by Segalowitz, Poulsen, & Segalowitz (1999). Comparing RT changes on switch trials to RT changes caused by increasing task demands, the authors demonstrated that the CV was differentially sensitive to the involvement of control processes. Only when performance was slowed down by the intervention of executive control mechanisms on switch trials was a change in CV observed.

While it is not theoretically justified to compare CVs across tasks, one could train subjects on individual tasks until their performance reflects a qualitative change. This would provide an independent measure of the tasks' automaticity prior to having subjects perform in a switching context.

A related question to the issue of automaticity concerns the way dominance ratings are obtained. Should we look at base RTs, familiarity ratings, or rely on interference measures? Whichever choice is made, it needs to be based on strong theoretical grounds. Monsell et al. (2000) chose to look at interference measures obtained in pure blocks, following the Stroop tradition. Given the large body of literature that exists on this, it would seem a logical choice to make at this point.

Finally, when we designed the present sets of experiments, we wanted to stay close to the logic of Wylie and Allport's three-stage design methodology. However, a more complete test of their hypothesis should involve conditions that completely cross the valence factor with tasks in Stage 2. In this manner, we could verify what happens when it is the non-dominant task in Stage 2 that is bivalent. According to the Inertia hypothesis, little interference should accrue from the inhibition of the non-dominant task on dominant trials. As a result, the Inertia hypothesis would predict that neither tasks should exhibit larger switch costs in this stage relative to Stage 1.

To really stay close to a test of the automaticity hypothesis, it would be ideal to keep one task constant across experiments, say task A, and vary the relationship the other task has to it: symmetrical and automatic, asymmetrical and automatic, asymmetrical and controlled. For example, a question that follows from the findings we obtained with the "automatic" location task in Experiment 3 is what would happen if we used a pair of tasks that were equally automatic. In Experiment 1, we used two semantic categorization tasks that we assume involved more controlled processing. This led to evidence favoring the Reconfiguration hypothesis. This assumption, however needs to be verified with other tasks for which independent measures of automaticity can be obtained.

Implications and Future Directions

The results of the experiments reviewed in the present thesis indicate that switch performance cannot be studied separately from individual task performance. Tasks can vary along a number of dimensions which may play a crucial role in the determination of shift cost patterns: semantic-episodic retrieval demands, degree of automaticity, familiarity, complexity, to name a few. In order to start drawing a map of executive control mechanisms, we need to develop a better understanding of the role these task-related factors play in the determination of shift costs.

We demonstrated in the present set of experiments that different task combinations can lead to very different patterns of shift costs. We speculated that one of the reasons for this was the inclusion of a dominant automatic task which by reason of its automatic activation required that the task-set be inhibited on non-dominant trials (Monsell et al., 2000). If this is the case, we still need to find out whether the larger shift cost accruing from this interference reflects the intervention of an additional endogenous control processes mobilized on shift trials to overcome the interference (Monsell et al., 2000), or as Allport and colleagues would argue, the time needed for the system to settle on a unique response. Evidence from other studies (Arbuthnott & Frank, 2000; Mayr & Keele, 2000; Mayr, 2002) seems to indicate that a low-level control is applied to inhibit the previous task-set during the disengagement phase. However, this only occurs when subjects know in advance which task they will be performing next. The advantage of the paradigm these authors used to support their conclusions is that it permits a comparison of pure switch costs (CBA) to those involving the repetition of a task previously abandoned (ABA). Given this, it would be interesting to further investigate how asymmetrical tasks differing in degree of automaticity interact with this backward inhibition control process.

The importance of understanding the role of automaticity and inhibition in the context of executive mental control processes has larger implications for studies examining attentional biases in anxiety disordered populations. A large body of literature has already developed to research these biases, and robust attentional biases have been documented in these populations (for a review, see Williams et al., 1996). There has been controversy, however, over the interpretation to give to these biases (e.g., Fox, 1993; Lavy & van den Hout, 1994; Mathews, 1990; de Ruiter & Brosschot, 1994). Do they reflect a form of automatic pre-attentive bias, or do they reflect a form of response inhibition after the stimuli have been encoded? Task-switching methodologies may help us refine our understanding of the attentional control processes involved in these disorders. Research conducted in our lab (Poulsen & Segalowitz, 2000) has shown that prior motivation can selectively bias executive control mechanisms while leaving conceptual representations and lower-level controls unaffected. This research specifically examined the effects of positive motivation. An interesting avenue for future research would be to examine whether 'negative' incentives of the form seen in anxiety disorders (which nevertheless hold positive value insofar as they inform about the potential for threat in the environment) demonstrate these selective influences.

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APPENDIX A

Sample of Instructions from Experiment 1

Instructions: Part 1

In a moment you will be shown a pair of characters in the centre of a square on the computer screen. Each character pair will be made up of either a symbol (#, +, &, %) and a letter, or a symbol and a digit.

For the **letter task**, you are to indicate if the letter is a consonant (G, K, M, R) or a vowel (A, E, I, U) while ignoring the other character.

If the letter is a **consonant**, press the "**←**" key with your **left** index finger.
If the letter is a **vowel**, press the "**→**" key with your **right** index finger.

Example 1	Example 2
G+	#U
(consonant)	(vowel)
[←] [→]	[←] **[→]**
(L index)	**(R index)**

For the **digit task**, you are to indicate if the digit is even (2,4,6,8) or odd (3,5,7,9), while ignoring the other character.

If the digit is **even**, press the "**←**"key with your **left** index finger.
If the digit is odd, press the "**→**" key with your **right** index finger.

Example 1	Example 2
&8	3%
(even)	(odd)
[←] [→]	[←] **[→]**
(Left index)	**(R index)**

TASK SUMMARY CHART

	(left)	(right)
	←	→
Letter task:	consonant	vowel
Digit task:	even	odd

POINTS

You will complete 8 blocks of trials, each consisting of a sequence of 24 letter trials followed by a sequence of 24 digit trials, or vice-versa.

You will earn 1 point for every CORRECT response and lose 3 points for every INCORRECT response. If you make an INCORRECT response, you will hear a "boing" and will be given extra time to prepare for the next trial. ***Please try to make as few errors as possible.*** If you make fewer than 3 errors on a given block, a bonus of 5 points will be added to your total score for that block. An extra bonus of 5 points will be added if your performance on a block is faster than that of the preceding block.

At the end of each block, you will receive a summary of your performance. Please record the number of points you earned, your total number of errors, your bonus points, and your total score on the form provided, and give it to the experimenter at the end of Part 1. If you make no errors on a block, you will get 25 points plus your 5 bonus points for making no errors, and a possible 5 points for being faster in the current block than in the preceding block.

Note that this is a task for which the challenge level is adjusted at the end of each block. ***A good player is expected to score in the 20-30 point range on each block.***

TIP: To ensure that you can respond quickly, keep your fingers resting lightly on the keys at all times!

Do you have any questions?

You may press any key to begin. ***Good Luck!!***

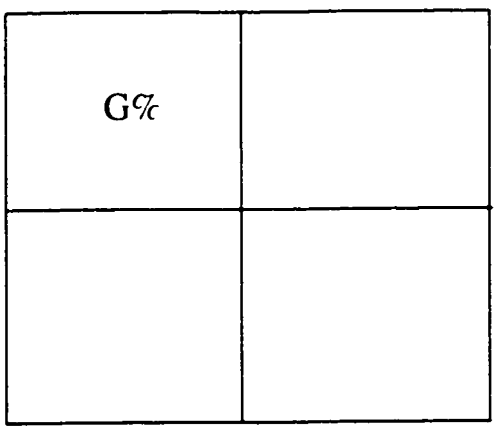
Instructions: Part 2

Part 2 will involve 3 different stages. In each stage, you will be shown a pair of characters in one of four quadrants appearing on the computer screen. Each character pair will be made up of a letter and an irrelevant character or a number and an irrelevant character. On successive trials, the position of the character pair will move clockwise to the next quadrant.

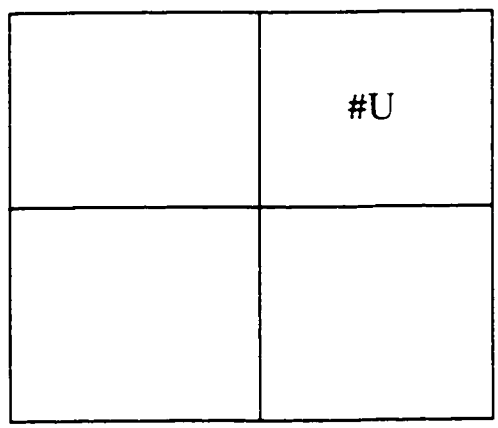
When the character pair is in either of the **two top quadrants**, you are to perform the **letter task**. As in Part 1, you are to indicate if the letter is a consonant (G,K,M,R) or a vowel (A,E,I,U) while ignoring the other character.

If the letter is a **consonant**, press the "🡐" key with your **left** index finger.
If the letter is a **vowel**, press the "🡒" key with your **right** index finger.

Example 1



Example 2



(consonant)

(vowel)

(L index)

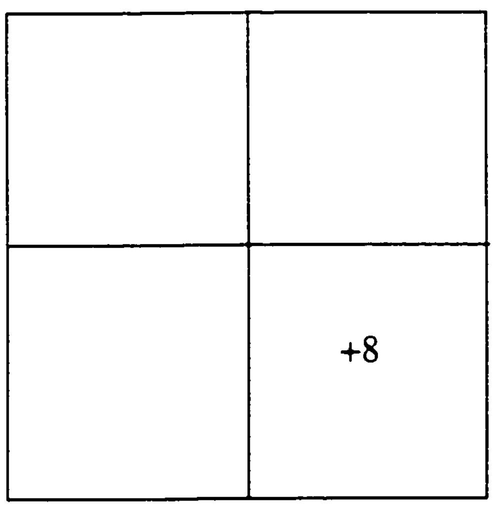
(R index)

When the character pair is in either of the **two bottom quadrants**, you are to perform the **digit task**. As in Part 1, you are to indicate if the digit is even (2, 4, 6, 8) or odd (3, 5, 7, 9) while ignoring the other character.

If the digit is **even**, press the "🡐" key with your **left** index finger.

If the digit is **odd**, press the "🡒" key with your **right** index finger.

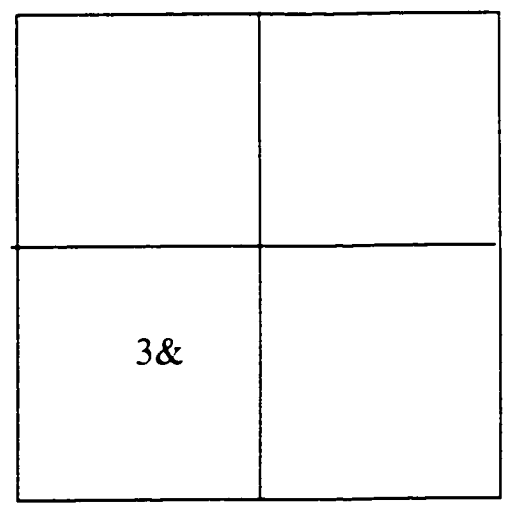
Example 1



(even)

(L index)

Example 2



(odd)

(R index)

POINTS

Each section begins with a practice block of trials. This is followed by 8 game blocks.

You will earn 1 point for every CORRECT response and lose 3 points for every INCORRECT response. If you make an INCORRECT response, you will hear a "boing" and will be given extra time to prepare for the next trial. ***Please try to make as few errors as possible.*** If you make fewer than 3 errors on a given block, a bonus of 5points will be added to your total score for that block. An extra bonus of 5 points will be added if your performance on a block is faster than that of the preceding block.

Again, at the end of each block, you will receive a summary of your performance. Please record the number of points you earned, your total number of errors, your bonus points, and your total score for that block on the form provided, and give it to the experimenter at the end of the experiment.

Note that this is a task for which the challenge level is adjusted at the end of each block. ***A good player is expected to score in the 45-55 point range on each block.***
If you make no errors on a block, you will get 50 points plus your 5 bonus points for making no errors, and a possible 5 points for being faster in the current block than in the preceding block.

Instructions: Part 2A

In Part 2A, the irrelevant character accompanying the letter in the LETTER task and the number in the NUMBER task will be a symbol (#, +, &, %). You are to ignore this irrelevant character and perform each task as indicated above.

TIP: To ensure that you can respond quickly, keep your fingers resting lightly on the keys at all times!

Do you have any questions?
You may press any key to begin. ***Good Luck!!***

<u>**TASK SUMMARY CHART**</u>

letter task	letter task
digit task	digit task

	(left)	(right)
	←	→
letter task:	consonant	vowel
digit task:	even	odd

Instructions: Part 2B

Part B is similar to Part A in that you are again to perform the LETTER task in the upper two quadrants and the NUMBER task in the lower two quadrants. However, this time, when you are performing the LETTER task, the irrelevant character accompanying the letter will be a number. You are to continue, as before, to ignore the irrelevant character, and decide whether the letter is a consonant or a vowel. The NUMBER task is the same as in Part A. In sum, when doing the LETTER task, you ignore the number character, and in doing the NUMBER task, you ignore the irrelevant symbol character.

You might notice that the task in Part B is a little more challenging than that of Part A. ***Just try to make as few errors as possible while trying to respond as fast as you can.*** Remember that each correct response affords you one point, and each error costs you three points, while fast and accurate responses may contribute 10 more points to your total score for each block. Continue as before to record your performance after each block on the form provided to that effect.

Do you have any questions?
You may press any key to begin. ***Good Luck!!***

TASK SUMMARY CHART

G8 letter task	**7M** letter task
3$ digit task	**%8** digit task

(left)	(right)
←	→
Consonant Even	Vowel Odd

Instructions: Part 2C

In Part C, you are again to perform the LETTER task in the upper two quadrants and the NUMBER task in the lower two quadrants. However, this time, the irrelevant character in the NUMBER task is a letter, and the irrelevant character in the LETTER task is a number. You continue to ignore the irrelevant character and perform each task as before. In sum, when doing the LETTER task, you ignore the irrelevant number character, and in doing the NUMBER task, you ignore the now irrelevant letter character.

You might notice that the task in Part C is a little more challenging than that of Parts A and B. *Just try to make as few errors as possible while trying to respond as fast as you can.* Remember that each correct response affords you one point, and each error costs yo three points, while fast and accurate responses may contribute 10 more points to your total score for each block. Continue as before to record your performance after each block on the form provided to that effect.

Do you have any questions?
You may press any key to begin. ***Good Luck!!***

TASK SUMMARY CHART

G8 letter task	**7M** letter task
3R digit task	**E8** digit task

(left)	(right)
←	→
Consonant even	vowel odd

APPENDIX B

Tables of Mean RTs. Switch Costs and Interference Indices

Table B1

Mean RT (ms) and Switch Costs (ms) for Each Task Across Stages in Experiments 1

	Stage 1			Stage 2			Stage 3		
Trial Type/Cost	Task A	Task B	*M*	Task A	Task B	*M*	Task A	Task B	*M*
Experiment 1(n = 16)									
Switch	780	746	763	932	795	864	1061	1059	1060
Repeat	560	555	558	642	572	607	688	700	694
Switch Cost	219	190		289	223		373	359	

Note. Task A corresponds to the Letter task and Task B corresponds to the Digit task

Table B2

Mean RT (ms) and Switch Costs (ms) for Each Task Across Stages in Experiment 2 (n = 24)

	Stage 1			Stage 2			Stage 3		
Trial Type/Cost	Task A	Task B	*M*	Task A	Task B	*M*	Task A	Task B	*M*
Switch	718	920	819	932	971	951	1040	1251	1145
Repeat	590	772	681	674	789	732	682	977	830
Switch Cost	129	148		257	183		358	275	

Note. Task A corresponds to the Letter task and Task B corresponds to the Digit task .

Table B3

Mean RT (ms) and Switch Costs (ms) for Each Task Across Stages in Experiment 3 (n = 16)

	Stage 1			Stage 2			Stage 3		
Trial Type/Cost	Task A	Task B	*M*	Task A	Task B	*M*	Task A	Task B	*M*
Switch	475	774	624	501	800	650	585	892	738
Repeat	447	669	557	459	645	551	461	720	590
Switch Cost	28	105		42	156		125	172	

Note. Task A corresponds to the Location task and Task B corresponds to the Letter task .

Table B4

Mean interference indices(ms) obtained on Repeat and Switch Trials for each task in Experiments 1, 2, and 3

	Experiment 1 (n = 16)		Experiment 2 (n = 24)		Experiment 3 (n = 16)	
Trial Type	Task A	Task B	Task A	Task B	Task A	Task B
Repeat	128	144	92	205	14	51
Switch	281	313	322	332	110	118

Note. Task A corresponds to the Letter task in Experiments 1 and 2, and to the Location task in Experiment3. Task B corresponds to the Digit task in Experiments 1 and 2, and to the Letter task in Experiment 3.