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SIMILARITY EFFECTS ON TASK SWITCHING

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EXPLORATIONS IN TASK SPACE:
SIMILARITY EFFECTS ON TASK SWITCHING

By

Catherine M. Arrington

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ABSTRACT

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By

Catherine M. Arrington

Task switching paradigms involving rapid transitions between simple but potentially conflicting tasks have been widely used to study executive control processes. The current research explores the importance of considering the representational task space within which these executive control processes are acting. In four experiments, task space is manipulated by varying the similarity among tasks.

Experiment 1 introduces a manipulation of task similarity based on shared attentional components of the task. Four two-choice discrimination tasks form two pairs of tasks: height judgments and width judgments; color judgments and brightness judgments. Within each pair the dimensions of the stimulus that must be attended in order to respond are similar and previous research shows that attending to one dimension actually entails attending to the other when the stimulus is encoded. Across pairs, the dimensions are dissimilar and can be attended independently. Task similarity facilitates switching between tasks as seen in reduced switch costs when switching between similar tasks in comparison to switching between dissimilar tasks. Experiment 2 further examines the task similarity effect demonstrated in Experiment 1 through manipulations of the timing of trial elements designed to isolate automatic and controlled processes involved in task switching. The similarity effect disappears when participants are

provided with a longer preparation interval, the time between the task cue telling what judgment will be performed and the target stimulus, suggesting a controlled process that establishes attentional control settings.

Experiments 3 and 4 are parallel to the first two experiments, but define task similarity based on shared response modality—manual or vocal—rather than judged stimulus dimension. Switching between similar tasks again shows facilitation, indicating the robustness of the similarity effect across different manipulations of similarity. Decreases in the similarity effect occur both with increases in delay interval, the time between the response to the previous task and the onset of the stimulus for the current task, and preparation interval. These results indicate that both automatic and controlled processes are acting on the response component of the task set during task switching.

These task similarity effects demonstrate the importance of considering switches between tasks in the context of the relationships among tasks in task space. Findings from the current research provide a starting point for building a model of how tasks are represented relative to one another and how specific executive control and automatic processes act on individual cognitive components of task sets when moving from one point in task space to another.

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To my grandparents who bequeathed to me through their children my inquisitiveness and wonder in the world.

Francis C. Higgins

Catherine B. Higgins

Charles A. Arrington, Sr.

Ottie W. Arrington

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1 Introduction

In stimulus rich environments that allow for varied behavioral responses, the human cognitive system is noteworthy for its flexibility. The coordination of perceptual input, storage and retrieval of information in memory, and performance of goal directed behavior occurs through a combination of controlled and automatic processes.

Controlled processes are voluntary, effortful, and goal directed; while automatic processes are involuntary, effortless, and stimulus driven. The interplay of controlled and automatic processes has been at the core of several influential models of cognitive function (Norman & Shallice, 1986; Posner & Snyder, 1975; Schneider & Shiffrin, 1977). Understanding the complex relationships between these two modes of processing information is critical to explaining how individuals deal with the demands of an ever changing environment.

Several models have been put forth specifying when executive control is necessary for or involved in appropriate performance of goal directed behavior. Norman and Shallice's (1986) attention to action model outlined five types of task situations that require executive control: 1) planning and decision making, 2) troubleshooting or error correction, 3) novel or unfamiliar action sequences, 4) dangerous or difficult tasks, and 5) overcoming habitual or prepotent responses. Under these conditions when tasks cannot be performed automatically, the necessary executive control is carried out by the supervisory attention system (SAS). Within a more focused analysis of situations involving coordination of cognitive functions, Logan (1985) presented a model of executive control emphasizing the importance of strategy in guiding behavior. He proposed that executive functions choose among competing strategies, develop and

maintain strategies during task performance, and disable strategies once the behavior has been completed or is no longer relevant. In the experimental paradigms developed for studying the interaction between executive control processes and automatic processes in the laboratory setting, researchers have attempted to capture these conditions—generally through the use of dual task environments. Recently, there has been increasing interest in using task switching paradigms to study executive control.

1.1 Task Switching

1.1.1 Methodology

The task switching paradigm involves simple tasks such as identifying a digit or naming a color that are interleaved in environments that ask for fast reaction. Performance of these simple tasks is disrupted when a switch from one task to another is required. This disruption is evident when contrasting the performance of a given task, say task A, on a trial that follows the performance of a different task B, to the performance of task A when it follows another trial of task A. The *task switch* condition (B-A) results in slower and less accurate performance than the *task repetition* or *no switch* condition (A-A). The difference between these two conditions is referred to as *switch cost*. Switch costs are thought to reflect the time required for executive control processes that must be engaged when transitioning between tasks and/or the interference in performing a task due to recent performance of a different task.

The task switching methodology was first introduced by Jersild (1927), but remained largely unused until the early 1990s when the revival of the methodology led to an explosion of empirical studies. The basic task switching paradigm involves the performance of two or more tasks presented in sequential order at a rapid pace. These

tasks are most often simple categorization tasks such as deciding whether a digit is even or odd or less than or greater than five (Sudevan & Taylor, 1987), or deciding whether a letter is a consonant or vowel (Rogers & Monsell, 1995); identification tasks such as color naming or word reading using Stroop (1935) stimuli (Allport, Styles, & Hsieh, 1994); or simple mental operations such as addition or subtraction (Jersild, 1927; Spector & Biederman, 1976). Typically stimuli in the task are multivalent, meaning that the same set of stimuli can afford several tasks. Such multivalent stimuli produce larger and more consistent switch cost than univalent stimuli where the stimuli are unique for each task in the experiment (Meiran, 2000a). Additionally the responses, which typically involve simple button presses or vocal responses, are often multivalent as well, such that the same two responses are used to indicate the stimulus values for each task. In these task environments where stimuli and responses for multiple tasks can be multivalent, the overlapping nature of the stimulus-response (S-R) mappings results in a degree of interference or cross talk among tasks, which may be a critical boundary condition for finding switch costs (Monsell & Rogers, 1995; Spector & Biederman, 1976).

Since the tasks are interleaved and the multivalent nature of the stimuli does not uniquely specify the task to be performed, the appropriate task on any given trial must be specified in some manner. Researchers have developed a number of methods for indicating the current task including presenting tasks in a pre-set or alternating order (i.e. AABBAABB; Rogers & Monsell, 1995), linking a feature of the target display to the identity of the task such as location or color of the stimulus (Sohn & Anderson, 2001), or providing instructional cues that indicate the appropriate task. Cues can either occur on each trial (Meiran, 1996; Sudevan & Taylor, 1987) or prior to a run of trials on which the

same task will be performed until another cue appears (Altmann & Gray, 2002). Clearly, the permutation of these various task elements presents an almost endless variety of potential task switching experiments, many of which will be discussed in more detail later.

The task switching paradigm provides an excellent experimental environment for studying how executive control and automatic processes interact in the coordination of task performance when an individual is presented with multiple, potentially competing tasks. Task switching implements a number of conditions theorized to require executive control such as planning, performing novel behaviors, and switching and maintaining strategies. Furthermore, the critical focus of task switching is not on the performance of the individual tasks, but rather on the processes that are engaged when transitions are made between tasks. In particular, the switch cost measure is calculated by subtracting task repetitions from task switches. Thus, switch costs are thought to capture processes associated with transitioning between tasks while removing or subtracting out the time associated with the processes involved specifically in task performance. If the controlled and automatic processes that coordinate task performance are separate from the cognitive operation executed in the performance of individual tasks, then the switch cost measure provides an opportunity to assess these processes.

1.1.2 Controlled and Automatic Processes in Task Switching

Out of an increasingly large body of research using the task switching methodology, a number of proposals have been made to account for the experimental findings in terms of the processes thought to underlie task switching. Generally speaking, these proposed mechanisms may be divided into processes that are either

controlled or automatic. Additionally a second factor that can be used to categorize these proposals is whether the process results in facilitation or inhibition of a given task set¹.

Several theories link the time associated with switching tasks to controlled processes of preparing for the upcoming task. Rogers and Monsell's (1995) *task set reconfiguration* model was an early and influential model of task switching that focused on this preparatory component. Using the alternating tasks procedure and manipulating the amount of time that elapsed between the response to the previous trial and the onset of the stimulus for the current trial, they demonstrated a marked decrease in the magnitude of the switch cost when the time between trials increased. They proposed that the increase in time between the two tasks allows for reconfiguration of the task set, which requires time to carry out. However, they also found that even at relatively long intervals between trials there remained a cost of switching, which they called *residual switch cost*. They accounted for the residual switch cost by positing an additional control component that is initiated by the onset of the new target stimulus, the so-called *stimulus-cued completion hypothesis*. DeJong (2000; DeJong, Berendsen, & Cools, 1999) also proposed an active preparation account of task switching. However, he attributed the

Footnote 1 In the task switching literature, the term *task set* has been used in two distinct, but closely related and often interchangeable forms tied to two different definitions of the word *set*. The first definition of *set* is "a state of psychological preparedness". Thus *task set* refers to the state of being prepared to perform a particular task. The second definition of *set* is a "a number of things...that belong or are used together". Based on this definition, *task set* refers to the group of cognitive operations that are necessary for performance of a particular task. This second meaning of the phrase emphasizes the separable nature of task components and the fact that preparing for a task is multifaceted. Further, task sets have associated levels of activation that determine which task set will control current behavior. Thus the notion of preparedness for the upcoming task can be described in terms of the activation level of the task set in comparison to other available task sets. I will use of the term *task set* in this second sense—as a group of cognitive operations.

residual switch cost to a failure to engage the appropriate task set that occurs more often on switch trials than on no switch trials. Thus, he concluded that residual switch costs result not from a need to complete task set reconfiguration on every trial, but from a higher proportion of trials where task preparation does not begin until the target stimulus appears.

While providing an important starting point for considering switch costs in terms of the controlled processes that are involved in preparing for an upcoming task, Rogers and Monsell gave very little consideration to what the nature of the processes involved in task set reconfiguration might be. Several more recent models have attempted to more specifically describe these processes. Rubinstein, Meyer, and Evans (2001) proposed two separate and additive control processes associated with switching between task sets: goal-shifting and rule-activation. Goal-shifting involves updating working memory, while rule-activation involves either retrieving from long term memory or activating the production rules associated with a particular task. Another account of task switching that focuses on updating of memory processes is Altmann and Gray's (2002) model. They describe task switching within a larger functional decay theory of cognitive control. Basic to the functional decay model is the concept that task performance is guided by the memory for the current task and that this memory decays over time. Thus at any point when an instructional cue is presented—typically but not necessarily associated with switch trials in the task switching paradigm—a time consuming encoding of the cue and related task set must occur.

Along with Rogers and Monsell, another early and influential account of task switching was Allport, Styles, and Hsieh's (1994) hypothesis of *task set inertia*.

According to the task set inertia hypothesis, switch costs are the result of proactive interference of S-R mappings between the previous task and the current task. When tasks are performed in rapid succession, the activation associated with a recently performed task decays slowly over time, such that the relevant S-R mappings for the previous task may interfere with the performance of the current task. In support of the task set inertia hypothesis, Allport et al. presented evidence that the nature of the task being switched *from* is critical for determining the size of the switch costs. They argued that if switch costs result from the time required to prepare for the upcoming task then the characteristics of the upcoming task should influence the magnitude of the switch costs rather than the characteristics of the task that has just been completed. Unlike the task set reconfiguration hypothesis that focuses on active preparation for the upcoming task, the dissipation of task set inertia occurs passively indicating an automatic process that determines costs associated with switching among tasks.

Mayr and Keele (2000) have proposed an additional mechanism that may be involved in task switching that focuses on active inhibition of the previous task set in order to overcome the type of interference such as that proposed in the task set inertia model. Using a paradigm in which three different tasks were presented in a pseudorandom order, Mayr and Keele examined the effects of task order beyond simple task switch versus task repetition, which is defined in terms of the task on Trial N and Trial N-1, by looking at the effect of the task identity on Trial N-2 (lag-2 effects in their terminology). The key finding in their experiments was that trials in which the participant must return to a task that has been recently switched from led to poorer performance than trials that did not involve a return to a recently abandoned task. Thus,

performance on the second task C in sequences such as C-B-C was slower than performance of task C in sequences such as A-B-C where all tasks were unique. They labeled this finding backward inhibition and suggested that the process of rapidly switching between tasks is carried out in part by inhibiting the task set for the task that is being switched from as a way of increasing the difference in activation between the current task and the previous task. This inhibition of the previous task set then results in slower reactivation of that task set when the sequence of trials requires a return to a task soon after the participant has switched from the task.

Recently, a number of researchers have been focused on developing integrated accounts of the processes involved in task switching. Several theories have proposed two-component models that include both controlled and automatic processes. A model of cognitive control in task switching put forth by Meiran (2000b; Meiran, Chorev, & Sapir, 2000) includes mechanisms for both active preparation for the upcoming task and passive dissipation of interference from the previous task set. This model attempts to reconcile the task set reconfiguration and task set inertia theories. In these experiments Meiran used a cueing paradigm to independently manipulate the preparation interval during which controlled task set reconfiguration can be carried out and the overall delay interval between trials over which automatic interference effects would decay. Using this method he found evidence supporting both mechanisms.

Sohn and colleagues (Sohn & Carlson, 2000; Sohn & Anderson, 2001) have proposed another two component model of task switching that includes active task preparation and passive task repetition effects. They separated the controlled preparation effects from automatic effects associated with repeating a task by varying whether the

participant had foreknowledge of the identity of the upcoming task. Even when the upcoming task was not known and therefore controlled preparation for the task could not be implemented, performance was better if the task repeated across trials. This finding suggests a priming from the previous trial to the current trial that benefits performance of a task when the task is repeated. This model differs from that of Meiran et al. (2000) in that while both models include a controlled task preparation component, the automatic component in Sohn's model proposes a mechanisms for facilitating the upcoming task through repetition priming, while Meiran et al.'s model suggests that the automatic processes are associated with interference from previous task sets that inhibit performance of the current task. In sum, the theoretical work presented thus far suggests that task switching may be achieved through a combination of controlled or active preparation for the upcoming task and automatic or passive interactions between the previously active task set and the new task set.

1.1.3 Task Characteristics that Influence Task Switching

With the primary focus of task switching experiments on the executive control processes that are engaged during the time between performance of each task, instead of the processes engaged in order to carry out the performance of a task, little attention has been paid to the characteristics of the actual tasks being performed. Indeed as noted above, a wide range of tasks has been used in previous task switching experiments. While the particular cognitive demands of specific tasks and the relationships between tasks have been largely ignored, evidence does exist that suggests that task characteristics may influence the size and nature of switch costs. For example, Mayr and Kliegl (2000) examined the effect of task difficulty on task switching. They found that some

manipulations of task difficulty, such as the extent of the retrieval demands, do affect switch costs. However, other manipulations of task difficulty do not affect switch costs, such as inverting the stimuli thus making the perceptual aspect of task performance more difficult.

Led by early reports of Allport and colleagues (Allport et al., 1994; Allport & Wylie, 2000) a number of researchers have studied task properties that result in asymmetric switch costs—larger switch cost when switching in one direction between two tasks than when switching in the other direction. Based initially on findings from Stroop-like tasks, Allport proposed that differential dominance of a task (word reading versus color naming in the Stroop task) can affect the efficiency of task switching, such that it is easier to switch to a less dominant task than to a more dominant task. Meuter and Allport (1999) have found similar asymmetric switch costs when bilinguals switch between their dominant and non dominant languages. Across these studies, Allport and colleagues concluded that pre-experimental experience with individual tasks can influence and indeed be used to understand the processes involved in task switching. These conclusions recently have been called into question. Monsell, Yeung, and Azuma (2000) reviewed the effects of task dominance or relative task strength under a variety of different manipulations of the construct, including pre-experimental experience, stimulus-response compatibility, and practice within the experiment. Their survey presented a more complex picture of differential switch costs, demonstrating conditions in which asymmetrical switch costs can be eliminated or even reversed. Interestingly these findings of asymmetrical switch costs associated with task dominance or relative task

strength suggest that not only characteristics of specific tasks, but also the relationships among tasks may be critical in determining the processes involved in task switching.

1.2 Representational Task Space

As can be seen from this brief review, researchers have begun investigating how task characteristics may affect task switching. However, there has been even less research investigating how the larger task environment influences switching processes. This lack of consideration of what I will call “task space” is surprising since the specific processes under study in task switching experiments are executive control processes. These processes are generally conceived of as acting at a level separate from and above individual task demands. It should be apparent, therefore, that understanding and even manipulating not only the elements (individual tasks) within the task space, but also the relationships among those elements is critical to studying executive control processes. Indeed, these relationships among tasks define the task space in which executive control processes act and may prove to impact these processes to a greater extent than the characteristics of individual tasks taken in isolation.

1.2.1 Task Switching within the Context of a Task Space

A notable exception to the disregard for relationships among tasks is the recent work of Kleinsorge and colleagues. In a series of studies, they addressed the question of how the organization and structure of task space influence the processes of task switching. Kleinsorge and Heuer (1999; Kleinsorge, Heuer, & Schmidtke, 2001a) defined a task environment where four potential tasks were formed through an orthogonal manipulation of the type of judgment to be made on a stimulus, either spatial or numerical, and the response mapping, either compatible or incompatible. They referred

to this set up as a dimensionally organized task space and focused on the hierarchical nature of the relationships among tasks: task judgment is superordinate to task mapping, which is in turn superordinate to specific responses made with either the left or right hand. The hierarchy in the task space that they described appears to be based on the temporal order in which task components or dimensions can be carried out: knowing which judgment is to be performed logically must occur prior to choosing and making responses.

In these experiments, numerical stimuli appeared on a display where the position of the stimulus indicated which judgment was to be made and color of the stimulus indicated which judgment-to-response mapping was to be used to respond to the current stimulus. Task performance was analyzed based on whether the trial involved switches of the judgment portion of the task, the judgment-to-response mapping of the task, or the specific responses. The basic finding was that switches of a higher-order dimension resulted in automatic switches of subordinate dimensions. For example, if the trial called for a switch in the judgment being made from a numerical to a spatial judgment, the performance was fastest if there was also a switch at the level of the judgment-to-response mapping. However, if a switch at the lower level was not called for, participants' responding was slowed. They interpret this result as evidence for generalizing of the switch operation, such that when a switch is carried out on a higher level of task structure it generalizes and results in switches at lower levels whether they are indicated by current task demands or not.

In follow-up work, Kleinsorge, Heuer, and Schmidtke (2001b) altered the task space by expanding the task dimensions such that three judgments and three response

mappings were possible for each stimulus. This manipulation resulted not only in an overall increase in response time, which would be expected as the number of potential S-R mappings increases, but also in a qualitatively different pattern of data for the different types of switches when compared to the earlier experiments involving binary task possibilities. In this more complex task space, where a switch from a task involved a choice of switched-to tasks rather than simply a change to the only other task available, the “generalizing switching operation” identified in the earlier work no longer occurred. A switch in the higher-order judgment component of the task did not result in a cost associated with not switching the subordinate task component. Rather, increases in total numbers of switches at any level in the hierarchy resulted in a monotonic increase in response time. The exact same shift between two specific tasks occurred differently when a third task was introduced into the task environment even when that task was not involved in the particular pair of trials defining the switch condition. What is clear from these findings is the fact that changing the overall task environment (e.g. increasing the number of potential tasks) appears to result in a qualitatively different pattern of performance suggestive of a change in the executive control processes governing the shifts between individual pairs of tasks. Although they do not cast their analysis in terms of task space, Allport and Wylie (1999, 2000) have evidence in line with the proposal that increasing the number of tasks available in task space influences switching among tasks. In a series of studies, they introduced participants to different tasks performed on the same set of stimuli in a sequential fashion across phases of the experiment. Introducing new tasks, and thus manipulating the task space in which the earlier tasks

were presented, resulted in large changes in the switch costs associated with individual tasks.

While the work of Kleinsorge and colleagues lays some important ground work for considering the issue of task space in examining executive control processes involved in task switching, their approach to describing task space is limited. The focus of Kleinsorge's description of task space is on the hierarchical logic and temporal order of task components: does the switch involve a change in judgment or a change in response mapping? This approach begins to consider how task space might be organized in terms of relationships among tasks that can be described in terms of components of the task themselves. However, Kleinsorge considers only the order of the elements in the task set as the manipulation of the task space, asking whether the changes in the task set are a result of components that occur early or late in the performance of the task. While the order of components in a task set is certainly one important way of defining task space, order is only one dimension of what will obviously be a complicated set of inter-task relationships. Thus this approach is only a start toward providing a full model of task space that might prove useful in furthering our understanding of the executive control processes that act within this space.

1.2.2 Analogies from Other Areas of Cognition

In light of the limited consideration of representational task space in the literature on task switching and executive control, drawing on analogies from other areas of cognition is useful. Several highly researched cognitive processes and the representational environments in which they occur may provide a framework for building an understanding of how task space might be expected to influence executive control

processes. Two such areas of study are orienting of visual attention and retrieval of information from semantic memory.

Orienting of visual attention. An analogy between orienting of attention in visual displays and executive control processes involved in task switching is compelling. Indeed, the very idea of task switching conjures images of movement or translation from one task set to another in much the same way that orienting moves attention from one location in visual space to another. Cashing out this analogy, the attentional mechanisms involved in orienting map to the executive control processes active in task switching, while the feature and spatial parameters of the visual display map to tasks in task space. Consider how such an analogy might serve to focus the somewhat jumbled theoretical models of executive control. Posner's (1980) simple model of visual orienting includes three components: disengaging attention from the current focus, shifting attention to a new location, and engaging attention at the new location. The description of executive control processes involved in task switching might easily be placed in a parallel form: disengage executive attention from the current task set, switch executive attention to the new task set, and engage executive attention at the new task set. Using such a model as a starting point provides structure for considering the various effects currently pouring from the laboratories investigating task switching. For instance, disengaging a task set may include active inhibition such as the phenomenon of backward inhibition described by Mayr and Keele (2000). Other effects may best be thought of as influencing the time that it takes to engage a new task set, such as Rogers and Monsell's (1995) stimulus-cued completion hypothesis, which explains residual switch costs in terms of a process that cannot occur until the stimulus for the upcoming task appears. Meiran's (2000a)

demonstration that the complexity of the response mapping associated with an upcoming task affects residual switch costs might be thought of as a manipulation that varies the time necessary to engage the upcoming task set. This analogy is not completely unused in the task switching literature. In particular, the idea that task sets are engaged and disengaged as part of the task switching process has shown up in discussions of task switching (Allport & Wylie, 1999). Further this analogy may offer new approaches to considering task switching. For example, the idea that one aspect of task switching may involve a shift of executive attention through a task space might be suggested by this analogy. This idea will be considered more fully below.

The second aspect of the analogy between attentional orienting and executive control attempts to explicate task space by comparing it to visual space. Two known effects of features of visual displays may be informative as to how to begin carving up and measuring task space: distance effects and grouping effects. One easily apparent aspect of visual displays is the distance between elements in the display, both in plane and in depth. Researchers studying both overt and covert shifts of attention have manipulated distance in order to measure the time necessary to shift attention as a function of the distance between elements in the display (Tsal, 1983; but also see Kwak, Dagenbach, & Egeth, 1991). If task space is to be thought of in analogy to visual space, then manipulations of distance in task space may provide insight into the executive control processes that act within task space. However, unlike visual space where there is a clear three-dimensional Euclidean metric for distance, finding, manipulating, and measuring distance in what will surely be a multidimensional task space may prove a difficult problem.

Grouping of elements in visual displays impacts the processing of these elements. Recently it has been clearly demonstrated that such grouping factors affect attentional processes. Kramer and Jacobson (1991) examined the effects of grouping on the distribution of attention in a visual display. Distractor lines that were grouped with a target line based on shared color or connectivity resulted in greater compatibility effects—defined by faster responding when the distractors were the same as the target compared to when the distractors were different from the target—than distractor lines that were grouped separately from the target. These results indicate a greater degree of attention to distractors when they were grouped with the target line. Other research suggests that locations in visual displays can be grouped within object boundaries and that shifts of attention from one location to another within an object occur more easily than shifts of attention between locations in different objects (Egley, Driver, & Rafal, 1994). By analogy, task space may also be prone to effects of grouping whereby tasks sharing a common feature may have overlapping processing much as the distractor and target lines in the Kramer and Jacobson study, or tasks that are grouped within some common boundary (or region of task space) may be easier to switch between. These examples are clearly speculative and the analogy is likely not to completely capture the complexities of executive control in task switching. However, the link between processes of attentional orienting and executive control may serve as a reasonable starting point for trying to understand executive control in task switching environments, in particular, the effects that manipulations of task space have on implementation of these control mechanisms.

Retrieval from semantic space. Models of semantic memory make up another highly studied area of cognitive psychology that may instruct a conceptualization of task space and the processes that operate on and within it. Unlike visual attention where the spatial representation has a clearly Euclidean metric, defining semantic space is a more difficult problem and may thus make a better analogy to the idea of task space, which is likely to be at least as complex.

During the early 1970's, several theories describing the representational space underlying semantic memory were developed. One of the earliest and most influential of these models was the spreading activation model of Collins and Quillian (1969), later expanded by Collins and Loftus (1975), which proposed a hierarchical network organization of semantic memory. Within this model, semantic space is represented as a series of nodes (concepts) that are connected by links that describe the relationships between nodes. These links also provide a loose measure of semantic space in that links between more highly related semantic items are conceived of as being shorter, evidenced by faster response times for related items in sentence verification and semantic priming tasks.

In contrast to the hierarchical network models are feature models, which propose that concepts within semantic memory are represented in terms of feature lists. The similarity relations among concepts are captured by their relative locations in a multidimensional space defined by the dimensions from which feature values are drawn. The best known of these models is that of Smith, Shoben, and Rips (1974). They proposed that storage of semantic items involves not only the individual lexical word forms, but also lists of semantic features including defining and characteristic features.

These feature models provide a far simpler, or at least more systematic, structure for the representation of semantic memory than do network models. However, this is coupled with a more complex set of processes involved in retrieving and comparing semantic items in memory (see Kintsch 1978 for a review of these two classes of models). In analogy to task space, the organization of semantic memory in terms of a list of features corresponds rather nicely to an organization of tasks within task space in terms of a list of task components. Such a model of task space implies a structure to task space where shared or similar components between tasks may influence how shifting between tasks occurs.

In addition to describing the representation of semantic concepts, these and other researchers investigated the processes involved in retrieval of semantic memories from this representational space. Just as orienting mechanisms may serve as an analogy to executive control in task switching, so might the processes of retrieving semantic information from different locations in semantic space. Early work with the lexical decision task by Schvaneveldt and Meyer (1973) serves as a good example. They compared two models of how retrieval from semantic memory is affected by the presentation of associated words: a spreading activation model where semantic items receive excitation when an associated or “nearby” semantic item is retrieved from memory and a location shifting model where semantic items are retrieved from one memory location at a time and a shift to a new location requires varying amounts of time depending on the distance between the two memory locations. The task used to test these two models involved lexical decision for three simultaneously presented items, such that participants responded “yes” only if all three items were words. By manipulation of the

associations between words in the list and the order of the associated and unassociated items, the researchers were able to demonstrate that associative benefit is better explained by a spreading activation model than by a location shifting model.

Drawing on such research may inform development of models of how executive control works to shift between multiple tasks in a task switching experiment, raising questions such as whether switch costs result from residual activation that causes interference between competing task sets or from the time necessary to shift between the locations of two tasks in representational task space. The rich body of theoretical and experimental work on semantic priming that followed the early work just reviewed offers numerous findings that may benefit consideration of the executive control processes engaged in task switching. An obvious example is Posner and Snyder's (1975) proposal that while automatic priming results from spreading activation ala Schvaneveldt and Meyer (1973), an additional source of controlled priming based on conscious expectations arises from location shifting—explicit movement of attention from one concept to another. This seminal idea stimulated Neely's (1977) examination of the relationship between controlled and automatic influences on priming as a result of expectancy and timing of elements in the priming task. Several current models of task switching evoke dual processes reminiscent of this work on priming (Meiran et al., 2000; Sohn & Carlson, 2000). Other work demonstrating the combination of facilitatory and inhibitory processes involved in semantic priming effects (Houghton & Tipper, 1994; Dagenbach & Carr, 1994) may inform current investigations of facilitation (Allport & Wylie, 1999; Sohn & Carlson, 2000) and inhibition (Mayr & Keele, 2000) in task switching.

In sum, while the notion of a representational task space has been largely unstudied, the development of an understanding of task space may benefit from consideration of other areas of study where more work has been devoted to questions of how representational space is organized and the impact that it has on the cognitive processes that act within it. I have briefly reviewed issues of orienting of visual attention and structure and retrieval of semantic memory in order to present some possible analogies to how task space might be represented and the mechanisms by which executive control processes may act within this task space. Clearly there will not be a direct mapping between either visual attention or semantic memory and processes engaged in task switching, rather they should be thought of simply as a starting point for considering task switching processes within a model of task space. I will turn next to an examination of the dimensions that might define a representational task space.

1.2.3 The Structure of Task Space

Two factors define task space: the specific task sets that are included in the task space and the relationships among these individual task sets. Task sets can generally be thought of as involving all information necessary for performing a particular task. This view of task sets dovetails nicely with component processing models where cognitive tasks are thought to require a sequence or combination of separate processes that are more or less distinct from each other in terms of their activity and implementation and that can be manipulated independently. Thus task sets are built up from separate component processes. At a highest level approximation, the task set would include three major components: perception or encoding of the stimulus, manipulations of or judgments about the stimulus, and response selection and programming. Additionally

there may be some information concerning the circumstances under which the task set becomes relevant for guiding task performance (e.g. cue to task links).

The representation of tasks as collections of component operations suggests that executive processes involved in task switching might act on individual components of a task in different ways and on different time scales. Despite early reports to the contrary, recent reports provide wide spread support for this view. Early evidence suggested that switch costs were not affected by the number of task components changing from one task to another, in contrast to results that might be expected if executive control processes acted separately on individual task components in a serial or additive fashion. Allport et al. (1994, Experiment 1) reported that task switches involving one component of a task—either the dimension of the stimulus display on which the decision was being made or the nature of the decision being made—resulted in switch costs equal to that of task switches involving both task components. Recently however, consideration of task sets and the processes that act upon them in terms of separable components has received support in a number of experiments. Hübner, Futterer, and Steinhauser (2001) presented viewers with “global/local” stimuli where small “local” digits were positioned in a display in such a way as to form a larger “global” digit. In the different tasks, participants made either odd/even or less than/greater than judgments on either the local or global dimension of the stimulus. Like in the Allport et al. study, task switches could involve either a change in the dimension of the stimulus or in the nature of the judgment or both. Unlike Allport et al., the task was cued prior to the onset of the stimulus and the response times for individual trials were recorded rather than the time to complete the entire list. Hübner et

al. consistently found larger switch costs in switches involving two components of the task set as compared to one component.

A particularly interesting approach to separating task components and switching processes has been developed by Badre and colleagues (Badre, Jonides, Hernandez, Noll, Smith, & Chenevert, 2000). Their approach investigated differences in switching between objects held in working memory and between operations that manipulated those mental representations. Participants began each run with two numbers or counters that they were to hold in working memory. Over successive trials in a run, instructions were given to either increment or decrement one or the other of the counters. Based on instructional cues, the participants switched either the operation being performed (increment or decrement), the counter on which the operation was being performed, both the counter and the operation, or neither. Their results indicated separate costs for switching operations and switching counters (mental representations). Furthermore, these separate effects were additive in conditions involving both types of switches. This research cleverly demonstrates that components of the task set have independent effects on the overall time associated with switching tasks.

Finally, Meiran (2000a) recently proposed a model of task switching that depended on a division of task sets into “stimulus task sets” and “response task sets”. In a pair of experiments, he independently manipulated whether stimuli or responses were univalent or bivalent. The effect of changes to the stimulus set on switch costs varied as a function of the preparation interval, while changes to the response set affected the residual switch cost. Taken together the findings from these and other studies indicate the importance of considering individual components of the task sets when examining the

processes involved when switching from one task to another. The idea that the executive control processes involved in switching between tasks may depend on the particular components of the task set that differ between the task will be pursued below.

Individual task sets only partially define task space. The second aspect of task space is the relationships among the task sets: how do we organize a group of tasks within a larger task space that might influence how we are able to transition among those tasks? While it is relatively straightforward (though not necessarily simple) to describe the component operations that make up a task set, it is less clear how the relationships among tasks should be described. Drawing from the literature on the representation of concepts in semantic space discussed above, there are two potential ways to conceive of the relationships among task sets. The first would be to consider individual task sets as nodes in a larger network made up of all task sets. Describing the links between task sets would then serve to define task space. However, it is not clear a priori how links between task sets should be defined or how they are formed.

Alternatively, a representation of task space might be developed based on the analogy to the feature model of Smith et al. (1974). The feature model approach is appealing for a number of reasons. As noted above, task sets involve a number of different components, making an easy analogy to feature lists in semantic memory. Following from the feature model, the relationships among tasks then can be described as a function of the task components or cognitive operations shared by each task. If the mental representation of a task is thought of in terms of the set or group of cognitive operations that must be carried out or implemented for task performance, then describing the relationships among tasks in terms of which of these operations are shared across

tasks appears to be a straight forward approach. Task space then may be thought of as a multidimensional space in which individual components of task sets, or cognitive operations, form the dimensions and a particular task is placed within this task space based on the cognitive operations involved in performing that task.

Thus having defined task space, the next step in studying the effect that task space has on the executive control processes acting within that space is to find a way to define and manipulate task space. There are several potential ways to manipulate task space either through changes to the task components (the elements included within task space) or the relationships between tasks that define the broader task environment. For example, the number of tasks in task space could be increased or the difficulty of specific tasks could be altered. The approach I have taken in the current research focuses not on the characteristics of individual tasks, but rather on the relationships among tasks. I propose to use the concept of similarity as a measuring stick for the relationships among tasks.

1.3 Task Similarity

The concept of similarity has been widely used within cognitive psychology and the effects of similarity have been examined in many areas of cognition (Tversky, 1977). Similarity is primarily conceptualized in terms of either distance based models relying on methods of multidimensional scaling or shared component models based on methods of task analysis. Multidimensional scaling procedures have been widely applied to study cognitive similarity particularly in the areas of perception and categorization (for review see Ashby & Perrin, 1988; c.f. Nosofsky & Johansen, 2000). The method of multidimensional scaling is linked to models of mental representations that emphasize the structure of the mental space where concepts are stored and evaluated (Keele, 1973).

Thus distance in mental space can be defined in terms of the similarity of concepts on each of multiple dimensions that define the concepts. Shared component models of similarity emphasize the importance of shared features of concepts particularly in circumstances where dimensions may be difficult to specify (Tversky, 1977). Such shared components models have been more widely used in studies in learning and transfer of training of motor and other complex skills, where the analysis of task components is the critical descriptor of tasks (Proctor & Dutta, 1995).

Similarity within task space can be represented in ways that reflect both definitions of similarity: as shorter distances between two tasks in a multidimensional task space, or alternatively as shared components between tasks. Tasks may be conceived of as positioned within a multidimensional task space. The dimensions on which a given task space are defined represent the individual cognitive operations necessary to carry out particular tasks. The distance of any two tasks within task space is determined by the similarity of the tasks on each of the dimensions or cognitive operations. Thus tasks that have similar or shared operations on a given task dimension are closer in task space. The shared operations approach to similarity fits nicely with the feature model approach to task space in which differing cognitive operations involved in performance of a task describe that task within a larger task space. Similarity can therefore be operationally defined as shared task components which result in an overlap of two tasks within task space: for any given component process, tasks increase in similarity when they share that process and decrease in similarity when they do not. This is the approach to defining task similarity that I will take in the current line of research.

Predictions about the effect that similarity between tasks will have on the processes involved in switching between tasks fall into two categories. Conventional wisdom has it that task similarity will interfere with performance of tasks that are presented close together in time. In reviewing the effect of task similarity in dual task experiments, Pashler (1998) states that “there is little doubt that task similarity can exacerbate interference” (p. 294). Additionally, similarity has been linked to confusability between perceptual stimuli (Ashby & Perrin, 1988). Similarity between two tasks may result in confusion and interference when switching between tasks. Within this context, the manipulation of task similarity in the task switching paradigm might be expected to result in larger switch costs when switching between similar tasks.

On the other hand, the current conceptualization of tasks as a part of a larger task space and executive control processes involved in task switching as implementing movement or shifting within task space suggests the opposite effect. Similarity between two tasks can be conceived of as either decreasing the distance between those tasks within a multidimensional task space or as grouping those tasks together within task space. Then by analogy to the visual orienting and semantic priming literature discussed above, task similarity would be predicted to facilitate switching between two tasks. Just as decreasing the distance between two targets decreases the time associated with shifting between targets in visual space, shifting in task space may also occur more easily when tasks are “nearby”.

1.4 Overview of the Current Research

In the following chapters, I present four experiments that examine the notion of similarity in task space and its relationship to the processes involved in task switching.

The basic experimental design presents multiple tasks in a task switching environment where the tasks are cued on each trial and occur in a random order. The tasks involve simple discriminations of multivalent visual stimuli. The task space developed in each experiment is defined by the relationships between pairs of tasks in the experiment. In the first two experiments, task similarity is defined in terms of shared attentional components of the tasks—similar tasks involve discrimination of stimulus features that are processed under the same attentional control setting. Experiment 1 introduces a task space involving four tasks, divided into two pairs of tasks where the tasks are similar within a pair but are dissimilar across pairs. Experiment 2 builds on the findings of a task similarity effect from Experiment 1, trying to localize the similarity effect to automatic or controlled processes involved in task switching. Experiments 3 and 4 mirror the first two experiments, but with task similarity defined in terms of response modality rather than attentional components.

2 Task Similarity as Shared Attentional Control Settings

The initial step in developing a task switching experiment suitable for examining the question of task similarity in task space was to generate a set of tasks that manipulated similarity. Considering the current definition of similarity among tasks as shared cognitive operations, there are clearly multiple ways of defining similarity through systematic manipulation of tasks such that various cognitive operations are either shared or not between pairs of tasks. The tasks developed for the first two experiments implemented a definition of task similarity that was based on a shared attentional component of the task sets. The tasks involved the presentation of a simple visual stimulus that could afford multiple two-choice discrimination tasks. The stimuli were colored rectangles that varied along the dimensions of height, width, color, and brightness. Each task required the participant to indicate with a simple key press the value of the stimulus on one of the four dimensions. These dimensions were chosen based on the fact that they can be grouped into two pairs (height and width; color² and brightness) where within a pair the tasks involve attention to a similar perceptual dimension, while between pairs the tasks involve attention to dissimilar dimensions. The similarity of these dimensions is rooted in models of selective attention.

Garner (1974) put forward a model of selective attention that categorized perceptual dimensions as either separable or integral. According to this model, separable dimensions can be selectively attended, while integral dimensions cannot be selectively

Footnote 2 The use of the term *color* here describes the stimulus dimension more rightly referred to as hue. The more generic term *color* was used when naming the tasks and providing instructional cues to participants, because it was thought that this would be simpler for participants who might be unfamiliar with the term hue.

attended. Evidence for this distinction came from a large body of psychophysical and attentional experimentation. Typically such experiments involved a discrimination task based on a single dimension such as height (Felfoldy, 1974). The stimuli varied not only on the attended dimension, but also on a second dimension that the participant was instructed to ignore. The presentation of stimuli then varied such that specific values of the secondary dimension were either uncorrelated with values of the primary dimension, or correlated such that each value of the dimension on which the decision was being made was always paired with the same value of the secondary dimension. If the secondary dimension was integral with the primary dimension (e.g. width in the case of attention to height) then correlated stimulus values resulted in a speed-up of responses on the discrimination task compared to uncorrelated values. On the other hand, if the two dimensions were separable (e.g. color in the case of attention to height) then response times did not vary based on whether the values were correlated across the two dimensions. Garner interpreted these results as indicating that attending to certain stimulus dimensions automatically implies attention to and processing of other dimensions. He referred to these dimensions as integral.

Based on Garner's work, the stimulus dimensions for the tasks in Experiments 1 and 2 were chosen such that they formed two pairs of tasks in which the attended stimulus dimensions are integral within a pair, but separable across pairs. The operational definition of similarity in this task space then becomes a shared task component in terms of attention to the perceptual dimension on which the decision is being made. Since attention to height results in automatic processing of width and vice versa, and attention to color results in automatic processing of brightness and vice versa,

the task component of attention to perceptual features is common for the two tasks within a pair—Height and Width, or Color and Brightness. When tasks are combined across pairs—such as Height and Color or Width and Brightness—then the tasks are dissimilar with respect to attention to the perceptual dimension on which the decision is being made.

Another way to think of this task component is as an attentional control setting (Folk, Remington, & Johnston, 1992). Folk et al. introduced the notion of attentional control settings in order to account for why certain stimulus characteristics such as color or abrupt onset appear to capture attention exogenously in some experimental situations but not in others. They suggested that the exogenous system “can be ‘configured’ or ‘set’ to respond selectively to a property” and that “any particular system configuration, or ‘attentional control setting’ is assumed to be a function of current behavioral goals.” (p. 1041) The remarkable similarity of this description of attentional control settings and Monsell and Rogers’ (1995) discussion of task set reconfiguration is noteworthy, suggesting a link between the two lines of research that is worth considering (Klein & Shore, 2000). Within the context of the current experiments, the Height and Width tasks might be said to require the same attentional control setting, for example *form*. Likewise, the Color and Brightness tasks may be considered to involve an attentional control setting for *color*. The task cue for a given trial sets up the current behavioral goals for the participant in the task switching environment including what aspect of the upcoming stimulus is to be attended. If attentional control settings are shared by tasks within a pair, switching between similar tasks (e.g. Height and Width) does not require a change in the

attentional control setting, whereas switching between dissimilar tasks (e.g. Height and Color) does require that the attentional control setting be reconfigured.

Having operationally defined task similarity, it is now possible to consider how task similarity influences task space. The four tasks and the relationships among these tasks described above serve as the building blocks for the task space as it might be constructed by a participant in this experiment. Figure 1 presents one possible conceptualization of this task space.

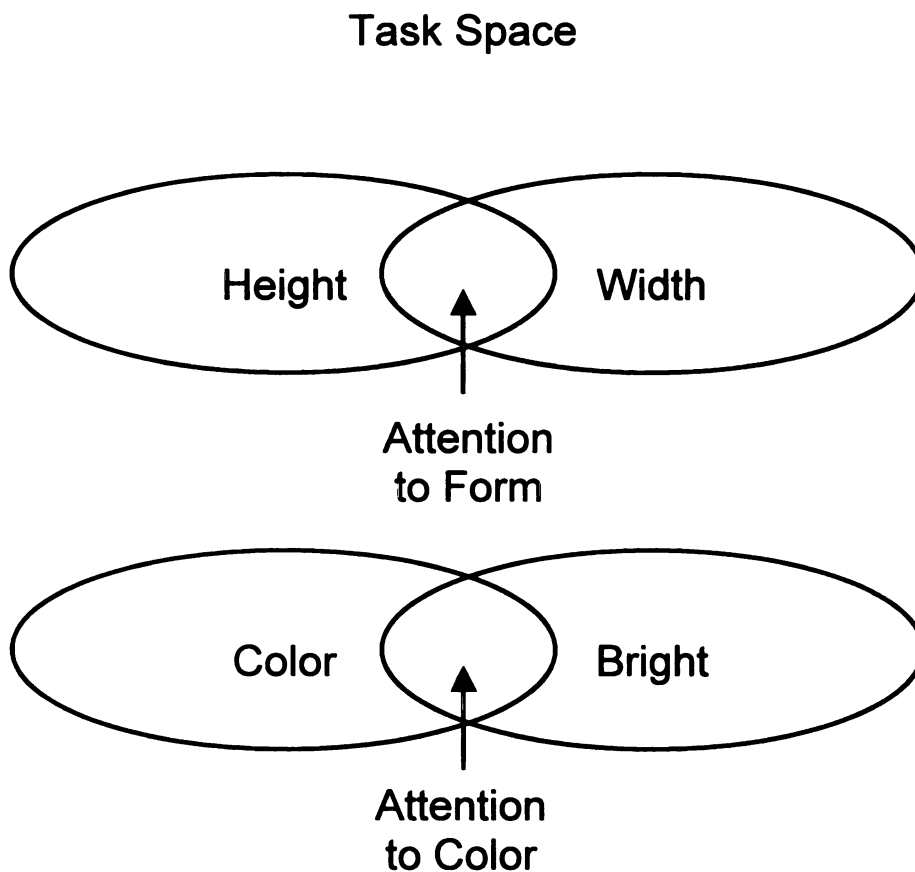


Figure 1. Schematic diagram of four tasks from Experiment 1 presented in a representational task space. Ovals represent the task set for each task. Overlap between tasks sets indicates a shared task component—attentional control setting.

Each task has an associated task set, represented by the ovals. The task sets include all cognitive operations necessary for carrying out a given task, such as decision rules, S-R mappings, and, of particular interest for the current experimental tasks, attentional control settings. The similarity among tasks is represented as an overlap in the task sets for two tasks. Conceptually this overlap represents the component that is shared by two task sets. As indicated in Figure 1, in the case of Experiments 1 and 2 this overlap would be in the attentional control setting. In terms of this two-dimensional representation of task space, the overlapping in task sets results in less overall distance between the two task sets than for two task sets that are non overlapping. Translating this two-dimensional image into a multidimensional task space suggests a model in which similar task sets are “closer” in task space. The empirical question then becomes whether distance between task sets manipulated by similarity between tasks affects the executive control processes that shift between task sets in a task switching paradigm.

2.1 Experiment 1

The primary goals of Experiment 1 were to develop a task switching paradigm where the overall task space could be manipulated based on the similarity among individual tasks and to investigate the impact that such task similarity manipulations might have on the executive control processes engaged during task switching. The manipulation of task similarity was accomplished through the choice of tasks that involved either attention to similar features of a stimulus (defined by their integrality) or attention to dissimilar features (defined by their separability). These tasks were then presented in a random order with the task cued on each trial. This design enabled comparisons of performance on various types of trial pairs including task repetitions, task

switches from a similar task, and task switches from a dissimilar task. These comparisons illuminate how the relationships between tasks impact the processes involved in switching between those tasks.

2.1.1 Method

Participants. Participants in Experiment 1 were 20 undergraduate psychology students who participated in partial fulfillment of course requirements. All participants reported normal or corrected-to-normal visual acuity and color vision. All participants were naïve to the purpose of the experiment.

Apparatus. Presentation of stimulus displays and recording of responses were controlled using the E-Prime software running on a Dell Dimension (Psychological Software Tools, Inc., 2000). Responses were made using a standard keyboard.

Stimuli. All stimuli were presented against a white background. Cue stimuli were printed in black uppercase 18 point font presented just above the center of the screen. The four cue words were HEIGHT, WIDTH, COLOR, and BRIGHT. The target stimuli were 16 rectangles that varied along the four task dimensions. The rectangles were four different shapes formed by crossing two heights (32 or 48 pixels) and two widths (64 or 96 pixels). Each size rectangle appeared in four different color/brightness combinations: light green (BGR 85 255 85), light blue (90 90 254), dark green (0 120 0), and dark blue (0 0 170). The colors used were developed within the Microsoft Office drawing palette by first setting the hue for each of the colors. Next the luminance was initially set at 80 for the dark shades and 160 for the light shades. However the perceived luminance was not equal, with the green colors appearing brighter. A brief psychophysical experiment was carried out in order to better match the colors in terms of perceived luminance.

Using the dark blue and light green stimuli as standards (the largest span of perceived luminance), a sample of nine viewers adjusted the luminance on the dark green and light blue stimuli until they matched as closely as possible the dark blue and light green standards, respectively, in terms of perceived luminance. The mean judgments of the nine viewers were then used to develop the stimuli used in the experiment.

Procedure. A cueing paradigm was used to present tasks in a randomly ordered sequence. The trial line is represented in Figure 2. Trials began with the presentation of the instructional cue. Following a 500 ms cue to target interval (CTI), the target appeared just below the instructional cue and both displays remained on the screen until a response was made. The screen was then blank for a 100 ms response to cue interval (RCI) until the start of the next trial. The experimental session began with single task practice blocks of 16 trials for each of the four tasks, presented in order based on the response finger (index, middle, ring, little) for the task. Four different task-to-finger mappings were counterbalanced across subjects. The four mappings were chosen such that each task was mapped to each finger in one of the mappings. Further, two of the mappings linked similar tasks to adjacent fingers and two of the mappings linked dissimilar tasks to adjacent fingers. Responses were made on the home keys of a standard keyboard. Two blocks of trials involving mixed trials of all four tasks followed. In the first mixed practice block, a “cheat sheet” showing the mapping of tasks, stimulus values, and responses was given at the top of the screen. During this block participants were encouraged to work slowly and accurately, and to focus on memorizing the appropriate responses for each task. The second block of practice trials was identical to the data collection blocks and participants were encouraged to work more quickly. Participants

then completed 12 blocks of data collection. Trials were run in blocks of 128 (64 task/target combinations x 2 cycles). Trials occurred in random order without replacement for each cycle. Average response time and accuracy feedback were provided for participants at the end of each block and participants recorded these values on a performance sheet so that they could track their progress through the experiment. Participants were given goals of working as accurately and quickly as possible, making sure that their accuracy stayed above 90% and trying to decrease response time from block to block throughout the experiment. The experimenter was present during the practice blocks and during the first block of data collection, but then left the room during the remainder of data collection.

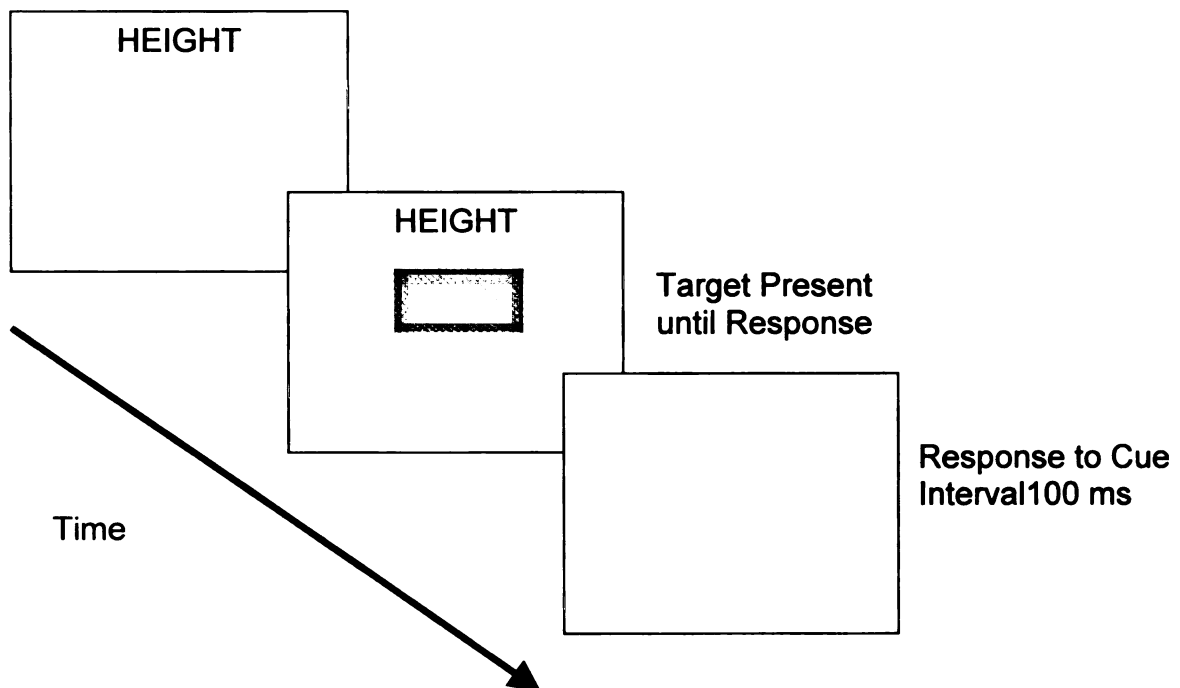


Figure 2. Example trial line for cued task paradigm used in Experiment 1. Elements are not presented to scale.

2.1.2 Results

Data processing. Response time and accuracy data were collected for all trials. Because trials were presented in a random order within each block, trials first had to be grouped into conditions based on the task indicated on Trial N, the current trial, and the task indicated on Trial N-1, the previous trial, resulting in 16 trial conditions. Of the 16 trial conditions, four (one per task) involved task repetitions (e.g. a Height trial that followed a Height trial), four involved task switches from a similar task (e.g. a Height trial that followed a Width trial), and eight involved task switches from a dissimilar task (e.g. a Height trial that followed a Color trial and a Height trial that followed a Bright trial). Mean response times per condition were calculated as follows. The first two trials in each block were excluded from data analysis. Error trials and the two trials following errors were all excluded from calculations of the mean response times. Overall response accuracy was high (96.8%, range 91.9% to 97.9%). Following removal of trials by this procedure, there remained on average 89.5% percent of the data, ranging for individual participants from 77.1% to 94.6%. Data were then trimmed through removal of all response times less than 200 ms, which were considered anticipations, and greater than three standard deviations of the cell means for each trial condition. Response time trimming resulted in the removal of a further 2.1% (range 1.6% to 2.7%) of the trials. Following the trimming procedure, participants' mean response times for the 16 trial conditions were calculated based on an average of 84 trials per cell (range 56 to 117.) Table 1 shows means and standard errors for response times (A) and accuracy (B) for each trial condition.

A

Trial N-1	Trial N			
	Height	Width	Color	Bright
Height	615±22	796±50	818±50	980±65
Width	882±45	569±19	857±51	946±56
Color	933±52	883±61	547±20	913±48
Bright	962±56	882±64	794±40	601±16

B

Trial N-1	Trial N			
	Height	Width	Color	Bright
Height	98.1±0.5	96.2±0.7	96.2±0.7	96.5±0.7
Width	96.7±0.7	98.3±0.5	96.5±0.6	96.2±0.7
Color	96.4±0.9	96.4±0.8	98.1±0.4	96.6±0.6
Bright	96.5±0.7	96.4±0.7	96.9±0.4	97.1±0.6

Table 1. Mean ± Standard Error for Response Times (A) and Accuracies (B) for Trial Conditions Based on Task on Trial N and Trial N-1 for Experiment 1

Switch cost analysis. In order to address the primary question of this experiment concerning the effect of task similarity on switching between tasks, switch costs (task switch minus task repetition) were calculated. Throughout the following analyses, unless otherwise indicated, the term *similarity* is being used to refer to the relationship between the tasks performed on Trial N and Trial N-1. Figure 3 shows mean switch costs separated by similarity and the identity of the task performed on Trial N. These data were entered into a 2 similarity (similar or dissimilar) by 4 task (Height, Width, Color, or

Bright) repeated-measures ANOVA. The analysis revealed a main effect of similarity $F(1,19) = 15.6, p < .01, MSE = 9619.3$, with switch costs significantly smaller following a switch from a similar task ($M = 263$ ms) than following a switch from a dissimilar task ($M = 324$ ms). Importantly this task similarity effect did not interact with which task was being performed, $F(3,57) = 1.2, p = .32, MSE = 2972.5$, nor was there a significant main effect of task, $F(3,57) = 2.0, p = .12, MSE = 20622.8$. The fact that the similarity effect did not interact with task indicates that the similarity effect cannot be attributed to specific tasks that are more or less difficult to switch from or to, but rather that the effect results from the particular relationships between specific pairs of tasks. Combined these results indicate that task switching is facilitated by similarity between tasks.

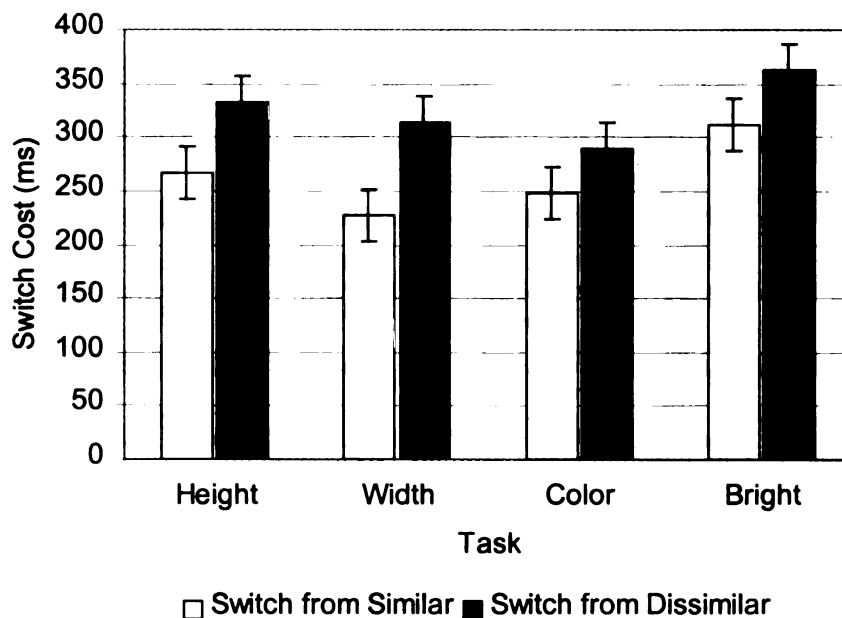


Figure 3. Mean switch costs when switching from similar and dissimilar tasks for each task type in Experiment 1. Error bars represent 95% confidence intervals calculated based on the error term for the interaction of similarity by task as described in Loftus and Masson (1994).

The response accuracy data were also examined in order to rule out the possibility that a speed accuracy trade-off was driving the similarity effect. Response accuracy was highest on task repetition trials ($M = 97.9\%$) followed by switches from similar tasks ($M = 96.6\%$) and switches from dissimilar tasks ($M = 96.4\%$). Importantly, this pattern of data, in particular the difference between switches from similar and dissimilar tasks, provided no evidence for a speed accuracy trade-off in responding that could bring into question the interpretation of the response time data in the previous analysis. The 2 similarity (similar or dissimilar) by 4 task (Height, Width, Color, or Bright) repeated-measures ANOVA on the response accuracy data showed no significant effects.

Stimulus transition analysis. In addition to the transitions between tasks that occur across trials, there are also stimulus transitions and it is important to rule out the possibility that the switch costs and similarity effects seen in the first analysis result from the repetition or switching of stimulus values rather than the higher-level similarity of task transition. For example, if repeating a stimulus value along an attended dimension resulted in faster processing of the stimulus on the second trial, this could lead to faster responding on switches from similar trials. Based on the integrality of the stimulus dimensions, the value of the stimulus dimension attended on Trial N and Trial N-1 may benefit from such facilitation if the value of the stimulus dimension is repeated across trials. Therefore, a secondary analysis was performed examining the effects of stimulus transition along with task transition. Stimulus transitions were defined based on the individual dimension of the stimulus that was attended either on Trial N or Trial N-1. So in the case of a task repetition, the attended dimension was the same for both trials and stimulus repetition versus switch would be defined based on the value of the stimulus

dimension on which the task was being performed. In the case of a task switch, stimulus transitions were analyzed both as a function of the stimulus dimension attended on Trial N and as a function of the stimulus dimension attended on Trial N-1. Examining stimulus transitions for the stimulus dimension on the current trial examines the influence of repeating a stimulus dimension that was previously task irrelevant but is now task relevant; while examining stimulus transitions for the stimulus dimension relevant to the task on Trial N-1 assesses the influence of repeating a previously task relevant dimension that is not relevant for the current task.

In order to test whether the similarity effect found in the analysis of switch costs could be accounted for by stimulus repetition rather than shifts between higher order task sets, three variables were entered into a 2 by 2 by 2 repeated measures ANOVA: similarity of tasks on Trial N and Trial N-1 (similar or dissimilar), stimulus dimension transition (repetition or switch), and trial on which the stimulus dimension was attended (Trial N or Trial N-1). The main effect of stimulus transition was non significant, $F(1,19) = .48, p = .5, MSE = 785.9$, and stimulus transition did not interact with similarity, $F(1,19) = 1.4, p = .25, MSE = 636.3$. Based on these findings the task similarity effect found in the first analysis cannot be attributed to the repetition of stimulus dimensions.

In a separate analysis, the effect of stimulus transition was examined for task repetitions. When the task relevant stimulus dimension was repeated participants responded more quickly ($M = 557$ ms) than when the relevant stimulus dimension switched between trials ($M = 610$ ms), $t(19) = 3.7, p < .01$. Because each dimension was mapped to a different pair of fingers, it was only in the case of task repetitions that the

stimulus repetition also involved a response repetition. The faster responses associated with stimulus repetitions when the task is also repeated may be the result of a repetition in the response rather than in processing of the repeated stimulus. The current design does not allow for separation of these two factors.

Within trial compatibility analysis. While the primary analysis shows a facilitation associated with task similarity in cases of switching between similar tasks, it is possible that similar tasks might still result in interference of task performance if examined from a different perspective. In the analysis of switch cost performed above, the trials are categorized in terms of the identity of the task on Trial N and Trial N-1. The focus in this analysis was on the effect of the task transition, without consideration of the effect that specific stimulus characteristics might have on performance of a trial. However, task performance on a given trial may also be affected by the specific characteristics of that trial such as the stimulus on which the task is being performed. In particular the stimuli in the current experiment are tetravalent meaning that they can afford four possible responses, only one of which is correct for the task indicated for a given trial. However, the responses indicated by the values of the stimulus dimensions relevant for the other tasks may influence the performance of the current task. For example, if the task is to judge the height of the rectangle and the rectangle is tall this might indicate a response with a finger on the left hand. This same rectangle will also have a value for each of the other stimulus dimensions--width, color, and brightness--and those values would indicate an appropriate response for the other three tasks. These responses might be either compatible with the current response (i.e. also left hand responses) or incompatible with the current response (i.e. right hand responses).

Researchers have examined whether such compatibility of responses on stimulus dimensions relevant for other tasks affects performance in task switching paradigms. Typically, compatible or congruent stimuli result in faster responding than incompatible or incongruent stimuli (Rogers & Monsell, 1995). The current situation differs slightly from this previous work where congruency referred to the exact same response being indicated by both dimensions of a stimulus since all tasks were mapped to the same two button press responses (bivalent response mapping). In the current experiment, each response is unique and compatibility simply refers to the hand with which the response indicated for unattended dimensions would be made. However, it may still be possible to examine whether this measure of compatibility influences responding for a particular task by stimulus combination. Critically the question can be asked of whether the effect of the unattended dimension varies as a function of the similarity of that dimension to the current task dimension. So for example, will the compatibility of the width dimension have a greater impact on the performance of the Height task than the compatibility of the color or brightness dimensions?

This question was addressed in a 2 by 2 by 4 repeated measures ANOVA examining the similarity of the task irrelevant dimension to the task relevant dimension (similar or dissimilar) and the compatibility of the response indicated by the task irrelevant dimension (compatible or incompatible), as a function of the task being performed on the trial. The interaction of dimension similarity and compatibility was significant, $F(1,19) = 16.8, p < .01, MSE = 324.1$. For the similar dimension (e.g. width in the case of a Height trial) compatible dimensions resulted in faster responding ($M = 810$ ms) than incompatible dimensions ($M = 818$ ms). For the dissimilar dimension (e.g.

color or brightness in the case of a Height trial) compatible dimensions resulted in slower responding ($M = 818$ ms) than incompatible dimensions ($M = 809$). This result is suggestive of an interference effect for similar stimulus dimensions as described above. However, the magnitude of the effect is small and additionally the pattern did not hold for all four tasks, but varied significantly for individual tasks as seen in a significant three-way interaction, $F(3,57) = 6.2$, $p < .01$, $MSE = 1378.8$. The size and variability of this effect may result from the fact that compatibility was defined in terms of hand that would be used to response to a value of a stimulus dimension. Since the responses were univalent this incompatibility may not result in any great degree of interference. Perhaps if the tasks were designed such that responses were bivalent with the same fingers being used for all tasks, the size of this compatibility effect would be more robust and show a larger effect of similarity of the unattended dimensions on processing the currently task relevant stimulus dimension.

2.1.3 Discussion

The facilitation of task switching based on the similarity of the tasks is a novel finding with interesting implications. This discovery highlights the importance of considering task space and the role that it plays in determining how coordination of tasks and transitions among tasks occur in multitask environments. This finding differs from previous research that demonstrated that the specific task characteristics such as practice with or difficulty of a task can affect the switch costs, in that the similarity effect is not task specific, but rather results from the relationships between tasks. Performance on each of the four tasks varied as a function of the similarity between the task on the current trial and the task on the previous trial, rather than as a function of the

characteristics of any individual task. This result clearly indicates that relationships between tasks have an influence on the process of switching between tasks. Furthermore, the fact that the task similarity effect resulted in a benefit when switching between similar tasks, while predicted by the task space model presented here, is an unexpected finding based on previous research showing that similarity generally decreases performance in dual task situations (Pashler, 1998).

The mechanisms of the task similarity effect are not known; however, two potential mechanisms may be speculated. First, the effect may be attributable to a reduction in the amount of controlled preparation that must be carried out in order to switch between similar task sets as compared to dissimilar task sets. In relation to the model of task space developed above, this might be thought of as a decrease in the distance between two task sets resulting in a reduction in the time necessary to switch between the two task sets. This interpretation would be reminiscent of the location shifting model proposed by Schvaneveldt and Meyer (1973) for retrieval from semantic space. The same process may also be conceptualized in terms of the number of cognitive processing units or modules that have to be changed from the performance of one task to another (i.e. how many features differ between the two task sets). If there are fewer components in the task set that must be reconfigured, less reconfiguration is necessary. If reconfiguration of individual task components occurs in a serial fashion or in parallel but at a speed proportional to the number of components being reconfigured, then this would translate into a larger preparation interval necessary to fully activate the appropriate task set for the upcoming trial in the case of switches between dissimilar tasks.

Within models of task switching, task set reconfiguration is a thought to be an active or controlled process. These controlled processes can be carried out prior to the onset of the task stimulus when the upcoming task is known. Thus one possible mechanism for the task similarity effect is through a decrease in the controlled processes that must be carried out in order to prepare for an upcoming task.

Second, the task similarity effect may involve a passive or automatic priming of the upcoming task when a similar task is performed on the previous trial. Several models of task switching propose some sort of automatic mechanism resulting in switch costs; however, these models take various forms. Allport et al.'s (1994) task set inertia model focused on a passive mechanism of proactive interference by which task performance following a switch is slower because of interference from residual activity associated with the S-R mappings from the previous task. Other models cast this automatic process in terms of repetition priming where aspects of a task are preformed more rapidly on task repetitions because they are primed from the previous trial (Sohn & Anderson, 2001; Sohn & Carlson, 2000). Both cost associated with interference following a task switch and benefit following a task repetition would result in the pattern of responding typically referred to as switch cost. However, when considering how the task similarity effect might result from automatic processes, the repetition priming model appears to offer a more probable mechanism than the proactive interference suggested in the task set inertia model. If the task sets for similar tasks involve an overlap, as depicted in Figure 1, then in the case of a task switch from a similar task, residual activation associated with the task set for the Trial N-1 task would include some activation of the Trial N task set. The result of the residual activation would thus be to boost the starting level of activation for

the current task set and the result would be “repetition priming” for the portion of the task set that overlapped with the task set activated on the previous trial.

Whether the mechanisms behind the task similarity effect turn out to involve controlled or automatic processes, the implication of the findings of the current experiment is clear. The task space in which tasks are presented affects the process of switching between tasks. These results support the idea that examination and manipulation of task space provides a useful tool for understanding the executive control processes that act on the tasks and task space.

2.2 Experiment 2

The aim of Experiment 2 was to further examine the task similarity effect by separating out potential effects associated with a controlled preparation for an upcoming task and with automatic priming from the task set activated on the previous trial in order to identify the mechanisms by which the task similarity effect occurs. One approach for separating automatic and controlled processes in the task switching paradigm is through parametric manipulation of the time over which these processes are engaged (Meiran et al., 2000). The logic behind such temporal manipulations is as follows: a controlled process that is carried out in order to prepare for an upcoming task cannot occur until the identity of the upcoming task is known. Manipulating the time between the instructional cue and target stimulus for the current trial (preparation interval or cue target interval, CTI) impacts the degree of controlled processing that can occur prior to the onset of the target stimulus. On the other hand, any automatic effects resulting from priming associated with residual activation of the previous task set would be expected to decrease over the entire delay interval between the response to the previous trial and the onset of

the target stimulus for the current trial. So manipulating the time between the response ending the previous trial and the presentation of the target stimulus for the current trial (delay interval or response target interval, RTI) affects the amount of residual activation associated with the task set from Trial N-1 and thus the degree to which this residual activation affects performance on Trial N. The cueing paradigm used in Experiment 1, where tasks are presented in random order with an instructional cue indicating the task to be performed on a given trial, is well suited for the independent manipulation of delay interval and preparation interval. First, the overall delay interval can be lengthened while holding the preparation interval constant by increasing the amount of time between the response to the previous trial and the onset of the cue for the upcoming trial (response cue interval, RCI). Alternatively, the preparation interval can be manipulated by varying CTI, while holding the delay interval constant.

Previous studies that used manipulations of these temporal measures have demonstrated the effect of both controlled and automatic processes on task switching by showing reductions in switch costs associated with both increasing preparation interval and increasing delay interval. Meiran (1996; Meiran et al., 2000) found decreases in switch cost associated with increases in both RTI and CTI in a cueing procedure. Sohn and Anderson (2001) showed decreases in switch costs with increasing RTI even in conditions when no foreknowledge about the upcoming task was provided. In neither case did the switch cost completely disappear even with very long delay and preparation intervals, thus indicating the presence of the residual switch cost.

While this previous research has demonstrated that both automatic and controlled processes are engaged during task switching and influence the magnitude of the switch

cost, it is not known whether these processes might be selectively acting upon specific component operations of the task set. Rubinstein et al. (2001) suggested that it was important to specify “when, where, and to what extent” these two types of mechanisms are involved in task switching. It may be that the similarity effect discovered in the first experiment will provide a tool for answering these questions. In the research discussed above manipulating timing of events in a cueing paradigm, the changes in the switch cost associated with different timing parameters is interpreted as reflecting the sum of the processes taking place during task switching. If, however, we examine not the overall changes in switch cost, but rather the changes in the similarity effect, this measure will reflect the specific processes acting on the component of the task set on which similarity is defined. Thus by looking at the impact of temporal manipulations on the size of the similarity effect, we can begin to isolate the processes, controlled or automatic, that act on a particular component of the task set, in the case of the current tasks—the attentional control setting.

Experiment 2 uses manipulations of the timing of elements in the trial line in order to address the question of what mechanisms underlie the task similarity effect. The manipulation of the delay interval through increasing the RCI while maintaining the same CTI varies the automatic influences on task performance while holding constant the controlled influence. Manipulating both the CTI and the RCI and thus varying preparation interval within a constant delay interval allows examining controlled processing while holding automatic influences stable. If the task similarity effect results from a reduction in the amount of reconfiguration that must occur between similar tasks, then changes in the time available for controlled reconfiguration processes to be carried

out (i.e. an increase in preparation interval) should affect the task similarity effect. If, however, the task similarity effect arises from the repetition priming of a portion of the task set that overlaps between the current task and the previous task, then changes in the amount of automatic processes (i.e. an increase in the overall delay interval) should affect the task similarity effect.

2.2.1 Method

Participants. Participants were drawn from the same population as Experiment 1. A total of 75 individuals participated. Data from three participants was removed due to low accuracy (below 90%) or failure to complete all blocks in the experiment, resulting in 24 participants per between-subjects condition.

Stimuli and apparatus. The equipment was identical to Experiment 1. The stimuli in this experiment were a subset of those used in Experiment 1, reflecting the change to a three task design. The switch to a three task version of the experiment was made so that the experimental sessions would not be made overly long by changes in the timing of the trials, while still allowing for an adequate number of trials per cell in the experimental design. The task cues HEIGHT, WIDTH, and COLOR were used. The target stimuli consisted of eight of the rectangles from Experiment 1 (the light luminance stimuli). The three tasks by eight target stimuli resulted in 24 unique cue target pairs.

Procedure. The sequence of trial events was the same as in Experiment 1, but the timing of the trial events now varied and was manipulated between subjects. The levels of the timing variable were 100 ms RCI/500 ms CTI (Group 1/5, identical to Experiment 1), 700 ms RCI/500 ms CTI (Group 7/5), and 100 ms RCI/1100 ms CTI (Group 1/11). The timing conditions are illustrated in Figure 4.

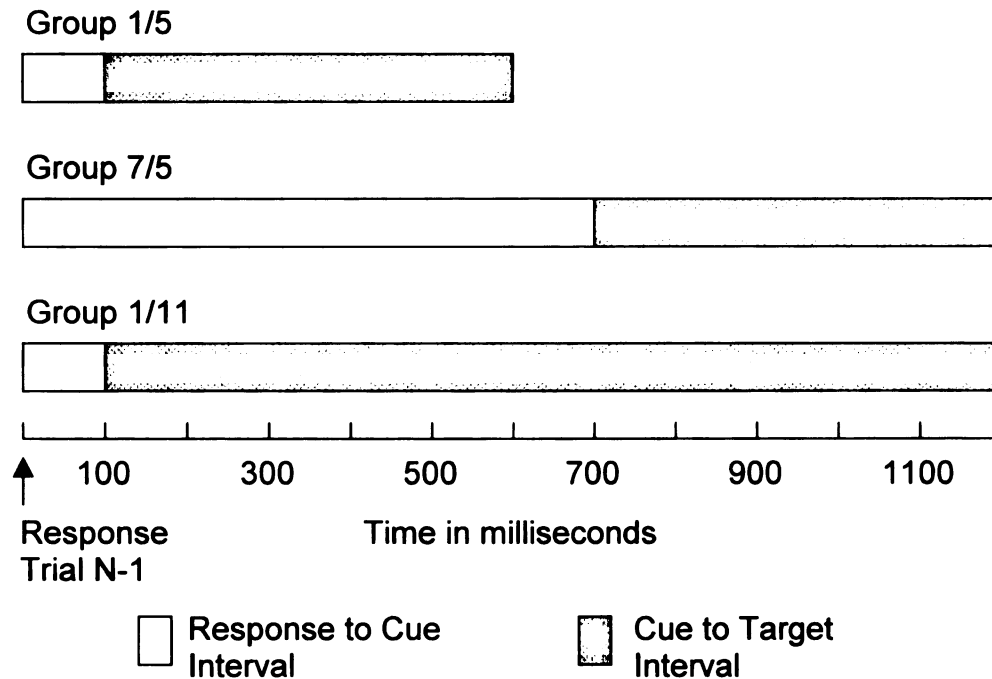


Figure 4. Timing of elements in the trial line for the three groups in Experiments 2 and 4. Group 1/5 and Group 7/5 have the same preparation interval, but different delay intervals. Comparing these conditions equates for the amount of controlled processing that can take place once the identity of the upcoming task is known, but varies the amount of time over which decay of activity associated with the task set from Trial N-1 occurs. Group 7/5 and Group 1/11 have the same delay interval but different preparation intervals. Comparing these conditions varies the amount of controlled processing while equating for the decay of activity associated with the task set from Trial N-1.

Participants responded using the index, middle, and ring fingers of both hands.

The mapping of task to finger pair was counterbalanced across participants. The left hand responses were made on the *c*, *d*, and *s* keys, while right hand responses were made on the *m*, *k*, and *l* keys. This offset hand position provided a more comfortable wrist position than the use of the home keys. The session structure was similar to Experiment 1. Following practice with individual task and mixed task blocks, participants performed

12 blocks of trials for which data were collected. The trials were run in blocks of 96 trials (24 cue target pairs x 4 cycles). The entire session lasted between 60 and 90 minutes depending on the trial length based on the timing manipulation.

2.2.2 Results

Data processing. The procedures for data processing were the same as used in Experiment 1. Response accuracy was high (96.9%, range 92.8% to 100%). Following removal of error and subsequent two trials 89.3% (range 77.5% to 97.9%) of the trials remained. Response time trimming with a low end cut off of 200 ms and high end based on 3 standard deviations of participants' mean response time per trial conditions (defined by task type on Trial N and Trial N-1) resulted in the further removal of 2.2% (range 1.5% to 3.2%) of the trials. As in Experiment 1, trials were initially sorted into conditions based on task type on Trial N and Trial N-1, resulting in nine different trial conditions. Means and standard errors of response times (A) and accuracies (B) for all nine trial conditions separated by timing condition are given in Table 2. Calculations of mean response times for individual participants were based on an average of 112 trials per cell in the design (range 70 to 143 trials). All three tasks could occur as task repetitions, however, in the case of the Color task, all switch trials were the result of a switch from a dissimilar task. Only for the Height and Width tasks could the trials involve either a switch from a similar task or a switch from a dissimilar task. For this reason the primary analyses of task similarity involved analysis of data from only Height and Width trials.

A

Timing Condition 100/500

Trial N-1	Height	Trial N	
		Width	Color
Height	606±20	706±26	578±23
Width	721±32	575±16	566±25
Color	753±42	741±35	490±16

Timing Condition 700/500

Trial N-1	Height	Trial N	
		Width	Color
Height	522±20	626±33	477±18
Width	614±37	494±18	473±17
Color	652±42	668±42	413±12

Timing Condition 100/1100

Trial N-1	Height	Trial N	
		Width	Color
Height	550±29	645±39	517±22
Width	655±39	518±23	534±22
Color	649±40	630±40	449±16

Table 2. Mean ± Standard Error for Response Times (A) and Accuracies (B) for Trial Conditions Based on Task on Trial N and Trial N-1 Separated by Timing Condition for Experiment 2

Table 2 (cont'd).

B

Timing Condition 100/500

Trial N-1	Height	Trial N	
		Width	Color
Height	96.5±0.7	96.5±0.2	97.7±0.4
Width	97.1±0.4	96.9±0.5	97.5±0.5
Color	96.4±0.5	96.5±0.5	98.0±0.4

Timing Condition 700/500

Trial N-1	Height	Trial N	
		Width	Color
Height	96.7±0.4	95.7±0.7	97.2±0.5
Width	96.4±0.6	97.7±0.3	97.1±0.4
Color	95.7±0.6	96.1±0.6	98.5±0.3

Timing Condition 100/1100

Trial N-1	Height	Trial N	
		Width	Color
Height	95.8±0.6	95.7±0.6	98.0±0.4
Width	96.3±0.5	97.2±0.5	98.5±0.5
Color	95.8±0.7	96.5±0.6	98.6±0.3

Switch cost analysis. The primary question of this experiment is whether the task similarity effect seen in Experiment 1 varies as a function of the temporal parameters of the elements in the trial. In order to address this question, a 2 similarity (similar or

dissimilar) by 2 task (Height or Width) by 3 timing condition (Group 1/5, Group 7/5, or Group 1/11) mixed ANOVA was conducted on switch costs, calculated by subtracting response times for task repetitions from response times for task switch conditions.

Switch costs were significantly greater for the Width task ($M = 143$ ms) than for the Height task ($M = 115$ ms), $F(1, 69) = 11.9, p < .01, MSE = 4602.0$. However, the task variable did not enter into any significant interactions. Interestingly, while the data are suggestive of a decrease in overall switch costs for both increases in delay interval and increases in preparation interval, a finding that would be in line with previous research showing decreasing switch costs, the main effect of timing condition was non significant, $F(2, 69) = 0.37, p = .69, MSE = 59854.0$. The main effect of task similarity was found in the expected direction based on the results from Experiment 1, with smaller switch costs for switches from similar tasks ($M = 119$ ms) than for switches from dissimilar tasks ($M = 138$ ms), $F(1, 69) = 5.3, p < .05, MSE = 5015.7$, thus providing a replication of the results from Experiment 1. The smaller magnitude of the switch costs in the current experiment as compared to Experiment 1 may reflect the fact that there were only three rather than four possible tasks in the task space. Critically for the focus of the current experiment, the similarity effect interacted significantly with the timing manipulation, $F(2, 69) = 4.8, p < .05, MSE = 5015.7$. This interaction can be seen in the graph of the data in Figure 5, which shows switch costs collapsed across tasks for switches from similar and dissimilar tasks as a function of the timing condition. As demonstrated in the graph of the data, the similarity effect appears to be present for Group 1/5 and Group 7/5, but to be absent for Group 1/11.

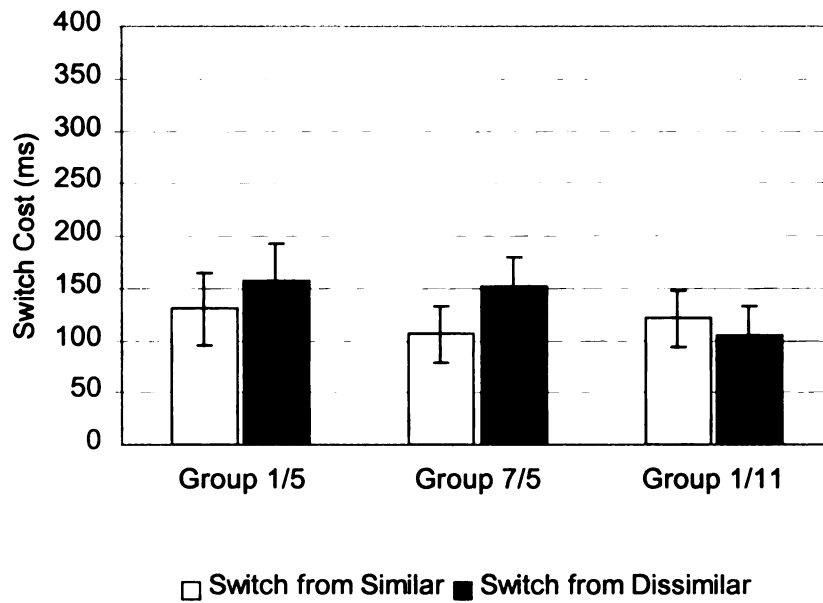


Figure 5. Mean switch costs when switching from similar and dissimilar tasks for each timing condition in Experiment 2. Error bars represent 95% confidence intervals calculated based on the error term for the similarity effect for ANOVAs calculated for each between subjects condition separately.

The timing conditions were chosen to separately manipulate the delay interval (during which residual activation associated with the previous task would presumably decay) and the preparation interval (during which the participant could prepare for the upcoming task) and thus to manipulate the degree of automatic and controlled processing, respectively. Therefore, the interaction of similarity by timing condition found in the first analysis, was broken down in separate analyses. The first analysis compared the Group 1/5 and Group 7/5 data, focusing on automatic mechanisms for the similarity effect, and the second analyses compared the Group 7/5 and Group 1/11 data, focusing on controlled mechanisms for the similarity effect. The analysis of the Group 1/5 and Group 7/5 conditions showed a main effect of similarity, $F(1, 46) = 11.8, p < .01, MSE = 5408.2$, that did not interact with the timing condition, $F(1, 46) = .90, p = .38, MSE =$

5408.2. This pattern of results indicates that the similarity effect does not vary with a change in the overall delay interval between the response from the previous task and the onset of the target for the current task. However, the analysis of the Group 7/5 and Group 1/11 conditions revealed a significant interaction of similarity and timing condition, $F(1, 46) = 11.1, p < .01, MSE = 4147.4$. This pattern of results confirms that an increase in preparation interval from 500 ms to 1100 ms resulted in a significant decrease, and in fact, the elimination of the similarity effect.

As in Experiment 1, the response accuracy data were also considered in order to assess the possibility of a speed accuracy trade-off. Again, response accuracy did not suggest a speed accuracy trade-off with accuracy highest on task repetition trials ($M = 96.8\%$) followed by switches from similar tasks ($M = 96.3\%$) and switches from dissimilar tasks ($M = 96.2\%$). The 2 similarity (similar or dissimilar) by 4 task (Height, Width, Color, or Bright) by 3 timing condition (Group 1/5, Group 7/5, or Group 1/11) mixed ANOVA was performed on the response accuracy data. The only significant effect was the interaction of similarity by task, $F(1, 69) = 7.2, p < .01, MSE = .00027$. For the Height task response accuracy was in the expected direction with responding more accurate for switches from similar tasks than for switches from dissimilar tasks, 96.6% and 95.9%, respectively. However, for the Width task response accuracy was in the opposite direction, with response accuracies of 96.0% and 96.4% for similar and dissimilar switches respectively. The cause of this cross over interaction is unclear and the effect is not seen in the analysis of the response time data where there was no interaction of similarity by task.

Stimulus transition analysis. As in Experiment 1, the effects of stimulus dimension repetitions were assessed in order to rule out the possibility that the similarity effects found in task transitions might result from repetition of an attended stimulus dimension. A 2 by 2 by 2 by 3 mixed ANOVA was conducted looking at similarity of the task transition from Trial N and Trial N-1 (similar or dissimilar), stimulus dimension transition (repetition or switch), trial on which the stimulus dimension was attended (Trial N or Trial N-1), and timing condition (Group 1/5, Group 7/5, or Group 1/11). As in Experiment 1, the similarity of the task transition did not enter into any significant interactions with stimulus transition, thus indicating that the similarity effect found in the first analysis cannot be the result of stimulus repetition. The main effect of repeating the value of a stimulus dimension was significant, $F(1, 69) = 7.8, p < .01, MSE = 1788.6$, with responding slower on trials when an attended stimulus dimension was repeated ($M = 675$ ms) than when none of the attended stimulus dimensions were repeated ($M = 668$ ms). This effect must be considered in light of a significant interaction of the stimulus transition effect with the trial on which that dimension of the stimulus was attended. When the stimulus repetition is defined based on the dimension of the stimulus that is attended on Trial N, for which the response time data is being collected, then repeating the stimulus dimension slows performance ($M = 679$ ms) compared to switching the value of the stimulus dimension ($M = 665$ ms). However, if the stimulus transition is defined based on the dimension of the stimulus that is attended on Trial N-1, then stimulus transition has no effect on response time ($M = 671$ for both conditions). This interaction indicates when switching to a task the processing of the stimulus dimension relevant for the performance of that task is affected by the previous exposure to that task

dimensions. Specifically if the value of the stimulus dimensions on the current task is repeated from the previous task (when that stimulus dimension was not task relevant) then performance of the task is slower. This pattern would be expected if processing of a recently ignored stimulus value is slowed.

Stimulus transitions were also analyzed for task repetition trials where the same stimulus dimension was attended on both Trial N and Trial N-1. In this case when the task is repeated, stimulus repetitions resulted in response repetition as well. Unlike Experiment 1 where there was a significant benefit for stimulus repetitions under these conditions, a 2 stimulus transition (repeat or switch) by 3 task (Height, Width, or Color) by 3 timing condition (Group 1/5, Group 7/5, or Group 1/11 mixed ANOVA revealed no significant effects involving stimulus repetition. In sum, repetition of the stimulus dimensions across Trial N and Trial N-1 showed very little impact of task performance and could not be a cause of the task similarity effects described above.

Within trial compatibility analysis. Trials were again analyzed for the compatibility of the response indicated by the unattended stimulus dimensions with the response indicated by the currently task relevant dimension. A 2 compatibility of the response by 2 similarity of the unattended and attended dimensions by 2 task (Height or Width) repeated measures ANOVA was conducted. There was a significant main effect of compatibility, $F(1, 69) = 30.0, p < .01, MSE = 674.2$, such that responding was faster if the unattended stimulus dimension indicated a response with the same hand as the response indicated by the attended stimulus dimension ($M = 627$ ms) than if a response with the opposite hand was indicated ($M = 639$ ms). This effect did not interact with either of the other two factors.

Trial N-2 sequence analysis. As well as examining switch costs for task transitions defined based on the task performed on Trial N and Trial N-1, trials can also be categorized based on the task transitions over the course of three trials, Trial N, Trial N-1, and Trial N-2 . Table 3 gives means and standard errors for response times (A) and accuracies (B) for each of the 27 conditions generated by combining the three tasks

A

	Trial N Task								
	Height			Width			Color		
Trial N-1	Height	Width	Color	Height	Width	Color	Height	Width	Color
Group 1/5									
Trial N-2									
Height	599±21	737±32	812±48	681±27	587±18	766±41	558±23	555±29	494±16
Width	618±23	700±37	740±44	736±28	574±19	771±34	577±25	549±21	496±17
Color	598±20	730±32	713±41	700±27	564±16	688±34	597±23	595±28	480±16
Group 7/5									
Trial N-2									
Height	513±18	625±40	671±42	594±31	507±20	681±43	470±20	469±19	414±12
Width	542±23	602±36	644±45	656±36	479±18	672±44	467±16	466±16	420±13
Color	511±20	606±37	643±44	627±33	495±18	650±42	492±19	487±20	402±12
Group 1/11									
Height	548±30	683±43	674±43	635±40	520±25	655±48	505±21	523±22	447±16
Width	551±31	630±40	660±42	664±37	520±26	620±35	519±22	524±22	455±17
Color	549±30	656±39	613±39	638±42	512±23	613±42	530±25	558±23	444±17

Table 3. Mean ± Standard Error for Response Times (A) and Accuracies (B) for Trial Conditions Based on Task on Trial N, Trial N-1, and Trial N-2 Separated by Timing Condition for Experiment 2

Table 3 (cont'd).

B

	Trial N Task								
	Height			Width			Color		
Trial N-1	Height	Width	Color	Height	Width	Color	Height	Width	Color
Group 1/5									
Trial N-2									
Height	97.0±0.8	97.1±0.6	96.4±0.5	96.5±0.7	96.7±0.6	97.2±0.6	98.1±0.4	98.0±0.4	98.0±0.6
Width	96.2±0.9	96.9±0.7	96.4±0.6	96.6±0.9	97.0±0.8	95.0±1.0	97.6±0.7	97.5±0.7	98.2±0.4
Color	96.5±1.0	97.3±0.5	96.5±0.8	96.4±0.6	96.9±0.5	96.8±0.6	97.6±0.6	97.2±0.6	97.7±0.6
Group 7/5									
Trial N-2									
Height	96.8±0.8	96.7±0.7	95.7±0.7	95.5±1.1	96.9±0.6	96.0±0.7	97.1±0.7	97.3±0.5	98.7±0.3
Width	96.6±0.6	96.6±0.7	96.1±0.9	94.7±1.1	98.1±0.4	96.9±0.8	97.0±0.6	97.1±0.6	98.2±0.4
Color	96.5±0.7	95.8±0.9	95.2±0.9	96.7±0.8	98.3±0.6	95.9±0.9	97.5±0.7	96.9±0.6	98.6±0.7
Group 1/11									
Trial N-2									
Height	97.5±0.6	96.3±0.7	95.8±0.7	96.5±0.6	97.1±0.6	95.7±0.9	98.5±0.5	98.5±0.4	99.0±0.3
Width	94.7±0.8	96.1±0.7	95.6±1.0	95.8±0.8	98.0±0.6	96.4±0.7	98.0±0.4	98.9±0.6	98.4±0.4
Color	95.6±0.8	96.4±0.6	96.0±1.0	95.1±0.9	96.9±0.6	97.6±0.6	97.7±0.6	98.0±0.5	98.1±0.4

across each trial sequence. In looking at runs of three trials when the tasks on Trials N and N-1 differ from each other (B-C), three types of sequences can occur: *unique tasks sequence* where each trial involves a different task, A-B-C; *alternating tasks sequence* where the task is the same on Trial N and Trial N-2, C-B-C; and *repeat-switch tasks sequence* where the task is the same on Trial N-1 and Trial N-2, B-B-C. The effect of the three trial sequences was assessed in a 3 task sequence (unique tasks, alternating tasks, or repeat-switch tasks) by 2 similarity of Trial N and Trial N-1 (similar or dissimilar) by 2

task (Height or Width) by 3 timing condition (Group 1/5, Group 7/5, or Group 1/11) mixed ANOVA. The main effect of sequence was significant, $F(2, 138) = 42.8, p < .01, MSE = 3823.2$. Response times were the slowest in the alternating tasks sequence ($M = 694$ ms), intermediate in the unique tasks sequence ($M = 675$ ms), and fastest in the repeat-switch tasks sequence ($M = 647$ ms). This pattern of results was mirrored in an analysis of response accuracy ($M = 96.1\%, 96.2\%,$ and 96.3% , respectively) although no effects in the response accuracy analysis reached significance. Thus, at the most general level, this pattern of results replicates previous findings for these sequence effects (Arbuthnott & Frank, 2000; Arrington, Altmann, & Carr, 2001; Mayr & Keele, 2000). However, the sequence effect did not hold across all of the various conditions. Two different three-way interactions involving sequence were significant: sequence by similarity by timing condition, $F(4, 138) = 3.4, p < .05, MSE = 2742.4$, and sequence by similarity by task, $F(2, 138) = 7.0, p < .01, MSE = 2333.3$. In each three-way interaction the pattern of the sequence effect shown above held for all cells in the design except one: dissimilar by Group 1/11 condition in the first interaction and dissimilar by Width condition in the second interaction. In these cases the unique tasks sequence resulted in slower responding than the alternating task sequence. So while there appears to be some systematicity in response times based on three trial sequences, the effect is dependent on task and timing conditions. This finding will be more thoroughly considered in the General Discussion.

2.2.3 Discussion

The results of Experiment 2 clearly indicate that the task similarity effect, defined within the current context as a shared attentional control setting, arises from a mechanism

governed by controlled preparation for the upcoming task. The cost of switching from a dissimilar task as compared to a similar task was completely eliminated when the time available for preparing for the upcoming task was increased, while at the same time being unaffected by a similar increase in the overall delay interval. This result can be accounted for by considering that the task set reconfiguration that occurs during switches from a dissimilar task includes an added component that is not present for switches from a similar task: the need to reconfigure the attentional control setting. When the preparation interval is short, 500 ms in the case of Group 1/5 and Group 7/5, then the reconfiguration of the attentional control setting cannot be completed prior to the onset of the target stimulus and thus the performance of the task following a switch from a dissimilar task is slowed. The longer 1100 ms preparation interval for Group 1/11 provides enough time for the reconfiguration of the attentional control setting. Thus in the case of both a switch from a similar task and a switch from a dissimilar task the attentional control setting is established by the time the target for the current task appears, making performance following either type of switch equally rapid. This finding is in direct contradiction to claims by Allport and Wylie (1999) that there is no evidence that preparation for the upcoming task involves enabling operations involved in perceptual processing.

The fact that the similarity effect does not decrease between Group 1/5 and 7/5, suggests the attentional control setting does not change or degrade with the increase in delay time. Such degradation would be expected to result in a reduction of the similarity effect, which is not seen in the current data. The logic behind the manipulation of the delay interval in the current experiment is that the residual activity associated with a task

set decays over time resulting in the decrease of any automatic processes that might affect performance on Trial N (see Meiran et al., 2000 for a similar discussion). Therefore, the conclusion from the current results must then be that automatic processes that result from priming associated with residual activity from the previous task set are not involved in attentional aspects of the task. However, these conclusions are certainly limited to the time interval chosen for the current experiment and it is possible that over this time interval there was not enough passive decay in activation of the attentional control setting to affect performance. A longer delay interval might result in a decrease of the similarity effect even when the preparation interval is relatively short such as the 500 ms interval in the current experiment. If the task similarity effect is seen as a benefit in terms of not having to reconfigure the attentional control settings between trials, then anything that disrupted the attentional control setting between Trial N-1 and Trial N might eliminate the similarity effect. Thus a longer delay or a disruption during the delay, would result in equivalent switch costs for switches from similar and dissimilar tasks, since in both cases the attentional control setting would have to be configured prior to performance of the task on Trial N.

As noted earlier, changes in the similarity effect are indicative of processes acting on particular aspects of the task sets. Understanding such processes allows us to begin to carve up the larger task space. The most straight forward interpretation of the current findings is that the establishment of the attentional control setting occurs through a controlled process and thus requires time to perform once the identity of the upcoming task is known.

It is worth noting that while there were significant changes in the similarity effect with changes in timing, the overall switch cost did not decrease as a function of either increases in delay interval or increases in preparation interval. This finding appears to be in conflict with previous reports of decreases in switch costs following similar experimental manipulations (DeJong, 2000; Goschke, 2000; Meiran et al., 2000). One methodological difference between the current experiment and others that show decreases in switch cost with increases in delay or preparation interval is that the timing intervals are manipulated between subjects in the current experiment. In previous research participants saw multiple timing conditions either mixed randomly within a block (DeJong, 2000; Meiran et al., 2000) or across blocks in the same experimental session (Goschke, 2000). It may be that strategic effects that arise when participants know there are variable timings of trial elements impact the controlled processes of preparation such that preparation varies as a function of the timing of the trial. Such strategic effects would not occur when participants are only exposed to one timing condition.

2.3 Interim Conclusions

Taken together Experiments 1 and 2 provide evidence that manipulating the relationships between tasks can impact the executive control processes involved when switching between tasks. While this result may seem intuitive, the question is not one that has been widely considered previously in the task switching literature. Experiment 1 demonstrated that task similarity provides a systematic benefit for switches between similar tasks as compared to switches between dissimilar tasks. These findings can be accounted for within the model of task space put forward in the introduction. Similar tasks are closer in a multidimensional task space resulting in faster transitions between

similar tasks as compared to dissimilar tasks that are further from each other in task space. Building on the initial findings from the first experiment, Experiment 2 showed how the similarity effect could be used to examine the nature of the controlled and automatic processes involved in the specific component of the task set on which similarity was defined. Thus these experiments demonstrate not only that the manipulations of the representational task space impact processes of executive control, but that this effect can be used to begin to describe the relationship between individual task components (such as attentional control settings) and controlled versus automatic processes involved when switching between tasks. While these conclusions are being cast in terms of a general quality of task space, they have only been shown to occur in terms of a manipulation of the attentional component of the task set. In the following chapter, I extend the study of the task similarity effect to another group of tasks using a different component of the task set to define task similarity: the response modality.

3 Task Similarity as Shared Response Modality

The next two experiments follow the general structure and logic of the first pair of experiments; however, the tasks are now designed so that the similarity among tasks is defined based on the response component of the task set rather than the attentional component. In order to test the hypothesis that task similarity facilitates task switching, it is necessary to consider task similarity defined in terms of other component operations, extending beyond the attentional component used to define similarity in the first two experiments. For several reasons, response modality is a good component operation on which to manipulate similarity. Response modality is a clearly separate component of the task set from the attentional component that served to define similarity in the first two experiments. Thus manipulating similarity through shared response mode provides a fine compliment to the earlier experiments. Further, response selection has been implicated in psychological refractor period (PRP) experiments as the process that results in the central bottleneck in dual task performance (Pashler, 2000). The implications of this finding in terms of the role that executive control must play in response selection makes this component of the task set particularly interesting when considering processes involved in task switching.

Experiment 3 introduces four new tasks that form two pairs of similar tasks, with similarity a function of the response modality. In each task participants make a simple judgment about whether a rectangle is tall or short and indicate that decision with a response that varies based on the current task. Two tasks involve manual responses: one using the first or index finger of the right and left hand to indicate target height; the other using the second or middle finger of each hand. The other two tasks involve vocal

responses: one where the participants respond by saying a number, either “one” or “two”; one where the participant respond by saying a letter, either “A” or “B”. The responses for each task are unique and were chosen such that there were equally arbitrary mappings of the decision about the target stimulus to the response. Pre-potent responses such as using “short” and “tall” for vocal responses would result in a task where there is already an established S-R mapping that would set the vocal task apart from the manual tasks. While the tasks are equivalent in terms of the perceptual, encoding, and decision processes, they are different in terms of the response.

Task similarity for these new tasks can again be defined in terms of a shared component, which in this case is the response modality. While the individual responses for each task are unique (just as the stimulus dimensions on which the decisions were being made for the tasks in the first two experiments were unique), the tasks are grouped based on the response modality: manual or vocal. The separation of manual and vocal responses into two separate response streams is supported by both psychological and neurophysiological evidence. Within the dual task literature, a number of studies have examined situations involving both manual and vocal responses. McLeod (1977) provided an early demonstration that manual and vocal responses involved different processing streams. In a dual task environment, participants performed a primary task involving visual tracking that required a manual joystick response. The secondary task was the presentation of a tone that participants responded to either by making a manual response or a vocal response. The results showed interruption of the primary task only when responses to the secondary task were made in the same modality. Based on these findings, McLeod concluded that “the vocal and manual responses are produced by

independent processors, but the two streams of manual responses are produced by interacting processes” (p. 659). Other behavioral evidence further supports this separation of response modality including work using the Stroop task (Keele, 1973) and the PRP paradigm (Pashler, 1990).

In addition to the behavioral evidence cited above, response similarity is also implemented at the level of the neurophysiological systems underlying the individual responses. Not only are there clearly muscular level differences between the effector systems of these two response modalities, but cortical control of these effector systems is separated. The motor cortex is organized somatotopically such that representations of different body regions are laid out in an organized fashion in the motor cortex (Schieber, 1999). The cortical representation of the first and second fingers involves adjacent and indeed overlapping regions of motor cortex (Sanes, Donoghue, Thangaraj, Edelman, & Warach, 1995). The finger representations are separated in the so-called sensorimotor homunculus from the motor regions controlling speech (Huang, Carr, & Cao, 2001). Thus in the current set of tasks, response similarity also may be thought of in terms of the neural regions involved in production of the response.

The organization of tasks into a representational task space for the present experiments could occur in much the same fashion as was explained in detail for the first experiment (refer to Figure 1). The similarity of the task sets for tasks involving the same response modality would be indicated by overlap. The overlap now would represent the response modality of the task rather than the attentional control setting. Recall that the overlap in task set also results in an overall decrease in the “distance” between two tasks, thus providing a conceptual representation of the degree of similarity

between two tasks. Based on both the model of task space put forward in the introduction and the results from the previous experiments, it would be expected that task similarity would facilitate switches between tasks. However, it is interesting to note that the similarity in response modality has more often been associated with interference of task performance in dual task environments. Consider the evidence from Pashler (1990) showing greater PRP effects—slowed responding to the second of two stimuli presented in quick succession—when each task involved responses in the same response modality as compared to separate response modalities. The PRP paradigm is in many respects similar to the task switching paradigm except that the performance of the tasks is overlapping in time rather than sequential as it is in task switching. In the PRP paradigm, response similarity results in costs in performance of the second task rather than benefits. This finding would suggest a different prediction than the current model of task space for the effect that task similarity defined in terms of response modality would have on switching between tasks. The differences between the PRP and task switching paradigms will be considered in greater detail in the General Discussion.

As the following two experiments will be compared to the first two, which they mirror in design, it is important to examine the two groups of tasks used across the pairs of experiments in order to clarify the differences between task environments. In the first pair of experiments, the tasks varied based on the stimulus dimension on which the stimulus was being judged. Thus, task switching required possible changes in the attentional control setting and the decisions being made for each task, while the responses were always made in the same response modality, manual. In the second pair of experiments, this pattern is reversed. The attentional aspects of the task and the judgment

being made are the same for all tasks, but the response modality changes among the tasks. Clearly, the new set of tasks involves fewer differences in component operations than the set of tasks used in the first two experiments. The tasks differ only in terms of the responses, but are in all other respects the same. While the differences in component operations among tasks used in the first set of experiments included the decision being made as well as the attentional control setting. However, in both cases the tasks are grouped as similar or dissimilar based on a single cognitive component of the task that is shared within pairs of similar tasks—attentional control setting in the previous experiments and response modality in the upcoming experiments.

3.1 Experiment 3

Experiment 3 introduces two new pairs of tasks in which tasks within a pair are similar and tasks between pairs are dissimilar. As described above, task similarity is defined now in terms of response modality rather than attentional control settings as in Experiment 1. Otherwise, the two experiments are parallel.

3.1.1 Method

Participants. The participants were 21 undergraduate psychology students who participated in partial fulfillment of course requirements. One participant was eliminated for failure to complete all experimental blocks during the one and one half hour session. As in the first two experiments, all participants reported normal or corrected-to-normal vision and in addition all participants were native English speakers.

Apparatus and stimuli. The apparatus was the same as in the first two experiments, with the exception that responses were made using the E-Prime button box and microphone. The microphone was positioned directly in front of the participant

approximately two to three inches from the participant's mouth and the button box was positioned just beyond the microphone in easy reach of the participant. The stimuli were also similar to those used in the earlier experiments. Instructional cues were FIRST, SECOND, NUMBER, and LETTER. The two target stimuli were the wide, light blue rectangles from the first experiment varying only in terms of height, either tall (48 pixels) or short (32 pixels). The combination of four task instructional cues and two targets resulted in eight unique trial types.

Procedure. The trial, block, and experiment procedures paralleled that of the first experiment. Instructional cues appeared 500 ms before the onset of the target and both stimuli remained on the screen until a response (button press or voice key activation) was detected. The screen then remained blank during the 100 ms RCI. Blocks were constructed of 128 trials. In order to equate the number of possible task repetitions with those in Experiment 1, trials were presented randomly without replacement for eight examples of each of the eight trial types (16 instances of each task) for 64 trials (equal to the number of possible trial types in Experiment 1). Then the cycle was repeated.

The experimental session began with an instruction and practice period during which participants were introduced to and given practice with each of the tasks in separate blocks of 16 trials. Tasks were presented in a set order: First, Second, Number, and Letter. Responses to the First and Second tasks were button presses made with the first and second digits, respectively. The responses to the Number task were "one" and "two" and to the Letter task were "A" and "B". Stimulus to response mappings for each task were counterbalanced across subjects. During the practice for the two vocal tasks, participants were given instructions on the appropriate placement of and volume

necessary for the microphone. Participants then completed two blocks of trials in which all four tasks were presented in a randomly mixed order. During the first mixed block of practice trials, participants were given verbal feedback and redirection by the experimenter in addition to having a “cheat sheet” presented at the top of the screen that indicated the appropriate response for each task and stimulus value. Participants were encouraged to work slowly and accurately in order to correctly memorize the appropriate responses for each of the tasks. During the second mixed block of practice trials, participants were encouraged to work more quickly. Participants then complete ten experimental blocks of trials. As before, participants were given feedback at the end of each block as to the accuracy and average response time for that block and recorded this information on sheets provided for this purpose. Participants were again given goals of working as accurately and quickly as possible, making sure that their accuracy stayed above 90% and trying to decrease response times from block to block throughout the experiment.

Unlike the first two experiments, the experimenter remained in the room with the participant throughout the experiment. The experimenter sat to the right and behind the participant and coded the participant’s vocal responses using five keys on the standard keyboard: one key for each appropriate vocal response and a final key used to indicate microphone errors such as failure to register an appropriate vocal response or triggering to non response noises. Experimenters received practice in coding vocal responses with at least one practice subject prior to the start of data collection. In addition, audiotape recordings of the sessions were made for later checking of the accuracy of the vocal responses.

3.1.2 Results

Data processing. Experimenter coding of the participants' vocal responses was cross-checked to audio tapes of each experimental session. Trials on which the participant stuttered or made multiple utterances, typically occurring in the form of self correction, were considered microphone errors. Trials on which the participant clearly stated a single response were counted as useable trials and coded as either correct or incorrect for the current task and stimulus. Following coding of the vocal responses, the data processing procedures were the same as the first two experiments. The first two trials in each block were removed. Response accuracy was high (96.9%, range 93.9% to 99.0%). Error trials (both microphone and response errors) and the two subsequent trials were removed leaving 91.4% (range 83.7% to 97.1%) of the trials for the calculation of mean response times. In addition the response time trimming procedures based on a low cutoff of 200 ms and a high cutoff of three standard deviations above the mean for trials conditions resulted in the further removal of 2.2% (range 1.4% to 2.7%) of the data. Table 4 gives means and standard errors for response times (A) and accuracies (B) for the 16 trial conditions created based on the task indicated on Trial N and Trial N-1. The calculations were based on an average of 70 (range 48 to 89) trials per cell in the design.

Switch cost analysis. Again, the primary analysis focused on addressing the question of whether task transitions were affected by the similarity of the tasks being performed. Switch costs were calculated by subtracting task repetition conditions from task switch conditions, separately for switches from similar tasks and switches from dissimilar tasks. These values were entered into a 2 similarity (similar or dissimilar) by 4 task (First, Second, Number, or Letter) repeated measures ANOVA. The results mirror

A

	Trial N			
Trial N-1	First	Second	Number	Letter
First	551±20	764±42	847±38	829±44
Second	728±45	580±29	873±48	838±45
Number	764±68	828±55	622±17	777±37
Letter	759±68	847±53	793±41	617±16

B

	Trial N			
Trial N-1	First	Second	Number	Letter
First	98.5±0.4	97.6±0.4	96.5±0.7	97.4±0.5
Second	97.2±0.4	97.6±0.5	96.0±0.7	97.6±0.5
Number	97.2±0.5	97.9±0.4	98.9±0.3	97.8±0.4
Letter	98.1±0.4	97.8±0.5	97.4±0.4	98.9±0.3

Table 4. Mean ± Standard Error for Response Times (A) and Accuracies (B) for Trial Conditions Based on Task on Trial N and Trial N-1 for Experiment 3

those found in Experiment 1. The main effect of task similarity was significant, $F(1,19) = 15.4$, $p < .01$, $MSE = 8640.1$, with switch costs smaller when the task transition involved a switch from a similar task ($M = 173$ ms) than a switch from a dissimilar task ($M = 231$ ms). The magnitude of the switch costs is somewhat smaller than the comparable conditions in Experiment 1, potentially due to the fact that the attended stimulus dimensions and the decision being made were the same for each of these four tasks. Additionally, the similarity effect did not interact with task, $F(3,57) = 0.8$, $p = .51$, $MSE = 4036.6$, indicating that the similarity effect was equivalent for all tasks. Nor did switch

costs differ based on the task for which they were calculated, $F(3,57) = 0.5$, $p = .69$, $MSE = 16062.1$. Figure 6 shows the switch costs for switches from similar and dissimilar tasks separated by task performed on Trial N.

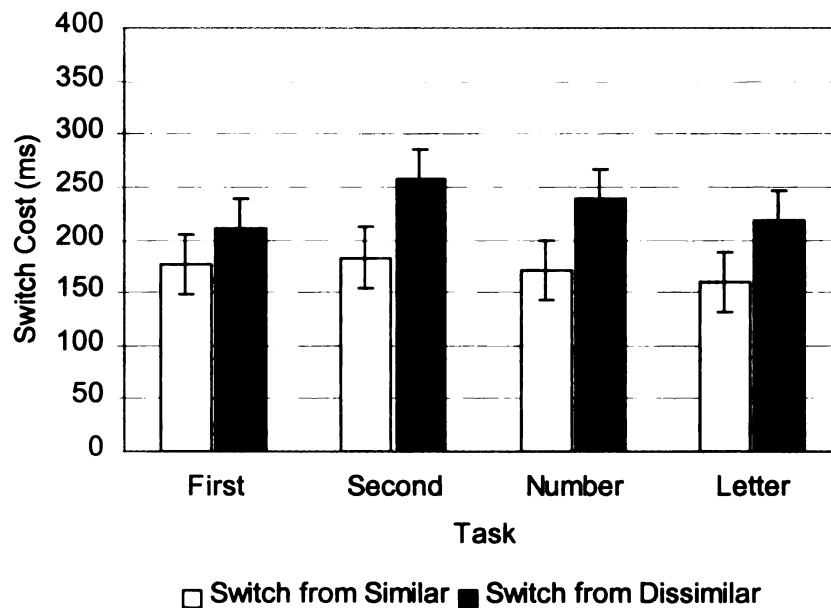


Figure 6. Mean switch costs when switching from similar and dissimilar tasks for each task type in Experiment 3. Error bars represent 95% confidence intervals calculated as in Experiment 1.

Once again, the response accuracy data were examined in order to rule out the possibility that a speed accuracy trade-off was driving the similarity effect. The pattern was very similar to Experiment 1, with response accuracy highest on task repetition trials ($M = 98.5\%$) followed by switches from similar tasks ($M = 97.5\%$) and switches from dissimilar tasks ($M = 97.3\%$). This pattern of data again rules out the possibility that the similarity effect found in the response time data might result from a speed accuracy trade-off. The 2 similarity (similar or dissimilar) by 4 task (First, Second, Number, or Letter) repeated measures ANOVA on the response accuracy data showed no significant effects.

Stimulus transition analysis. As in the first two experiments, the possibility that the similarity effect found in the switch cost analysis might arise from processes associated with stimulus level transitions rather than task transitions was considered. Unlike the first two experiments, only two stimuli were used in the current experiment and the same decision (height) was made in all four tasks. Therefore the stimulus transition analysis was relatively simple. Again two separate analyses were conducted. The first considered the two task switch conditions (switch from similar and switch from dissimilar) thus allowing for the consideration of the similarity effect in light of possible stimulus transition effects. Differences in the mean response times for the stimulus repetition and stimulus switch conditions were relatively small (6 ms and -10 ms for the switch from similar and dissimilar tasks, respectively) suggesting that stimulus transition properties had little impact when a task transition occurred. This observation was confirmed in the 2 stimulus transition (repetition or switch) by 2 similarity (similar or dissimilar) repeated measures ANOVA. The main effect of stimulus transition was non significant, $F(1, 19) = 0.05, p = .83, MSE = 4724.7$. In addition the interaction of the stimulus transition and task transition was non significant, $F(1, 19) = 1.9, p = .18, MSE = 2821.4$, confirming that the similarity effect seen in the first analysis was not a function of stimulus repetition.

A separate analysis conducted to examine the stimulus transition effect in the case of task repetitions confirmed that participants were significantly faster to perform a trial on which the stimulus was repeated from the previous trial showing a repetition benefit of 55 ms, $F(1, 19) = 19.0, p < .01, MSE = 6378.0$. As noted previously when the task repeats, a stimulus repetition also involves a response repetition, therefore the current

effect may be viewed as a benefit of response repetition. Interestingly, this stimulus or response repetition effect did interact with task, $F(3, 57) = 4.3, p < .01, MSE = 1838.9$. Stimulus repetition benefits were larger in the First and Second finger tasks (62 ms and 92 ms respectively) than in the Number and Letter tasks (47 ms and 23 ms, respectively). This difference in stimulus repetition benefit across response modalities was confirmed in an analysis of the repetition benefit comparing manual and vocal tasks, $t(19) = 2.4, p < .05$. This finding would further suggest that response repetition rather than stimulus repetition is the cause of the benefit since response characteristics rather than stimulus encoding demands differed between the two groups of tasks.

3.1.3 Discussion

The results of the current experiment are strikingly similar to those of Experiment 1. The task similarity effect replicated in an entirely new group of tasks for which the definition of similarity depended upon the response component of the task set rather than the attentional component. This finding strengthens the argument that the higher order variable of task similarity rather than any characteristic specific to the individual tasks led to the differences in switch costs found in both experiments. Further, this finding reinforces the notion that task space organized based on relationships among tasks can have regular and predictable effects on executive control processes. While fitting nicely in the current framework, this finding might be considered surprising based on the known interference effects in dual task situations involving responses in the same modality (Pashler, 1990). Consideration of how the task similarity effect may provide insight into differences between task switching paradigms and other experimental paradigms involving multiple tasks will be considered more fully in the General Discussion.

The mechanisms for the task similarity effect again cannot be determined within the current experimental design and may involve either controlled or automatic processes. Similarity of the responses between two tasks may reduce the task set reconfiguration that must take place in order to prepare for an upcoming task. If the participant has just made a vocal response on the Letter task, saying “A” for example, the switch to the number task does not require the participant to reconfigure the motor response system to a new modality, but rather the Number task involves the same response modality. Alternatively residual activation associated with the task set for the previous task may result in a benefit in performing a similar response through priming of the response modality of the current task. Thus, performing the First finger task may lead to residual activation in the neural regions that control not only movement of the first finger, but also the regions associated with moving the second finger. These possible mechanisms are examined in Experiment 4.

3.2 Experiment 4

The previous experiment demonstrated that task similarity, when defined in terms of response modality, facilitates switching between tasks. Experiment 4 more closely examines the potential controlled and automatic processes that might drive the similarity effect. Experiment 4 follows the same logic as Experiment 2, with manipulations of the timing parameters of the task being implemented to isolate automatic and controlled processes. The results from Experiment 2 indicate that the similarity effect defined on attentional control settings disappear with increasing preparation time, suggesting that the attentional control setting for a task is a function of a controlled preparatory process. If task sets are composed of component processes that are independent, then there is no

reason to believe that the task similarity effect when similarity is defined in terms of the response modality will behave in the same way as when similarity is defined in terms of the attentional control setting. Meiran (2000a) demonstrated that manipulations of the complexity of the response set could be seen in the size of the residual switch costs presumably unrelated to preparation interval. On the other hand, the effects of changes in the stimulus set were linked to changes in preparation interval. These results suggest that the similarity effect defined in terms of response modality may be impacted by changes in overall delay interval.

3.2.1 Method

Participants. Participants were drawn from the same population as Experiment 3. Seventy-six individuals participated in this experiment. Data were removed from four participants who either failed to maintain an alert state throughout the session or failed to restrain task irrelevant vocalization resulting in excessive microphone errors. Thus there were 24 participants in each between-subjects condition.

Procedure. The stimuli and apparatus were the same as those in Experiment 3 and the tasks were a subset of the tasks used in Experiment 3: FIRST, SECOND, and NUMBER. The trial procedure was the same except for the manipulation of the timing intervals. The timing intervals were manipulated between subjects and involved the same timing intervals as were used in Experiment 2: 100 ms RCI/500 ms CTI (Group 1/5, identical to Experiment 3), 700 ms RCI/500 ms CTI (Group 7/5), and 100 ms RCI/1100 ms CTI (Group 1/11).

The session structure was similar to previous experiments. Following practice with individual task and mixed task blocks, participants performed 12 blocks of trials for

which data were collected. The trials were run in blocks of 96 trials (8 cue target pairs run in 4 cycles of 24 trials). This presentation was intended to equate the total possible repetitions of the same task with that possible in Experiment 2. The entire session lasted between 60 and 90 minutes depending on the trial length, which was a function of the timing manipulation. The experimenter again remained in the room throughout the session and coded the participants' vocal responses during data collection using three keys on the number pad to code each of the vocal responses and microphone errors. The data collection portion of the experiment was audiotaped.

3.2.2 Results

Data processing. Experimenter coding of the vocal responses made by the participants was compared to audio tapes of the experimental session for blocks on which the experimenter indicated at the time of coding that a coded response was incorrect. This restricted checking procedure was adopted after complete cross-checking of two data files per experimenter suggested that experimenter coding and awareness of coding errors was highly accurate (approximately 99.9%). Since the participants' vocal responses were also highly accurate, the chance of mistakenly including a trial that should have been excluded from the data analysis (one on which the participant responded incorrectly and the experimenter miscoded the response) was extremely low. Thus the less extensive cross-checking of data files was deemed appropriate. Microphone errors and incorrect vocal responses were coded in the same manner as Experiment 3. Following coding of the vocal responses, the data processing procedures were the same as the earlier experiments. The first two trials in each block were removed. Response accuracy was high (97.6%, range 93.8% to 99.8%). Error trials

(both microphone and response errors) and the two subsequent trials were removed leaving 91.7% (range 81.3% to 98.8%) of the trials. In addition the response time trimming procedures based on a low cutoff of 200 ms and a high cutoff of three standard deviations above the mean for trial conditions based on the tasks indicated on Trial N and Trial N-1 resulted in the further removal of 2.1% (range 1.0% to 2.8%) of the data. Table 5 gives the means and standard errors for response times (A) and accuracies (B) for the nine trial conditions separated by the between subjects timing condition. Mean response time calculations per participant were based on an average of 112 (range 73 to 142) trials per cell in the design.

Switch cost analysis. As in Experiment 2, the primary analysis of this experiment examined the effect of timing condition on the similarity effect. Switch costs were calculated for the First finger and Second finger tasks where both switch from similar task and switch from dissimilar task conditions could be defined. A 2 similarity (similar or dissimilar) by 2 task (First finger or Second finger) by 3 timing condition (Group 1/5, Group 7/5, or Group 1/11) mixed ANOVA was conducted.

While the comparison of results from Experiments 1 and 3 show the same pattern of effects of similarity even with the changes in tasks that altered how similarity was being defined, several interesting differences between the results of the current experiment and the parallel analyses from Experiment 2 can be seen. These results indicate differences between response processes (current experiment) and attentional processes (Experiment 2) involved in task switching. The main effects of all three variables were significant. The similarity effect was in the expected direction with switches from similar tasks showing smaller switch costs ($M = 125$ ms) than switches

from dissimilar tasks ($M = 191$ ms), $F(1, 69) = 58.8, p < .01, MSE = 5333.9$. In addition, switch costs were larger for the Second finger task ($M = 180$ ms) than for the First finger task ($M = 136$), $F(1, 69) = 37.5, p < .01, MSE = 3751.8$. Finally, the timing condition had

A

Timing Condition 100/500

Trial N-1	First	Trial N	
		Second	Number
First	543±16	702±21	741±21
Second	669±21	560±15	758±20
Number	748±28	846±32	612±17

Timing Condition 700/500

Trial N-1	First	Trial N	
		Second	Number
First	525±31	724±57	654±38
Second	652±49	539±32	651±39
Number	718±62	790±65	570±25

Timing Condition 100/1100

Trial N-1	First	Trial N	
		Second	Number
First	471±15	564±25	558±17
Second	548±23	472±14	564±19
Number	556±28	597±33	524±14

Table 5. Mean ± Standard Error for Response Times (A) and Accuracies (B) for Trial Conditions Based on Task on Trial N and Trial N-1 Separated by Timing Condition for Experiment 4

Table 5 (cont'd).

B

Timing Condition 100/500

Trial N-1	First	Trial N	
		Second	Number
First	98.1±0.3	98.3±0.2	98.7±0.3
Second	98.2±0.4	97.7±0.3	97.6±0.5
Number	97.4±0.4	98.0±0.3	99.1±0.3

Timing Condition 700/500

Trial N-1	First	Trial N	
		Second	Number
First	98.1±0.3	97.0±0.4	96.7±0.8
Second	97.0±0.5	96.8±0.4	95.6±0.9
Number	96.4±0.4	96.4±0.6	97.8±0.7

Timing Condition 100/1100

Trial N-1	First	Trial N	
		Second	Number
First	97.8±0.4	97.4±0.5	98.5±0.2
Second	97.3±0.5	97.3±0.5	98.0±0.3
Number	97.3±0.5	97.8±0.5	99.0±0.2

a significant effect on switch cost $F(2, 69) = 4.4, p < .05, MSE = 64513.5$, such that the switch costs were reduced for Group 1/11 ($M = 95$ ms) compared to the other two conditions ($M = 190$ and 189 ms for Group 1/5 and Group 7/5, respectively). Unlike Experiment 2 where the overall switch costs did not differ with respect to timing of the trial presentation, the current results indicated that switch costs decreased with an

increase in the preparation interval, a finding in line with previous research on the effects of preparation on switch costs (Meiran, 1996).

The critical two-way interaction of similarity and timing condition was significant, $F(2, 69) = 9.2, p < .01, MSE = 5333.9$. This interaction can be seen in Figure 7 showing the mean switch costs for switches from similar tasks and switches from dissimilar tasks separated by timing condition. The pattern of data suggests decreases in the similarity effect across both changes in delay interval and changes in preparation interval. Again this interaction was broken down in two separate ANOVAs in order to isolate the effects due to automatic processes and controlled processes.

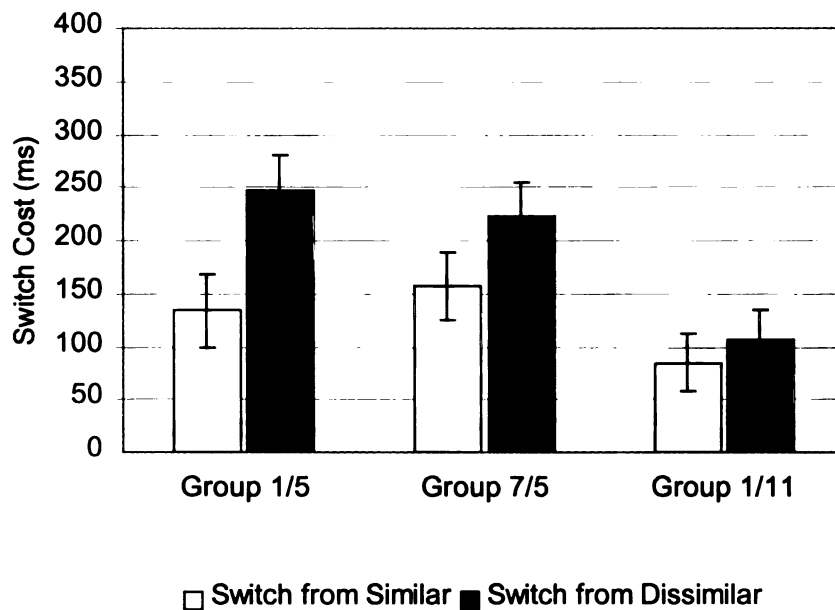


Figure 7. Mean switch costs when switching from similar and dissimilar tasks for each timing condition in Experiment 4. Error bars represent 95% confidence intervals calculated as in Experiment 2.

Comparing Group 1/5 to Group 7/5 found that increasing the overall delay interval between the response to the previous trial and the onset of the target for the current trial significantly decreased the size of the similarity effect, $F(1, 46) = 4.3, p < .05, MSE = 5930.7$. Additionally, comparing Group 7/5 and Group 1/11 found that increasing the preparation interval from onset of task cue to onset of target stimulus also decreased the similarity effect, $F(1, 46) = 5.0, p < .05, MSE = 4819.0$. These findings confirm that increases in delay interval as well as increases in preparation interval result in decreases in the similarity effect when similarity is defined in terms of the response modality (manual or vocal). Unlike the findings from Experiment 2 where the reduction in the similarity effect resided completely in the controlled processes, the current analyses indicated both automatic and controlled processes impact the similarity effect.

The two-way interaction of similarity and timing demonstrated that both active preparation and residual activation from previous trials influence the response component of the task set during task switching. Additionally, there was also a three-way interaction of similarity, timing condition, and task (First finger or Second finger), $F(2, 69) = 4.7, p < .05, MSE = 1438.3$. The nature of this three factor interaction can be seen in examining the ANOVAs isolating controlled and automatic processes. In the comparison of Group 7/5 and Group 1/11 examining controlled processes changing over increased preparation interval, the decrease in the similarity effect associated with the increase in preparation interval did not interact with the task variable, $F(1, 46) = 1.3, p = .25, MSE = 1505.7$, such that both First finger and Second finger tasks resulted in a decreases in the similarity effect of 57 and 32 ms, respectively. On the other hand, in the comparison of Group 1/5 and Group 7/5 the increase in delay interval resulted in significantly different effects on

the similarity variable for the First finger and Second finger tasks, $F(1, 46) = 6.7, p < .05$, $MSE = 1978.2$. The First finger task had a significantly smaller decrease in the similarity effect (12 ms) than did the Second finger task (78 ms). This interaction of task with the variables of similarity and timing is a departure from findings in the earlier experiments where interactions of the similarity effect with tasks were not discovered. Understanding why the task interacted with timing and similarity will be discussed more thoroughly below and may help to shed light on how task specific characteristics affect the larger task space in which executive control is acting.

As in previous experiments, the response accuracy data were examined in order to rule out the possibility of a speed accuracy trade-off. The pattern was very similar to the previous experiment, with response accuracy highest on task repetition trials ($M = 98.0\%$) followed by switches from similar tasks ($M = 97.7\%$) and switches from dissimilar tasks ($M = 97.2\%$). The 2 similarity (similar or dissimilar) by 4 task (First, Second, Number, or Letter) by 3 timing condition (Group 1/5, Group 7/5, or Group 1/11) mixed ANOVA showed no significant effects. This pattern of data again rules out the possibility that the similarity effect found in the response time data might result from a speed accuracy trade-off.

Stimulus transition analysis. The analysis of stimulus transition effects closely mirrored those from Experiment 3. Analysis of the stimulus transition effect was again performed separately for task repetitions and task switches. For the First finger and Second finger tasks where task switches from similar and dissimilar tasks could be defined, the effect of stimulus repetition was analyzed as a function of similarity of task transition to insure that the similarity effect found in the switch cost analysis could not be

attributed to stimulus repetition effects. The 2 similarity (similar or dissimilar) by 2 stimulus transition (repetition or switch) by 2 task (First or Second) by 3 timing condition (Group 1/5, Group 7/5, or Group 1/11) mixed ANOVA, did produce a significant interaction of similarity by stimulus transition, $F(1, 69) = 7.4, p < .01, MSE = 2285.5$, such that the benefit for repeating the stimulus was present (15 ms) for switches from the similar, other finger task and absent (-6 ms) for switches from the dissimilar, vocal task. This effect may reflect the fact that a stimulus repetition for a switch from First finger to Second finger task (or vice versa) involved a response with the same hand although a different finger on that hand as opposed to a stimulus switch involving a change in both the finger and the hand between trials. As discussed more thoroughly below, sequential responses using the same hand may benefit from the overlap of neural representation of the two effectors, while switching hands would not provide the same benefit. While this significant interaction is in the direction that would increase the similarity effect when comparing switches between similar vs. dissimilar tasks, the size of the stimulus repetition effect was relatively small and cannot account for the larger similarity effect.

For the task repetitions as seen Experiment 3, there was a significant benefit for stimulus repetition of 38 ms, $F(1, 69) = 33.2, p < .01, MSE = 4778.0$. The stimulus repetition benefit differed significantly for the three tasks, $F(4, 138) = 40.0, p < .01, MSE = 1363.2$, with the benefit being largest for the Second finger task (73 ms), smaller for the First finger task (46 ms), and non existent for the Number task (-4 ms). Stimulus transition also interacted with the timing condition, $F(2, 69) = 4.5, p < .05, MSE = 4778.0$, with the stimulus repetition benefit being significantly smaller for Group 1/11 (12 ms) than for both Group 1/5 and Group 7/5 (60 ms and 43 ms, respectively).

Trial N-2 sequence analysis. As in Experiment 2, the data were again divided into conditions based on the sequence of tasks of Trials N, N-1, and N-2. Table 6 gives means and standard errors for response times (A) and accuracies (B) for each of the 27 conditions generated by combining the three tasks across each trial sequence.

A

			Trial N Task						
			First	Second				Number	
Trial N-1	First	Second	Number	First	Second	Number	First	Second	Number
Group 1/5									
Trial N-2									
First	556±20	655±20	776±31	671±21	561±16	857±34	725±22	740±23	610±13
Second	548±17	651±22	753±33	709±21	564±17	863±34	709±22	737±22	617±19
Number	529±16	698±25	710±25	728±25	556±17	817±32	790±25	808±20	611±17
Group 7/5									
Trial N-2									
First	500±29	647±52	744±69	711±58	546±32	798±62	636±34	641±36	573±26
Second	541±34	633±44	720±60	718±55	525±36	815±69	654±40	644±42	573±28
Number	529±33	676±54	692±62	742±59	546±33	752±66	670±39	678±41	559±22
Group 1/11									
Trial N-2									
First	472±16	558±26	565±29	559±28	468±15	601±37	558±18	550±18	520±14
Second	467±16	542±23	564±29	573±27	470±14	609±31	552±16	565±21	517±14
Number	473±17	547±24	539±28	560±24	479±16	578±32	566±19	582±21	538±14

Table 6. Mean ± Standard Error for Response Times (A) and Accuracies (B) for Trial Conditions Based on Task on Trial N, Trial N-1, and Trial N-2 Separated by Timing Condition for Experiment 4

Table 6 (cont'd).

B

		Trial N Task								
		First			Second			Number		
Trial N-1	First	Second	Number	First	Second	Number	First	Second	Number	
Group 1/5										
Trial N-2										
First	97.6±0.7	97.6±0.5	97.5±0.5	99.0±0.3	97.7±0.5	98.0±0.5	98.7±0.4	99.1±0.3	99.5±0.3	
Second	98.1±0.5	98.9±0.4	97.2±0.6	98.0±0.4	98.1±0.4	97.2±0.6	99.0±0.4	97.6±0.8	99.0±0.4	
Number	98.7±0.4	97.9±0.7	97.4±0.5	97.9±0.5	97.6±0.6	98.7±0.3	98.2±0.4	95.8±0.9	98.8±0.5	
Group 7/5										
Trial N-2										
First	96.5±0.2	96.6±0.7	95.4±0.7	96.9±0.8	96.7±0.6	96.3±0.7	96.8±0.9	96.9±1.1	97.8±0.9	
Second	97.4±0.4	97.2±0.6	96.3±0.7	96.8±0.6	96.9±0.7	96.2±0.8	96.7±1.1	96.2±0.7	97.2±0.6	
Number	98.5±0.4	96.8±0.8	97.3±0.5	97.4±0.4	96.6±0.6	96.3±0.8	95.6±1.0	94.0±1.0	98.1±0.8	
Group 1/11										
Trial N-2										
First	97.6±0.5	97.3±0.6	97.3±0.6	98.2±0.6	97.3±0.5	97.7±0.6	98.9±0.3	98.3±0.4	98.8±0.4	
Second	97.6±0.6	96.9±0.8	96.9±0.7	96.6±0.8	96.6±0.9	97.8±0.5	98.4±0.4	97.8±0.5	98.8±0.4	
Number	98.4±0.5	97.4±0.6	97.7±0.6	97.4±0.5	97.7±0.6	97.7±0.7	98.2±0.4	98.0±0.5	99.5±0.3	

The effect of the three trial sequences was assessed in a 3 task sequence (alternating tasks, unique tasks, or repeat-switch tasks) by 2 similarity of Trial N and Trial N-1 (similar or dissimilar) by 2 task (First finger or Second finger) by 3 timing condition (Group 1/5, Group 7/5, or Group 1/11) mixed ANOVA. While the effect of sequence was found to be significant, $F(2, 138) = 21.7, p < .01, MSE = 4478.6$, the pattern of data was clearly qualified by a significant interaction with similarity, $F(2, 138)$

$= 7.1, p < .01, MSE = 3086.4$. There were no other significant interactions involving the sequence effect. When the task switch prior to Trial N involved a switch from the dissimilar, Number task, the sequence effect showed the same pattern of response times as was seen in the Experiment 2: slowest responding on alternating tasks sequence, intermediate for unique tasks sequence, and fastest for repeat-switch tasks sequence ($M_s = 729, 715, \text{ and } 681 \text{ ms}$, respectively). However, when the task switch prior to Trial N involved a switch from the similar task, First finger to Second finger or Second finger to First finger, the pattern differed: response times were now intermediate for the alternating tasks sequence, slowest for the unique tasks sequence, and again fastest for the repeat-switch tasks sequence ($M_s = 643, 659, \text{ and } 628 \text{ ms}$, respectively). So while the benefit for switching away from a task that has just been repeated held across all conditions, the comparison of the alternating tasks and unique tasks conditions shows that the similarity of the intervening task may have an influence on whether so-called backward inhibition effects are present in the current set of tasks. The complimentary analysis on response accuracy data did not show this complex interaction of similarity by sequence. The only significant effect in this analysis was the sequence effect, $F(2, 138) = 4.7, p < .05, MSE = .00065$, with the pattern of data the same as was found in Experiment 2, least accurate responding on alternating tasks, intermediate for unique tasks, and best for repeat-switch tasks, ($M = 97.0\%, 97.3\%, \text{ and } 97.7\%$, respectively). These findings and the comparison to the comparable analysis from Experiment 2 will be considered in the General Discussion.

3.2.3 Discussion

The results of Experiment 4 form an interesting contrast to the parallel analyses performed in Experiment 2. When task similarity is defined in terms of response modality, the size of the task similarity effect decreased not only with increasing preparation interval, which suggests controlled processes are involved in producing the similarity effect, but also with increasing overall delay interval. The interpretation of this second result is that some automatic processes are involved in the task similarity effect in the current group of tasks. Since similarity is defined in terms of the response modality the implication is that automatic processes associated with task switching costs arise at least in part from the response component of the task set. This finding is in contrast to the results in Experiment 2 where only an increase in preparation interval affected the magnitude of the task similarity effect, suggesting automatic processes that dissipate over the present time interval (500 to 1100 ms) are not involved in switching between the attentional control settings of the task set. The differences between the current results and those from Experiment 2 are important because they support the idea that the processes involved in task switching may be localized to specific components of the task set. This idea will be considered more fully in the General Discussion.

While the current results clearly indicate that both controlled and automatic processes are involved in the response component of task switching, it appears to be a more complicated matter to understand exactly what those effects might be. The three-way interaction of task (First finger or Second finger), similarity, and timing condition should be considered as it may provide some insight into when automatic and controlled processes influence switching between responses. Motor control for the first and second

fingers is unequal, with individuals having better control over the first finger, evidenced by a greater degree of independent motion for the first finger (Hager-Ross & Schieber, 2000). The larger switch costs associated with the Second finger task in the current experiments likely reflect this unequal degree of control. As the less controlled and less independent response, the Second finger task may receive greater priming from recent first finger movement than vice versa, thus explaining the large similarity effect for the Second finger task in Group 1/5. That this similarity effect might be reduced as a function of increased delay interval is not surprising. Recent fMRI research shows a positive linear relationship between the frequency of finger tapping and the magnitude of the response in primary motor regions (Rao et al., 1996). This relationship indicates a buildup in the activation in motor areas with rapid movement suggesting that the neural activity associated with a finger movement dissipates over time resulting in less buildup of activation as movements are spaced further apart. In this case, the longer delay interval in Group 7/5 may allow for more dissipation of activity associated with the recent first finger movement and thus provide less priming of the second finger movement. Such a mechanism would account for the changes in the similarity effect with a change in delay interval for the Second finger task. However, the better controlled first finger response may not receive the same sort of benefit following the Second finger task. While this account is speculative, the current data suggest such an asymmetry may be occurring. The effect of stimulus repetition was greater for the Second finger task ($M = 24$ ms) than for the First finger task ($M = 8$ ms). Thus when a same hand response is involved in responding for Trial N-1 and Trial N, allowing for overlap in neural

representations for the fingers involved and priming of motor regions, the benefit was greater for the Second finger task.

The preceding account for the differences between the First finger and Second finger tasks might be tested by performing the experiments using different digits. The first finger and thumb both have a high degree of control of independent movement and more separate neural representations (Hager-Ross & Schieber, 2000). Repeating the experiment using responding with those digits might show similarity effects that are not influenced by overall delay interval. On the other hand, using the third and fourth digits where control is poor in both cases and there is greater overlap in neural representations would be expected to result in similarity effects that decrease over increasing delay intervals for both tasks. Additionally it would be interesting to discover how automatic and controlled processes affect the vocal modality. These various possibilities indeed paint a complicated picture of mechanisms affecting the response component of the task set that are yet to be worked out.

4 General Discussion

Across four task switching experiments similarity between tasks was shown to have a systematic influence on time associated with switching between tasks. In Experiments 1 and 2 task similarity was defined as a shared attentional control setting, while in Experiments 3 and 4 similarity was defined as a shared response modality. Despite these differences in the implementation of the task similarity manipulation, the conclusions were identical: task similarity facilitates task switching.

4.1 Task Switching as Movement through Task Space

The manipulation of similarity among tasks was designed to be a tool for describing the larger task space in which these tasks occurred. The current conceptualization of task space is founded on the belief that the mental representations on which executive control processes act to coordinate task performance in multitask environments should be conceived in terms of both the sets of cognitive operations necessary to perform each task and the relationships among all of the tasks included in the task environment. This proposal arises from an understanding that executive control processes are separate from the cognitive operations directly involved in the performance of any specific task. Therefore, limiting consideration to the representations of individual tasks cannot provide for a full accounting of the mental representations on which executive control processes act. Rather, it is necessary as well to consider the relationships among the individual tasks, since these relationships further define the mental representations engaged by executive control processes. By analogy to the visual attention literature, executive control may be thought of as orienting cognitive resources

to different locations in task space through processes of disengaging task sets, moving through task space, and engaging other task sets.

With this belief as a starting point, I proposed a simple model of task space. Task space can be represented in terms of a multidimensional space. The primary dimensions of this space are defined by the component cognitive operations that make up each of the tasks included in the task environment. These dimensions include but are not limited to the stimulus encoding, attentional processes, any mental transformations or judgments that are carried out on stimuli, and response selection, preparation, and implementation. The relationships among tasks can then be described in terms of their positions relative to each other within task space. By analogy to feature-based conceptions of similarity, tasks that share a component process are more similar, and overlap more in the task space, than tasks that do not share the same component process.

The implication of this model for the study of task switching is that the controlled and automatic processes involved in switching among tasks should be sensitive to the structure of task space. In order to test this assumption, I manipulated task space and measured the effect that these manipulations had on the processes involved in task switching. Task similarity was chosen to manipulate task space because similarity is a variable specifically defined in terms of the relationships between two or more tasks rather than as a characteristic specific to a particular task. Thus task similarity can be used to represent the relationship between two tasks within task space. The more similar two tasks are the closer they are in task space. In combination with the notion that the executive control processes serve to move resources between locations in task space, this

model of task space predicts that greater similarity between two tasks should reduce the time that it takes to switch between those tasks.

Across the four experiments presented here, this prediction was supported. The discovery of the task similarity effect demonstrates that manipulations of task similarity have systematic influences on the executive control and automatic processes acting within that space. These findings further support the model of task space presented in the introduction. Understanding that the executive control and automatic processes that coordinate performance in multitask environments are directly impacted by the task space in which they act should have powerful implications for the investigation and understanding of these processes.

4.2 Linking Processes to Task Components

Along with providing a measuring stick for task space, the task similarity effect also offers a new tool for linking various executive control and automatic processes to specific components of task sets and task performance. As discussed in the introduction, a variety of models propose either automatic or controlled processes or both as the mechanism behind switch cost in task switching paradigms. While there has been some speculation as to what specific task components are acted upon by various processes, the empirical work in this area has been limited (Meiran, 2000b; Rubinstein et al., 2001). The second critical component of the current research was the application of the task similarity effect to this question.

Although task similarity might be defined in a variety of different ways, the current research does so based on shared cognitive components between tasks. This way of defining task similarity also provides the ability to localize the effect of task similarity

to a particular component of the task set. By implication then, any changes in the size of the task similarity effect must be the result of processes that impact the particular cognitive component on which similarity is defined. Building on this logic, the current research examined the impact of trial timing allowing for varying degrees of controlled preparation for the upcoming task and passive dissipation of activity associated with the previous task that might have an automatic influence on performance of the current task.

Based on the results of Experiments 2 and 4, the beginnings of a model linking controlled and automatic processes to individual components of the task set can be developed. Experiment 2 found that when similarity is defined in terms of the attentional control setting, the similarity effect does not change with variation in delay interval, but completely disappears with a long preparation interval. This finding suggests that part of the controlled task preparation that occurs once the upcoming task is known is the establishment of the attentional control setting appropriate for performance of the task. On the other hand, Experiment 4 demonstrated that when similarity is defined by shared response modality the similarity effect changes both as a result of preparation interval and overall delay interval. These findings in turn suggest both controlled and automatic processes are acting on the response component of the task set. In combination, the results from these two experiments allow us to begin to link specific processes to different components of the tasks that they influence. Controlled preparation for an upcoming task must involve activating or enabling both the attentional systems necessary to process the stimulus information relevant to the task and the motor systems involved in responding appropriately to the task. On the other hand, only the response component of the task appears to have an automatic influence in the form of priming from one trial to

the next that dissipates over time. Thus a model may be envisioned in which various cognitive operations engaged in task performance are activated or deactivated by a variety of separable controlled and automatic processes. Filling in the details of this model of task switching will require further investigation.

4.3 Task Sequence Effects

In addition to the switch cost analyses, task performance for Experiments 2 and 4 was also analyzed as a function of the sequence of tasks over a three trial run. (The comparable analyses were not performed for Experiments 1 and 3 due to the small number of trials per cell in the four task versions of the experiments, which would make interpretation of any pattern of results suspect.) The analyses focused on three sequences: unique tasks, A-B-C; alternating tasks, C-B-C; and repeat-switch tasks, B-B-C. The focus of previous studies of the Trial N-2 sequence effects has been on the comparison of unique tasks and alternating tasks sequences as a marker of backward inhibition. A series of studies by Mayr (2002; Mayr & Keele, 2000) has attributed slower responding on alternating tasks to the inhibition of the task set that has recently been switched away from following performance of Trial N-2, but must be reinstated on Trial N. In addition to this apparent inhibition on alternating tasks sequences in comparison to the unique tasks sequence, which serves as a control, there is also evidence for a facilitation in responding on the repeat-switch tasks sequence as compared to the unique tasks sequence (Arbuthnott & Frank, 2000; Arrington et al., 2001).

The comparisons of alternating tasks and unique tasks sequences produced a complex pattern of results that differed across the two experiments. In Experiment 2, the most general level of analysis showed slowed responding in the alternating tasks

sequence, thus generally replicating the pattern of results associated with the inhibition of task set under conditions of alternating tasks. However, the sequence effect did enter into several significant interactions with the similarity, task, and timing interval variables indicating a complex set of factors that influence this effect. While Mayr and Keele (2000) found no changes in backward inhibition as a result of changing the timing of the trials, the current findings indicate that under some circumstances temporal manipulations do affect the alternating tasks effect. Recently, Arbuthnott and Woodward (2002) also have found task specific fluctuations in the alternating tasks effect. In Experiment 4, the alternating tasks effect showed an interesting interaction with similarity. The cost typically associated with returning to a recently abandoned task set was found when a dissimilar task intervened (e.g. First – Number – First). However, the reverse effect was found when the similar task intervened (e.g. First – Second – First) and response times were actually faster on these trials when compared to the unique tasks sequence (e.g. Number – Second – First). This finding suggests that the alternating tasks effect, which is considered as a marker of backward inhibition, is not universal. In particular, when the tasks are highly similar, differing only in terms of the particular effector (first or second finger) with which the response is made, the need to implement a mechanism of active inhibition of the previous task set may not occur when switching between tasks. This conclusion is speculative and further research will need to be conducted to more fully examine the conditions under which inhibitory processes are or are not involved in task switching.

Unlike the previous comparison of alternating tasks and unique tasks sequences, the comparison of repeat-switch tasks and unique tasks sequences showed a consistent

benefit across all tasks and timing conditions in both experiments, indicating that the effect is both replicable and robust. The mechanisms of this facilitated switching following a task repetition are unknown. It may result from processes associated with the ease of performing the task on Trial N-1 due to the fact that it is a task repetition trial. On task repetitions the activation of the task set may not need to be as strong for appropriate task performance, thus switching away from that task set may prove to be an easier process.

In sum, task performance in the multitask environment presented in these experiments is clearly affected by the extended sequence of events prior to the performance of a given trial including not only the preceding trial, but also more distal trials. Producing a model of the processes influencing task performance in multitask environments will necessarily require consideration of these issues.

4.4 Similarity in Task Switching and Other Dual Task Paradigms

The task switching paradigm is just one of a number of experimental methodologies that have been used extensively in recent research focusing on issues of control of cognitive processes in dual task environments. Other popular paradigms include the psychological refractory period (PRP) paradigm and the attentional blink (AB) paradigm. The experiments used in the current research exemplify the typical task switching methodology (but see Allport & Hsieh 2001 for an example of an alternative method for examining task switching). Individual trials include the presentation of a cue indicating the task on a given trial (sometimes this element is excluded or combined with the stimulus display), the stimulus, and the response. Only after the completion of each of these elements in the trial is the next trial initiated. The tasks are thus presented

sequentially with each task demanding a speeded response. In the PRP paradigm, the tasks also include the presentation of a stimulus and a speeded response, however the presentation of the stimulus for the second task can occur prior to the response to the first task. This simultaneous presentation allows for overlap in the performance of the two tasks. Finally the AB paradigm (Raymond, Shapiro, & Arnell, 1992) imbeds the target stimuli for the two tasks within a stream of distractor items presented in a rapid serial visual presentation (RSVP) format. Responses to both tasks are withheld until the end of the stimulus presentation and do not require speeded responding. Thus, while all three paradigms require performance of two tasks close together in time, there are distinct methodological differences among the paradigms.

These methodologies and associated phenomena traditionally have been considered separately. However, there has recently been a flurry of interest in relating findings and theories developed from various dual task paradigms used to study control of attention and performance: AB paradigm and PRP paradigm (Jolicœur, Dell'Acqua, & Crebolder, 2000; Ruthruff & Pashler, 2001), AB paradigm and task switching (Chun & Potter, 2001), and PRP paradigm and task switching (Pashler, 2000). Understanding the commonalities among these various paradigms appears to be critical in furthering our models of executive control and automatic processes acting in a variety of dual task environments both in and out of the laboratory. When comparing research from disparate paradigms, effects such as the impact of similarity on task performance can serve as critical tests of the continuity of the processes engaged across paradigms.

Some evidence for the impact that task similarity has on performance in the PRP paradigm was introduced previously. When the two tasks involve responses in the same

modality (manual-manual) interference is greater than when the two tasks involve responses in different modalities (manual-vocal; Pashler 1990). However, additional research focusing on similarity in the stimulus modality (visual-visual vs. visual-auditory) does not provide strong support for a parallel effect of similarity on dual task interference when similarity is defined in terms of sensory modality of the stimulus (reviewed in Pashler 1998). These findings have been interpreted within the context of a bottleneck at a central stage of processing. Stages prior to the bottleneck such as perceptual processing are thought to occur in parallel and thus similarity of stimulus features does not affect processing. On the other hand, processes that are involved in the central bottleneck, in particular response selection, occur in a serial fashion. The fact that similarity defined at this stage of processing impacts the interference effect in the PRP paradigm suggests that this serial processing stage is in some way affected by the similarity of task components that require this stage of processing. The results from the present experiments appear to differ from these results in that similarity facilitates switching when it is defined both in terms response modality and in terms of the attentional control settings of the tasks, which would presumably be occurring prior to a central bottleneck associated with response selection. Thus one might ask what the difference is between these two very similar experimental paradigms that would lead to the discrepant results. In the task switching paradigm, from one task to the next all task components are processed in series due to the sequential presentation of stimuli. Perhaps the serial nature of performance in task switching experiments is a key element in the facilitation associated with similarity in task switching.

The role of similarity between tasks in the context of the AB paradigm has also been studied recently. In a meta-analysis of AB experiments, Visser, Bischof, and DiLollo (1999) examined lag-1 sparing (high level of accurate performance on T2 if it appears immediately following T1) as a function of the type of switch occurring between T1 and T2. They found lag-1 sparing occurred with greater regularity when there was either no switch between T1 and T2 or a switch along a single dimension. Thus similarity appeared to facilitate processing of T2 when it occurred in close temporal succession (within approximately 100 ms) to T1. The relationship between lag-1 sparing and similarity was however independent of the AB measured over a longer time interval (approximately 200 to 600 ms). Visser et al. account for this finding of a similarity effect at lag-1 in a model that proposes top-down control of perceptual filters such that when two tasks are similar the imperative stimuli for both T1 and T2 can enter into the stream of information processing simultaneously if presented close in time (a notion that appears consistent with Folk et al.'s description of attentional control settings). This account differs from the discussion above in that similarity appears to have its effect through allowing for parallel processing of stimuli where as in the central bottleneck account of the PRP effect, the similarity effect appears to be acting at the central bottleneck where processing is serial. Interestingly, Visser et al. also note that the similarity results in the AB task are in contrast to established interference effects resulting from similarity in dual task situations. The results of the present set of experiments also provide an example of a processing benefit associated with similarity suggesting that proposal of greater interference effects in dual task environments associated with similarity may need to be reconsidered.

Clearly the role that similarity plays in task performance in dual task situations is complex. The current experiments present a consistent finding that similarity facilitates switching between tasks. However, there may also be multiple influences of similarity at various stages of task performance in the current experiments as well. In Experiment 1 there was the hint from the analysis of within trial compatibility effects that similarity may result in greater interference of task performance when similar stimulus dimensions indicate incompatible responses. This effect was small and would need to be replicated (which it was not in Experiment 2) before more specific claims can be made about the finding. Further consideration of the role that similarity plays across various dual task environments appears to be a useful avenue for future investigations.

4.5 Future Directions

One of the important contributions of the early stages of model development is the questions that are generated. The current research represents a starting point from which other questions may be fruitfully pursued. Let me speculate briefly about what some of these questions might be. Only two task components were examined in the current research. While the task similarity effect was consistent across both components, it will be important to consider further task components. For example, would similarity of different cognitive manipulations provide the same benefit? Jersild's (1927) initial instantiation of the task switching method had participants switching between addition and subtraction operations. Building on that method and the work of Badre et al. (2000), it would be possible to construct a set of tasks that involved different mathematical tasks (e.g. +3, +5, -2, -4) that were grouped in terms of similarity of the mathematical operations being performed. Based on the task space model, switches between the two

addition task might be expected to occur more rapidly than between addition and subtraction tasks.

The preceding discussion presents a model in which controlled and automatic processes can be linked to separate components of task sets. While it appears possible to separate out task components and examine the processes that act upon them, it would also be useful to consider the interactions among task components. In the current set of experiments, the similarity effect was found both when similarity was the result of shared attentional control settings and when similarity was the result of shared response modality. One interesting question that might be posed is whether the effect of similarity at these different components of the task set would result in additive effects if presented in the same task environment. If chosen properly, tasks might involve similarity along more than one dimension in task space. For example, a combination of the tasks involving shared attentional control settings (Height and Width vs. Height and Color) with a manipulation of the response modality (manual or vocal) could allow for tasks that are similar in terms of both attentional and response demands, similar on just one of the task components, or similar on neither task component. In such a design it would be possible to examine whether the similarity effects resulting from the manipulation of specific aspects of the task set combined in an additive fashion.

Finally, the task space approach to task switching should be expanded beyond simply looking for multiple and interacting effects of task similarity. It will become important to consider other approaches to defining task space in order to further explicate the role that task space plays in determining how executive control is implemented. The tasks that confront us in real world environments are often not easily defined in terms of

similarity. For example tasks may better be defined in terms of goals that they achieve or the environments in which they have been experienced in the past. Consideration of this larger application of task space to task switching should prove exciting.

4.6 Conclusion

Over the last decade, the task switching methodology has developed rapidly and been widely applied to questions of cognitive control. Our understanding of the variables that influence task switching has advanced. However, consideration of the underlying representations has remained relatively limited. In this dissertation, I presented one model of how task space might be organized in terms of a multidimensional space with various cognitive operations serving as the basic dimensions of this space. I then demonstrated that manipulating task space through varying the similarity among tasks has systematic influences on the processes engaged when switching between tasks. Finally, I used the task similarity effect to address questions of how and when executive control and automatic processes act on the individual cognitive operations involved in task performance. These explorations in task space supply structure to the expanding field of investigations in cognitive control.

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