

2011

The Effect of Hierarchical Task Representations on Action Selection in Voluntary Task Switching

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The Effect of Hierarchical Task Representations on Action Selection in Voluntary Task
Switching

by

Starla M. Weaver

A Dissertation

Presented to the Graduate and Research Committee

of Lehigh University

in Candidacy for the Degree of

Doctor of Philosophy

in

Psychology

Lehigh University

August 2011

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Approved and recommended for acceptance as a dissertation in partial fulfillment of the requirements for the degree of Doctor of Philosophy

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The Effect of Hierarchical Task Representations on Action Selection in Voluntary Task Switching

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Acknowledgments

I would like to express my sincerest gratitude to my advisor, Kate Arrington. Her insights and guidance have been instrumental to this dissertation and throughout my graduate career. I would also like to thank my committee members, Almut Hupbach, Glenn Wylie and Pat O'Seaghdha, for their insightful comments and suggestions and for pushing me to create a better manuscript than I otherwise would or could have. Finally, a special thanks to my husband, William Weaver for his continued support and encouragement. Without his constant strength, patience, and belief in me I would have never been able to achieve this milestone.

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Abstract

Actions can be represented at multiple levels. One can view an act as an isolated task or as part of a larger goal. The specific level at which one represents an action has the potential to influence how that action is performed. The current study explored the potential for hierarchical representations to also influence action selection within multitasking environments. The current study used the voluntary task switching paradigm to assess whether or not and under what conditions hierarchical task representations can be found within the free choice multitasking environments. In Experiment 1 participants switched between four individual task elements. Three manipulations of increasing complexity were used to encourage participants to represent these task elements hierarchically. While manipulations that took place only during the practice phase of the experiment were ineffective at establishing a hierarchical task representation, manipulations that persisted throughout the experiment influenced task selection. The results suggest that hierarchical representations had been formed. Experiment 2 explored the stability of hierarchical representations. The results suggest that, once established, the influences of hierarchical representations tend to persist, regardless of whether or not they are strictly required. A final experiment assessed the manner in which hierarchical representations are activated. A null result suggested that under the current experimental conditions all of the task elements that make up a hierarchical representation were not activated in unison. The current findings suggest that when actions are represented hierarchically, task elements that are part of the same

aggregate task as the task performed on the previous trial will be prioritized for selection. This prioritization increases the probability that tasks that are part of the same hierarchical representation will be performed in succession and can speed the task selection process. As a result, hierarchical representations are likely to influence both task choice and performance speed, but influences on measures of task choice are likely to occur sooner than influences on performance. I propose that the more immediate influence of hierarchical representations on task choice reflects the functional role that hierarchical representations play in the action selection.

The Effect of Hierarchical Task Representations on Action Selection in Voluntary Task Switching

Humans have the perception of volitional control. If while reading this sentence you choose to flip ahead and start reading the last page or turn back and reread the first sentence, you presumably do so because of internally formed goals. You are volitional, selecting actions according to your own intentions. Nevertheless, actions can seem less than intentional. When tired or distracted, one may perform unintentional acts, such as putting a carton of milk away in the cupboard instead of the refrigerator. Interestingly, these errors are not failures to perform an action correctly; the milk has not been spilt. Instead the failure seems to be in selecting the appropriate task to perform (Monsell, 1996). At times the events in one's environment appear to guide action selection. Extreme cases of stimulus-driven action can be seen in patients with frontal lobe damage (Lhermitte, 1986); however, stimulus-driven action errors can be seen in healthy populations as well (Monsell, 1996). Further, the absence of an error does not necessarily imply the presence of volition. When multiple actions are acceptable, the specific action one selects can be affected by internal processes or environmental factors that one is not even aware of (see Bargh & Chartrand, 1999 for review). Yet despite these potentially strong influences, action selection remains for the most part, an intuitively autonomous process, such that one typically has the perception that her actions are under her control. How are people able to select actions and accomplish goals in the face of these potential biases? It seems likely that cognitive mechanisms, which help to direct choice, exist. The current study will begin to address the broad question of action

selection by assessing one such potential mechanism, hierarchical representations. A hierarchical representation is a mental representation that is made up of components and nested subcomponents, where the structure of the superordinate components exert an influence on actions represented at the subcomponent level (Schneider & Logan, 2006). To understand how this type of mental representation may influence actions it is first necessary to understand how basic, non-hierarchical mental representations guide performance. I will thus begin with an overview of mental representations and how they become selected and activated so as to enable task execution. I will then review the literature on hierarchical representations and the effects these representations have previously been found to have on performance. Finally, I will discuss the potential for hierarchical representations to be adopted when performing volitionally selected actions and the influence hierarchical representation may exert on action selection.

Performing a single action involves multiple steps. Often, perceptual processes are needed to locate and identify the relevant stimulus. Additionally, motor processes will be needed to generate the relevant movements. Perceptual and motor processes have been highly studied in their own right. However, a large number of processes are often needed to connect the output of perceptual processes to the generation of specific relevant motor processes. Consider a mundane action such as stopping a car at a red light. Even after the perceptual system has identified the stoplight, attention will need to be oriented to the relevant aspect of the stimulus (i.e. concentrate on the light's color rather than its shape or luminance). The relevant stimulus-category classification will be needed in order to abstract the meaning of this otherwise arbitrary symbol (i.e. red means stop).

The relevant category-response rule will also be needed (i.e. to stop press the brake pedal with the right foot), all before motor processes can generate the required response movements. The role of choosing, enabling and coordinating performance has been assigned to executive processes (Logan, 1985). Executive control has been criticized as little more than a homunculus (Altmann, 2003), a term that simply serves as a stand in for processes of cognition that manage subordinate mental components (Baddeley, 1996). In fact Monsell (1996) referred to the understanding of executive processes as “a somewhat embarrassing zone of almost total ignorance” (p. 93). However, recent work has attempted to take on the ambitious assignment of dissecting the homunculus and uncovering the executive processes that allow for action selection (Logan, 2003; Logan, Schneider & Bundesen, 2007).

The empirical study of executive processes requires situations of action selection that are demanding enough to necessitate their employment. Not all actions will require executive control, as stimulus-driven, bottom-up processes are often sufficient to guide responses to specific environmental stimuli (Logan, 1988). However, bottom-up processes are not always sufficient to guide action selection. In particular, in situations of high conflict, such as those that involve decision making, troubleshooting, or overcoming strong habitual responses, top-down processes will be needed to ensure appropriate response selection (Norman & Shallice, 1985). To handle such situations, a top-down system that is able to supersede that of lower-level processes is needed to replace lower-level action biases with the careful, top-down selection processes that are the hallmark of volitional behavior (Miller & Cohen, 2001). Thus, a study of how executive processes

guide action selection requires the use of situations that are demanding enough to elicit their engagement.

One everyday instance of action selection that is likely to require executive processes is a multitasking situation. The need to maintain multiple tasks simultaneously or to perform tasks in quick succession requires that the appropriate action be selected, engaged, and then quickly disengaged to allow for the subsequent selection of a new action. Experimental paradigms that mimic the demands of real-life multitasking have been used to begin to elucidate the executive processes required in action selection (Law, Logie, & Pearson, 2006; Lien, Ruthruff, & Kuhns, 2006; Monsell, 2003).

Task Switching

One paradigm that has been particularly fruitful in the study of executive processes is task switching (see Kiesel et al., 2010; Vandierendonck, Liefoghe, & Verbruggen, 2010 for reviews). In task switching paradigms, participants are instructed on the performance of two or more simple tasks. Following instruction, the participant is presented with a series of stimuli, which afford both tasks, and is asked to perform one of the tasks on each stimulus in a specified serial order. Of interest in task switching is not performance on the simple tasks themselves, but a comparison of performance on repetition trials, in which the current task is the same as that performed on the previous trial, and switch trials, in which the current task is different. The seminal finding is that of switch costs: compared to repetition trials, switch trials take more time to perform and are more likely to result in error. Task switches may serve as an empirically testable

situation in which action selection and performance depend on processes of executive control (Monsell, 2005).

Experimental situations that require task switches allow the executive processes involved in action selection to be elucidated. Specifically, task switching research has generated a two stage model of how mental representations are selected and activated so as to guide task performance (Allport & Wylie, 2000; Logan & Gordon, 2001; Rubinstein, Meyer & Evans, 2001). If hierarchical representations guide action selection then they are likely to do so by influencing one of the two stages within this model. A description of each of these stages as they apply to basic non-hierarchical representations is provided below. Following Allport and Wylie (2000) I will refer to the first stage, in which task selection occurs, as the goal setting stage and the second stage, in which the parameters of the task set are implemented, as the performance readiness stage.

Task Selection: The Goal Setting Stage

The task selection processes that occur during the goal setting stage of task performance are understood less than those that occur during the performance readiness stage. This is because the majority of task switching studies have chosen to limit the process involved in task selection in order to better isolate and examine those processes that occur during the second stage of task performance. Typically, task switching studies have employed paradigms that explicitly specify the task that should be performed on each trial. Participants may be instructed to perform tasks in a prespecified order (Rogers & Monsell, 2005) or be given task cues that dictate performance on a trial by trial basis (Sudevan & Taylor, 1987). Nevertheless, task selection processes do influence

performance. For example, manipulations that vary the ease with which a cue can be processed (Bryck & Mayr, 2005; Rubinstien et al, 2001; Saeki & Saito, 2004; 2009) or the transparency with which a cue can lead to the selection of the desired task (Goschke, 2000; Miyake, Emerson, Padilla & Ahn, 2004; Logan & Schneider, 2006) result in changes in the time required to perform that task. Thus, the role that task selection processes play in the task performance can be seen by the contribution this stage makes to response time (RT) (Rubinstien et al, 2001).

Impacts of the goal setting stage can also be seen within error data. When task selection processes fail to select the specific task required on the current trial an error will occur. Arbuthnott and Frank (2000) used vocal responses in order to differentiate between decision errors, in which participants provided the wrong response for the correct task (i.e. saying large in response to the cue and stimulus: magnitude - 2) and wrong-task errors, in which participants made the correct response for a task that was not cued (i.e. saying even in response to the cue and stimulus: magnitude - 2). These two error types did not interact, suggesting that they resulted from different mechanisms. Specifically, decision errors were influenced by the complexity of the task required for performance on that trial, suggesting that they resulted from task level processes. Wrong-task errors on the other hand, were not influenced by task complexity but were impacted by the complexity of the transition being performed. When these errors occurred they most often took the form of an uncued task repetition. Wrong-task errors appear to reflect a failure of executive processes to correctly select the new task during the goal setting stage.

Task selection processes that occur during the goal setting stage can influence RT and error rates during task switching. However, as will be described below, these measures will also be influenced by the performance readiness stage, making explicit study of action selection via the task switching paradigm difficult. Further, as action selection that occurs outside of the laboratory is seldom explicitly specified in the constrained manner utilized by this paradigm, task switching may not be sufficient to capture the processes of action selection that occur when one must select actions in a voluntary manner. Fortunately, Arrington and Logan (2004) have developed a task switching procedure that allows for a better examination of the goal setting stage of task performance. The voluntary task switching paradigm uses a bivalent stimulus and allows participants to choose which task to perform on each trial. As in previous versions of task switching, voluntary task switching provides a measurement of the time required to switch to a new task. It also provides task choice as a dependent measure capable of independently revealing the outcome of the goal setting stage. During voluntary task switching participants are allowed to choose which task to perform on any given trial; however, participants are typically given the general instructions to attempt perform tasks equally often and randomly. These instructions serve two purposes. First, these instructions ensure that subjects switch between tasks. The relative speed of repetitions compared to switches can lead uninstructed participants to refrain from ever switching tasks (Arrington & Weaver, in preparation). Second, these instructions provide a baseline that can be used to reveal biases in task choice. By assessing whether or not task choice deviates from these instructions, the voluntary task switching paradigm can be

used to determine the factors that influence action selection. This paradigm's ability to provide a controlled examination of the factors that influence task selection makes it an ideal methodology for examining the influence that hierarchical representations may have on action selection.

Voluntary task switching.

True to its name, task selection in voluntary task switching relies primarily on top-down executive processes (Arrington & Logan, 2005). Task selection appears to be an active, task-specific process that can begin prior to the presentation of the specific stimulus to which the task will be applied. Increases in preparation time lead to reductions in switch costs, suggesting that participants are using this time to actively prepare for the upcoming task (Arrington & Logan, 2004). Part of this preparation involves selecting the task to perform on the upcoming trial. In voluntary task switching, participants are often instructed to order tasks randomly, a requirement that is known to require executive control processes (Baddeley, Emslie, Kolodny, & Duncan, 1998). To fully comply with these instructions participants should perform an equal number of task switches and task repetitions. However, participants tend to perform an increased proportion of task repetitions. Importantly, this repetition bias appears to be especially strong when executive control is limited. Reduction in the preparation time between trials increases the repetition bias (Arrington & Logan, 2005), while at long response-to-stimulus intervals (RSIs) the bias is often reduced or even eliminated (Liefoghe, Demanet, & Vandierendonck, 2009). Extended preparation time appears to allow participants to implement the executive control necessary to create less biased task

sequences. Repetition bias is also exaggerated by high working memory (WM) loads (Demanet, Verbruggen, Liefoghe, & Vandierendonck, 2010) and periods of mind wandering (Arrington, Stuart, & Weaver, in revision), both of which are thought to rely on executive processes (Baddeley, Chincotta, & Adlam, 2001; Teasdale et al., 1995). The biases in action selection found in situations that limit executive control suggest that when available, executive control processes help to guide bias-free action selection.

Yet despite its volitional nature, bottom-up influences on action selection have been found during voluntary task switching. External factors of the stimulus environment such as stimulus availability (Arrington, 2008), stimulus repetitions (Mayr & Bell, 2006), and ease of stimulus processing (Arrington & Rhodes, 2010) appear to affect task selection. Internal factors such as the load size and content of information in WM can also influence choice (Demanet et al., 2010; Weaver & Arrington, 2010). Task-specific factors such as task complexity (Liefoghe, Demanet, & Vandierendonck, 2010; Yeung, 2010) and experience-driven factors such as previous stimulus-response (S-R) pairings (Arrington, Weaver & Pauker, 2010) and task accessibility (Gollan & Ferreira, 2009) have also been found to impact action selection.

If task selection during voluntary task switching is under volitional control then why are patterns of task choice subject to these bottom-up influences? Arrington and Logan (2005) theorized that task choice may be characterized as the result of a competition between a representativeness heuristic and an availability heuristic. The competition between these two heuristics can be conceptualized as a horse race and task performance will be determined by the winner. The representativeness heuristic selects

the task that will make the pattern of recently performed tasks most closely comply with task instructions. The availability heuristic selects the task that is currently most accessible (Baddeley et al., 2001). Over a series of trials, patterns of task choice will reflect the competition of these two heuristics. Trials guided by the representativeness heuristic should ensure that patterns of task choice do not deviate too drastically from instruction, while trials guided by the availability heuristic should create a selective bias toward more available tasks. Task choice in voluntary task switching tends to fit this pattern. Participants instructed to perform tasks randomly perform patterns of repetitions and switches that are closer to chance than participants who do not receive randomness instructions (Liefoghe et al., 2010) suggesting that participants are attempting to generate a pattern of task choice that is representative of the instructions they receive. Further, factors that have been found to bias task selection, such as S-R bindings and stimulus availability, increase the activation of a specific task, thereby making it more likely to be selected by the availability heuristic. Thus task-specific biases are suggestive of the availability heuristic's role in task selection. Repetition biases can be similarly accounted for. Persisting previous task activation increases availability, and thus the likelihood that the task performed on the previous trial will be selected. As a result, trials driven by the availability heuristic will show a bias toward task repetitions.

Demanet et al. (2010) suggests that the repetition bias, particularly when it is found under conditions of reduced top-down control, may also result from a proportion of trials on which the stimulus serves to directly reactivate a response execution before task selection is able take place. According to this view, task selection can be bypassed if a

stimulus activates a response before task selection has a chance to occur. When task selection is bypassed, responding will proceed based on the configuration of the previous task set. The result will be a task repetition. Thus, patterns of task choice will show a tendency toward a repetition bias. The extent of this bias will depend on the top-down processes available for task selection. Under the increased executive control provided by extended preparation times, task selection will be more likely to take place and the repetition bias will be reduced or even eliminated. However, when executive processes are limited task selection will occur less often such that the repetition bias is increased. This pattern is consistent with the effects of top-down control found in voluntary task switching. The proposal receives further support from Vandamme, Szmalec, Liefoghe, and Vandereendonck, (2010) who used event-related potentials (ERP) to study lateralized readiness potentials (LRP) in participants performing one voluntary task switching task with each hand. The differential pattern of LRPs found on switch and repetition trials suggest that the previous task was initially reselected for performance on both switch and repetition trials. The ability to overcome this initial reselection may depend on top-down control, such that reselection is more likely to guide task choice when control processes are limited.

The repetition bias found in voluntary task switching may be due, in part, to trials on which the goal setting stage of task performance is bypassed (Demaneet et al., 2010; Vandamme et al., 2010). The same explanation was given to account for the high proportion of wrong-task errors that are uncued task repetitions within the cued task switching paradigm (Arbuthnott & Frank, 2000). It seems that both voluntary and non-

voluntary task switching can capture instances in which task selection does not occur. However, this failure of task selection will be observed more often within the voluntary task switching paradigm. The methods used to specify the to-be-performed task within non-voluntary task switching studies, help to ensure task selection by both eliminating the uncertainty concerning the task that should be performed next and by aiding in the retrieval of the representation of the to-be-performed task (Goschke, 2000). Further, because a task repetition never constitutes an error in voluntary task switching, participants may simply not attempt to prevent task reselection on a portion of trials in order to take advantage of the ease associated with not having to select the upcoming task.

Another manner in which strategic attempts to reduce cognitive work during voluntary task switching may contribute to a repetition bias is specified by Vandierendonck and colleagues (Demanet, 2010). According to their chain-retrieval model for voluntary task switching, participants store chains of task sequences in long-term memory (LTM). Task selection occurs by retrieving one chain into WM and then selecting tasks according to the sequence indicated by the retrieved chain. The length of each chain will vary depending on the participant's WM capacity and the demands of the voluntary task switching environment, but will typically be between three and six tasks long. Once all of the tasks within a chain have been performed, participants will retrieve another chain that can be linked to the chain that has just been performed so as to allow for a continuous stream of responding. For example, if the chain ABA has just been performed then the chain ABB may be retrieved next. The resulting performance output

would be the tasks ABABB where the middle A serves as both the last task in the first chain and the first task in the second chain. Participants instructed to perform tasks randomly will store chains with an alternation bias in LTM. However, the fewer alternations a chain contains, the more likely it is to be retrieved for performance. In this way participants will attempt to perform tasks randomly but still show a bias that takes advantage of the ease with which task repetitions can be performed. The chain-retrieval model assumes that task choice will also be subject to other, less strategic, types of bias. Bottom-up processes, such as stimulus-based priming, will guide performance on some trials, preventing participants from performing the task dictated by the task sequence they are currently holding in WM.

Both the heuristic competition explanation of task selection proposed by Arrington and Logan (2005) and the chain-retrieval model of task selection proposed by Vandierendonck and colleagues (Demanet, 2010) assume that task selection is the result of a combination of top-down processes that attempt to comply with instruction and bottom-up processes that sometimes override top-down processes and guide task choice. The main difference between these models is whether top-down processes guide choice in a retroactive manner, in which sequences of tasks that have been performed are remembered and used to guide current task performance, or a proactive manner, in which sequences of tasks that will be performed are retrieved and then used to guide current task performance. Determining which account of task selection should be endorsed is difficult, as whether tasks are selected retroactively or proactively may vary depending on individual differences or task context. Indeed Braver, Gray, and Burgess (2008) have

proposed that much of the variability found in cognitive control and WM processes can be explained by intrapersonal and interpersonal differences in the extent that retroactive and proactive processes are utilized in different situations.

Task Performance: The Performance Readiness Stage

Once a task has been selected within the goal setting stage of task performance, the parameters that will govern that task's performance will need to be activated. These parameters or rules are referred to as the task set. The task set is a mental representation that contains all the parameters needed to bridge the gap between perception and motor performance for a specific task. A number of parameters have been proposed to make up task sets including representations of task relevant stimuli, stimulus-category classifications, category-response rules, and response thresholds (Logan & Gordon, 2001). The particular parameters that make up a specific task set may depend on the complexity of the task being performed (Vanderiendonck et al., 2010) and the context. The number of parameters included in a specific task set appears to influence the speed with which that task set can be activated (Logan & Gordon, 2001; Mayr, 2002) and as a result task sets are likely to contain the minimum number of parameters necessary for that task's performance.

The performance readiness stage of task performance requires activating the appropriate task set. For novel tasks, new task sets that meet the demands of the to-be-performed task will need to be constructed (Meiran & Kessler, 2008). Once formed, task sets can be stored in LTM and retrieved when that task is encountered again (Bryck & Mayr, 2008; Mayr & Kliegl, 2000). Task sets appear to be held in WM during

responding (Rubinstein et al., 2001; Sohn & Anderson, 2001.) Parameters of the task set may also need to be transmitted to subordinate processes in order for the task to be fully implemented (Logan & Gordon, 2001). Once implemented a task set can guide responding. An activated task set focuses attention on task relevant aspects of a stimulus and reduces the extent that information that is irrelevant to or that falls outside of the parameters of the current task will influence responding (Dreisbach & Haider, 2008; 2009; Van Dillen, Lakens, & van den Bos, 2011). The task set then provides the appropriate response for that stimulus. As a single task set includes multiple parameters, it can allow for appropriate responses to any number of stimuli that fall within the parameters of the task.

Task Set Reconfiguration

The time required to activate a new task set on switch trials appears to be one of the largest contributors to switch costs. However, the specific reason for the increased cost on switch trials is debated. According to the task set reconfiguration view, during the performance readiness stage, task set activation is required on switch but not repetition trials (Monsell, 2005). Once a task set is activated it can continue to guide performance across multiple repetition trials. However, when a task switch is required the cognitive system must be reconfigured according to the demands of the new task. The previous task set must be removed or deactivated and a new task set will need to be activated. Task set reconfiguration, which needs to take place on switch but not repetition trials, is thought to take a certain amount of time to accomplish and this added time contributes to switch costs.

The task set reconfiguration view holds that switch costs are due to top-down processes required to instantiate a new task set on switch trials (Monsell, 2003; 2005; Rubinstein et al., 2001). Reconfiguration can begin directly after task selection occurs and prior to stimulus presentation (Rogers & Monsell, 1995; Sohn & Anderson, 2001). This view makes specific claims about how preparation time should affect switch trials. For example, within the cued task switching paradigm, in which the to-be-performed task is specified via a task cue that precedes the presentation of the stimulus, task set reconfiguration will be able to begin as soon as the cue is presented. Thus, if the cue-to-stimulus interval (CSI) is long, then task set reconfiguration may be almost finished by the time the stimulus is presented and RT, which is measured as the interval between the presentation of the stimulus and the performance of the response, would be small. However, if the CSI is short then the interval between cue and stimulus presentation would not be sufficient to allow for the time consuming reconfiguration processes. As a result reconfiguration of the new task set would still be occurring after the presentation of the stimulus, such that RT would be increased. Consistent with this view, Meiran (1996) found that switch costs were reduced with increased CSI. Importantly, this reduction was found even when the total RSI remained constant, suggesting that this decline in RT was due to active processes engaged in reconfiguration rather than passive decay of the previous task set.

While increased preparation does tend to lead to reduced switch costs, the temporal relationship between preparation intervals and switch costs is far from straight forward. If switch costs directly reflect the time required to reconfigure the task set, then

a one-to-one relationship between increased CSI and reduced switch cost time would be expected. However, large increases in preparation time can lead to relatively small preparation benefits (Allport & Wylie, 1999). Further, significant switch costs remain even following CSIs of considerable length (Allport, Styles, & Hsieh, 1994). Multiple explanations for these residual switch costs have been proposed by endorers of task set reconfiguration. De Jong (1992) proposed the failure to engage hypothesis, which notes that just because task set reconfiguration can begin upon presentation of the task cue does not mean that it always does. When assessing individual RTs of task switches following long RSIs, De Jong found a large distribution of RTs. The fastest trials had RTs equivalent to the fastest RT found on repetition trials, while the slowest RTs in the distribution were equivalent to the slowest RT of switch trials that followed short RSIs. De Jong proposed that preparation for a task switch is an all-or-none process that participants sometimes perform at the presentation of that task cue and sometimes do not perform until the presentation of the stimulus. Residual switch costs are a result of averaging the RTs of these two types of trials. Whether or not active preparation is engaged on a particular trial will depend on the participant and the extent to which the characteristics of the experiment sufficiently encourage early preparation. Indeed, Verbruggen, Liefoghe, Vandierendonck, and Demanet (2007) found that switch costs were eliminated following very brief cue presentations. Nevertheless, other attempts to eliminate residual switch costs have been less successful (Meiran & Chorev, 2005; Rogers & Monsell, 1995) and De Jong's strong claim that task preparation is a single-step, all-or-none process has been criticized as distributions of task switching data do not

always have the mathematical properties of bimodal distributions (Brown, Lehmann, & Poboka, 2006). Others have preferred to account for residual switch costs by proposing that reconfiguration can begin following presentation of the task cue, but that cannot finish until the actual stimulus is presented (Rogers & Monsell, 1995; Rubinstein et al., 2001). Under this view reconfiguration includes both those processes that occur during the goal setting stage and processes that occur during the performance readiness stage and the performance readiness stage cannot be completed until the stimulus is presented. For example, Rubinstein and colleagues (Rubinstein et al., 2001) propose a top-down control model of task switching that assumes two independent executive components: *goal shifting* and *rule activation*. During goal shifting the previously performed task goal is replaced within declarative WM with the goal for the new task. This stage can occur following a task cue and prior to the presentation of the stimulus and appears to be equivalent to the goal setting stage described above. During rule activation the specific rules that will allow for completion of the task goal are accessed. This stage follows the presentation of the stimulus and is proposed to be the source of residual switch costs.

Task Set Inertia

Task set inertia provides an alternative view of the processes that occur during the performance readiness stage (Allport et al., 1994). According to this view task set activation occurs on both switch and repetition trials. However, task performance will take longer on switch trials because of proactive interference. This interference arises because the task set activated on the previously performed trial will influence the speed with which the current task can be performed (Wylie & Allport, 2000). On repetition

trials, where the task set is the same as that activated on the previous trial, activation is facilitated. On switch trials, where the to-be-activated task set is different than that activated on the previous trial, persisting activation of the previously performed task set, or task set inertia, causes task set competition. The time required to overcome this competition and instantiate the new task set on switch trials is proposed to be the main source of switch costs.

If switch costs are a result of processes associated with activating a new task, as proposed by the task set reconfiguration view, then this cost should be dependent on the task being switched to. However, proponents of the task set inertia view note that switch costs also seem to be influenced by the task being switched away from (Allport et al., 1994; Meuter & Allport, 1999). For example, when Wylie and Allport (2000) had participants perform a word reading task on Stroop stimuli (e.g. reading the word “red” presented in the color blue) this task took more time to perform if participants had named the color of Stroop stimuli on the previous trial than if participants had named the color of non-Stroop stimuli. Further, Yeung, Nystrom, Aronson, and Cohen (2006) found that switch costs were correlated with the neural activity of the task being switched away from rather than the task being switched to. The more active the region associated with the previously performed task, the larger the cost associated with switching away from that task.

Nevertheless, passive interference processes associated with the task being switched to can also contribute to switch costs. When a task is performed on a specific stimulus that stimulus and task become bound in a stimulus-task episode (Hommel, 2002)

that is automatically retrieved when that stimulus is encountered again (Logan, 1988). As a result, performing a task on a stimulus that previously has been paired with a different task takes more time than performing the same task on a novel stimulus (Waszak & Hommel, 2007; Waszak, Hommel, & Allport, 2003). The effect of S-R episodes can be seen following only one pairing of a stimulus and task, can generalize to semantically related stimuli (Waszak, Hommel, & Allport, 2004) and remains even following intervening trials of another task (Pösse, Waszak, & Hommel, 2006). Further, this effect may interfere with performance to a greater extent on switch trials than on repetition trials (Waszak, Hommel, & Allport, 2005), suggesting that the interference associated with S-R episodes may contribute to switch costs.

Backward Inhibition

Inhibition applied when switching away from a recently performed task may also contribute to switch costs. In their seminal study, Mayr and Keele (2000) compared the cost associated with switching to a task that had been performed two trials ago (ABA) to the cost associated with switching to a new task (CBA). The authors reasoned that if task switching is being driven only by activation of the to-be-performed task set, then switching back to a task that has recently been switched away from should be easier than switching to a new task. The activation level of the task recently performed would be higher than that of a new task and performance would be facilitated. However, if inhibition is being employed during task switches, then switching back to a recently performed task should take longer than switching to a new task. The task recently switched away from would also have been recently inhibited and overcoming this

inhibition would take longer than switching to a new task. Consistent with an inhibition account of task switching, Mayr and Keele found that switching to a task that had been performed two trials ago took longer than switching to a task that had been performed a greater number of trials ago. Inhibition of the task recently switched away from, or backward inhibition, has since been replicated using a variety of stimuli, responses, and tasks (see Koch, Gade, Schuch, & Philipp, 2010 for review). It seems that backward inhibition aids in the ability to switch away from a recently performed task (Hübner, Dreisbach, Haider, & Kluwe, 2003). However, if one is required to switch back to that task, this same inhibition can reduce the speed of that switch. Thus, backward inhibition contributes to switch costs.

In sum, the task set reconfiguration view holds that during the performance readiness stage a new task set will need to be instantiated only on switch trials and switch costs are mainly due to the top-down processes required to instantiate a new task set on these trials. The task set inertia view, on the other hand, proposes that the performance readiness stage will require the instantiation of a task set on both switch and repetition trials. This view attributes the majority of switch costs to bottom-up processes that interfere with performance on switch trials. However, these two views may not be as incompatible as they first appear. Both views acknowledge that processes such as backward inhibition will also contribute to switch costs. Further, the two views become indistinguishable if task set reconfiguration is viewed as a top-down process that generates a bias toward the new task rather than a process that explicitly instantiates the new task. The potential compatibility of these two views is made evident by researchers

who conclude that switch costs are likely a result of a combination of top-down executive processes, as advocated by task set reconfiguration, and bottom-up interfering activation, as advocated by task set inertia (Sohn & Anderson, 2001; Meiran, 2000; Vanderiendonk et al., 2010).

It seems that both the goal setting and performance readiness stages of task performance are susceptible to bottom-up biases. During the goal setting stage, these biases can result in performance of an unintended task, while during the performance readiness stage they are likely to lead to reductions in the speed and accuracy with which the intended task can be performed. These biases are able to affect action by influencing how the mental representations of those actions are selected and implemented. Top-down executive processes act on mental representations in order to ensure that intended tasks are able to be selected and performed. The research reviewed thus far has revealed that a combination of top-down and bottom-up processes affect action selection and performance by influencing the selection and activation of mental representations of tasks. Next I will explore literature on whether the reverse is also true. Does the nature of a mental representation influence the top-down or bottom-up processes that lead to task performance? Specifically, how are the processes involved in action selection and performance different for tasks that are represented hierarchically?

Hierarchical Representations

In order to retain high levels of experimental control, tasks that have been utilized in voluntary task switching, and in the broader task switching literature, have been quite simple. Single stimulus-dimension categorizations are tied to a limited number of

specified responses (Monsell, 1996). For such “single-step tasks” the task goal, or representation of what is to be achieved by a task, is completely accomplished by a single instantiation of one task set. A great deal of information about how mental representations at the level of the task set influence task performance and task selection has been gained using these simple tasks. However, outside of the laboratory what is meant by the completion of a task is more complex. Tasks are often made up of multiple steps that may be represented hierarchically (Lashley, 1951). For example, in order to complete the task goal of making spaghetti, one of the steps one must take is to boil noodles. As a result it is difficult to say whether the task being performed when heating noodles on the stove is a “boiling noodles task” or a “making spaghetti task” or an even broader “making dinner task.” This is just one example of how natural actions are often nested within larger and larger task structures made of superordinate component levels and nested subcomponents. If mental representations guide the performance of tasks (Vanderiendonck et al., 2010), and actions can be represented at different levels (Vallacher & Wegner, 1987), then the level or nature of a task’s mental representation should influence the way that task is performed. Specifically, if one is performing a task that is represented hierarchically, then the presence of the broader component structure will exert an influence on the actions represented at the subcomponent level (Schneider & Logan, 2006).

Hierarchical representations can exist at varying degrees of complexity. For example a group of simple S-R associations may become represented hierarchically if they become subcomponents that are part of a superordinate task representation

(Dreisbach, Goschke, and Haider, 2007). Likewise, a group of tasks may come to be represented hierarchically if they serve as subcomponents that are part of a superordinate representation that exerts an influence at the task level (Altmann, 2007). In order to differentiate between tasks that are being represented individually and tasks that are being represented as subcomponents within a larger hierarchical representation, I will use the term *task element* to refer to tasks that are being represented as subcomponents within a larger hierarchical structure (Lien & Ruthruff, 2004). The term *aggregate task* will be used to indicate a hierarchically organized task that is made up of multiple task elements. Thus in the example above, making spaghetti would be an aggregate task that contains the task element of boiling noodles. Other tasks that would contribute to this larger aggregate task, such as making spaghetti sauce would also be included as a task element that is part of this aggregate task. In theory, multiple aggregate tasks may be represented within an even larger hierarchical structure; however, the current study will focus on two-level task representations in hopes of beginning to understand whether and how such hierarchical representations influence the selection of the task elements that make up those representations. Specially, the current voluntary task switching study will attempt to generate hierarchical representations at the aggregate level. Voluntary task switching typically employs very simple tasks, such as indicating, via a key press, whether a shape is a rectangle or an oval. If superordinate aggregate task-level groupings were created, these simple tasks could become task elements that are represented as part of a hierarchy. The current study will assess whether such aggregate tasks can be created within free choice multitasking environments.

Tasks and Task Sets

The presence of hierarchical task structures in real world action planning has led to the speculation that task sets, which allow for the implementation of the parameters that guide the performance of tasks during multitasking situations, may also be organized hierarchically. Kleinsorge (2004; Kleinsorge & Heuer, 1999; Kleinsorge, Heuer, & Schmidtke, 2001; 2004) proposed that task sets themselves are hierarchies whose parameters are organized into more and more subordinate components. If a switch is required, the effect of that switch on performance will depend on where that switch is located within the task set hierarchy. When a change occurs, all of the levels below that change will need to be reset, such that a change in the highest task-level will require complete resetting of all task set parameters and the cost associated with that change will be high. On the other hand, if the change occurs at a lower-level, the parameters that make up the top-level of the hierarchy can remain in place and the cost associated with that change will be relatively low.

To test the hypothesis that task sets are hierarchically organized, Kleinsorge and Heuer (1999) had participants perform task switching trials within a multitasking environment in which both task judgments and compatibility of response-mappings varied independently. On each trial participants saw two numbers and switched between making a high or low judgment on the central number and a left or right judgment on the position of the peripheral number. Compatibility of response-mappings also varied, such that participants were to make compatible responses (left response for low numbers and left position) when the stimuli were green and incompatible responses when stimuli were

red. When participants switched judgments, a cost was incurred, indicating that judgments were being represented as two distinct tasks. When a judgment repeated, switching between response-mappings produced a switch cost; however, when a judgment switched, performance was slightly quicker if the mapping also switched. The result suggests that each pair of mappings was being represented as a unique level within the larger judgment tasks. Finally, if both the judgment repeated and the compatibility of the mapping repeated, then switching responses produced a cost, but no cost for switching responses was found when the mapping or judgment also switched, suggesting that the actual motor response constituted a third level within the representation of the task structure. It seems that participants represented their actions within a tri-level hierarchical task space that included task judgments, response-mapping, and motor responses.

Not all evidence has supported the view that task sets are hierarchical organized (Allport et al., 2004; Hübner, Futterer, & Steinhauser, 2001; Kleinsorge et al., 2001; Logan & Gordon, 2001; Vandierendonck, Christianens, & Liefoghe, 2008). In fact when Hübner et al. (2001) had subjects switch between three task sets, they found an additive pattern of parameter switches, such that the size of the switch cost increased with the number of task dimensions that switched, regardless of the specific level of those parameters. An additive effect of parameter switches has been found when switching between three tasks (Hübner et al., 2001; Kleinsorge et al., 2001) and when switching between two tasks (Logan & Gordon, 2001). Yet another view has been endorsed by Vanderiendonck et al. (2008). They propose that the parameters within a task sets are all

bound together without any specific organization. According to this “flat view” of task sets, each time a switch of any one of the parameters within a task set is required, the entire task set will need to be reconfigured. As a result switch costs will be similar regardless of the specific parameters or number of parameters within a task set that need to switch. How the parameters within a task set are organized may vary depending on the specific task being represented and the context in which that task is being performed.

The parameters that make up an individual task set may or may not be organized hierarchically; nevertheless, a task set can be viewed as a hierarchical representation when the actions guided by this representation are compared to actions guided by more basic S-R associations. Dreisbach et al. (2007) demonstrated that actions that are represented as tasks are subject to switch costs while the same actions, when represented as individual S-R associations, are not. For example participants who learned to switch between making a first letter vowel/consonant judgment for words presented in red (e.g. when the stimulus is red press the left key if the first letter in the word is a vowel and press the right key if the first letter is a consonant) and making an animal/non-animal judgment for words presented in blue (e.g. when the stimulus is blue press the left key if the stimulus is not an animal and the right key if the stimulus is an animal) showed switch costs when switching between tasks; however, participants who learned that the word “raven” presented in red required a right hand response and the word “hedgehog” presented in blue required a right hand response made the same responses to the same stimuli as those who represented their actions as tasks but showed no switch costs when performing these actions based on basic S-R associations. For subjects representing their

performance as tasks, the task served as a larger component structure in which the individual S-R associations were nested and this component structure influenced the nature of the subcomponent responses, indicating the presence of a hierarchical representation.

Hierarchical representations, as indicated via switch costs, are found even when the S-R pairings required by the tasks being switched between are identical (Mayr & Bryck, 2005). In fact when one switches tasks, performing the same response can actually lead to worse performance than when a switch in tasks also involves a switch in response (Meiran, 2000). This finding may seem counterintuitive given that both task repetitions and response repetitions that are part of the same task lead to performance benefits (Meiran, 2000). However, the finding can be readily explained if each task is being represented as a hierarchical structure that includes responses as subcomponents. For example a right key press response may be represented as “low” when performing the magnitude task and “odd” when performing the parity task. If a switch between these tasks leads to a response repetition, then the differential representations of that response (i.e. “low” and “odd”) can compete and actually slow responding despite the fact that the physical motor response itself is being repeated.

Task Ensembles

Task ensembles are a type of aggregate task that contains task elements that must be performed in specific sequence. For example, within the alternating runs paradigm, popular in the task switching literature, participants are asked to perform tasks in a repeating ABBA sequence (Rogers & Monsell, 1995). This procedure was designed to

create runs of trials containing both task repetitions and task switches. A recently discovered unintended consequence of these instructions is that in addition to representing A and B as laterally distinct tasks, participants tend to represent the repeating ABBA sequence as an overarching aggregate task made up of individual A and B task elements (Altmann, 2007). The hierarchical representation of task ensembles, also referred to as task chunks, is revealed by the influence on performance the repeating sequence has on the task element level. For items represented individually, task repetitions result in quicker and more accurate performance than switches. Therefore, if all tasks within the alternating runs paradigm were represented individually, then repeating task A on trial five should result in the same level of performance as repeating task B on trial three. However, this is not the case. Instead the performance of the fifth trial results in a large performance cost that can even exceed the switch cost found when moving between tasks A and B (De Jong, 1995; Koch, Philipp, & Gade, 2006; Lien & Ruthruff, 2004; Schneider, 2007; Schneider & Logan, 2006; 2007). The presence of this cost associated with the first trial of an ensemble suggests that each task ensemble is being represented hierarchically and that the entire ABBA sequence is functioning as an aggregate task. Moving between aggregate tasks eliminates the benefit of repetitions at the level of the task elements. Thus the fifth trial repetition when performing a repeating ABBA ensemble is often performed at speeds similar to that of the fifth trial switch within a repeating AABB ensemble (Schneider & Logan, 2007). It seems that one cannot benefit from task element repetitions if that repetition spans two different aggregate tasks. In this case hierarchical task structures are revealed by the change they produce in the

speed of repetitions at the task element level. However, hierarchical representations can also be revealed by a change in the speed with which task switches are produced at the task element level. Task switches that occur within the same aggregate task will take less time than task switches which span an aggregate task. The current study will take advantage of these differences in within-aggregate and between-aggregate task switch speed in order to help determine whether hierarchical representations can be formed within a free choice multitasking environment.

The performance effects of switching and repeating actions appear to be consistent regardless of the hierarchical level at which the action is being represented. Switching from an ABBA task ensemble to an ABBB task ensemble results in a larger increase in RT than when either type of task ensemble is performed in succession (Schneider & Logan, 2006). Just as switching between task elements results in a performance cost compared to repeating task elements, switching between aggregate tasks results in a cost compared to repeating aggregate tasks.

In sum, hierarchical action representations exist. Individual tasks can be represented as being made of subcomponents (Kleinsorge & Heuer, 1999) or as being the components that make up a larger superordinate aggregate task (Lien & Ruthruff, 2004). The hierarchical nature of the mental representation changes the way that task performance occurs. However, these previous findings of hierarchical representations have been found within situations in which task element order was constrained. In each case it was the experimenter and not the subject who determined the specific serial order in which the task elements should be performed. Are hierarchical representations also

found in situations where subjects are free to order tasks themselves? In order to determine if this is the case it is necessary to understand under what situations hierarchical representations are found.

When Are Hierarchical Representations Found?

Current evidence from the multitasking literature suggests that participants are somewhat inclined to represent actions hierarchically whenever they recognize that the task environment supports a hierarchical structure. For example, Schneider (2007) effectively induced hierarchical representations by requiring participants to perform six trials in a memorized order. He informed participants that thinking of the six trial sequence as two pairs of triplets would make the sequence easier to remember. Consistent with his suggestion, participants appeared to represent the series of trials as two task ensembles. However, explicit knowledge tends to induce hierarchical representations even when such a representation is not suggested by the experimenter. Dreisbach et al. (2007) demonstrated that knowledge that S-R pairings could be represented as pairs of tasks was sufficient to cause participants to create task representations, even when the learning environment supported a more simple direct S-R pairing representation. In their study, words were categorized as animal or non-animal or beginning with a consonant or vowel. The specific task to be performed on each stimulus was indicated by the color the stimulus was presented in. Groups of participants learned to respond to stimuli either with or without knowledge of the underlying task rules that dictated the assignment of stimuli to responses. At the start of the experiment, participants in the informed condition were told these task rules while participants in the

uninformed condition were never explicitly told that the actions they would be performing could be considered tasks. During the experiment all participants were taught the specific responses to be performed for each of the eight stimuli used in the study. S-R pairings were introduced at a slow rate that allowed each to be memorized before new pairings were presented. Though all participants were exposed to this same learning environment, different patterns of data were found in each condition. Participants in the uninformed condition performed switches and repetitions at similar speeds and with similar accuracy. However, participants who were informed of the task rules prior to learning the S-R pairings showed significant switch costs. Participants informed about the task rules appear to have represented their actions as tasks and performance was impaired when they switched between those tasks. However, when the same actions were represented as simple S-R pairings, no switch costs were found. Further, when it was casually mentioned to a third group of participants, who were uninformed about the task rules at the start of the study that the S-R pairings they had already learned could be represented as tasks, these participants showed switch costs in the next block of trials. Even though these participants had learned and practiced representing each task as a sequence of unassociated S-R pairings, mere knowledge of the existence of task rules caused participants to begin representing the pairings as tasks. This change was found both when the stimuli were long and difficult to remember and when the stimuli were so short and easy to memorize that representing them as tasks actually impaired performance. Thus, explicit knowledge appears to be sufficient to allow for and encourage actions to be represented hierarchically.

Even without any explicit knowledge or suggestion, participants appear inclined to represent actions in a hierarchical task structure to the extent that the task environment is suggestive of this structure. Spatial and temporal manipulations of stimuli can lead to the spontaneous adoption of hierarchical representations. For example the temporal overlap in stimulus presentation within the psychological refractory period paradigm, in which two stimuli, each requiring a response are presented on each trial, can lead the two tasks to be represented as a task ensemble (Luria & Meiran, 2003). A similar finding was demonstrated by Lien and Ruthruff (2004) within the task switching paradigm. Over a progression of experiments, the authors gradually manipulated the extent that a series of magnitude and parity tasks appeared as a task ensemble. First the RSI between task ensembles was increased relative to the RSI within task ensembles. Then the spatial array where stimuli were presented was manipulated to make the tasks appear less and less like a continuous stream of trials and more and more like repeating sets. The extent that tasks were represented as ensembles was measured by comparing the performance of the first trial in a task ensemble when it was a task-level repetition but an ensemble-level switch to the first trial in a task ensemble when it was a task-level switch but ensemble-level repetition. During the first experiment, when no manipulation to the task environment was made, there was a strong benefit for task-level repetitions, suggesting that task elements were not being represented hierarchically. However, as the task environment changed to become more and more suggestive of the presence of task ensembles, the pattern of performance changed too, so that the task-level repetition benefit was reduced and then replaced with larger and larger task ensemble-level switch

costs. Participants adopted a hierarchical representation based on the stimulus structure of the tasks they were performing.

Participants appear to readily adopt hierarchical representations when performing tasks within a multitasking situation in which task order has been predetermined. Will such hierarchical representations also be found in multitasking situations in which participants are free to order tasks themselves? This is likely to depend on the reason that these representations are adopted and whether or not that reason is applicable within voluntary task switching environments. Three potential functions of a hierarchical representation are considered below.

Performance of Task Elements

Hierarchical representations may serve to increase the speed and accuracy with which the individual task elements that make up that representation can be performed. First, representing actions hierarchically may aid in action preparation. Rubinstein et al. (2001) proposed that performing actions is a two-stage process wherein one must first shift to the upcoming goal and then activate the rules associated with the performance of that goal. Schneider (2007) speculated that if a set of actions is represented as a number of different individual tasks, then performance of those actions will depend on the time required to shift to and activate the rules associated with each one. However, representing a series of tasks as one aggregate task allows all of the task elements within that aggregate task to be part of the same goal, such that the time required during the goal shifting stage is reduced. As a result each task element can be performed more quickly. Koch et al. (2006) highlight another potential benefit of representing a series of tasks as a

single aggregate task. They found that participants with explicit knowledge that the series of task switching trials they were performing was a repeating task ensemble showed less backward inhibition within blocks of trials that were made up of ensembles. Representing a series of tasks as an aggregate task appears to reduce the level of inhibition that is applied to its task elements. Thus, task elements represented within a hierarchy may benefit from increased speed of preparation and reduced levels of inhibition.

Representing tasks hierarchically may aid in the performance of the task elements within that aggregate task. However, performance benefits are not universal, and hierarchical representations appear to be adopted even when they do not lead to superior performance (Dreisbach et al., 2007). Indeed, plan specific knowledge can sometimes interfere with the task specific processes required to carry out that plan (Logan, 2007). Therefore, whether or not a hierarchical representation is adopted is not likely to be a product of the functional benefit that representation provides at the task element level.

Memory for the Serial Order of Task Elements

Another benefit of representing multiple individual task elements within a single hierarchical task structure is that doing so allows the entire group of actions to be stored and retrieved from memory as a single unit. Grouped representations are learned more easily (Gobet et al., 2001) and held more efficiently in WM (Wolters & Raffone, 2008). Thus, hierarchical representations allow for the potential action planning limitations inherent in a limited capacity system to be overcome.

If the hierarchical representations that have previously been found within the task

switching literature are adopted primarily to help retain task elements within a specified serial order, then this type of representation would not be expected to generalize to a voluntary task switching environment that contains aggregate tasks other than task ensembles. When performing task ensembles, representing that ensemble hierarchically would be beneficial, as a hierarchical representation would make remembering the order that task elements should be performed in easier (Schneider, 2007). Having advance knowledge of the task to be performed in the upcoming trials leads to quicker and more accurate performance (Dreher, Koechlin, Ali, & Grafman, 2002; Kleinsorge & Gajewski, 200; Sohn & Carlson, 2000). Thus, even when explicit memory of the task sequence is not required, the performance benefit associated with being able to plan for the upcoming task may be sufficient to encourage participants to hold the sequence in memory.

However, if the hierarchical representations found in task ensemble studies are primarily a product of the requirement to perform tasks in a specific, prespecified order, then hierarchical representations would not be expected within voluntary task switching where one can choose which task to perform on a trial by trial basis, such that retention of memorized sequences is not required. In fact within a free choice environment, remembering multiple task elements at once could cause interference during task set selection, which could slow performance. Therefore, if memory for serially ordered tasks is the primary function of hierarchical representations then hierarchical representations would not be expected to be formed within a voluntary task switching environment.

Action Organization and Selection

The inclination that participants display to represent actions hierarchically may be

an indication of a general tendency to utilize hierarchical representations in everyday action planning situations (Lien & Ruthruff, 2004). Hierarchical representations could serve as a mechanism for organizing all of the specific elements that make up an aggregate task in a way that becomes particularly beneficial in situations where task order is not explicitly specified. When task sequencing is unconstrained, action selection can be subject to bottom-up influences such as task set inertia (Vandamme et al., 2010), S-R bindings (Arrington et al., 2010), and task set inhibition (Lien & Ruthruff, 2008). Top-down control is required to overcome these influences and produce volitional behavior (Weaver & Arrington, invited revision). Representing actions within a hierarchy may be a mechanism that helps to hamper bottom-up influences so that less control is required. For example, if one needs to perform three individual tasks, then top-down control processes will be needed after the performance of each task in order to overcome the interference associated with the previously performed task and ensure that the appropriate new task is selected. However, if these three tasks are represented within a single hierarchical representation, then action selection and performance processes would be subject to less interference (Koch et al., 2006; Schneider, 2007).

Dreisbach and Haider (2008; 2009) propose that one function of task sets is to focus attention and prevent processing of irrelevant stimulus information that can interfere with performance. They demonstrated this function by comparing performance for participants maintaining a task set to those storing more basic S-R mappings (Dreisbach & Haider, 2009). In their study participants viewed compound stimuli made up of the name of a piece of clothing superimposed over a line drawing of either a piece

of clothing or an animal. Responses were made to the words based on either direct S-R mappings or based on task rules (i.e. does this item cover the leg). Participants who made responses using S-R bindings showed compatibility effects for clothing stimuli, such that they were faster to respond to stimuli for which the word and the picture led to the same response, and for animal stimuli, such that they were faster to respond to stimuli when the animal faced the direction of the to-be-performed response. Participants who made responses using task representations showed compatibility effects for clothing but not for animal stimuli. Animal information, which was not relevant to the task goal, was able to be ignored when participants adopted a task representation. Task representations appear to shield the task goal such that stimulus information not relevant to that goal fails to capture attention.

Hierarchical representations may serve a similar goal shielding function. By focusing attention only on those task elements that are part of the aggregate task, hierarchical representations could help constrain action selection. While this constraint may not always specify the particular order in which task elements that are part of that hierarchy would be performed, it would limit the number of options from which to choose. For example, when performing the aggregate task make spaghetti the environment in which one would perform this task (i.e. the kitchen) is likely to contain stimuli which afford this and many other tasks. As stimuli have the ability to automatically activate the tasks that they afford (Logan, 1988) simply entering the environment could lead to the activation of a number of potential tasks that would compete with the making spaghetti goal for performance. If this goal were not being

represented hierarchically then one would need to overcome this competition each time they switched tasks (e.g. when switching to the boil noodles task and again when switching to the make sauce task). Representing making spaghetti within a hierarchical task structure could help to reduce this competition by focusing attention on only those tasks elements that are part of the aggregate task goal. Thus, one would still need to decide whether their first task should be to boil noodles or make sauce, but task elements that fall outside of the aggregate task, such as load the dishwasher or eat a banana, would not be in direct competition. This reduced competition would help to reduce the time associated with choosing a new task (Arrington & Logan, 2005). Thus, rather than a product of the need to remember task order in situations in which tasks must be performed in a specified sequence, hierarchical representations may serve as a functional mechanism that aids in task selection within situations in which task order is unconstrained. If hierarchical representations serve this goal shielding function, then the benefit they have the potential to provide to task selection will sometimes become a cost, such as when required to move between the performance of task elements that belong to different aggregate tasks. This would make hierarchical representations similar to other cognitive mechanisms that serve to automate action performance; at times executive control will be required to overcome the more automatic cognitive process and ensure appropriate task performance (Dreisbach & Haider, 2008; Norman & Shallice, 1986).

Hierarchical Representations in Voluntary Task Switching

A hierarchical representation is a representation made up of components and nested subcomponents, where the structure of the components influences the

subcomponent level (Schneider & Logan, 2006). Previous research on aggregate level hierarchical task representations has been constrained to the study of task ensembles. Within a task ensemble the order in which task elements must be performed is constrained. The current study will attempt to demonstrate that other types of aggregate tasks also exist. Specifically, using the voluntary task switching paradigm, the current study will assess whether hierarchical representations of aggregate tasks can be more abstract, such that the task elements that make up an aggregate task can be maintained independent of any specific serial order that would constrain task choice.

Use of the voluntary task switching paradigm within the current study will also allow for a new assessment of the formation of hierarchical representations.

Previously, the influence that components have on the subcomponent level has been assessed only in measures of performance. Specifically, within a non-voluntary task switching paradigm evidence of the presence of a hierarchical representation could only be assessed by examining whether or not the existence of an aggregate task level, changed the speed or accuracy with which the task elements that were part of that aggregate task were performed. When assessing the existence of hierarchical representations within a voluntary task switching environment it is possible to examine potential changes in both task performance and task selection.

The use of the voluntary task switching paradigm in the current study allows for an assessment of the formation of hierarchical representations using both choice and performance measures. If hierarchical representations are found in voluntary task switching, then they may exert separate influences on task choice and performance.

Indeed, task selection and task performance processes appear to be somewhat dissociated. Within voluntary task switching, correlations between performance measures such as switch costs and task choice measures such as the probability of switching are quite small (Arrington & Yates, 2009; Mayr & Bell, 2006). Further, using the Attention Networks Test (Fan, McCandliss, Sommer, Raz, & Posner, 2002) Arrington and Yates (2009) found that selection and performance measures in voluntary task switching were associated with different attentional networks. Additionally, manipulations which influence voluntary task switching performance do not necessarily influence choice measures (Arrington & Weaver, in revision; Butler, Arrington, & Weywadt, 2011). These discrepancies demonstrate the dissociation between the processes involved in the selection and performance of actions.

This dissociation between the processes that guide task choice and the processes that guide task performance mirrors the division of processes proposed in several models of task switching. Task switching has repeatedly been conceptualized as a two-step process. For example, Allport and Wylie (2000) distinguish between “goal setting” which determines which task is performed and “performance readiness” which determines how quickly that task is able to be performed. A similar distinction between “goal shifting” and “rule activation” has been made by Rubinstein et al. (2001) and between “task level” and “parameter level” representations by Logan and Gordon (2001). Within the voluntary task switching paradigm factors which influence the first, goal setting step would be expected to influence task choice and performance speed, while

those that influence the second, performance readiness step should only influence task performance.

Previous research has demonstrated that hierarchical representations affect performance (Dreisbach et al., 2007; Schneider & Logan, 2006). As a result hierarchical representations are expected to influence task performance within the current study. If actions are being represented hierarchically, then the cost of switching between task elements that are part of the same aggregate task should be less than the cost associated with switching between task elements that belong to different aggregate tasks. As choice measures have not previously been assessed, it is unclear whether or not hierarchical representation will have an influence on choice. Nevertheless, there is reason to expect that hierarchical representations will affect choice as well as performance. Schneider proposed that hierarchical representations act on the first goal setting stage of task switching. Since this is the stage which determines task choice, a factor that influences this stage is likely to influence task choice. In his proposal, Schneider suggested that hierarchical representations exert their influence on this goal setting stage of by making the entire aggregate task, including all task elements, available at once, which he proposed reduced the time required to complete this stage of task switching. Indeed, Lien and Ruthruff (2004) found that the cost of switching into an ensemble increased as the complexity of that ensemble increased, suggesting that selection of a task ensemble may occur as a whole. If selecting one task element that is part of an aggregate task requires selection of the entire hierarchical representation, then all of the task elements within an aggregate task would be expected to be initially reselected on the following trial. As a

result participants would be expected to be more likely to switch between task elements that are part of that same aggregate task than to switch between task elements that are part of different hierarchical representations. This expected influence of hierarchical representations on task choice is consistent with hierarchical representation's proposed purpose of aiding in the organization and selection of actions by shielding against information that is irrelevant to the current goal (Dreisbach & Haider, 2008; 2009). Specifically, hierarchical representations may focus attention on task elements that are part of the current aggregate task in order to ensure that all of the task elements that make up that aggregate task are completed. If this is indeed the function of hierarchical representations, then this bias would be expected within the current voluntary task switching study, despite the voluntary task switching instructions to perform all task elements equally often and in a random order. When performing tasks within the current free choice multitasking environment, hierarchical representations are expected to influence action selection by making participants more likely to choose to perform tasks that are part of the same hierarchical representation as the task performed most recently.

Experiment 1: Hierarchical Representations in Voluntary Task Switching

The current study explores the effect of aggregate tasks, or hierarchically organized tasks that include multiple task elements, on action selection during voluntary task switching. Previous research has found evidence for the existence of hierarchical representations in multitasking environments. The present work extends these findings by assessing whether or not and under what circumstances such hierarchical structures are adopted within the free choice multitasking environment created by the voluntary task

switching paradigm.

Experiment 1 included four conditions, a control condition and three hierarchical conditions. As hierarchical representations have not previously been induced within a free choice multitasking environment, three manipulations of increasing complexity were employed in order to ascertain the conditions in which hierarchical representations are utilized (See Table 1).

Previously, hierarchical representations have been elicited via explicit instructions (Schneider, 2007) and via spatial and temporal stimulus manipulations (Lien & Ruthruff, 2004; Tlauka & McKenna, 2000). The hierarchical conditions in the current study used these three design features to introduce the task elements in a hierarchical manner. Using a cover story described in detail below, participants were explicitly told that the first two task elements they practiced were part of one aggregate task and that the second two task elements were part of another. Participants practiced task elements that were part of the same aggregate task in the same spatial location on the screen and practice blocks were temporally grouped according to aggregate task. This hierarchical introduction was in direct contrast to that used in the control condition, in which each task element was referred to as an individual task, was practiced in a separate spatial location, and was introduced as part of a continual temporal sequence.

All manipulations in the introduction condition took place only during the practice phase of the study. The additional two hierarchical conditions supplemented these introduction manipulations with manipulations that were continued within the multitasking portion of the experiment. In the after effect condition, the performance of

each task element was followed by an after effect (i.e. the stimulus moved horizontally to the right or left until it exited the screen), with the specific effect that occurred being determined by the aggregate task that was performed. As these after effects occurred during both the practice and multitasking portions of the study, they reminded participants of the hierarchical task structure throughout the experiment. The final hierarchical condition, the forced choice condition, went beyond reminding participants of the hierarchical structure by requiring maintenance of this structure throughout the experimental session. On a randomly selected 10% of trials the stimulus appeared in one of the locations in which the aggregate tasks had been practiced. On these forced choice trials, participants were required to choose to perform one of the task elements that made up the associated aggregate task. Successful completion of these forced choice trials required that participants establish and maintain aggregate task-level groupings. Because subjects could not predict when a forced choice trial would occur, aggregate task-level groupings had to be maintained throughout the study with the forced choice condition.

Arrington, Altmann, and Carr (2003) found that the time required to switch between similar tasks is less than that required to switch between dissimilar tasks. Therefore, aggregate tasks that are made up of similar task elements may appear to be represented hierarchically simply because of this similarity. To avoid this potential confound in the current study, the specific task elements that made up each aggregate task were counterbalanced between participants. For example, if the task elements A and B belonged to the first aggregate task for one participant, then a different participant would experience task elements A and C as part of the first aggregate task. Thus, any

effects of the properties of the individual task elements or their combinations were controlled for.

Naturally, occurring aggregate tasks are often made up of task elements that are more similar to each other than task elements that are part of different hierarchies. By controlling for potential similarities between task elements, the current experiment provides a stringent test of whether or not hierarchical representations can be formed within free choice multitasking environments. It also prevents the current results from being influenced by any preexisting impressions of similarity participants may have based on previous experience with a particular hierarchy. Thus, if hierarchical task representations can be found to guide task choice in the current study, then hierarchical representations in which the connection between task elements is more inherently apparent, would also be expected to influence action selection. Nevertheless, the somewhat arbitrary nature of the pairings used in the current study is not unlike some hierarchies found outside of the laboratory. For example, Lien and Ruthruff (2008) describe how hierarchies can come to exist between seemingly arbitrary or unrelated activities simply because they happen to be in the same location. If one's dry cleaner is in the same shopping center as their post office, while their gas station is in a different location, then that person may come to group going to the dry cleaner and going to the grocery store into one larger "running errands" aggregate task that would not include getting gas. The activities are grouped, not because picking up dry cleaning is more similar to getting groceries than to getting gas, but simply because these two activities have something in common with each other that they do not have in common with getting

gas, they share a geographic location. Thus one similarity can be enough to generate a hierarchical representation. In the current study, manipulations, which will be described in detail below, were used to indicate a commonality between the randomly paired task elements.

In order to assess whether hierarchical representations were adopted in the current study, analyses focused on two potential aggregate structure influences. First building on the previous literature reviewed above, the RT measure of task performance was used to assess the formation of hierarchical representations via an influence on performance. If participants were representing task elements hierarchically, the speed with which participants switched between task elements that were part of the same aggregate task (within-aggregate task switches) should be faster than the speed with which participants switched between task elements that were part of different aggregate tasks (between-aggregate task switches). However, if hierarchical representations were not established then all task switches should be performed at similar speeds regardless of the aggregate task to which the task elements belonged. The control condition provided a baseline switch speed to which the hierarchical conditions could be compared. Second, the use of the voluntary task switching paradigm allowed for an assessment of the formation of hierarchical representations via an influence on task choice. The proportions of within-aggregate task switches and between-aggregate task switches were compared. If task elements were being represented hierarchically then a greater proportion of within-aggregate task switches than between-aggregate task switches was expected.

Methods

Participants.

Sixteen Lehigh University undergraduates participated in each condition (for a total of 64 participants) in exchange for partial course credit or for \$10. All reported normal or corrected-to-normal vision.

Apparatus and stimuli.

The experiment was administered on a Dell Dimension computer running the E-prime 1.1 software package. Stimuli were a series of shapes that varied on four dimensions. Stimuli were either short or long, round or rectangular, solid or outlined, and oriented vertically or horizontally (see Figure 1). Short stimuli were two cm high and one cm wide when vertically oriented. Long stimuli were three and a quarter cm high and one cm wide when vertically oriented. Stimuli were black and appeared on a light gray background. During single task practice blocks, stimulus location varied by condition. In the control condition, stimuli for each of the four tasks appeared in separate quadrants of the screen, such that stimuli for the first task element appeared five cm to the left and five cm above the center of the screen, stimuli for the second task appeared five cm to the left and five cm below center, and stimuli for the third and fourth tasks appeared in corresponding top and bottom positions on the right side of the screen. In the hierarchical conditions stimuli were centered vertically on the screen with stimuli for the first aggregate task presented five cm to the left of the center of the screen and stimuli for the second aggregate task presented five cm to the right of center. During the multitasking practice block and all experimental blocks, all stimuli appeared in the center

of the screen in all conditions, with the exception that stimuli in the forced choice condition appeared either five cm to the left or right of the screen's center on forced choice trials. Responses were mapped to the *a, s, d, f, j, k, l* and ; keys of a standard QWERTY keyboard. The two responses for each task were mapped to corresponding fingers of each hand. Specific S-R mappings were counterbalanced with the constraint that task elements belonging to the same aggregate task were always mapped to contiguous fingers.

Procedure.

At the start of the experimental session participants were told that they would be playing the role of a quality control officer for a production plant. The computer would output symbols that represented products and their job was to assess the quality of those products by classifying the associated symbols. Throughout the study each of the classification tasks the participants performed were referred to as quality measures the participants should monitor. Four classification tasks, corresponding to the four dimensions of stimulus variation were employed. The size quality measure required judging the stimulus as short or long, the shape quality measure required judging the stimulus as round or rectangular, the fill quality measure required judging the stimulus as solid or outlined, and the orientation quality measure required judging the stimulus as oriented vertically or horizontally. The order in which the tasks were introduced was randomized, such that there was a random pairing of the specific categorization tasks that made up each "quality control" aggregate.

All participants were told that they would begin by monitoring a quality measure for production line A. They were then introduced to and practiced performing the first task element within a 20-trial practice block. Participants were then introduced to and performed a 20-trial practice block for each of the remaining three task elements. The labeling whereby these elements were introduced varied by condition. In the control condition each task element was introduced as being a quality measure for a different production line, such that participants monitored production lines A, B, C, and D in sequence. In the hierarchical conditions the second task element was introduced as a second quality measure for production line A and the third and fourth task elements were introduced as being quality measures for production line B. The spatial locations that task elements were practiced in also varied by condition. In the control condition, the stimuli on which participants practiced each task element appeared in a different location of the screen, such that participants practiced monitoring line A in the top-left location, line B in the bottom-left location, line C in the top-right location, and line D in the bottom-right location. In the hierarchical conditions, stimuli appeared in the left position when monitoring line A (i.e. five cm to the left of the center of the screen) and in the right position when monitoring line B. A temporal grouping manipulation was also employed. In the control condition, participants received instructions for the next task element directly after finishing the practice block for the previous task element. In the hierarchical condition, task elements that belonged to the same aggregate tasks were temporally grouped. After practicing the task elements that belonged to the same production line participants were presented with a reminder screen displaying the S-R

mappings for those task elements and were asked to take a minute to review the keys for that production line. The S-R mappings remained on the screen until participants indicated they wanted to move on. This screen created a temporal gap between learning of the two task elements that made up each aggregate task.

After performing the four individual task practice blocks, all participants received multitasking instructions. Participants were asked to choose the specific task element to be performed on any given trial, but were instructed to attempt to perform each task element equally often and in a random order. Participants performed this procedure in a final 20-trial practice block before completing 16 64-trial experimental blocks. On each trial a randomly-selected stimulus was presented and remained on the screen until a response was made. On all trials within the control, introduction, after effect conditions and on 90% of trials in the forced choice condition, the stimulus appeared in the center of the screen and participants chose to perform any one of the four task elements on that stimulus. A 500-ms RSI displaying a fixation cross in the center of the screen separated each trial.

An after effect manipulation was implemented within the after effect and forced choice conditions. During the RSI the stimulus moved horizontally from its position in the center of the screen to the right or left until it appeared to move off the screen. The direction that the stimulus moved depended on the specific task element that had been performed. If the task element was part of the first aggregate task (Line A), then the stimulus moved to the left; if it was part of the second aggregate task (Line B), then the stimulus moved to the right.

The forced choice condition contained a small number of forced choice trials. On five percent of trials in this condition the stimulus appeared on the left side of the screen and on five percent of trials the stimulus appeared on the right side of the screen. A fixation cross marked the center of the screen on these trials. Participants were instructed that when the stimulus appeared in one of these locations they should choose to monitor one of the two measures for that production line (i.e. one of the Line A measures when the stimulus appeared on the left and one of the Line B measures when the stimulus appeared on the right). On these forced choice trials only responses associated with one of the appropriate task elements would advance the participant to the next trial.

Results

Voluntary task switching trials were sorted into tasks based on response and into task transitions based on the tasks performed on trial n and trial $n-1$. Data from four participants in the control condition, two participants from the introduction condition and two participants in the after effect condition were removed because their accuracy fell below 90%. The first trial of each block, error trials, and trials following an error were excluded from the RT and choice analyses (8.3% of trials), as transitions could not be coded for these trials. Within the forced choice condition, forced choice trials and trials following forced choice trial were also excluded from analysis (19.5% of forced choice condition trials, 5.4% of total trials). Trials with RTs two standard deviations above a participant's mean RT were trimmed, resulting in a loss of 3.7% of trials. In order to ensure reliable data, a participant's data was excluded from the RT and choice analyses if

they could not contribute at least 20 data points to each cell within the RT analysis¹. As a result these analyses included 12 participants in the control condition, 13 participants in the introduction condition, 14 participants in the after effect condition and 14 participants in the forced choice condition.

In order to directly compare the types of transitions made in the control condition to the transitions made within the hierarchical conditions, the first two task elements and last two task elements introduced to participants in the control condition were coded as being part of the same aggregate task. The aggregate task structure of this experiment created three types of transitions. On each trial participants could repeat the task element performed on the previous trial (repetition), switch to the other task element that belonged the same aggregate task as the task performed on the previous trial (within-aggregate switch) or switch to one of the two task elements that belonged to the aggregate task not performed on the previous trial (between-aggregate switch). If participants switched evenly between all four tasks as instructed, then one fourth of transitions would be repetitions, one fourth would be within-aggregate switches, and one half would be between-aggregate switches (one fourth to each of the two between task elements). In order to directly compare switch probability across transition type, each

¹ Data from one participant in the introduction condition and two participants in the forced choice condition were excluded from the RT and choice analyses because they did not contribute a sufficient number of data points to each cell in the analyses. If transitions were made with the expected frequency, subjects should contribute at least 256 data points to each cell in the design. In previous research using the voluntary task switching paradigm, participants who do not perform each type of transition on at least ten percent of trials have been excluded from analysis. The requirement to produce at least 20 of the 256 possible instances of any type of transition was chosen in order to create a criterion that was slightly more conservative than the ten percent required in the literature. A failure to contribute at least 20 data points to any cell indicates that the participant did not select tasks in a random order as instructed.

participants' mean between-aggregate switch probability was divided by two prior to being submitted to analysis.

Response time.

RT was assessed as one measure for determining under what conditions hierarchical representations are found during free choice multitasking environments. If the four task elements performed during the multitasking phase are being represented as two aggregate tasks, then based on previous task ensemble research regarding how hierarchical representations affect task element performance, within-aggregate task switches should take less time than between-aggregate task switches. In order to test this hypothesis, RT was assessed as a function of transition and condition. Mean RTs are displayed in Figure 2. An inspection of Figure 2 reveals that responses in the forced choice condition, which had the longest RTs of all of the conditions, were performed significantly more slowly than responses in the after effect condition, which had the shortest RTs. No other differences in response speed by condition reached significance. As expected based on previous task switching literature, repetitions were performed more quickly than either type of switch across all conditions. Of primary interest was the comparison between within-aggregate and between-aggregate switches. Within-aggregate and between-aggregate switches were performed at similar speeds in the control, introduction and after effect conditions. However, within-aggregate switches were performed more quickly than between-aggregate switches in the forced choice condition suggesting the presence of a hierarchical representation within that condition. These observations were supported by a 3(transition: repetition, within-aggregate switch,

between-aggregate switch) x 4(condition: control, introduction, after effect, forced choice) analysis of variance (ANOVA) with transition as a within-subject factor and condition as a between-subject factor. The analysis found a main effect of transition, $F(2,48)=40.96, p<.001, \eta_p^2=.63$, and a main effect of condition, $F(3,49)=2.88, p<.05, \eta_p^2=.15$. These effects were qualified by a significant transition x condition interaction, $F(6,98)=2.29, p<.05, \eta_p^2=.12$. Planned contrasts comparing within-aggregate and between-aggregate switches in each condition found a significant difference only in the forced choice condition, $F(1,13)=8.33, p<.05, \eta_p^2=0.39$. No differences in the speed of within-aggregate and between-aggregate switches were found in the control condition, $F(1,10)=0.31, p=.59$, the introduction condition, $F(1,12)=1.11, p=.31$, or the after effect condition, $F(1,13)=0.042, p=.84$.

Task choice.

Next task choice was assessed as a second measure for examining whether hierarchical representations were established within the current free choice multitasking environment. Figure 3 displays the proportion of transitions as a function of transition and condition. If hierarchical representations that influence action selection were induced in the current experiment, then subjects would be expected to make a greater number of within-aggregate switches than between-aggregate switches. Inspection of Figure 3 indicates that the probability of within-aggregate and between-aggregate switches appears to vary as a function of condition. No differences between within-aggregate and between-aggregate switch probabilities were found in the control or introduction conditions; however, the predicated increased proportion of within-aggregate relative to

between-aggregate switches was found in the after effect and forced choice conditions. In order to statistically verify these observations, analyses of task choice focused on the proportion of each type of switch performed in each condition. The analysis used to assess hierarchical representations in RT (i.e. a 3(transition) x 4(condition) RM-ANOVA) would be an inappropriate measure of task choice due to the interdependence of the proportion of repetitions, within-aggregate switches and between-aggregate switches performed in each condition. In order to assess task choice, the proportion of total switches (i.e. within-aggregate switches and between-aggregate switches but not repetitions) that were within-aggregate switches was calculated for each condition. If subjects were switching between all tasks in a random order as instructed then one-third of their total switches should have been within-aggregate switches and two-thirds of their total switches should have been between-aggregate switches. A series of one-sample t-tests comparing the proportion of within-aggregate switches in each condition to the expected value of one-third confirmed that the proportion of total switches that were within-aggregate switches did not differ from one-third in the control condition ($M=0.34$), $t(11)=0.36$, $p<.72$ or the introduction condition ($M=0.34$), $t(12)=0.62$, $p<.54$. This comparison was significant in both the after effect condition ($M=0.38$), $t(13)=2.64$, $p<.05$, and the forced choice condition ($M=0.39$), $t(13)=3.08$, $p<.01$. The proportion of total switches that were within-aggregate switches did not vary as a function of condition, $F(3,49)=1.95$, $p=.13$.

Inspection of this Figure 3 also reveals that the repetition bias reported in previous voluntary task switching studies was present in this data, such that the probability of

performing task repetition was high, regardless of condition. The presences of this bias was confirmed by a series of one sample t-tests comparing the proportion of repetitions performed to the proportion of repetitions expected if subjects were switching between all four tasks in a random order as instructed (.25). Significant differences from the standard were found in the control condition ($M=.40$), $t(11)=2.78$, $p<.05$, the introduction condition($M=.39$), $t(12)=2.10$, $p<.05$, the after effect condition ($M=.49$), $t(13)=4.02$, $p<.01$, and the forced choice condition ($M=.40$), $t(13)=2.96$, $p<.01$. The large repetition biases seen in the current study are not surprising as the proportion of repetitions performed tends to increase with increased working memory loads (Demagnet et al., 2010). The need to retain the S-R rules for the large number of tasks in this study likely served to tax working memory thereby increasing the likelihood that subjects would repeat the task performed on the previous trial.

Additional analyses.

Accuracy was high ($M=96.3\%$) and did not vary by condition, $F(3,159)=1.68$, $p=0.17$. Accuracy data were not analyzed as a function of transition due to the difficulty associated with attempting to infer the specific task element participants attempted to perform on error trials. Previous voluntary task switching studies, in which participants performed the responses associated with each task on a single hand, have coded errors under the assumption that participants choose the correct hand (or task) but incorrect finger on error trials (Arrington & Logan, 2004). In the current study, in which the two responses for each task were mapped to corresponding fingers of different hands, it is difficult to determine whether participants intended to perform the task mapped to the

finger used for that response (e.g. index finger) but incorrectly selected the specific finger (i.e. left instead of right) that was appropriate for the current stimulus or selected the correct hand for the intended task but pressing the wrong digit (e.g. left index finger instead of left middle finger). Thus performance analyses were limited to measures of RT.

The specific categorization tasks assigned to each aggregate-task and the specific order in which participants were introduced to each task was randomized and therefore was not likely to vary as a function of condition. This assumption was verified in a series of ANOVAs on RT and choice as a function of categorization task and task order. The associated means and F values are reported in the appendix. Differences by categorization task were small, inconsistent and did not vary by condition. Analysis of task order produced no significant differences. These analyses confirm that the RT and task choice findings reported above were not likely to be a byproduct of the specific categorization task pairings or task order utilized in each condition.

Discussion

Experiment 1 assessed whether hierarchical representations could be found within a free choice multitasking environment by looking for an influence of the aggregate task structure on task performance and task choice. Support for the formation of hierarchical representations was found. Participants in the forced choice condition displayed longer RTs when switching between aggregate tasks than when switching within aggregate tasks. Further, participants in both the forced choice and after effect conditions showed a tendency to make a greater proportion of within-aggregate task switches than expected by

chance. Nevertheless, this result must be interpreted with caution as proportion of switches that were within-aggregate in these conditions did not vary from that found in the control condition.

Aggregate task influences were found in both the RT and choice measures in the forced choice condition. Interestingly, an effect on choice but not RT was found in the after effect condition. While within-aggregate and between-aggregate switches were made at similar speeds in this condition, a slightly greater proportion of within-aggregate than between-aggregate switches were performed. Previous task switching studies have demonstrated the presence of aggregate task representations via changes in response speed (e.g. Lien & Ruthruff, 2004). Task choice had not previously been assessed within a hierarchical task environment. It was therefore unclear whether hierarchical representations would influence choice. The current results suggest that not only is task choice influenced by hierarchical representations but that measures of choice may actually be more sensitive to the formation of hierarchical representations than performance measures. This increased sensitivity may be indicative of the role that hierarchical representations may play in action selection. If as asserted above, one function of hierarchical representations is to guide action selection by shielding the currently selected aggregate task from interference associated with other potential tasks it would be expected that evidence of this shielding may be especially likely to manifest itself in a measure of choice.

The strongest evidence for the formation of a hierarchical representation was found in the forced choice condition, where existence of the hierarchical task structure

was evident in both choice and performance measures. On ten percent of trials in the forced choice condition participants were required to choose only from tasks that were part of a specified aggregate task. Successful performance of these forced choice trials mandated that participants remember aggregate task pairings. These forced choice trials were intended to encourage the formation of a hierarchical representation by ensuring that subjects maintained and attended to the specific task elements that belonged to each aggregate task. The manipulation appears to have been successful in establishing a persistent hierarchical representation that influenced performance throughout the multitasking portion of the experiment. As is evident in Figure 4 the influence of the hierarchical representation was not any stronger directly following the performance of a forced choice trial. In fact a t-test comparing the proportion of between-aggregate switches performed on trials which directly followed forced choice trials ($M=0.39$) to the proportion of between-aggregate switches performed on trials which did not follow a forced choice trial ($M=0.38$), found no significant difference in the type of transitions that were likely to be performed on the trial following a forced choice trial, $t(13)=0.50$, $p=0.62$. Thus forced choice trials appear to have aided in the creation of a hierarchical representation which influenced performance throughout the experiment rather than simply increasing the speed or proportion of within-aggregate switches performed directly following a forced choice trial.

No evidence of a hierarchical representation was found in the introduction condition. This result is somewhat surprising given the apparent inclination to adopt hierarchical representations found in previous task switching studies (Altmann, 2007;

Schneider, 2007). The introduction condition utilized three hierarchical manipulations previously found to induce hierarchical representations (e.g Schneider, 2007; Lien & Ruthruff, 2004), including explicit experimenter suggestion. However, even experimenter expectation was not effective in inducing behavior representative of a hierarchical representation. Why were the manipulations used in the introduction condition unsuccessful in inducing a hierarchical representation in the current study? Two possible explanations of the failure for hierarchical representations to be induced in the introduction condition are considered. First, the strong hierarchical representation found in the forced choice condition may have resulted from the need for participants to perform forced choice trials. On ten percent of trials in the forced choice condition participants were required to choose only from tasks that were part of a specified aggregate task. Successful performance of these forced choice trials mandated that participants remember aggregate task pairings. None of the other conditions within Experiment 1 required this explicit maintenance of aggregate task structure, so this requirement may have ensured that a hierarchical representation established during the instruction phase was maintained in the forced choice condition. Hierarchical representations may only be maintained in situations where memory of aggregate task structure is required, such as those involving maintenance of an ordered task ensemble (Schneider & Logan, 2006). RTs in the forced choice condition were longer than those found in the other conditions suggesting that representing a collection of task elements within hierarchical task structures may hinder performance, perhaps by increasing WM load. Hierarchical representations which both slow and speed responding have been

found previously (Dreisbach et al., 2007). If hierarchical task structures reduce the speed with which task elements can be performed within the current free choice environment, then participants may be unwilling to maintain such structures unless they are required. Further, prior to the multitasking portion of the experiment subjects received instructions to attempt to perform each of the task elements equally and in a random order. Subjects may have avoided representing tasks hierarchically in the current context in order to ensure better compliance with these instructions. So even if a hierarchical representation had been induced via the introduction manipulations that occurred during practice, this representation would have been abandoned once multitasking performance began, as maintenance of this structure was not required by the multitasking portion of the experiment in these conditions.

Alternatively, strong hierarchical representations may have been found within the forced choice condition of Experiment 1 because this was the only condition that was successfully able to establish such a representation. The introduction condition attempted to induce a hierarchical representation by using manipulations that have previously proven effective in creating a hierarchical structure within a non-voluntary task switching paradigm. However, unlike in previous studies where these manipulations occurred throughout the experimental session (Altman, 2007; Schneider, 2007), in the current study all of these manipulations occurred during the practice phase of the experiment, in which participants were also required to memorize S-R mappings for four different task elements. At this time participants' primary goal was learning to perform the individual task elements. This taxing goal may have prevented them from learning aggregate task

structures at this time. Thus the formation of hierarchical task structures may be similar to the acquiring of a new skill. Before one can learn complex behaviors, the basic actions that compose these behaviors must be well learned (Rosenbaum, Cohen, Jax, Weiss, & van der Wel, 2007). Likewise, aggregate tasks may not be created until the task elements that would make up the aggregate task have been firmly established. If so then the failure of the introduction condition to induce a hierarchical representation would be unsurprising. Formation of such a representation would require that aggregate task manipulations occur following the learning of task elements. Both the after effect condition and the forced choice condition meet this requirement; however, the forced choice condition meets it more strongly. While the after effect condition includes an aggregate task manipulation throughout the multitasking portion of the experiment, it does not require that participants attend to this manipulation. This would explain why the after effect condition did not establish as strong a hierarchical representation as that found in the forced choice condition, which required that participants attend to and remember the hierarchical task structure during the multitasking portion of the study.

Experiment 2: The Persistence of Hierarchical Representations

Experiment 1 was successful in finding conditions in which hierarchical task representations could be induced within a free choice multitasking environment. Experiment 2 assessed the stability of such hierarchical representations. Are hierarchical representations maintained only in those situations where they are explicitly required for performance, or is it the case that once established, a hierarchical representation will continue to influence performance in situations where it remains applicable, regardless of

whether or not it is strictly required? Understanding under what conditions hierarchical representations are maintained could provide insight into the potential role of these representations. A hierarchical representation that is quickly established when needed then quickly abandoned when it is no longer required would be able to serve as a flexible mechanism of executive control that could be implemented strategically as needed (Logan & Crump, 2011). Conversely, a hierarchical representation that becomes firmly established with use is likely to be maintained, and in time come to be automatically implemented, when cued by the appropriate context (Logan, 1988). Such a representation would be able to serve as a means for increasing behavioral stability without depleting cognitive resources (Bargh & Chartrand, 1999).

In order to address the question of whether influences of hierarchical representations will be maintained in situations where they are not strictly required, the forced choice manipulation of Experiment 1 was used within the first half of Experiment 2. The participants were informed that the last half of the experiment would not contain any forced choice trials. This allowed performance and choice measures in the first half of the study, in which a hierarchical representation was required to be compared to performance and choice measures in the last half of the study, where it was not.

Methods

Participants.

Sixteen Lehigh University undergraduates participated in Experiment 2 in exchange for partial course credit. All reported normal or corrected-to-normal vision and none had participated in Experiment 1.

Apparatus, stimuli and procedure.

The apparatus and stimuli were the same as those used in the forced choice condition of Experiment 1. The procedure was also highly similar to that used in the forced choice condition. As in Experiment 1, the stimuli were introduced in a hierarchical manner during the practice phase. Participants were once again informed that they would be working as quality control officers whose job would be to assess quality by classifying symbols that represented products from different production lines. As in the forced choice condition of Experiment 1, the first two tasks were said to be from Production Line A while the second two tasks were said to be from Production Line B. Spatial and temporal manipulations occurred during the practice phase of the experiment and after effects occurred during both the practice and multitasking portion of the study. As in Experiment 1, the multitasking portion of the study consisted of 16, 64-trial blocks. The first half of the experiment included forced choice trials, in which the stimulus appeared either five cm to the right or left of the center of the screen and participants were required to perform one of the two task elements that belonged to the aggregate task which had been associated with that side of the screen during practice. Forced choice trials occurred on a randomly selected ten percent of trials during the first half of the experiment. After completing eight experimental blocks, the experimenter informed the participant that during the remainder of the experiment stimuli would always appear in the center of the screen and they would be able to choose between all four of the task elements on each trial. No forced choice trials appeared during the subsequent eight experimental blocks. After effects occurred throughout both halves of the experiment.

Results

Voluntary task switching trials were sorted into tasks based on response and into task transitions based on the tasks performed on trial n and trial $n-1$. Data from two participants whose accuracy fell below 90% were removed from analysis. Forced choice trials and trials following forced choice trials were not analyzed (9.8% of total trials). The first trial of each block, error trials, and trials following an error were excluded from the RT and choice analyses (12.5% of trials). Trials with RTs two standard deviations above a participant's mean RT were trimmed, resulting in a loss of 2.3% of trials. Data from one participant was excluded from the RT and task choice analyses because they could not contribute at least 20 data points to each cell within the RT the RT analysis. As a result these analyses included 13 participants.

Figure 5 displays mean RTs and mean proportion of transitions as a function of switch type and block. Inspection of this figure reveals that differences in the performance speed of within-aggregate switches relative to between aggregate switches as a function of block were minimal. A similar lack of variation in the proportion of within-aggregate relative to between-aggregate switches performed across blocks is evident. However, the large number of blocks in the current experiment, combined with the small amount of subjects that contributed to each block², prevents an analysis by block from being highly informative. It is likely that such an analysis would not have sufficient power to capture a switch type by block effect even if it were present. Thus,

² When data was dived as a function of block and transition, two participants were found to have not performed all three types of transitions in every block. Thus an analysis which included block would only be able to include 11 participants.

the analyses within the current study will compare response speed and task choice as a function of experiment half.

Response time.

RT was assessed as a measure of the maintenance of hierarchical representations during each half of the study (see Figure 6). Participants showed an expected effect of practice, responding overall more quickly during the second half of the experiment. The extent that RT was reduced with practice was greater for both types of switches (within-aggregate and between-aggregate switches) than it was for repetitions. Also as expected, repetitions were performed more quickly than either type of switch. Surprisingly, within-aggregate switches were found to be faster than between-aggregate switches during the last half of the study but not during the first half. A 3(transition: repetition, within-aggregate switch, between-aggregate switch) x 2(half: first, last) repeated-measure ANOVA confirmed a main effect of transition, $F(2,11)=14.53, p<.01, \eta_p^2=.73$; a main effect of half, $F(1,12)=23.45, p<.001, \eta_p^2=.66$; and a marginally significant transition x half interaction, $F(2,11)=3.24, p<.08, \eta_p^2=.37$. While the pattern of means was in the expected direction, planned contrasts found that RTs for within-aggregate and between-aggregate switches did not significantly differ from each other during the first half of the study, $F(1,12)=2.97, p=.11, \eta_p^2=.20$. Nevertheless, within-aggregate switch RTs were significantly faster than between-aggregate switch RTs during the last half of the experiment, $F(1,12)=4.85, p<.05, \eta_p^2=.29$.

Task choice.

The proportion of transitions as a function of transition and half are displayed in Figure 7. The pattern of transitions replicates that seen within the forced choice condition of Experiment 1 and appears stable in both the first and last half of the study. As in Experiment 1, task choice was assessed by calculating the proportion of total switches that were within-aggregate switches. A paired sample t-test comparing the proportion of within-aggregate switches in the first and last half of the study found no differences across experiment half, $t(12)=0.01, p=.99$. Additionally, one sample t-tests comparing the proportion of total switches that were within-aggregate switches to one-third, confirmed the effect to be significant in the first half of the study ($M=0.41$), $t(12)=2.53, p<.05$ and marginally significant within the last half ($M=0.41$), $t(12)=2.03, p=.06$. After collapsing across half, the proportion of total switches that were within-aggregate switches ($M=0.41$) varied significantly from one-third, $t(12)=2.15, p<.05$, suggesting the presence of a hierarchical representation.

The repetition bias seen in Experiment 1 was also present in the current experiment. The proportion of repetitions performed in the first half of the experiment ($M=0.37$), significantly exceeded the expected value of .25, $t(12)=2.62, p<.05$, while the proportion of repetitions performed in the last half of the experiment ($M=0.36$) showed a marginal difference, $t(12)=1.77, p=.05$.

Additional analyses.

Accuracy was high ($M=96.4\%$) and did not vary by half, $F(1,12)=0.20, p=0.66$. Categorization task and task order were assessed for potential influences on RT and task

choice during each half of the study (see Appendix). As in Experiment 1 differences by categorization task were small and importantly, did not vary as a function of half. No effect of task order was found in any analyses. Thus the aforementioned effects on RT and task choice do not appear to be a byproduct of the specific categorization tasks or task orders used in this experiment.

Discussion

Experiment 2 assessed whether hierarchical representations would be found only in situations in which they were required or whether such representations would continue to influence performance once they had been established, regardless of whether or not they were strictly required. To do this I used the forced choice manipulation from Experiment 1 to establish a hierarchical representation during the first half of the study then removed this manipulation during the second half of the study and examined the effect that the removal of this requirement had on RT and choice. The results were clear, evidence of the maintenance of a hierarchical representation were found in the second half of the study in both the RT and choice measures. It seems that once a hierarchical representation has been established, this representation will continue to influence performance, even when maintenance is not strictly required.

In Experiment 1 the forced choice condition was associated with increased RT compared to conditions in which a hierarchical representation had not been firmly established. This finding led to the speculation that hierarchical representations may place an increased load on WM thereby impairing performance. If hierarchical representations result in impaired performance then participants may seek to improve

performance by only maintaining hierarchical representations in cases where they are strictly required. The results of Experiment 2 speak against this interpretation of Experiment 1. Though participants in both Experiment 2 and the forced choice condition of Experiment 1 experienced the same manipulations, both of which appeared to result in the formation of a hierarchical representation, RTs in Experiment 2 ($M=1201$) were faster than those found in the forced choice condition of Experiment 1 ($M=1488$) and more consistent with those found in the other conditions of that experiment ($M=1171$).

Research directly assessing the potential load incurred by maintenance of a hierarchical representation is desirable; nevertheless, hierarchical representations do not always appear to lead to performance impairments. It is likely then, that the failure to find hierarchical representations in the introduction condition in Experiment 1 was due to a failure to firmly establish a hierarchical representation during the practice portion of this study rather than a failure of an established representation to be maintained during the multitasking portion of the study.

A significant effect of hierarchical representation on RT was found in the last but not first half of the study. This lack of effect was somewhat surprising given that the first half of this experiment was a direct replication of Experiment 1. Maintenance of the aggregate task structure was required during this first half of the study in order to complete the forced choice trials. The result suggests that hierarchical task representations may take time to become fully formed. However, this interpretation should be made with caution as the pattern of RTs during the first half of the study was in the expected direction. In fact the difference in RT between within-aggregate and

between-aggregate switches in the first half of the experiment (68 ms) was numerically larger than the difference between within-aggregate and between-aggregate switches in the last half (56 ms) indicating that the lack of significance may simply be a result of increased variance in the first half of the study. This increased variance is not surprising as the need to exclude forced choice trials and trials following forced choice trials from this half of the study reduced the total number of trials contributing to the analysis. Further, subjects had less experience with the experimental procedure during the first half of the study than during the second half, a condition that is also likely to lead to increased variance. Thus it is likely that hierarchical representations were formed during the first half of Experiment 2, but RT analysis did not have significant power to capture the effect. This reduced power also likely contributes to the size of the effects found in the first half of the experiment which were smaller than those found in Experiment 1. Whereas the forced choice condition of Experiment 1 analyses included 16 blocks of 64 trials, the first half of Experiment 2 included only eight blocks. The lack of power within this experiment is a limitation that seems to have made the data within the entire experiment somewhat unstable. Increasing the power in this study by either increasing the number of participants or the number of trials in this study would be required if the results of each half are to be compared to Experiment 1.

Once again, choice measures appeared more sensitive to the formation of hierarchical representation than performance measures. Despite the reduced power of the first half, choice measures showed a significant effect of hierarchical representation during both the first and last half of the experiment. This finding is consistent with the

increased sensitivity of choice measures to detect hierarchical structure found in Experiment 1, where RT measures showed evidence of a hierarchical task structure only within the forced choice condition but choice measures suggested that a hierarchical structure was present in both the forced choice and after effect conditions. It seems that as a hierarchical structure becomes established, this structure begins affecting choice measures prior to displaying an influence on RT.

Across two experiments, conditions have been found that led to the formation of hierarchical representations within free choice multitasking environments. Within such environments, hierarchical representations appear to exert an influence on both task choice and performance. Once it has been established, this influence appears somewhat sustained despite changes in the requirements to maintain aggregate-task pairings. Now that the ability for hierarchical representations to exert an influence on choice has been found, the next question of interest is by what mechanisms do hierarchical representations exert this influence. One potential mechanism is considered in Experiment 3.

Experiment 3: Are Hierarchical Representations Activated as Wholes?

The goal of Experiment 3 was to begin to uncover the mechanisms by which hierarchical representations exert an influence on task choice and performance during free choice multitasking environments. One potential candidate is that action selection may be affected because hierarchical representations are activated as a whole. Schneider (2007) proposed that adopting hierarchical representations may cause all of the task elements within an aggregate task to be shifted to simultaneously during the goal shifting

stage of task switching (Rubinstein et al., 2001). If all of the task elements within an aggregate task are switched to in unison then switching between these task elements would be facilitated. Such a mechanism would explain the pattern of reduced RT for within-aggregate switches compared to between-aggregate switches found in Experiments 1 and 2. If all of the task elements that belong to an aggregate task are switched to in unison, then the time required to select and perform the first task within a sequence of task elements that are part of the same aggregate task should depend on the number of task elements within that aggregate task. Specifically, the more task elements an aggregate task contains, the more time an aggregate-task switch should take. Indeed Lien and Ruthruff (2004) found that participants took longer to switch to more complicated task ensembles, suggesting that aggregate tasks may indeed be selected as a whole. However, in their study the complexity of each aggregate task was determined by the number of switches within that task ensemble, a measure that would not apply to aggregate tasks in which task order is unconstrained. A more direct assessment of whether all of the task elements within an aggregate task are selected simultaneously is therefore required.

Experiment 3 attempts to determine whether or not hierarchical representations are activated as wholes by comparing the speed of between-aggregate switches for aggregate tasks with differential complexities. If switching to a task element that is part of a hierarchical representation requires activating the entire representation, then switching to the more complicated aggregate task should take more time than switching to the less complicated aggregate task (Logan & Gordon, 2001; Mayr, 2002). In addition,

if the effort of selecting an aggregate task depends on the complexity of that task, then the probability of making between-aggregate task switches may decrease as the complexity of those aggregate tasks increases. Once a complex aggregate task has been activated, maintaining that hierarchical representation over a larger number of trials would be functional. Indeed, Yeung (2010) found that when voluntarily switching between tasks that differed in ease of performance, participants continued to perform the more difficult task once that task set had been established for a greater number of trials than they will continue to perform an easy task. Thus, if the task sets for all task elements within a hierarchical representation are activated in unison then participants should be more likely to switch between task elements that are part of a complex aggregate task than to switch between task elements that are part of a simple aggregate task, even after correcting for the number of available transitions in each condition.

In order to test these hypotheses subjects were introduced to two aggregate tasks of varying complexity. Task complexity was manipulated by varying the number of task elements contained within an aggregate task. The more complex aggregate task was made up of three task elements while the less complex aggregate task consisted of only two task elements. The manipulations used in the forced choice condition of Experiment 1 were used to induce hierarchical representations. Subjects were explicitly informed that they would be monitoring two production lines. During the introduction spatial and temporal manipulations encouraged subjects to distinguish between the quality measures that belonged to each production line. The formation of hierarchical representations was further encouraged by after effects and forced choice trials. Following data collection the

speed and proportion of within-aggregate switches made within the more and less complex aggregate tasks were compared in order to determine whether or not aggregate tasks were being activated as wholes.

Methods

Participants.

Sixteen Lehigh University undergraduates participated in Experiment 3 in exchange for partial course credit. All reported normal or corrected-to-normal vision and none had participated in Experiment 1 or 2.

Apparatus, stimuli and procedure.

The apparatus, stimuli, and procedure for Experiment 3 differed from that used in the forced choice condition of Experiment 1 in the following ways. Participants performed five task elements, three belonging to one aggregate task and two belonging to the other. The specific aggregate task that contained three task elements (line A or line B) was counterbalanced. An extra dimension of variability was added to the stimuli in order to create a fifth classification task. Stimuli were either black or white and a shade quality measure required classification of stimulus color. In order to allow for the performance of five tasks, responses were mapped to the *q*, *w*, *e*, *r*, *v*, *n*, *u*, *i*, *o*, and *p* keys and participants used all ten fingers to respond. As in the previous experiments, the two responses for each task were mapped to the same finger of each hand and S-R mappings were counterbalanced among participants. The manipulations of hierarchy that occurred during the forced choice condition of Experiment 1 were used in the current experiment. During the practice phase subjects were explicitly told which task elements belonged to

which production line. Temporal and spatial separation of the task elements within each aggregate task occurred during practice. Aggregate task-dependent after effects occurred during both the practice and multitasking portion of the experiment and forced choice trials occurred on a randomly selected ten percent of trials during the multitasking portion of the study.

Results

Voluntary task switching trials were sorted into tasks based on response and into task transitions based on the tasks performed on trial n and trial $n-1$. Data from two participants whose accuracy fell below 90% were removed from analysis. Forced choice trials and trials following forced choice trials were not analyzed (19.5% of trials). The first trial of each block, error trials, and trials following an error were excluded from the RT and choice analyses (6.5% of trials). Trials with RTs two standard deviations above a participant's mean RT were trimmed, resulting in a loss of 1.9% of trials. Data from one participant who did not contribute at least 20 data points to each cell within the RT analyses was excluded from the RT and choice analyses, such that 13 participants were included in these analyses.

Response time.

Mean RTs as a function of transition and aggregate task complexity are displayed in Figure 8. If aggregate tasks are accessed as a whole, then it should take more time to make a between-aggregate switch to a more complex aggregate task than to make a between-aggregate switch to a less complex aggregate task. However, between-aggregate switch speed did not vary as a function of aggregate task complexity. In fact

RTs were similar for the more and less complex task across transition type. For both complexities repetition trials were performed more quickly than either switch type. A 3(transition: repetition, within-aggregate switch, between-aggregate switch) x 2(aggregate task complexity: more complex, less complex) repeated-measures ANOVA found a main effect of transition, $F(2,24)=31.55, p<.001, \eta_p^2=.72$. Neither the main effect of aggregate task complexity, $F(1,12)=0.23, p=.64$, nor the interaction reached significance, $F(2,24)=.07, p=.93$. Planned contrasts found no difference between the response speed of between-aggregate switches in the more complex condition and between-aggregate switches in the less complex conditions, $F(1, 12)=0.004, p=.95$.

Task choice.

Figure 9 displays proportion of transitions as a function of aggregate task complexity and transition type. If aggregate tasks are switched to as a whole then it is likely that participants would make a greater number of within-aggregate switches in the more complex condition than in the less complex condition. However, this effect was not found. While the proportion of total switches that were within-aggregate switches performed was greater than expected (0.2) in both the more complex condition ($M=0.29$), $t(12)=6.92, p<.001$, and less complex condition ($M=0.32$), $t(12)=3.65, p<.01$, the extent that the proportion of within-aggregate switches exceeded the proportion of switches expected by chance did not vary based on aggregate task complexity. A paired sample t-test comparing the proportion of total switches that were within-aggregate switches in each condition confirmed the lack of effect, $t(12)=0.82, p=.43$. As in the previous experiments the proportion of repetitions performed exceeded the expected value in both

the less complex condition, ($M=0.32$), $t(12)=3.04$, $p<.01$, and the more complex condition, ($M=0.39$), $t(12)=3.07$, $p<.001$.

Additional analyses.

As in the previous experiments, accuracy was high ($M=96.6\%$) and did not vary as a function of task complexity, $F(1,12)=0.75$, $p=0.40$. Analyses of categorization task and task order can be found in the Appendix.

Discussion

Experiment 3 assessed the hypothesis that when maintaining a hierarchical task structure, aggregate task switches require activating all elements within a given aggregate task. The current study did not find evidence of this mechanism of task activation. Between-aggregate switches for more and less complex aggregate tasks were switched to at similar speeds. Further, the proportion of within-aggregate switches did not vary as a function of aggregate task complexity. These null effects are consistent with the idea that aggregate tasks are not activated as a whole. Nevertheless, such an interpretation may not be warranted by the current data. Experiment 3 compared performance of a two-element aggregate task to that of a three-element aggregate task. This minimal difference in task elements was chosen due to the challenges associated with requiring participants to learn and maintain more than five task elements within one experimental session. Nevertheless, the aggregate task sizes employed may not have been different enough from each other to effectively test the current hypothesis. Indeed general differences in mean RT between the more and less complex aggregate tasks were not found, suggesting that this manipulation may not have been effective. Further experimentation, using

aggregate tasks whose complexities differ from each other to a greater extent than those used in the current study would be desirable.

Nevertheless, a null result may have been found even if larger differences in the task complexity had been created simply because aggregate tasks may operate differently within a free choice environment than in situations where task order is constrained. . Consider how the manipulation of aggregate task complexity used in Experiment 3 differed from that used in previous studies of aggregate tasks. Studies of task ensembles have defined task complexity as the number of switches required within that sequence and have tended to hold the number of tasks required within that sequence constant (Lien & Ruthruff, 2004; Schneider, 2007; Schneider & Logan, 2006). Such a measure of task complexity cannot be manipulated when task order is unconstrained; however, the measure is highly relevant when tasks must be performed in a specified order. Task switches are difficult due to the persisting activation of the task performed on the previous trial (Allport et al., 1994). Preparing for the sequence of task switches to be performed within the task ensemble prior to beginning the first task element would be advantageous, as it would allow for advanced preparation of these difficult task transitions. However, when task order is unspecified, the reason for shifting to all of the task elements that belong to a task ensemble at once is less clear. Doing so may actually impair performance. Indeed, keeping a greater number of tasks active than necessary is likely to reduce the speed with which the current task could be performed (Basak & Verhaeghen, 2011). Thus mechanisms other than the activating of all of the task elements that belong to an aggregate task at once, may better explain the influence of

hierarchical representations on action selection and performance found in the current set of studies.

General Discussion

The current study explored the effect of hierarchical representations of tasks on action selection. The circumstances in which hierarchical representations would be induced and maintained were assessed using the voluntary task switching paradigm. Across three experiments, evidence of hierarchical representations was found under some but not all circumstances. Following manipulations that occurred during the multitasking portion of the study, when participants had successfully learned the S-R mappings associated with each task element, participants were faster to perform within-aggregate task switches than to perform between-aggregate task switches. Participants were also more likely to switch between task elements that were part of the same aggregate task than to switch between task elements that were part of different aggregate tasks, under these conditions. It seems that hierarchical task representations that guide task choice can be established within free choice multitasking environments. Below I consider how the current results can inform on when and how hierarchical representations are formed, how these representations become activated and the function these representations may serve.

The Formation of Hierarchical Representations

Previous research has demonstrated that hierarchical representations are formed when participants are performing multiple tasks in a prespecified order (Schneider & Logan, 2006; 2007). The current study extended this research by demonstrating that hierarchical representations can also be formed within a free choice multitasking

environment in which task selection does not follow a strict serial order. Experiment 1 used three conditions of increasing complexity to attempt to induce a hierarchical representation with the voluntary task switching paradigm. No evidence of hierarchical representations was found in the introduction condition, which included explicit instruction concerning which task elements belonged to which aggregate tasks, and spatial and temporal manipulations designed to introduce task elements in a hierarchical manner. In the after effect condition, which used an aggregate task-level after effect to reinforce the aggregate task structure set up during practice, task choice data but not RT data was suggestive of the establishment of a hierarchical task representation. Only in the forced choice condition, in which participants were required to maintain the aggregate task structure throughout the experiment, was evidence of a hierarchical task representation, in both task choice and performance measures, found. The results of Experiment 2 suggest that it was the ability to establish a hierarchical representation, rather than the requirement to maintain such a representation, that resulted in the hierarchical task structure found in the forced choice condition of Experiment 1. Once a hierarchical representation was established, via the forced choice manipulation in Experiment 2, that representation was maintained throughout the study, even when the requirement to retain aggregate task structure was removed.

That a strong hierarchical representation, able to influence both RT and choice measures, was established in only one of the three hierarchical conditions employed in Experiment 1 was unexpected given the general tendency that participants in previous research have shown toward establishing hierarchical representations. For example, task

ensembles have previously been found to occur simply as a result of the requirement to perform tasks in a prespecified order, a manipulation that was so subtle that experimenters using this type of paradigm have often been unaware that a hierarchical representation may be induced (Altmann, 2007). More direct attempts to establish hierarchical representations, through explicit experimenter suggestion (Schneider, 2007) and spatial and temporal stimulus manipulation (Lien & Ruthruff, 2004) have also proved highly effective. Yet, within Experiment 1 a combination of all three of these manipulations (explicit suggestion, spatial stimulus manipulation, and temporal stimulus manipulation) during the practice phase of the study was ineffective at producing a hierarchical representation.

The results of Experiment 2 suggest that the introduction condition of Experiment 1 failed to effectively establish a hierarchical representation during the practice phase of the study. Indeed, previous studies that have employed these manipulations have done so throughout the entire experimental session, such that measurements of RT suggestive of an aggregate task structure always occurred while the manipulations that induced that structure were taking place (e.g. Lien & Ruthruff, 2004). Experiment 2 demonstrated that hierarchical representations persist after these manipulations have ceased, so long as the hierarchical representation has been sufficiently established. Nevertheless, the establishing of that structure may only take place once the task elements that make up an aggregate task have been successfully learned, except in cases where establishing a hierarchical representation would preclude the requirement to establish more basic behaviors (Barde, Kayser, & D'Esposito, 2010). This finding is consistent with literature

on skill acquisition, which proposes that complex behaviors made of multiple actions will not be acquired until the basic behaviors that will make up these complex actions have been successfully learned (Rosenbaum et al., 2007).

Vallacher and Wegner's (1987) theory of action identification provides a further potential explanation for why manipulations employed during the practice phase were ineffective at creating a hierarchical representation. According to their theory every action can be identified at multiple, hierarchical levels but the specific level at which an action will be identified at any given time will vary according to specific principles. Generally, when both higher-level and lower-level identities are available, there is a tendency for the higher-level to become prepotent. However, higher-level identifications will not always be able to sustain behavior. Lower-level identities will allow one to focus on the more basic features required by a task. As a result lower-level identities will tend to become prepotent when an action cannot be maintained in terms of a higher-level identity. For example when one is first learning to ride a bike she will tend to identify the action at a low level, such as peddling or steering the bike. The low level representation reflects the focus of her action on specific motor movements. Once one becomes skilled at bike riding she is likely to identify the action at a higher level, such as getting exercise or exploring the neighborhood. However, if the path she is traveling was to suddenly become difficult, for example if she encountered a number of potholes, identification would return to a lower-level (e.g. steering around potholes). This theory of action identification suggests that skill level and familiarity with an action will influence how that action is identified, with less skilled actions being identified at lower-levels.

Vallacher and Wegner's (1987) theory of action identification could explain why the manipulations within the introduction condition were ineffective at inducing a hierarchical representation. These manipulations all occurred during the practice portion of the experiment. During this time participants were struggling to learn arbitrary S-R mappings for four new tasks. The need to perform this difficult learning behavior is likely to have caused participants to identify their action at a low level (i.e. at the level of the individual categorization tasks). As a result manipulations that required focus on the higher-level aggregate task structure were likely to have gone unattended. Only after these basic categorization tasks had been learned sufficiently would participants have been able to shift to a higher-level identification and form a hierarchical representation of their actions. These same introduction manipulations may have been effective if the responses required by each task had been less difficult to learn. For example if subjects had made transparent verbal responses to each classification (e.g. saying "short" in response to the size quality measure) the ease with which their responses had been performed may have allowed them to represent their actions at a higher level such that the hierarchical manipulations would have been attended to. An empirical test of this hypothesis would be helpful in determining the specific situations required for the formation of hierarchical representations within a free choice multitasking environment.

Even after the task elements that make up an aggregate task have been learned, the influence of hierarchical representations appears to occur in a somewhat gradual manner. Within Experiment 1 evidence of a hierarchical representation was found in the forced choice condition within both measures of RT and measures of task choice.

However, within the after effect condition the effect was only found within task choice measures suggesting that the hierarchical representation had been less firmly established within this condition. It seems that choice measures were more sensitive to hierarchical task formation. The specific mechanisms that lead to an influence of hierarchical representations on choice prior to their influence on performance are considered in the next section.

The graded influence of hierarchical representations found in the current study is consistent with the finding of Lein and Ruthruff (2004). They manipulated the extent that task elements could be viewed as aggregate tasks over the course of five experiments. Each manipulation led to larger and larger restart costs. It appears that hierarchical representations can result in influences that exist at different strengths depending on the extent to which one's experience with a set of task elements suggests an aggregate task structure.

If variations in the strength of hierarchical representations exist and the strength of a single hierarchical representation's influence can increase with increased use, it is also likely that the influence of hierarchical representations may sometimes become weaker with reduced use. If the aggregate task structure is not supported, the influence of the hierarchical representation would be expected to weaken, and effects on performance and action selection would fade. For example, the influence of the hierarchical structure would be expected to weaken if the task elements that belonged to the aggregate task were performed more often within an environment suggestive of an individual representation rather than a hierarchical representation, or if the task elements were to

become part of a different aggregate task. The results of Experiment 2 suggest that fading does not occur immediately. No evidence of a reduced influence of hierarchical representations was found during the eight blocks of the second half of that experiment. However, such effects may be expected if the task elements had been performed in a context not previously associated with hierarchical representations or perhaps even in the same context after extended periods of responding. Further research assessing the situations that strengthen and weaken the influence of hierarchical representations is likely to provide insight into behavioral flexibility.

The Activation of Hierarchical Representations

Once it was determined that hierarchical representations could be established within a free choice multitasking environment, the next question of interest was by what mechanisms do hierarchical representations exert an influence. One possibility was that all elements of an aggregate task are switched to at once (Schneider, 2007). If switching to an aggregate task results in activation of all of the task elements within that aggregate task then this within-aggregate activation would make within-aggregate switches both faster and more likely. Experiment 3 attempted to assess this hypothesis as an explanation of the influences of task choice and performance found in Experiments 1 and 2. However, the results of Experiment 3 did not provide support for the proposal that aggregate task elements are activated in unison. The time required to switch to a more complicated aggregate task containing three task elements did not differ from the time required to switch to a less complicated aggregate task containing two task elements. Additionally, the proportion of within-aggregate task switches did not vary as a function

of task complexity. Nevertheless, it is unclear whether this lack of support was due to a failure of the hypothesis to explain the influence of hierarchical representations on task choice and performance or a failure to effectively manipulate differences in task complexity within Experiment 3.

While the results of Experiment 3 may not be sufficient to rule out the possibility that aggregate tasks are activated in unison, the lack of an effect of aggregate task complexity does suggest that other explanations of the effect of hierarchical representations on choice and performance during a free choice multitasking environment may be required. Two potential mechanisms are considered below.

Spreading activation.

One possibility is that hierarchical representations affect action selection due to spreading activation. Spreading activation between lexical representations and between conceptual representations has been proposed to account for priming effects within these domains (Estes & Jones, 2009; Inoue, 1991). Spreading activation has also been proposed to function between similar task sets (Arrington et al., 2003). When a single representation is activated, the activation will flow to those representations to which it is most closely related. As a result those related representations will be activated more quickly. In fact facilitation specific to related items is found even in situations where participants are expecting to have to produce an unrelated item (Neely, 1977). Spreading activation could work in a similar manner within a hierarchical task structure. Task elements that are part of the same aggregate task may be bound together more strongly than individually represented task elements or task elements that are part of two different

representations. Even if an individual task element were activated independently, because the task element is part of an aggregate task, the activation could quickly travel to and activate the other elements within the aggregate task. Thus, performance of task elements that are part of the same aggregate task could be facilitated via spreading activation in a way that makes within-aggregate switches both faster and more likely.

However, the findings of Experiment 3 may speak against spreading activation as the mechanism by which hierarchical representations exert their influence. Fan models suggest that when activation spreads passively from one representation to another, the strength of this spreading activation will be divided between all of the representations to which the initially activated representation is bound (Radvansky, 1999). As a result, the strength of spreading activation will be inversely proportional to the number of representations to which the initial representation is connected. If it is assumed that spreading activation occurs similarly between task elements, then the strength with which any one task element within an aggregate task is activated should depend on the number of task elements within that aggregate task. In Experiment 3, in which the number of task elements in each aggregate task varied, within-aggregate activation should have been stronger for the less complex aggregate task, and within-aggregate switches should have been facilitated. However, as described above, neither task choice nor task performance varied as a function of aggregate task complexity in Experiment 3. Thus the current study fails to support spreading activation as a mechanism by which hierarchical representations exert an influence. Nevertheless, the same limitations of Experiment 3 that prevent the outright rejection of the hypothesis that all of the task elements within an

aggregate task are activated at once, also prevents the rejection of spreading activation as a mechanism by which hierarchical representations exert an influence. A more direct test of the impact of spreading activation on hierarchical representations is warranted.

Prioritization strategy.

An alternative to the spreading activation account is that the effect of hierarchical representations on task choice and performance may result from a prioritization strategy in which task elements that are part of the same aggregate task as the task element performed on the previous trial, receive priority for selection. Shomstein and Yantis (2002; 2004) have proposed a prioritization strategy to account for object-based effects of attention during visual search tasks. If the location where the target will be presented is known with 100% certainty, such as when the location is validly cued, this information can be used to successfully guide visual search and configural or object-based information will not be needed. However, in situations of uncertainty, when multiple shifts of attention may be required in order to locate a target, configural information will prioritize attentional shifts. Specifically, when one is attending to a location within an object, other locations within that object will be prioritized, such that attention will be shifted toward within-object locations prior to shifting to locations that fall outside of the object or that fall within another object.

A similar prioritization strategy may be adopted during task element selection. As in visual search, if the to-be-selected task element is known with absolute certainty, such as when the upcoming task is cued, then the configuration of task representations would not be relevant to task selection. However, when the specific task element

required for performance on an upcoming trial is unknown, as is the case during voluntary task switching, then internal shifts of attention may be prioritized toward task elements that are part of the same aggregate task as the task element performed on the previous trial. A prioritization mechanism would be able to account for the influence of hierarchical representations on task choice and performance found in the current study. Further, the account would not make differential assumptions regarding the proportion of within-aggregate switches or speed of within-aggregate switches that would be made for tasks of varying complexity. A shift of attention is an all-or-none process that would be expected to be made toward one of the task elements that belong to the aggregate task performed on the previous trial, regardless of the number of total task elements that aggregate task contained. Thus a prioritization strategy could account for both for the findings in the current set of experiments, that participants tend to make a greater number of within-aggregate task switches than between-aggregate task switches and the finding in Experiment 3 that the proportion of within-aggregate switches performed does not vary as a function of aggregate task complexity.

A prioritization strategy could also prove to be strategic in everyday action selection situations. Within the current study the similarity of the task elements that made up each aggregate task was controlled for. However, within more naturalistic circumstances task elements that are part of the same hierarchical representation are likely to be more similar to one another than task elements belonging to different hierarchies. Similar tasks are likely to share task set parameters (Arrington et al., 2003). As a result switching between task elements that are part of the same aggregate task may

require that only a subset of the parameters within the task set be changed. This shorter reconfiguration process would be expected to lead to quicker task performance (Logan & Gordon, 2001).

Empirical tests are clearly required in order to ascertain the specific mechanism by which hierarchical representations exert their influence on task selection and performance. However, if the influence of hierarchical representations is to be fully elucidated, it is also necessary to attempt to model where within the task performance process hierarchical representations exert an influence. Performing a task is a two stage process (Allport & Wylie, 2000; Logan & Gordon, 2001; Rubinstein et al., 2001). First, during the goal setting stage the to-be-performed task will need to be selected. Then during the performance readiness stage the task set, or parameters that will allow for the performance of the selected task, will need to be implemented. Within voluntary task switching, task choice allows for a distinct measure of the task selection processes that occur during the goal setting stage (Arrington & Logan 2004). However, the presence of this stage was identified prior to the development of the voluntary task switching paradigm, based on the independent contribution that goal setting processes make toward the time required to perform a task (Rubinstien et al, 2001). Whereas task choice will be dictated by the processes that occur during the task selection phase of task switching, RT will be determined both by the processes occurring during task selection and by processes occurring during task set implementation.

Schneider (2007) proposed that hierarchical representations are likely to influence the initial goal setting stage of task switching. Specifically, hierarchical representations

were proposed to speed up the task selection process. If hierarchical representations do indeed exert their influence on task selection then within the voluntary task switching paradigm hierarchical representations would be expected to influence both task choice and performance. The current findings support this hypothesis. Across three experiments hierarchical representations were found to influence both the probability that one would switch to a specific task element and the speed with which that switch was made. Interestingly, hierarchical representations appeared to exert an influence on task choice prior to exerting an influence on RT. This suggests that hierarchical representations were influencing the outcome of the goal setting stage prior to the time when they influenced the speed with which that stage could be completed. If hierarchical representations exert an influence on the goal setting stage by biasing task selection toward specific task elements, then this would be expected to have an immediate influence on task choice. This bias would also have the potential to speed the goal setting process by reducing the uncertainty associated with task selection. However, it may take time to learn to utilize this bias in a manner that is automatic enough to benefit task performance. Thus influences on RT may lag behind the influence on choice.

Hierarchical representations appear to influence the goal setting stage of task performance. Of the two stages of task switching, goal setting is the less understood (Vanderiendonck et al., 2010). A descriptive explanation of task selection has been provided by Arrington and Logan (2005) and a somewhat more specific model has been proposed by Vandierendonck and colleagues (Demanet, 2010). While these proposals vary in their specific details, both share a general theme. That is, both propose that

within free choice multitasking environments, task selection will reflect a combination of top-down processes that guide performance according to a participant's intention and bottom-up processes that exert systematic biases on task choice. Hierarchical representations have the possibility of influencing either of these processes. For example, Arrington and Logan (2005) have proposed that task selection is the result of a competition between an availability heuristic and a representativeness heuristic. According to this proposal, participants will maintain a short series of the most recently performed tasks within WM and attempt to select tasks that will make this series best comply with the instructions to perform tasks randomly. However, this choice will be subject to bias based on which task is currently most available. Hierarchical representations could bias task selection by exerting an influence on the availability heuristic. Specifically, when a task element is performed this could cause the other task elements that belong to that aggregate task to become more available (e.g. due to spreading activation or to a prioritization strategy). As a result, task elements that are part of the aggregate task performed on the previous trial may be more likely to be selected by the availability heuristic and thus more likely to be performed.

Alternatively, hierarchical representations could exert their influence by changing the way that sequences of tasks are selected. Both the heuristic competition explanation of task selection and the chain-retrieval model of task selection assume that participants use top-down control to select tasks in a manner that allows them to create a sequence of tasks that will comply with voluntary task instructions (Arrington & Logan, 2005; Demanet, 2010). They may do this either by maintaining a sequence of the most recently

performed tasks in memory and then selecting the next task based on their perception of what will keep this task sequence random or by retrieving small chains of tasks that comply with the randomness instructions and then selecting tasks in the order indicated by the retrieved chains. Generating sequences of tasks when switching between only two tasks is likely to be less taxing than generating sequences when selecting between four or five tasks. Hierarchical representations may be a way of organizing tasks that becomes strategic for the generation of sequences when a large number of potential tasks are available. For example, Vandereendonck and colleagues (Demanet, 2010) have proposed that some of the repetition bias found in voluntary task switching may be part of a strategic plan implemented by the participant. Participants are sensitive to the ease of task repetitions relative to task switches (Botvinick & Rosen, 2009) and as a result sequences of tasks that have a greater number of task repetitions than task switches will be more likely to be selected for performance. Thus, task selection occurs in a strategic manner that takes advantage of the ease of repeating tasks. A bias toward performing task elements that are part of the aggregate task performed on the previous trial could be another strategic bias that may be particularly useful when switching between more than two tasks. For example when deciding which task to select next a mechanism (such as a prioritization strategy) that directs attention to one specific task element when multiple task elements are available for performance could speed the task selection process. Nevertheless, this benefit for within-aggregate switches is likely to become a cost when one is required to make a between-aggregate switch. This would account for the findings

of greater between-aggregate than within-aggregate switch costs found in the current study.

Hierarchical representations may influence action selection either through a bottom-up bias or a top-down strategy. The nascent literature on task selection and voluntary task switching makes differentiating between these alternatives difficult. Nevertheless, if hierarchical representations exert their influence as part of a top-down strategy that directs and speeds task selection, then this could explain their function.

The Function of Hierarchical Representation

If hierarchical representations are adopted within free choice multitasking environments, then there is likely to be a functional explanation for their generation. In the introduction I laid out three possible functions that hierarchical representations may serve. First, hierarchical representations may be adopted because they aid in the performance of the task elements that make up that representation. Both Koch et al. (2006) and Schneider (2007) found performance benefits for task elements performed as part of an aggregate task. However, performance benefits are not universal (Dreisbach et al., 2007), and therefore seemed unlikely to be the primary function of hierarchical representations. Nevertheless, if hierarchical representations tend to lead task element performance benefits in most situations, then people may be inclined to consistently adopt hierarchical representations, regardless of whether or not these benefits are applicable within the present situation. The current study does not support this explanation. Hierarchical representations did not lead to improvements in task element performance in any of the current experiments. Further in the forced choice condition of

Experiment 1, in which a hierarchical representation was clearly present, mean RT was slowed compared to the other conditions. Thus it does not seem likely that hierarchical task representations typically lead to enhanced task element performance during voluntary task switching. These results are in line with those of Dreisbach (Dreisbach et al., 2007) who has argued that as performance is not improved for actions represented at the task level compared to those represented as SR mappings, speeding action performance cannot be the function of hierarchical representations (Dreisbach & Haider, 2008). Thus potential task element benefits are not likely to drive the formation of hierarchical representations.

A second proposed function of hierarchical representations was that these representations may allow task order to be more easily maintained within situations in which one is required to complete tasks in a specific serial order. The benefits to memory associated with creating higher order groupings are well known (Gobet et al., 2001). However, if this was the primary function of hierarchical representations then one would not expect them to ever be adopted within any of the experiments or conditions in the current study in which task order was unconstrained. The presence of hierarchical representations in the current study suggests that this is not the primary purpose of hierarchical representations. This is not to say that memory does not play a role in the formation of hierarchical representations. Indeed the ability to remember which task elements belong to a specific aggregate task would be a necessary condition for forming a representation of that task, and this memory requirement within the forced choice condition appears to have led to the formation of hierarchical representations. Further, it

is likely that hierarchical representations do aid in the maintenance of task order in situations where such order is required. Indeed, this additional benefit may explain why hierarchical representations seem to be more readily adopted within situations where serial memory of task elements is required. However, the current findings of hierarchical representations within a situation in which maintenance of task order is required, suggest that hierarchical representations serve a function beyond simply aiding in the maintenance of serially ordered tasks. Finally, hierarchical representations may serve to aid in the organization and selection of actions. If a primary function of hierarchical representations is to aid action selection, then hierarchical representations would be expected to influence task choice. This result was found in the current study. Across three experiments subjects choosing tasks within the free choice environment showed influences of hierarchical representation on task choice. Situations were found in which subjects were more likely to switch between task elements that were part of the same aggregate task than to switch between task elements that were part of different aggregate tasks. Not only were hierarchical representations found to affect task choice, but task choice measures seemed to be even more sensitive to the formation of hierarchical representations than were measures of task performance. This sensitivity may reflect the functional role that hierarchical representations typically play in action selection.

The number of stimuli affording action at any given time will always exceed the number of actions that one can perform simultaneously. It is therefore necessary for one to select which actions to perform at any given moment. Given the ability of stimuli to

automatically activate tasks that they afford (Logan, 1988; Norman & Shallice, 1986), ensuring that only actions consistent with one's current goals are actually performed may be strenuous and require executive control (Arrington & Yates, 2009; Weaver & Arrington, invited revision). Hierarchical representations may aid in this process by constraining the tasks that stimuli activate (Mayr & Keele, 2000), and focusing attention on only those actions that are part of one's current goal. This view of action selection assigns hierarchical representation a goal-shielding function similar to that proposed to drive the formation of task sets (Dreisbach & Haider, 2008; 2009). In both cases the hierarchical representations focus attention and shield the task goal from the influence of irrelevant information. Just as task sets can prevent irrelevant stimulus information from influencing task performance, hierarchical representations may prevent irrelevant tasks from influencing action selection. Indeed the current study demonstrated the potential for hierarchical representations at the aggregate task level to serve this function. Once a task element belonging to a specific aggregate task had been performed, participants showed a tendency to continue to select task elements that were part of the same aggregate task rather than to switch to new task elements. Hierarchical representations biased task choice, presumably by exerting an influence on the goal setting stage of task switching. So while all possible task elements were equally available within the stimulus environment on each trial, the representations of task elements that belong to the aggregate task performed on the previous trial may have been more available for task performance. As a result participants choose to persist in the performance of task elements that belonged to the same aggregate task. This type of within-aggregate task

persistence occurred as a bias within the current study in which subjects were instructed to switch between all tasks randomly. However, this bias would be functional within a typical multitasking situation, in which hierarchical representations can be conceptualized as multicomponent goals. When performing tasks outside of the laboratory, within-aggregate task persistence would typically help to ensure that all of the steps required to complete a goal are performed before goal-irrelevant behaviors are selected for performance. For example, when engaged in the goal of making spaghetti, a within-aggregate bias would ensure that after performing one task element, such as boiling noodles, that other task elements that were part of the same task, such as making sauce, would be prioritized for selection over other tasks that would be equally afforded by the stimulus environment, such as washing dishes. Thus, hierarchical task representations would help to ensure that every task within a multi-task goal is accomplished.

People engage in action selection and performance many times on a daily basis. The activity is intuitively volitional, yet research has shown that the process is subject to a great deal of external influence (Bargh & Chartrand, 1999). Bottom-up processes can guide attention and influence action. Cognitive control can be used to overcome these biases; however these cognitive resources are limited and can be depleted (Braver et al., 2008). Mechanisms that can reduce potential biases without utilizing valuable cognitive resources would therefore be desirable. Hierarchical representations may be one such mechanism. Once a higher order goal has been selected, hierarchical task representations can help shield that goal from irrelevant, distracting information, and constrain task

choice to those task elements that fall within the desired aggregate goal, thus helping to ensure goal completion.

Table 1. Manipulations that were used in each of the conditions in Experiment 1.

	Explicit	Spatial	Temporal	After	Forced
	Instruction	Introduction	Introduction	Effects	Choice Trials
Control:	-	-	-	-	-
Hierarchical:					
Introduction	X	X	X	-	-
After Effect	X	X	X	X	-
Forced Choice	X	X	X	X	X

Figure Captions

Figure 1. Depiction of the parameters on which stimuli could vary in Experiment 1.

These stimuli are only four of the 16 stimuli used in this experiment.

Figure 2. Mean RTs for Experiment 1 as a function of condition and transition type.

Error bars in this and all figures are 95% confidence intervals calculated from the error term for the within-subject variable as suggested by Masson and Loftus (2003). Standard error values are presented within the base of each of this and all graphs.

Figure 3. Mean proportion of transitions for Experiment 1 as a function of condition and transition type.

Figure 4. Mean RT (A) and proportion of transitions (B) as a function of transition type and the number of trials since the last forced choice trial was performed within the forced choice condition of Experiment 1.

Figure 5. Mean RT (A) and proportion of transitions (B) as a function of switch type and block within Experiment 2. The lines following block eight represent the point within the experiment in which the procedure was changed such that it no longer included forced choice trials.

Figure 6. Mean RTs for Experiment 2 as a function of half and transition type.

Figure 7. Mean proportion of transitions for Experiment 2 as a function of half and transition type.

Figure 8. Mean RTs for Experiment 3 as a function of aggregate task complexity and transition type.

Figure 9. Mean proportion of transitions for Experiment 3 as a function of aggregate task complexity and transition type.

Figure 1

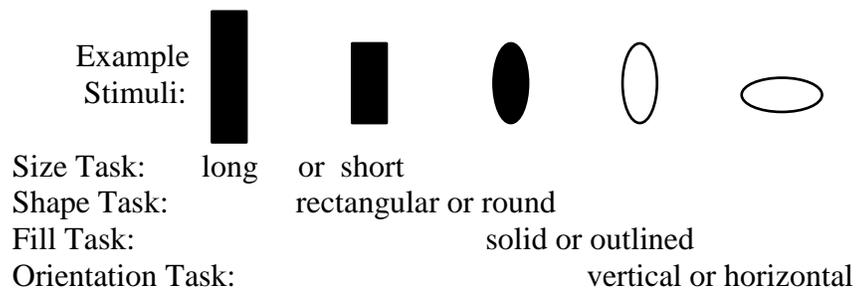


Figure 2

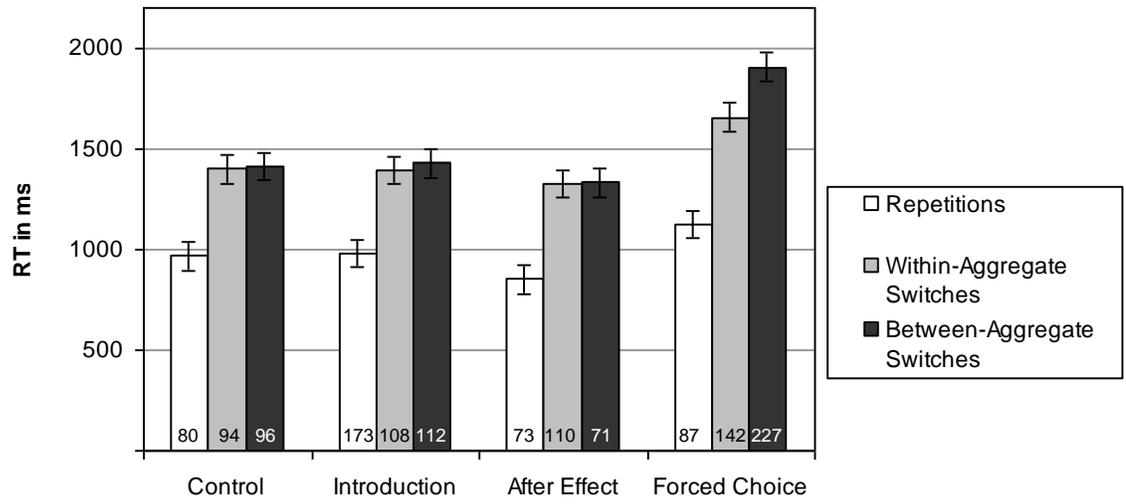


Figure 3

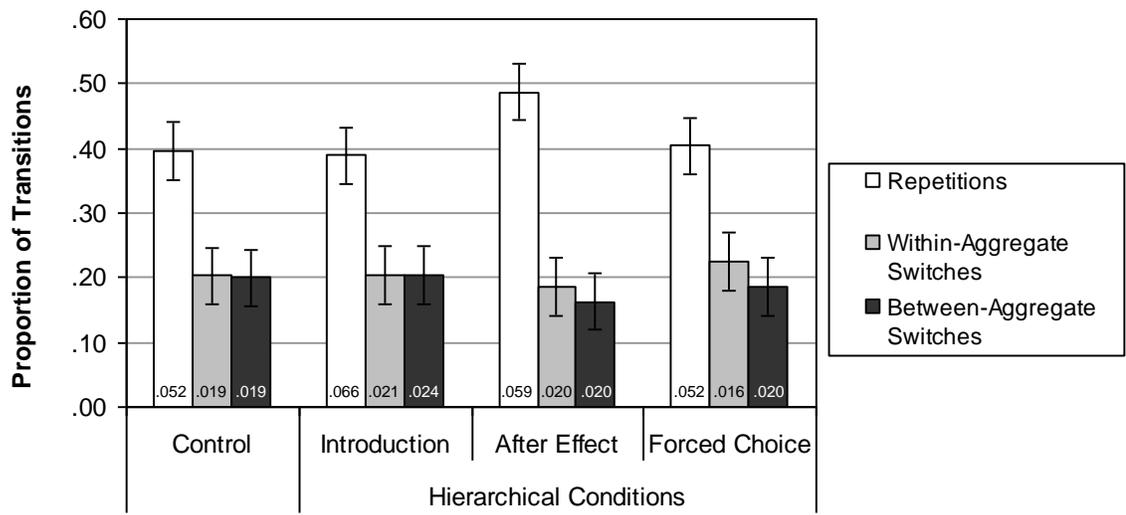
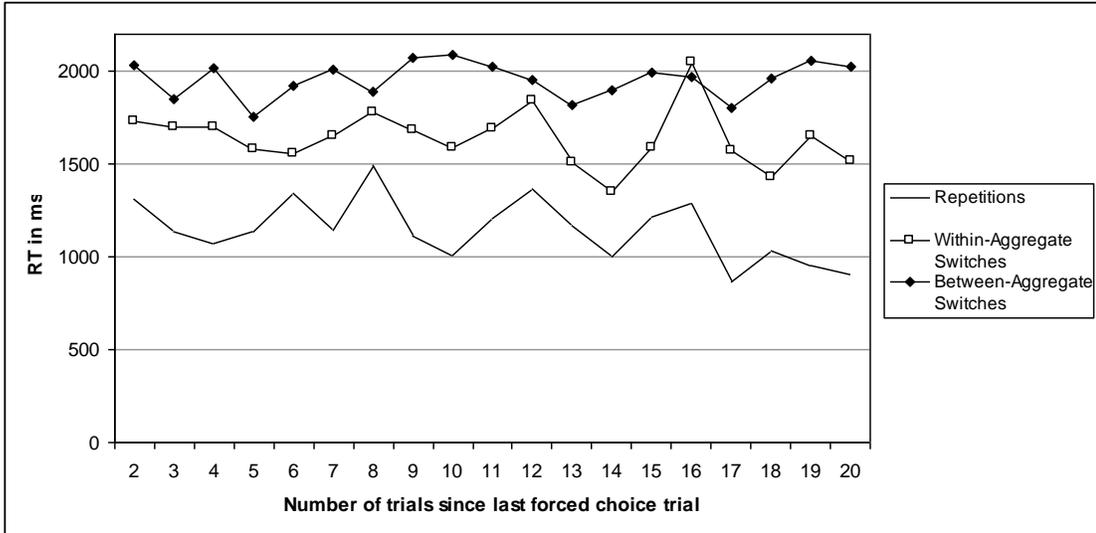


Figure 4

A)



B)

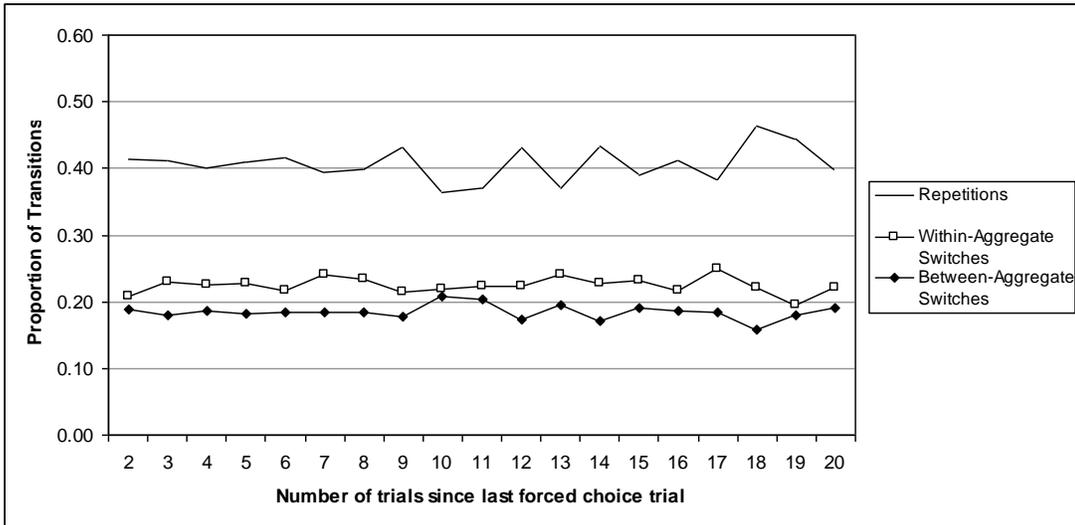
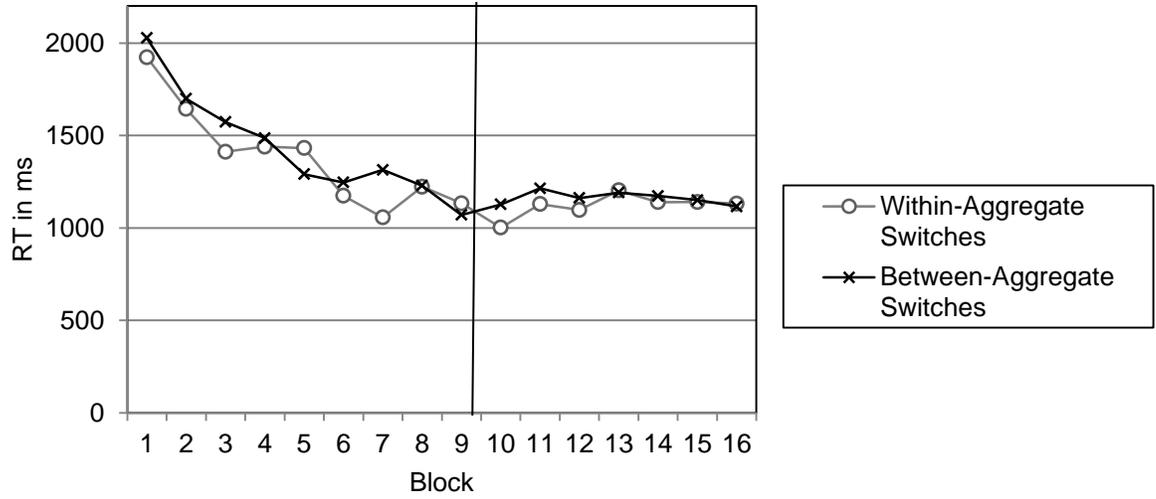


Figure 5

A



B

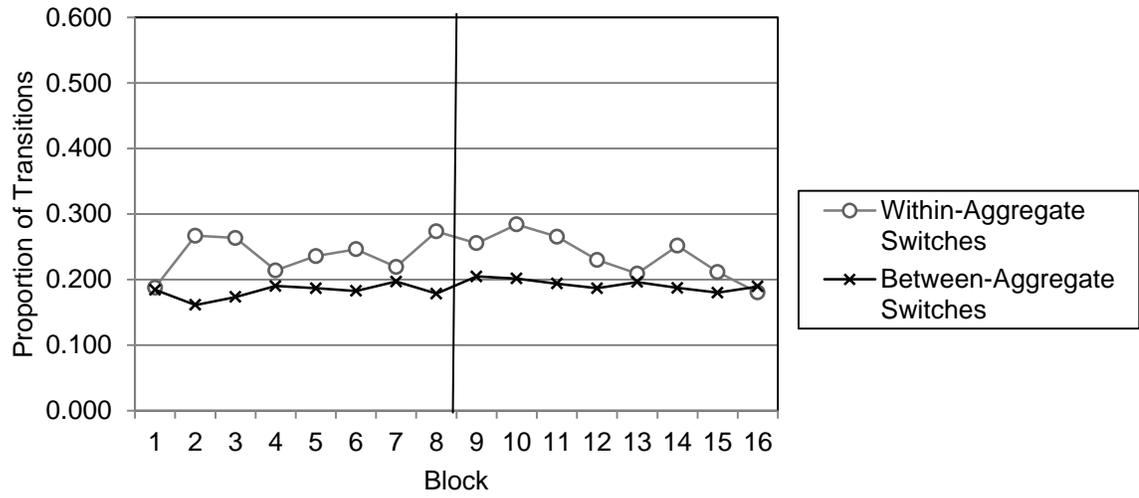


Figure 6

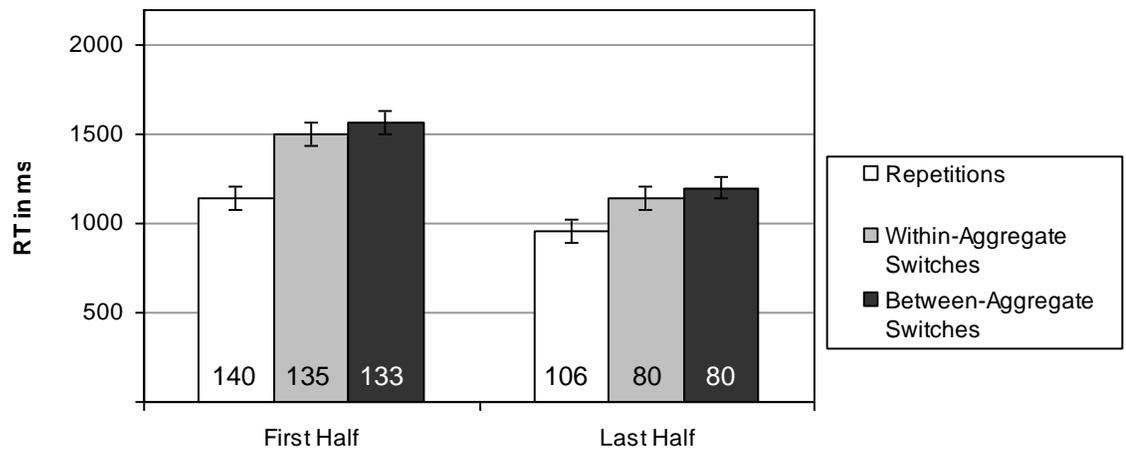


Figure 7

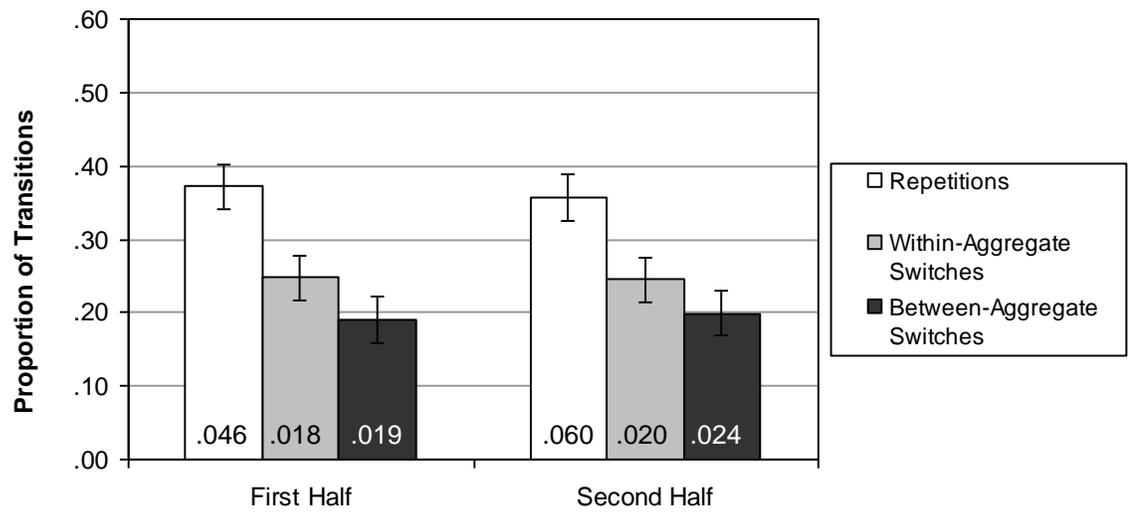


Figure 8

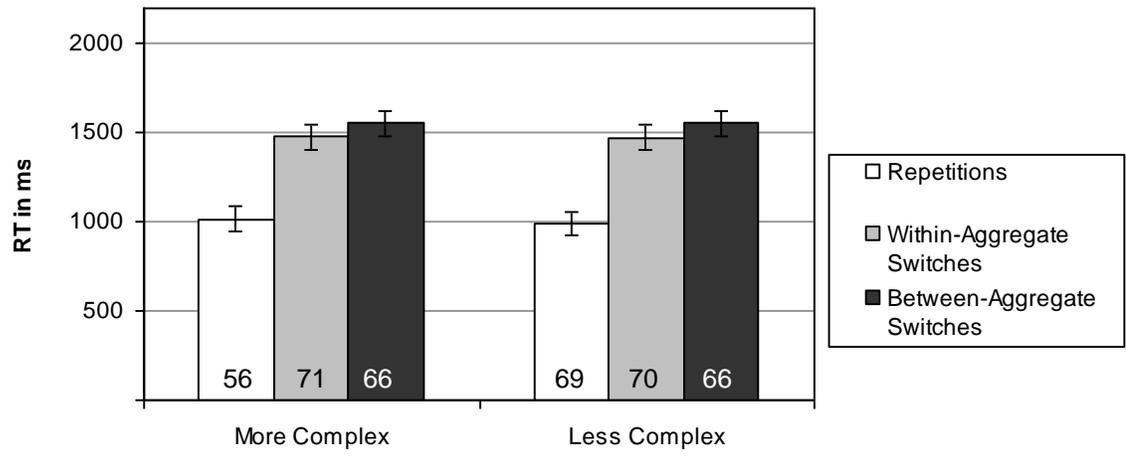
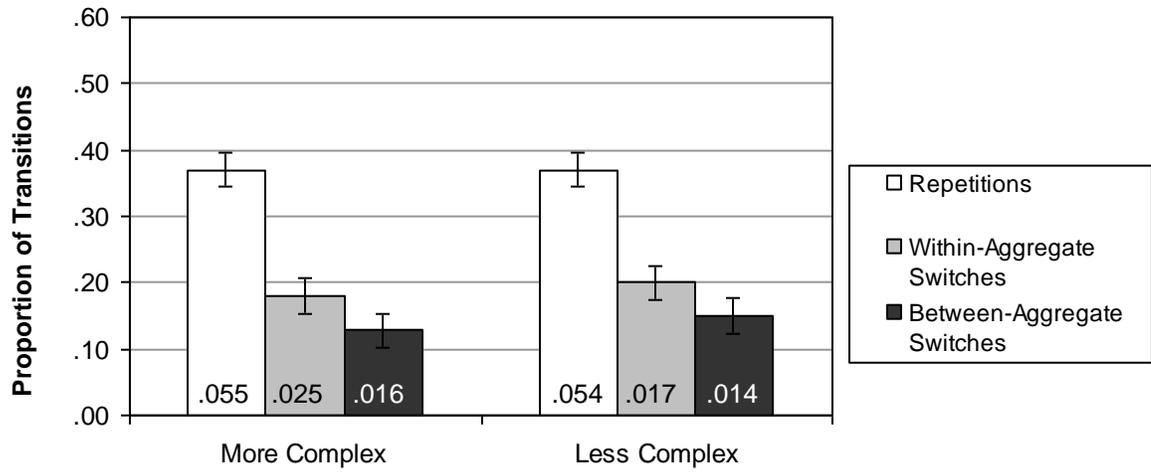


Figure 9



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Appendix

Experiment 1

Task type was also assessed in order to determine whether the specific categorization tasks performed affected performance or choice measures (see Table A1). Across conditions, the shape task was performed slightly more slowly than the size task and was performed slightly less often than the fill task. Importantly, the effect of task type did not vary as a function of condition. A 4(condition: control, introduction, after effect, forced choice) x 4 (task type: fill, orientation, shape, size) ANOVA with condition as a between-subjects factor and task type as a within-subject factor was conducted on RT data. A marginally significant main effect of task type was found, $F(3,159)=2.51$, $p=.06$, $\eta_p^2=.05$. Post hoc test revealed a marginally significant difference between the fastest of the tasks, the size task, and the slowest of the tasks, the shape task, $p=.09$. Neither the main effect of condition, $F(3,53)=2.01$, $p=0.12$, nor the interaction, $F(3,159)=0.89$, $p=.54$, reached significance. A marginal effect of task type was also found when the same analysis was conducted on the task choice performed, $F(3,51)=2.28$, $p=.09$, $\eta_p^2=.12$. In this case post hoc tests indicated that the fill task was performed on a greater proportion of trials than the shape task. Once again, neither the main effect of condition, $F(3,53)=0.00$, $p=1.00$, nor the interaction, $F(9,159)=1.00$, $p=.44$, reached significance.

A final set of analyses were conducted in order to ascertain whether task order influenced performance or choice measures or varied by condition (see Table A2). As indicated above, task order determined which tasks were paired together, with the first

two presented task elements becoming part of the first aggregate task and the second two tasks elements becoming part of the second aggregate task. Task order did not affect performance or choice measures, nor did it interact significantly with condition. A 4(condition: control, introduction, after effect, forced choice) x 4 (task order: first, second, third, fourth) ANOVA with condition as a between subjects factor conducted on RT data found no significant effect of task order, $F(3,51)=0.70, p=.56$, no main effect of condition, $F(3,53)=2.01, p=0.12$, and no interaction, $F(9,159)=0.30, p=0.97$. The same analysis conducted on task choice also failed to find a significant effect of task order, $F(3,159)=1.83, p=.15$, condition, $F(3,53)=0.00, p=1.00$, or an interaction, $F(9,159)=1.02, p=0.55$.

Experiment 2

The effect of categorization task on RT and choice measures was assessed as a function of experiment half (see Table A3). The fill task was performed more quickly than the orientation or the shape task. The size task was performed slightly more quickly than the orientation or shape task. As in Experiment 1, the fill task was also performed on a greater proportion of trials than the shape task. None of the task type effects varied as a function of experiment half. A 2 (half: first, last) x 4 (task type: fill, orientation, shape, size) repeated-measures ANOVA on RT found a main effect of task type, $F(3,39)=8.72, p=.06, \eta_p^2=.05$. The interaction was not significant, $F(3,39)=0.50, p=.69$. Post hoc tests revealed a significant difference in speed between the fill task and the orientation task $p<.05$ and the fill task and the shape task, $p<.05$ with the fill task being performed more quickly than either the orientation or fill task. In addition marginally

significant differences between the size task, and the orientation task, $p=.06$, and the size task and the shape task, $p=.08$, were found with the size task being performed more quickly than orientation or shape task. A main effect of task type was also found when the same analysis was conducted on the task choice performed, $F(3,11)=10.96$, $p<.01$, $\eta_p^2=.75$. In this case post hoc tests indicated that the fill task was performed on a greater proportion of trials than the shape task. Task type did not interact with half, $F(3,39)=1.30$, $p=.29$.

The potential influence of task order on RT and choice during each half of Experiment 2 was also assessed (see Table A4). Task order did not affect performance or choice measures, nor did it interact significantly with half. A 2(half: first, last) x 4 (task order: first, second, third, fourth) repeated-measures ANOVA on RT found no significant effect of task order, $F(3,39)=0.51$, $p=.68$ or interaction, $F(3,39)=0.27$, $p=0.85$. A similar analysis on task choice also failed to find a significant effect of task order, $F(3,11)=1.41$, $p=.29$, half, $F(1,13)=0.09$, $p=0.78$, or an interaction, $F(3,39)=1.20$, $p=0.32$.

Experiment 3

Categorization task did not influence RT or task choice in Experiment 3 (see Table A5). A one-way repeated-measures ANOVA on RT found no significant effect of task type, $F(4,56)=1.09$, $p=.37$. The same analysis conducted on task choice also yielded no significant effect of task type, $F(4,56)=.65$, $p=.36$. Task order also had no effect on RT as revealed by a one-way repeated-measures ANOVA, $F(4,52)=1.35$, $p=.26$ (see Table A6). The same analysis on task choice also failed to reach significance, $F(4,52)=0.55$, $p=.70$. The counterbalancing of specific categorization

across task complexity level prevents the ability to assess the effect of task complexity on the speed or proportion of categorization task performed.

Table A1. Mean (SE) RT and proportion of switches as a function of condition and task type for Experiment 1.

	Fill	Orientation	Shape	Size
RT				
Control	1238 (123)	1245 (94)	1274 (116)	1171 (88)
Introduction	1183 (145)	1208 (144)	1228 (134)	1201 (124)
After Effect	973 (62)	1091 (72)	1094 (103)	1084 (113)
Forced Choice	1407 (114)	1475 (129)	1443 (101)	1339 (110)
Task choice				
Control	.269 (.015)	.257 (.019)	.256 (.015)	.218 (.012)
Introduction	.294 (.024)	.252 (.015)	.232 (.015)	.222 (.013)
After Effect	.296 (.027)	.230 (.014)	.228 (.012)	.246 (.015)
Forced Choice	.261 (.023)	.236 (.017)	.240 (.015)	.263 (.018)

Table A2. Mean (SE) RT and proportion of switches as a function of condition and task order for Experiment 1.

	First	Second	Third	Fourth
RT				
Control	1205 (117)	1261 (116)	1240 (110)	1221 (79)
Introduction	1215 (129)	1212 (137)	1683 (133)	1225 (147)
After Effect	1032 (70)	1093 (113)	1014 (78)	1025 (95)
Forced Choice	1392 (123)	1432 (117)	1424 (110)	1418 (110)
Task choice				
Control	.278 (.020)	.240 (.014)	.240 (.010)	.242 (.016)
Introduction	.256 (.014)	.255 (.026)	.242 (.015)	.247 (.015)
After Effect	.252 (.130)	.258 (.014)	.279 (.029)	.217 (.012)
Forced Choice	.294 (.024)	.220 (.014)	.237 (.015)	.249 (.136)

Table A3. Mean (SE) RT and proportion of switches as a function of half and task type for Experiment 2

	Fill	Orientation	Shape	Size
RT				
First Half	1287 (127)	1457 (138)	1463 (124)	1356 (135)
Last Half	1023 (73)	1178 (124)	1122 (97)	1027 (66)
Task choice				
First Half	.296 (.014)	.251 (.010)	.226 (.012)	.227 (.017)
Last Half	.286 (.015)	.240 (.014)	.235 (.008)	.239 (.013)

Table 4A. Mean (SE) RT and proportion of switches as a function of condition and task order for Experiment 2.

	First	Second	Third	Fourth
RT				
First Half	1382 (145)	1387 (133)	1407 (128)	1387 (124)
Last Half	1066 (79)	1057 (87)	1141 (116)	1086 (91)
Task choice				
First Half	0.276 (.017)	0.251 (.014)	0.250 (.010)	0.223 (.018)
Last Half	0.268 (.013)	0.55 (.014)	0.239 (.012)	0.239 (.015)

Table 5A. Mean (SE) RT and proportion of switches as a function of task type for Experiment 3.

	Fill	Orientation	Shape	Size	Shade
RT	1339 (108)	1346 (86)	1273 (82)	1334 (100)	1299 (109)
Task choice	.199 (.016)	.206 (.015)	.193 (.015)	.177 (.014)	.226 (.016)

Table 6A. Mean (SE) RT and task choice for Experiment 3 as a function of task order.

	First	Second	Third	Fourth	Fifth
RT	1297 (97)	1379 (100)	1372 (91)	1423 (80)	1340 (95)
Task choice	.204 (.018)	.211 (.019)	.211 (.015)	.179 (.012)	.195 (.017)

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Submitted Manuscripts

Weaver, S. M., & Arrington, C. M. *Tracking the multitasking mind: Examining the source of switch costs in voluntary task switching*. Submitted Manuscript

Arrington, C. M., & Weaver, S. M. *Conflict-control mechanisms in voluntary task switching*. Manuscript in revision.

Arrington, C. M., Stuart, J. A., & Weaver, S. M. *Mind wandering during multitask performance*. Manuscript in revision.

Manuscripts in Preparation

Arrington, C. M., & Weaver, S. M. *Tracking the influences of preparation, congruency, and task switching on task performance during explicit task cueing*. Manuscript in preparation.

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