

AN ABSTRACT OF THE THESIS OF

David Kuhns for the degree of Master of Arts in Interdisciplinary Studies in Psychology,

Psychology, and Gerontology presented on June 1

Title: The Effects of Endogenous and Exogenous Cues on Task-Set Inhibition

Abstract approved:

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Task-set inhibition has been proposed to be an important mechanism for cognitive control in task switching. Its existence is supported largely by the observation of the N-2 repetition cost (e.g., A-B-A is slower than C-B-A). Many studies have reported an N-2 repetition cost, but several have not. Because of the numerous methodological differences between previous studies, no firm conclusions can be drawn regarding the conditions necessary to produce inhibition. To better understand inhibition and its role in task switching, we manipulated factors thought to cause the absence or presence of the N-2 repetition cost in 4 experiments. In Experiments 1-3 where a predictable, repeating task sequence was used, we consistently found an N-2 repetition cost, even under the aforementioned conditions, which have previously been associated with the absence of inhibition. However, when a random task sequence was used in Experiment 4, the N-2 repetition cost was eliminated, at least in the condition where the task set was solely cued by location. The persistence of the N-2 repetition cost in Experiments 1-3 and absence of it in Experiment 4 suggest that spatial information can be useful for improving performance, but only under specific circumstances.

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June 1, 2007

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The Effects of Endogenous and Exogenous Cues on Task-Set Inhibition

By
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A THESIS

Submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Arts in Interdisciplinary Studies

Presented June 1st, 2007
Commencement June 2008

Master of Arts in Interdisciplinary Studies thesis of David Kuhns presented on JUNE 1, 2007.

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

David Kuhns, Author

ACKNOWLEDGEMENTS

I express my sincere appreciation to Dr. Mei-Ching Lien, Dr. Eric Ruthruff, and Dr. Michael R. Levenson for their valuable knowledge, guidance, and support that they provided throughout the development of this work. Dr. Mei-Ching Lien, especially, has been a model and inspiration for success. I would also like to thank the Oregon NASA Space Grant Consortium for the award of the Oregon NASA Space Grant Graduate Fellowship.

CONTRIBUTION OF AUTHORS

Dr. Mei-Ching Lien and Dr. Eric Ruthruff assisted with the development of experiment programs and data analysis. I would also like to acknowledge current and former Attention & Performance lab members Zachary Goodin, Logan Cornett, Glen Morrison, Rena McGrath, James Warren, Sarah Hulse, Thuy Le, Mark Little, Jon Engle, Dongbin (Tobin) Cho, and Emily Hatch for assisting with running experiments and/or the data collection.

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CHAPTER 1: COGNITIVE CONTROL

The brain has many functions at its disposal for carrying out a wide variety of complex behaviors and mental processes. Underlying most of the conscious mental operations, however, there is some mechanism controlling them. Moreover, we are able to guide any number of these functions as we see fit in the service of some goal. The control processes that are responsible for managing our mental operations are referred to as *cognitive control*. Cognitive control, specifically, is the regulation of operations such as attention, inhibition, updating and maintenance of working memory, and retrieval of information from long-term memory. Every moment the brain is thinking, cognitive control functions are in control. It is because of cognitive control that we can focus our resources and perform non-routine complex actions. Cognitive control functions, therefore, are essential for achieving the flexible behavior that is the strength and defining feature of human cognition.

Each action, or set of actions, that we complete requires a unique mental program in order to successfully reach the desired end state of whatever goal is being completed. Interacting with computers, driving a car, or flying an airplane requires the flexible control of our thoughts to shift attention, identify an appropriate response, and initiate the correct action. Since there are so many mental operations available and they are so critical for achieving flexible and efficient human performance, it is important for us to understand the limitations of cognitive control.

The cognitive control is the essential component for efficiently moving from one task to another. However, in nearly all circumstances cognitive control is not perfect and switching tasks comes with a cost. The present study aims to better understand the

limitations and the processing mechanism(s) underlying cognitive control. The ultimate goal is to provide a general and parsimonious theory of cognitive control.

CHAPTER 2: TASK SWITCHING

One very useful method for understanding control processes is by investigating how a task is performed successfully. Researchers have proposed that the representation of stimuli, response mappings (i.e., response set), and all other information are required to complete the task (Allport, Styles, & Hsieh, 1994; Rogers & Monsell, 1995). The aggregate of all a task's components are referred to as a task-set. A task-set is made up of the information that acts as the impetus, associated stimuli, and action rules or response information for responding. For a task to be completed, a cue from the environment (known as an exogenous cue) or/and internal goal (known as an endogenous cue) must be loaded into working memory to facilitate the retrieval of proper stimuli and responses that belong in a specific task-set. One example of this may be detecting a road sign while driving. If a sign were to cue the task of exiting a highway in 1 mile, the driver will begin to search for an exit. Once the stimulus (i.e., exit) is identified, the appropriate action will be to shift to necessary lane. In order for all of this to be completed, the task-set must be retrieved from memory and applied to the current stimuli available (Goschke, 2000; Mayr & Kliegl, 2003)

Endogenous and Exogenous Control

As may now be clear, the impetus to a task can be either stimulus driven (i.e., exogenous) or goal driven (i.e., endogenous). An example of the former in its purest manifestation would be an unconditioned or conditioned (i.e., learned) response to some stimulus. The latter is presumed to reflect internal cognitive control processes over the functions such as attention, inhibition and memory, which are required to execute and complete a task. This concept is perfectly illustrated by the modern computer. There are

an extremely large number of actions available to the computer user at any given moment. When you sit in front of your computer, you could write a letter, check an email account, listen to music, and the list continues. The number of images, text, colors, and shapes that represent a task are often ambiguous in that they are shared by multiple tasks. It is only by internal, or endogenous, control processes are we able to attend to the relevant stimulus to select an appropriate action and then carry out that action. Neither in real life nor the laboratory, however, are the cues that signify the appropriate task so linguistically meaningful. The green traffic light, for example, means an intersection is clear to travel through. In the cognitive laboratory, the same color green in an experiment could signal to a participant to search for a vowel in an array of letters. Although the meaning of a color cue is by nature more flexible than a linguistic cue, both serve the same purpose. The input, selection and output processes are what constitute the task-set reconfiguration process (Rogers & Monsell, 1995).

Task Switching Paradigm and the Switch Cost

One especially informative method for investigating cognitive control of task-sets is to use the task-switching paradigm. There are several renditions of task-switching paradigms for conducting task-switching research. All of these methods allow for the observation of behavioral or neurological measures, which reflect the control processes needed to shift from completing one task to reconfigure the cognitive functions needed for the upcoming new task.

Jersild (1927) is credited as one of the first researchers to study task switching. In his original design, he recorded the self-paced length of time participants took to complete lists of arithmetic tasks. The lists contained either a repeating single arithmetic

task (e.g., addition) or alternated between two arithmetic tasks (e.g., addition and subtraction). Jersild compared the response time (RT) obtained from the single task list (i.e., the pure-task condition) and the two task lists (i.e., the alternating-task condition). He observed that RT to complete the lists in the alternating-task condition was longer than the pure-task condition. The difference in RT between the alternating-task condition and the pure-task condition is referred to as the *task-switch cost*. Jersild's findings and subsequent replications (e.g., Spector & Biederman, 1976) clearly demonstrate that a cost in the form of increased RT and error rates results from switching between tasks with ambiguous stimuli.

Task-Set Inertia

In a series of seven experiments, Allport et al. (1994) replicated and extended Jersild's (1927) findings. Allport et al. adopted the Jersild paradigm where participants complete lists of tasks that contain either a single task or multiple tasks. They noticed an increase in the switch cost when switching away from a task with a weak stimulus-response (S-R) mapping to a task with a strong S-R mapping (e.g., switching from word reading to color naming in the Stroop task). However, the switch cost dissipated after the first few trials of each list. Allport et al. attributed the increased cost to interference from the previous competing task sets, a theory known as task-set inertia (TSI).

Task-Set Reconfiguration

Rogers and Monsell (1995), however, argued that the switch cost obtained in the Jersild study (as well as in Allport et al.'s, 1994, study) is confounded with the need to maintain two task sets in memory in the alternating-task condition. To avoid this confound, Rogers and Mosell use an AABB paradigm (known as the alternating-runs

paradigm), where task repetition and task switch trials were presented in a fixed sequence within blocks. The switch cost was calculated by the RT difference between task-repetition trials and task-switch trials. One of the major findings was that the switch cost persisted despite a sufficient amount of time for interference to dissipate and for preparation to be completed. Here the so-called *residual switch cost* that remained was concluded to be the result of task-set reconfiguration (TSR) processes. Thus, the switch cost is hypothesized to arise from two factors: (1) the time needed to mentally reconfigure the task set and (2) the fact that task-set reconfiguration cannot be completed without the presence of the task stimulus (De Jong, 2000).

Is the Switch Cost from Task-Set Inertia or Task-Set Reconfiguration?

One problem associated with both Allport et al. (1994) and Rogers and Monsell (1995) is that the time for TSI to dissipate is confounded with the time for TSR to be carried out. If the activation of the previous task set is carried over to the next trial, then increasing the length of time between the previous response and the stimulus onset for the upcoming task (i.e., response-stimulus interval; RSI) will allow the activation to dissipate. However, during that same RSI participants can actively prepare/reconfigure for the upcoming task. To isolate the contributions of TSI and TSR, Meiran (1996) used a cuing paradigm. In the cuing paradigm, tasks are presented in a random sequence. On a trial-by-trial basis, the participants are explicitly informed of the upcoming task by some signal (i.e., a task cue). By keeping the RSI constant, the presentation of the cue can be manipulated within that time to allow for either more time for dissipation of TSI or more time for TSR. The time from the point that the cue is presented until the stimulus onset for the upcoming task set is called the cue-stimulus interval (CSI).

Moreover, the time interval from when the response to the previous task is made until the cue onset is the response-cue interval (RCI). One advantage of Meiran's design is that preparation for the upcoming task can proceed only during the CSI. No preparation can be made during the RCI and, therefore, during this interval, the only thing that can reduce switch costs is dissipation of proactive interference from the previous task. By holding the total RSI constant, but manipulating the RCI and CSI, there is either more or less time for the reduction of TSI or time to complete TSR (see Figure 1). Using this paradigm, Meiran found that switch costs are attributed to both TSI and TSR, with TSR being the primary cause.

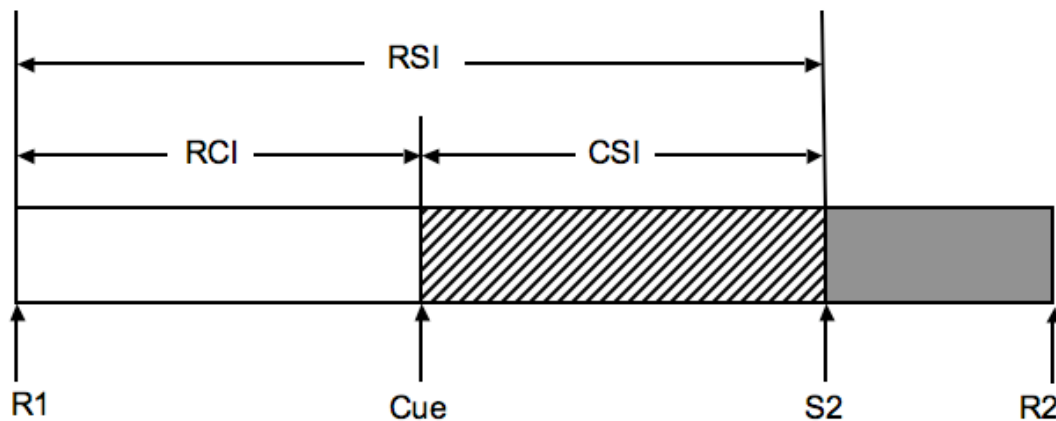


Figure 1. A diagram illustrates a cuing paradigm. A cue is presented during the interval from the previous response (R1) to the upcoming stimulus (S2), known as response-stimulus interval (RSI). The interval between R1 and the cue for the next task is response-cue interval (RCI), whereas the interval between cue and S2 is cue-stimulus interval (CSI).

The Residual Switch Cost

Despite convincing evidence that the switch cost is in part due to TSI and to TSR,

neither account provides an explanation of exactly how TSR is carried out. To this end, several studies have proposed a memory retrieval component to task-set reconfiguration (Goschke, 2000; Mayr & Kliegl, 2001; Mayr & Kliegl, 2003). Goschke (2000) provided evidence in support of a retrieval stage by having participants on each trial either verbally repeat the task cue or say an irrelevant word (e.g., Monday or Tuesday). Goschke observed that when an irrelevant word was spoken, the performance for performing the task was hindered. Thus, he concluded speaking the irrelevant word blocked the configuration of the task set. While Goschke argued for a retrieval stage, others have specified the pathway of retrieval from long-term memory to working memory (Mayr & Kliegl, 2000, 2003). Mayr and Kliegl (2000), for instance, observed that the switch cost was larger when retrieval demands were increased (i.e., episodic retrieval). Additionally, Mayr and Kliegl (2003) observed that the switch cost was not further reduced after the first repetition of a task. Once the relevant task-set has been retrieved, it is applied (without additional memory retrieval) to the current stimulus available. Further evidence supporting the two-stage reconfiguration model also comes from a variation of the cuing paradigm, where two different types of cues are associated with one particular task (i.e., 2:1 cue to task mapping). By using 2:1 cue-task mappings, each trial could be (1) a cue repetition and task repetition, (2) a cue switch and task repetition, or (3) a cue switch and task switch. For trials where the cue switches and task repeats, a cost is observed compared to trials where the cue repeats and task repeats. But, the cost of switching cues alone is not as great as when the cue switches and the task switches. This cue switch cost was interpreted as the time for the retrieval of the relevant task-set from long term memory (for an alternative explanation see Logan & Bundeson, 2003).

Once a task-set has been retrieved from long-term memory there would presumably be two task sets simultaneously active in working memory. At some point the irrelevant task-set is inhibited to reduce any possible interference between competing task sets in working memory, (Mayr, 2002; Mayr & Keele, 2000; Schuch & Koch, 2003). Evidence for task-set inhibition comes from the so-called backward inhibition paradigm, which was developed to provide some clue as to what processes are used to control sequences of tasks and to resolve the conflict that arises during the reconfiguration of a task set (Mayr, & Keele, 2000). In the backward inhibition paradigm, participants perform one of three tasks that are presented in a random sequence. Often, but not always, stimuli afford performance to more than one task (i.e., ambiguous). The appropriate task is cued with some type of task cue, often a verbal cue (e.g., “magnitude” for a greater-/less-than 5 task). The evidence for task-set inhibition comes from the contrast between the performance of a trial where a task is repeated after an intermediate trial (e.g., ABA; N-2 repetition) is compared to a trial where three task switches are performed consecutively (e.g., CBA; N-2 switch). It is typically observed that RT and error rates are increased in the N-2 repetition condition relative to the N-2 switch condition (Kuhns, Lien, & Ruthruff, in press; Mayr, 2002; Mayr & Keele, 2000, Schuch & Koch, 2003). Mayr and Keele (2000) theorized that in order for TSR to be carried out, the task set that is being switched away from must be inhibited to reduce conflict between active task sets in working memory. The longer RT for the N-2 repetition trials than the N-2 switch trials is hypothesized due to the need to undo the task-set inhibition that was recently applied on the previous trial. Because the task-set inhibition decays over time, there is not as much residual inhibition to slow performance in the N-2 switch condition.

Task-Set Inhibition

Task-set inhibition has been hypothesized to reduce the conflict that sometimes occurs between simultaneously activated task-sets or response sets. Evidence supporting this has been obtained by using a paradigm in which some trials require a response, but other trials require no response (Schuch & Koch, 2003). Schuch and Koch hypothesized that task-set inhibition arises during the response-selections processing. Thus, the absence of response selection should eliminate the task-set inhibition. Consistent with this hypothesis, Schuch and Koch found no N-2 repetition cost when no response was required for trial N-1. Conversely, the N-2 repetition cost was present when a response was required for trial N-1. Thus, simply activating a task-set alone is not sufficient for producing an N-2 repetition cost. It is the combination of making a response. Schuch and Koch concluded that task-set inhibition must be applied to reduce conflict between the possible correct responses.

Summary

In summary, task switching is the process of mentally shifting gears from one task set to another. Research on how tasks are switched between is one useful method for investigating cognitive control. The switch cost that is observed is partially contributed to by task-set inertia. In addition to task-set inertia, the need to reconfigure the task-set currently active in working memory to the new task-set that is being switched to also makes up a significant portion of the switch cost. In this process, switching task sets can be initiated through an internal or external impetus. Once a switch to a new task begins, the new task set is retrieved from long-term memory and then loaded into working memory.

To eliminate conflict between the task-set that has just been switched to and the task-set that has been switched away from, the switched-away from task-set is inhibited. The task-set inhibition is the active suppression of a response set or task set, which serves to resolve conflict between competing responses (Schuch & Koch, 2003). After a task-set has been inhibited, the strength of suppression dissipates over time. Evidence for task-set inhibition comes from the backward inhibition paradigm, where one of three tasks is performed on each trial, at random, and the relevant task is indicated with some type of task cue. Trials that form an N-2 repetition sequence (ABA) are compared to trials that form an N-2 switch sequence (CBA). The N-2 repetition cost, which is assumed to arise from task-set inhibition, is hypothesized to partially reflect the difficulty in returning to a previously inhibited task.

CHAPTER 3: THE PRESENT STUDY

In some circumstances, flexible cognitive control requires both switching and returning to a task. Although the use of task-set inhibition to achieve cognitive control is well supported by empirical data, there still remain unanswered questions regarding when task-set inhibition is used. Some of the previous task-switching studies have shown that the N-2 repetition cost can be eliminated (e.g., Arbuthnott, 2005; Arbuthnott & Woodward, 2001; Hübner, Dreisbach, Haider, & Kluwe, 2003; Koch, Gade, & Philipp, 2006). The cause of the occasional disappearance of N-2 repetition costs would appear to provide strong clues as to the nature of task-set inhibition. At present, however, the cause is still mysterious. The following experiments were therefore designed to examine several factors that might plausibly modulate the N-2 repetition cost.

Evidence consistent with task-set inhibition has been well replicated in a multiple variations of the backward inhibition paradigm. However, two factors that seem to be common among the studies that do not show an N-2 repetition cost are (a) the repeating task-sequences and (b) the use of non-verbal task cues. In the former, a purely fixed and repeating task sequence is confounded with the absence of any explicit task cue. In paradigms where task sequences repeat, such as the alternating-runs paradigm, the predictable sequence itself represents an implicit and endogenous cue on its own; thus, eliminating the need for an explicit, exogenous cue. On the other hand, in cuing paradigms used to study backward inhibition, participants must depend on the explicit task cue to switch tasks. Because in most cases ambiguous stimuli that afford properties to multiple task sets are used, an explicit task cue is necessary in order to reveal which is relevant and irrelevant task to perform.

Repeating Task Sequences

In all studies that report evidence consistent with task-set inhibition, a cuing paradigm has been used. Two notable exceptions used a predictable task sequence show inconsistent results. One study was by Koch et al. (2006). In their study, certain blocks of experimental trials used a repeating task sequence that the participants were either fully, partially, or not aware of the pattern. For instance, in the full-foreknowledge condition, participants were provided written instructions “the following sequence will be ABACBA” prior to each block. In the partial-foreknowledge condition participants were told that there would be a repeating sequence of tasks, but not the identity of the tasks. In the no-foreknowledge condition participants were completely naïve. They found that the N-2 repetition cost was eliminated only in the full knowledge condition. Koch et al. concluded by informing participants as to the patterns with which tasks would be presented, they could then form advance representations of task sequences. By representing the sequences in chunks, no task-set inhibition was needed.

Lien, Ruthruff, and Kuhns (2006) also examined task-set inhibition, using a variation of the alternating-runs paradigm. They found no evidence for task-set inhibition, indicating that switch cost is not caused by the task-set inhibition. However, the absence of N-2 repetition cost in their study could be due to the use of the predictable repeating sequence, as suggested in Koch et al. (2006).

Clearly, repeating task sequences play some important role in understanding when and how task-set inhibition will be present. The fact that the Koch et al. (2006) and the Lien et al. (2006) studies are the only two examples where a repeating sequence was used to investigate task-set inhibition and neither obtained evidence consistent with task-set

inhibition when participants were aware of the repeating task sequences. It is possible that the act of endogenously switching between tasks eliminates the need to inhibit the switched-away-from task. Therefore, based on this hypothesis, when a repeating sequence is used, then there should be no N-2 repetition cost.

One hypothesis for why the N-2 repetition cost is eliminated when repeating task-sequences are used is that repeating task sequences facilitate preparation of the upcoming task, and consequently reduce the need to eliminate competition between simultaneously activated task-sets. Although there is no direct evidence that repeating sequences actually do facilitate preparation, this assumption is entirely plausible. Repeating task sequences eliminate the need to rely on an exogenous task cue, and thus eliminate the need to interpret the task cue (which is itself an additional task).

Furthermore, studies with repeating task sequences often present each task in a unique location. Therefore, the perception of a stimulus in a particular location might help to automatically activate the correlated task set. If any of these speculations are correct, it follows that the upcoming task would be better prepared with fixed task sequences. If so, then there would be less need for task-set inhibition. It would be premature, however, to conclude that fixed task sequences eliminate task-set inhibition. One reason is that no studies have directly compared fixed and random sequences using similar stimuli, tasks, and methods.

Exogenous Cues

Another possible factor other than or in addition to the repeating task sequence that may modulate the N-2 repetition cost is the type of exogenous task cue used. In several of the cases where no N-2 repetition cost was observed, a non-verbal task cue

(i.e., non-text based cue) was used. As discussed earlier, when a repeating task sequence is used, tasks are endogenously cued. Furthermore, it should be pointed out that when a task is endogenously cued, there is no need for an explicit task cue. Consistent with this line of reasoning, both Koch et al's (2006) and Lien et al's (2006) studies contained no exogenous task cue. However, in the no-foreknowledge condition of Koch et al's study, a significant N-2 repetition cost was observed. Given the findings in the no-foreknowledge condition, the absence of a verbal task cue is likely not the sole factor for determining the presence or absence of the N-2 repetition cost.

There is also evidence that suggests the absence of a verbal task cue is important in the traditional backward inhibition paradigm as well. In Hübner, Dreisbach, Haider, and Kluwe's (2003) study, task-set inhibition was investigated in two experiments with a total of three separate cue types. For all experiments, there was either a color cue (i.e., the word "new" color coded for each task) that explicitly revealed the type of trial (switch or repeat) and the identity of the task, a cue that only indicated the type of trial, or no cue. In all cases, no N-2 repetition cost was observed. Furthermore, only in the explicit color cue condition was there any evidence consistent with task-set inhibition.

Arbuthnott (2005) argued that task-set inhibition is facilitated when a task is cued with a verbal task cue. She further asserts that using an exogenous spatial task cue will eliminate task-set inhibition. This prediction is based on the hypothesis that strength of the association between a task and cue directly affects the overall strength of activation for a task set. When a task is cued with a weak cue-to-task association, the competition between task-sets is reduced; thus, the need for task-set inhibition is also reduced. To test this hypothesis, Arbuthnott used either verbal cue or spatial cue. In the spatial cue

condition, a string of asterisks was presented in one of three unique spatial locations. Each of the three tasks participants performed was assigned with one of the three locations (e.g., task A in the lower right corner). In the verbal cue condition, tasks were cued by the task mapping (e.g., odd – even). She found that the switch cost on RT was larger when the task was cued with the spatial cue relative to the verbal task cue. Furthermore, the N-2 repetition cost was present in the verbal cue condition but was absent in the spatial cue condition.

The N-2 repetition cost is assumed to reflect task-set inhibition. Despite the findings of Mayr and Keele (2000) being well replicated, there are several cases where the N-2 repetition cost would be expected to be observed, but is not. In the present study, two broad factors were investigated for their role in predicting when task-set inhibition will, or will not, be used. Endogenously switching between tasks or chunking task sequences is one possible factor that reduced the need to use task-set inhibition. In the various cuing paradigm studies where no N-2 repetition cost was observed, the type of exogenous cues could be an important factor. The absence of a verbal task-cue is often a common factor in several studies where no N-2 repetition cost was observed (e.g., Arbuthnott, 2005; Arbuthnott & Woodward, 2001; Hübner et al., 2003). Arbuthnott (2005) specifically argued that a spatial exogenous cue would eliminate the N-2 repetition cost. However, in all studies discussed above, there are often additional co-occurring factors that obfuscate the true source of the elimination of the N-2 repetition cost (see Table 1 for a summary). The purpose of the present study, therefore, was to systematically examine what the necessary conditions are for producing, or eliminating, the N-2 repetition cost (e.g., predictable task sequence, fixed location for each task,

absence of a verbal task-cue).

Table 1. A summary of task-set inhibition studies including the type of task sequence used, the type of cue, and whether or not an N-2 repetition cost was observed.

Study	Task Sequence	Cue Type	Task-Set Inhibition
Arbuthnott (2005)	Random	Spatial	No
		Verbal	Yes
Arbuthnott & Woodward (2002)	Random	Spatial	No
		Verbal	Yes
		Symbolic	Yes
Gade and Koch (2005)	Random	Form	Yes
Hübner et al. (2003)	Random	Color	Yes
		Color	No
		None	No
Koch, Philipp, & Gade (2006)	Repeating	Non-verbal	No
Kuhns, Lien, & Ruthruff (in press)	Random	Verbal	Yes
Lien et al. (2006)	Repeating	Task sequence	No
Mayr & Kliegl (2003)	Random	Symbolic	No
Mayr & Keele (2000)	Random	Verbal	Yes
Mayr (2001)	Random	Verbal	Yes
Mayr (2002)	Random	Verbal	Yes
Philipp & Koch (2005)	Random	Verbal	Yes
Schuch & Koch (2003)	Random	Form	No

CHAPTER 4: EXPERIMENT 1

Experiment 1 was designed to test the hypothesis that the use of a repeating task sequence facilitates task preparation, thus reducing the need for inhibition. A fixed, repeating task sequence of ABCACB was used. This sequence allows for a completely predictable task order with, importantly, both N-2 repetition trials and N-2 switch trials. Participants performed a parity task (odd versus even), a magnitude task (less than 5 versus greater than 5), or a distance task (near or far from 5) on a digit. One of three tasks was presented within one of six segments of an equally divided hexagon (see Figure 2), so that each task appeared in two of the segments on every run of six trials. In addition to task order, task identity was also cued through colored coded segments, so that each color was associated with only one task (e.g., red is parity) and an explicit task cue. The stimuli rotated clockwise around the hexagon from trial to trial. If the just performed task set is not inhibited when an endogenous switch is made, then it should be relatively easy to switch back to that task after an intermediate trial (i.e., N-2 repetition) compared to three consecutive switch trials (i.e., N-2 switch) and therefore reduce the N-2 repetition cost.

Method

Participants

A total of 36 undergraduates participated in exchange for extra course credit. All had normal or corrected-to-normal vision.

Apparatus and stimuli

Stimuli were presented on a 19-inch CRT monitor. A hexagonal frame 15.2 cm in diameter consisting of six segments was presented in the screen center (see Figure 2).

The segments were colored red, black, or blue, with each color being in two segments. On each trial, a white digit (0.7 cm wide and 1 cm tall) appeared in one of these segments. At an average viewing distance of 55 cm, the digit subtended a visual angle of $0.73^\circ \times 1.04^\circ$. Responses were made into a standard English keyboard on horizontally aligned keys.

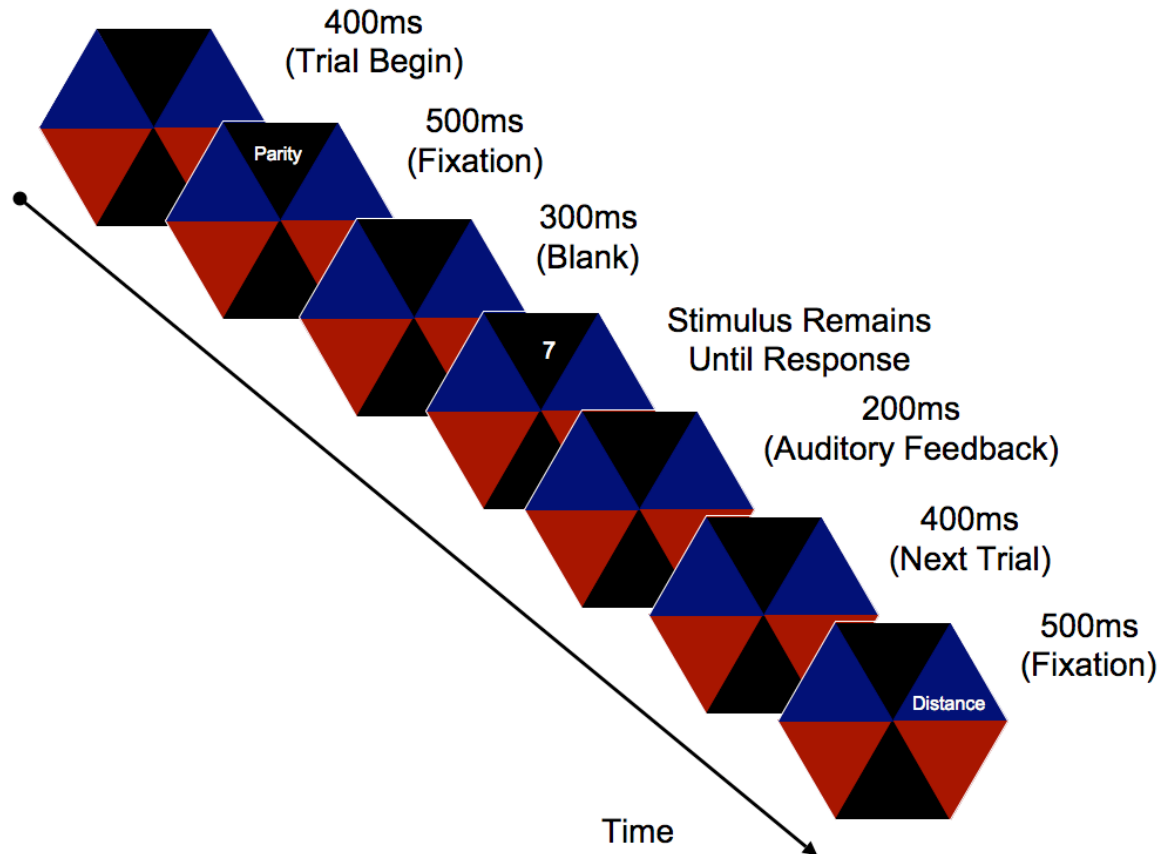


Figure 2. A sample sequence from Experiment 1 showing the hexagon figure divided in to six equal segments.

Design and procedure

On each trial, participants performed a parity task, a magnitude task, or a distance task. For the parity task, participants pressed the “Z” key for odd digits (1, 3, 7, or 9) and the “M” key for even digits (2, 4, 6, or 8). For the magnitude task, participants pressed

the “Z” key for less-than-5 digits (1, 2, 3, or 4) and the “M” key for greater-than-5 digits (6, 7, 8, or 9). For the distance task, participants pressed the “Z” key for near by 5 digits (3, 4, 6, or 7) and the “M” key for far from 5 (1, 2, 8, or 9). Participants pressed the “Z” and “M” keys with their left-index and right-index fingers, respectively.

Following Rogers and Monsell (1995), the first stimulus of each block appeared in the top segment (see Figure 2). Each subsequent stimulus appeared in the segment located immediately clockwise from the previous one. Each trial started with an explicit verbal task cue, which remained on the screen for 400 ms. The task cue “parity”, “magnitude”, or “distance” appeared in the center of the segment for 500 ms. After a 300 ms blank period, the stimulus appeared. If participants responded incorrectly, auditory feedback (a beep on error trials, silence on correct trials) was presented for 200 ms. The task cue for the next trial appeared 400 ms later in the segment located immediately clockwise from the previous one. Consequently, the total RCI was 600 ms and the CSI was 800 ms. Furthermore, the hexagonal frame was on the screen all the time throughout the entire block.

Six different task sequences were used: ABCACB, ACBABC, BACBCA, BCABAC, CABBCA, and CBACAB. Each participant received only one particular task sequence for all blocks. Equal numbers of participants were randomly assigned to one of the six sequences. As shown in Figure 2, the segment was colored black, blue, red, black, red, and blue clockwise from the top segment regardless of what task sequence participants were assigned. Thus, the color was associated with only one particular task, varied across participants.

Participants performed one practice block and 6 regular blocks with each

contained 72 trials. In the written instructions, both speed and accuracy were equally emphasized. After each block, participants received feedback regarding their mean RT and accuracy for that block. They were encouraged to rest before beginning the next block.

Results

Trials were excluded from analysis if RT was less than 100 ms or greater than 4,000 ms (1.15% of trials). Trials following an error were also omitted from the final data analyses. For RT analyses, only the trials with correct responses were included. Data were analyzed as a function of N-2 task transition (repetition versus switch).

Table 2 shows the mean RT and mean proportion of error (PE) for both N-2 repetition and switch trials. The main effect of N-2 task transition was significant on RT, $F(1, 35) = 17.53, p < .001, MSE = 6,656$; the mean RT was 1,057 ms in the N-2 task repetition condition and was 977 ms in the N-2 task switch condition. In contrast to RT, the PE revealed no significant main effect of the N-2 task transition, $F(1, 35) = 1.15, p = .29, MSE = 0.0003$; the PEs were .056 and .051 in the N-2 task repetition and N-2 task switch conditions, respectively. Thus, the N-2 repetition cost was 80 ms on RT but was only .005 on PE.

Discussion

One would expect that task-set inhibition is only applied when a possible conflict is expected between the just completed task and the upcoming task set. Experiment 1 was designed to reinforce the mental representation of the task sequence through the use of fixed, repeating task sequences. Moreover, participants were provided the implicit, endogenous cue of the fixed, repeated task sequence and the explicit, exogenous cues of

color, spatial location, and verbal task cue to aid in the preparation of the upcoming task set. Despite the strong incentives for engaging in advance preparation for the upcoming task set, the N-2 repetition cost persisted. Even with complete foreknowledge of the upcoming task set that would be needed to the participants in advance, nevertheless, we still observed a substantial N-2 repetition cost of 80 ms on RT. These findings, inconsistent with the findings of Koch et al. (2006) and Lien et al. (2006), suggest that using the fixed, repeating task sequence does not eliminate entirely the task-set inhibition.

CHAPTER 5: EXPERIMENT 2

Experiment 1 used a fixed, repeating task sequence and still produced an N-2 repetition cost. This result is not consistent with previous studies, which have shown no N-2 repetition cost with a fixed, repeating task sequence. The discrepancy between these studies could be due to the inclusion of several redundant task-set cues (e.g., color, location, etc.) in the current Experiment 1, but not in the previous studies (see the exception of the spatial task cue in Lien et al., 2006). It is therefore possible that the absence of the N-2 repetition cost in the previous studies is the result of no verbal cuing of the upcoming task. Experiment 2 was designed to test if the absence of a verbal cue eliminates the N-2 repetition cost.

The design of Experiment 2 was similar to that of Experiment 1, with the exception that the verbal task cue was replaced with a task-neutral fixation cross. If the presence of N-2 repetition cost is primarily due to the presence of a verbal task cue, then one would expect the absence of N-2 repetition cost when the verbal task cue was absent.

Method

Participants

There were 36 participants, drawn from the same participant pool as in Experiment 1. None had participated in Experiment 1.

Apparatus, stimuli, and procedure

The apparatus, stimuli, and procedure were the same as in Experiment 1, except the verbal task cue in Experiment 1 was replaced with a neutral fixation point (e.g., +).

Results

The data analysis was similar to that of Experiment 1. Application of RT cutoffs

eliminated 1.03% of responses. The main effect of N-2 task transition was significant on RT, $F(1, 35) = 8.46, p < .01, MSE = 9,637$, and on PE, $F(1, 35) = 6.98, p < .05, MSE = 0.0004$. The mean RT and PE for N-2 task repetition transitions were 1,058 ms and .050, respectively. For N-2 task switch transitions RT and PE were 999 ms and .040, respectively. The N-2 repetition cost was 58 ms on RT and .010 on PE.

Discussion

In Experiment 2, we removed the verbal task cue. The N-2 repetition cost was still obtained in both RT and PE data. Thus, the absence of a verbal cue alone is not sufficient to eliminate the N-2 repetition cost.

CHAPTER 6: EXPERIMENT 3

Another common design among the studies showing no N-2 repetition costs is that each task was presented in a unique location (Arbuthnott, 2005; Arbuthnott & Woodward, 2001; Hübner et al, 2003). In our previous experiments, each task was associated with two different spatial locations (e.g., Task A in the sequence of ABCACB was associated with the top and bottom segments). One might argue that participants might not fully utilize the spatial task cue to engage in advance preparation for the upcoming task set. As a consequence, it is more difficult to overcome the inhibition of the just-performed task set, leading a large N-2 repetition cost. Experiment 3 was designed to examine whether the N-2 repetition cost can be reduced or eliminated when each task is associated with only one unique spatial location.

Method

Participants

There were 36 participants, drawn from the same participant pool as in previous experiments. None had participated in the previous experiments.

Apparatus, stimuli, and procedure

The apparatus, stimuli, and procedure were the same as in Experiment 2, except for the following changes. Instead of presenting a hexagonal frame, we presented a circular frame, divided into three segments (see Figure 3). These segments were colored black, blue, and red for the top, right and left segments, respectively. The same three digit tasks (parity, magnitude, and distance, for Task A, B, C, respectively) from Experiments 1 and 2 were used. As in previous Experiments 1 and 2, the same six task sequences were used. Additionally each task appeared only a single, unshared location

within the circular frame. The task sequence always began in the top segment, then rotating right, left, top, left, and right. The sequence of tasks resembled the tick-tock movement of a pendulum. The whole sequence repeated again.

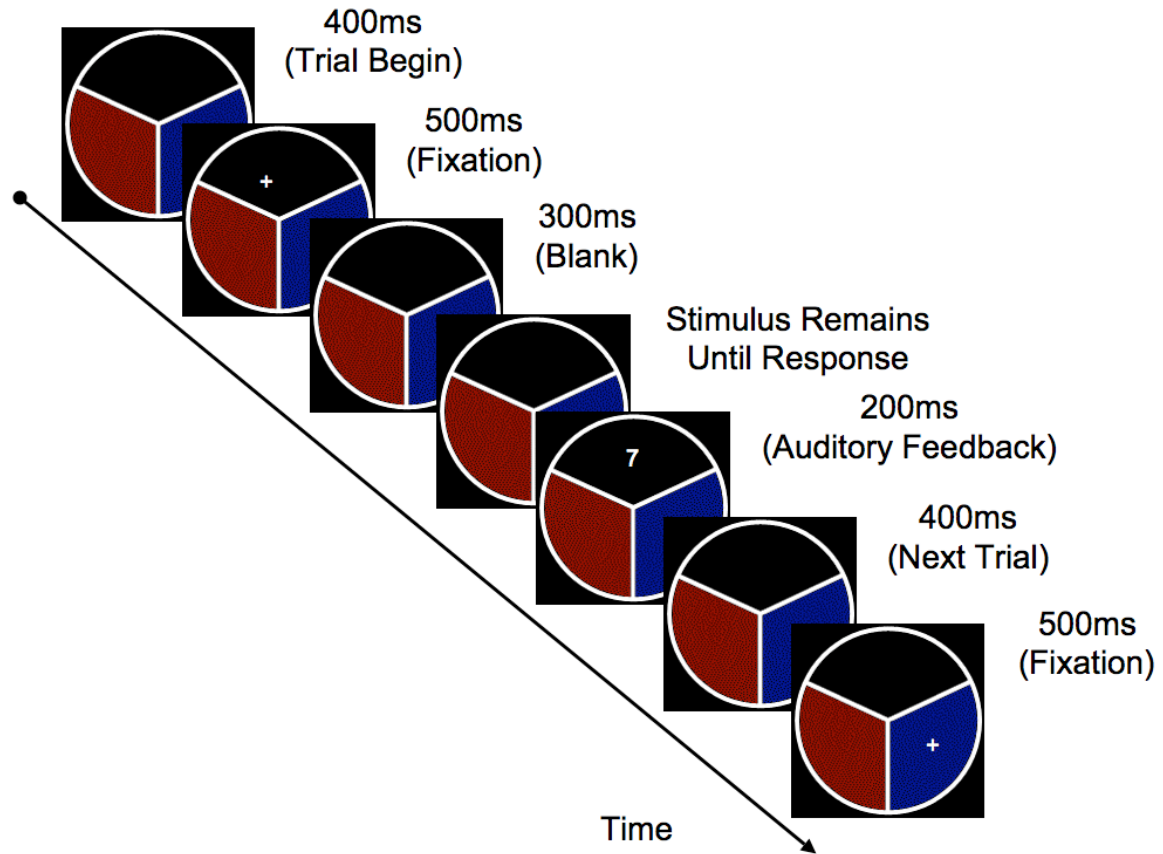


Figure 3. A sample sequence from Experiment 3 showing the circular figure divided in to three equal segments.

Results

The data analysis was similar to that of previous experiments. Application of RT cutoffs eliminated 1.02% of trials. The main effect of N-2 task transition was significant on RT, $F(1, 35) = 8.46, p < .01, MSE = 9,637$, and on PE, $F(1, 35) = 6.98, p < .05, MSE = 0.0004$. The mean RT and PE for N-2 task repetition transitions were 995 ms and .048, respectively. For N-2 task switch transitions RT and PE were 953 ms and .051,

respectively. The N-2 repetition cost was 42 ms on RT and -.003 on PE.

Discussion

Even when each task was associated with a unique spatial location, a large N-2 repetition cost of 42 ms was still obtained. This finding is surprising given that previous studies have shown the elimination of the N-2 repetition cost when the task set was cued by its associated spatial location (Arbuthnott, 2005; Arbuthnott & Woodward, 2001; Hübner et al., 2003). Given the findings of Arbuthnott (2005) and Koch et al. (2006), one would expect that no N-2 repetition cost would have been observed in Experiments 1, 2, or 3.

CHAPTER 7: EXPERIMENT 4

In Experiments 1-3, a fixed, repeating tasks sequence was used. Regardless of the presence/absence of the verbal task cue (Experiments 1 and 2) and presence of a unique spatial task cue for each task (Experiment 3), a substantial N-2 repetition cost was still obtained. These findings suggest that these exogenous cues by themselves are not sufficient to eliminate task-set inhibition.

In previous studies of task-set inhibition, a random sequence of tasks was used. In Experiment 4, stimuli were presented in a random order, but in fixed and unique locations. Tasks were spatially cued by presenting a fixation cross in the unique location of the upcoming task. Through the fixation cross and thus spatial location, the identity of the current task was revealed. In previous studies investigating cue types, it was found that spatial location based cuing of a task eliminates the N-2 repetition cost (Arbuthnott, 2005). Thus, if the relevant task identity is only known through where it is presented, then there should be no N-2 repetition cost.

Method

Participants

There were 36 participants, drawn from the same participant pool as in previous experiments. None had participated in these experiments.

Apparatus, stimuli, and procedure

The apparatus, stimuli, and procedure were the same as in Experiment 3, except as noted below. Instead of presenting tasks in a predictable repeating sequence, they were presented in a random order. The same three digit tasks (parity, magnitude, and distance) were used. Depending on where the stimulus appeared, the participants were to

respond to the proper task set.

The following six task-location assignments were used such that the tasks appeared in the upper, lower right, or lower left segments within the figure: ABC, ACB, BAC, BCA, CAB, and CBA. Each participant received only one particular task-location association for all blocks. Equal numbers of participants were randomly assigned to one of the six task-location assignments. The segments were colored black, blue, and red clockwise from the top segment regardless of what task sequence participants were assigned. Thus, the color was associated with only one particular task, varied across participants.

Results

The data analysis was similar to that of Experiment 1. Application of RT cutoffs eliminated .69% of trials. Different from Experiments 1 to 3, the main effect of N-2 task transition was not significant on RT, $F(1, 35) = 1.71, p = .20, MSE = 2,127$. The N-2 repetition cost was -14 ms. On the other hand, the PE data revealed a significant effect of N-2 task transition, $F(1, 35) = 4.64, p = .04, MSE = 0.0002$. The mean RT and PE for N-2 task repetition transitions were 1,064 ms and .051, respectively. For N-2 task switch transitions RT and PE were 1,077 ms and .045, respectively. The N-2 repetition cost was -13 ms on RT and .006 on PE.

Discussion

In Experiment 4, a random task sequence was used. The critical manipulation was that each task was associated with a unique spatial location. Different from previous experiments, the N-2 repetition cost was absent. This is the only condition of four that replicated findings from Arbuthnott's (2005).

CHAPTER 8: GENERAL DISCUSSION

Summary of findings

The purpose of the current study was to test several of the conditions that would eliminate or modulate the N-2 repetition cost. Table 2 summarizes the results in Experiments 1-4. In Experiments 1-3, a fixed, repeated task sequence was used. Additional factors, such as the presence or absence of a verbal task cue and spatial cue were also tested in Experiments 1-3. An N-2 repetition cost was observed despite tasks being presented in a fixed, repeating task sequence. Thus, endogenously cuing a task alone does not eliminate the N-2 repetition cost. In addition, Experiment 1 demonstrated that providing all possible cues through combining a fixed, repeating task sequence with a variety of exogenous cues did not eliminate the N-2 repetition cost. Experiment 2 showed that the absence of a verbal cue alone is also not sufficient to eliminate the N-2 repetition cost. Finally, Experiment 3 showed that associating a task with a single, unique location does not eliminate the N-2 repetition cost either.

Table 2. Mean Response Times in Milliseconds (Proportion of Errors in Parentheses) in Experiment 1-4 as a Function of N-2 Task Transition (Task Repetition and Task Switch).

	N-2 Task Transition		<i>N-2 Repetition Cost</i>
	N-2 Task Repetition	N-2 Task Switch	
Experiment 1	1,057 (.056)	977 (.051)	79 (.005)
Experiment 2	1,058 (.050)	999 (.040)	58 (.010)
Experiment 3	995 (.048)	953 (.051)	42 (-.003)
Experiment 4	1064 (.051)	1077 (.045)	-13 (.006)

In contrast to Experiments 1-3, Experiment 4 used a random task sequence where the exogenous task cues must be relied upon in order to prepare for the upcoming task. Furthermore, each task was cued by a unique spatial location. While the exogenous cues had no effect on the N-2 repetition cost in Experiments 1-3, the spatial cue eliminated the N-2 repetition cost in Experiment 4 (see Figure 4).

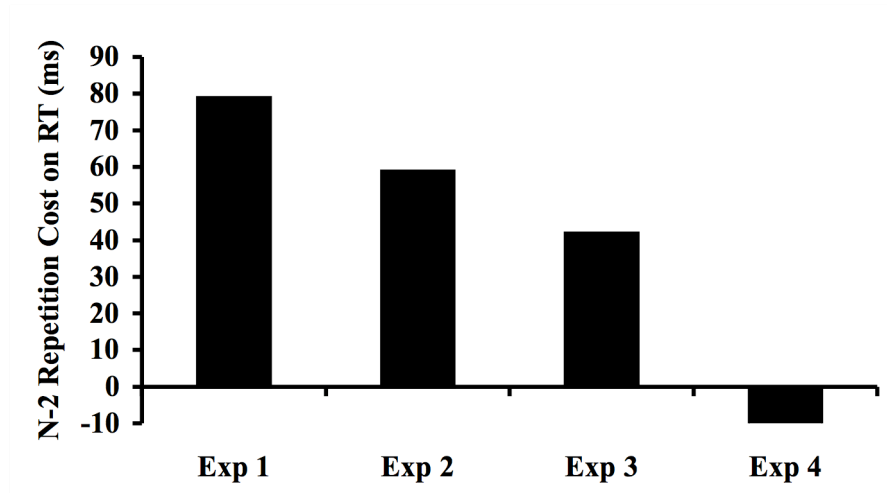


Figure 4. The N-2 repetition cost from Experiments 1-4.

Repeating Task Sequences vs. Chunking

Although Experiments 1-3 rule out the hypothesis that an endogenously cued sequence of tasks will eliminate the N-2 repetition cost, it does not contradict the hypothesis that within a chunked sequence of tasks will decrease the need for task-set inhibition. Additionally, the inferences from Experiments 1-3 are limited to only concluding that the modulation of the N-2 repetition cost in Koch et al.'s (2006) study were not purely the result of the endogenous switching between tasks. In Koch et al.'s study, the chunked task sequences of ABA and CBC were emphasized to the participants in the fully aware group. This instruction was used to encourage participants to form two distinct chunks with N-2 task repetitions and task switch transitions. The analysis of N-2

task transition was within a chunking structure. In the current experiments, tasks were emphasized as individual tasks within sequences of 6 (e.g., ABCACB). For Experiments 1-3, an N-2 task switch transition was analyzed between strings of six. If chunking does modulate the N-2 repetition cost, it should be expected that a larger N-2 repetition cost would be observed between chunking structures compared to within (e.g., Koch et al., 2006).

Exogenous Cues

Another factor that has now been ruled out as eliminating the N-2 repetition cost is the absence of a verbal task cue. In several prior studies, a failure to observe an N-2 repetition cost was accompanied with using non-verbal task-cues (Arbuthnott, 2005; Hübner et al, 2003). In Experiments 2 and 3, no verbal cue was used; however, an N-2 repetition cost was observed.

Arbuthnott (2005) argued that the N-2 repetition cost is eliminated when tasks are cued using a fixed, unique spatial location because the spatial cue preferentially activates response sets resulting in reduced competition between simultaneously activated task-sets; thus, reducing task-set inhibition. In effect, the separate locations are more distinct, thus reducing the competition between tasks. Arbuthnott stated that the need for task-set inhibition is reduced, “because of the special status of spatial information in human cognition” (p. 1041). Arbuthnott’s facilitated activation account asserts that any pairing of task to special location should reduce or eliminate an N-2 repetition cost. This should hold true regardless of whether the task switch is endogenously or exogenously cued. In the present study, however, an N-2 repetition cost was only eliminated when tasks were presented in a random sequence. Clearly the benefits from assigning a task to a fixed,

unique location is not the end all to modulating the N-2 repetition cost.

CHAPTER 9: IMPLICATIONS

Chunking and Endogenous Control

Clearly an endogenous switch cued by a fixed, repeating task sequence alone will not eliminate the N-2 repetition cost. However, in the present study the long sequences of tasks create uncertainty as to whether or not the task sequence was represented as a single chunk of six, multiple chunks, or if any chunking occurred at all. Moreover, if any chunking occurred, it is unclear where the chunk boundaries fell. If the chunking of, and not the endogenous switching between, tasks is what eliminates the N-2 repetition cost, then N-2 task transitions must be compared within and between chunking structures. In Experiment 3, the clear emphasis would have been to chunk ABC and ACB as two units because of the tick-tock pattern that the tasks were presented in. This would have created more N-2 task switch transitions within chunks than between chunks. All of the N-2 task repetition transitions would have been assessed between chunks. As previously stated, Koch et al.'s (2006) hypothesis is that within a chunk RT will be modulated relative to a N-2 task repetition transition. If this is correct, it is reasonable to assume that N-2 task switch RT could also be modulated by chunking. If this is true, then the assessment of the N-2 repetition cost would be exaggerated in Experiments 3. Because most of the N-2 task switch transitions were within chunks, RT performance would be speeded for N-2 task switch transitions, which would create an N-2 switch benefit where the N-2 task repetition transitions would be slowed increasing the N-2 repetition cost. In the case of Koch et al., the reverse is true. Their design created two chunks of ABA and CBC. This would create more within chunk N-2 task repetition transitions than between chunk N-2 switch transitions. The within chunk N-2 repetition cost should be reduced

(i.e., shorter RT) where the between chunk N-2 switch benefit should be also be reduced (i.e., longer RT). Therefore, in both cases the exact use of task-set inhibition is obscured by the within vs. between chunk assessment of the N-2 repetition cost and N-2 switch benefit.

To more closely examine the question of chunking and task-set inhibition, a different sequence of tasks is needed. One way to more carefully examine how chunking and endogenous switching affect the use of task-set inhibition would be to use a hybrid of the cueing paradigm and fixed, repeating sequence. This could simply be achieved by exogenously cuing chunks of three task trials rather than exogenously cuing individual tasks on a trial-by trial basis or purely endogenously through a fixed, repeating task sequence. This would allow for endogenous switching within a chunk, but more importantly, it would also allow for within and between assessment of N-2 repetition and switch task transitions. Most importantly, this would eliminate the confound present in both the current study and in Koch et al.'s (2006).

This novel paradigm creates specific predictions regarding the N-2 repetition cost and N-2 switch benefit for the hypothesis presented here and for the hypothesis proposed by Koch et al. (2006). Koch et al.'s hypothesis asserts that task-set inhibition is not needed for chunked tasks. The hypothesis presented here is that the confound of the within and between N-2 task transition comparison either exaggerates or masks the N-2 repetition cost for chunked tasks. If Koch et al.'s hypothesis that task-set inhibition is not needed to control the task-sets within a chunk is correct, then within-chunk comparisons should modulate the N-2 repetition cost or eliminate it completely. However, if this hypothesis is not correct, then the N-2 repetition cost will be observed. On the other

hand, the between-chunk comparisons would produce the presence of an N-2 repetition cost. The N-2 repetition cost should be eliminated when the N-2 repetition cost is assessed based on a between chunk N-2 task switch transition to a within chunk N-2 task repetition transition.

The Special Case for Location

Although the conclusions reached by Arbuthnott (2005) about why the spatial cuing of tasks modulate the N-2 repetition cost is inconsistent with the present study's findings, there is strong evidence that spatial information and location do play an important role in task switching and cognitive control. The elimination of the N-2 repetition cost in Experiment 4 clearly illustrates that location and spatial information have some special influence on task switching. However, it is still not clear why the spatial cue modulates the N-2 repetition cost. The primary question that remains unanswered is whether cue-location association, task-location association, or both are modulating the N-2 repetition cost.

Three possible methods for investigating whether the cue-location association leads to the modulation are to (a) present a non-spatial location cue in a neutral location and the tasks in fixed, unique spatial locations, (b) use a purely non-spatial, non-location cue that is arbitrary associated with a fixed unique task location, and (c) remove any exogenous cue completely.

Both in Arbuthnott (2005) and in the present Experiment 4, spatial information is defined as the physical location of the cues and tasks in visual space. If location does have special status, it stands to reason that any location shift should eliminate the N-2 repetition cost. It is possible to have a verbal task cue that is spatial, but is not location

based. The non-spatial location cue could be created by verbally directing attention to a fixed, unique task location (e.g., top, right, left). If the non-spatial location cue were presented centrally relative to the three task locations, then it would require a purely endogenous shift of locations. In both Arbuthnott and the present study, the spatial task-cue is an exogenous cue. The cue appears in one location and then attention is drawn to that spatial location where the cue is present, and finally the task appears in that same location. A non-spatial location cue presented in a neutral location would require an endogenous shift to that location and then the stimulus would need to be interpreted. If the N-2 repetition cost were observed, it would be strong evidence that location does have special status and that special status is true for both endogenous and exogenous shifts of attention in visual space.

One alternative for removing the exogenous shift of attention to a unique spatial location is to use a task cue that is purely arbitrarily associated to a location. By using auditory tones of different frequency (e.g., low, medium, high), the attentional shift to a fixed unique task location would be purely endogenous. The same method could be executed using an arbitrary visual stimulus (e.g., color patches); however, using an auditory rather than visual cue would eliminate any exogenous direction of visual attention from one spatial location to another. In sum, the auditory cue would require a purely endogenous shift to a specific spatial location.

Neither Arbuthnott (2005), Experiment 4, nor the proposed experiments clarify whether cue location or task location is important. The simplest method for answering the question about spatial task cues and location is to eliminate all exogenous spatial cues entirely. In the two aforementioned examples, the endogenous shift of visual attention

from one location is exogenously cued. If a task is associated with a single fixed, unique location in space, no exogenous cue of any kind should be needed. The stimulus could simply appear in its associated location and maintain the same effect on the N-2 repetition cost. If the N-2 repetition cost is observed, this would indicate that the cue-location association is what is important for modulating the N-2 repetition cost and not the task-location association. An observation of the N-2 repetition cost would be consistent with the findings in Experiments 1-3, which suggest that there is more to modulating the N-2 repetition cost than task-location associations. Provided that an N-2 repetition cost is observed when all exogenous cues are eliminated, the next logical step to confirm the hypothesis that the N-2 repetition cost is modulated by cue-location associations and not task-location associations would be to present the cues in fixed, unique locations and the tasks in a neutral location. If the cue-location association is what is important, then the N-2 repetition cost should be eliminated despite the fact the tasks all appear in a single location.

Attentional control and aging

Age-related differences in cognitive functions have been a heavily researched in the past few years, especially with regard to cognitive control (for a review, see Rogers & Fisk, 2001). For safety's sake in dynamic environments, such as driving under divided attention circumstances, research on attention is especially important for understanding processing capacity and processing limitations (Strayer & Johnson, 2001). Moreover, the decline of attentional control with age is an important for applied questions such as what is a safe driving age or what defines competency for safe driving? Many drivers continue to stay on the roads up until 80 years of age and in some cases even older. Since 1959,

the Federal Aviation Administration (FAA) has not allowed commercial pilots over the age of 60 to operate commercial aircraft. In 1997, the FAA extended the so-called Age 60 Rule to commuter aircraft as well. In both the case of driving and operating aircraft, understanding changes in the control of attention is important for determining what an appropriate age cutoff is and whether an absolute cutoff (e.g., 60 years of age) is appropriate and justified. Clearly, understanding the changes or stability of the processing capacity and limitations of attention in old age is crucial for both theoretical and applied research.

Inhibition and Attention

Inhibition has been shown to be extremely important for attentional control. Control processes such as attending to a specific dimension of an ambiguous stimulus (Stroop, 1935; West, 2004), ignoring irrelevant and distracting information (Eriksen & Eriksen, 1974), the control of memory retrieval (Anderson & Levy, in press), and for switching between tasks (Mayr, 2002; Mayr & Keele, 2000). Furthermore, age-related declines in inhibitory control are consistent with the results of a variety of studies documenting age-related deficits in cognitive functions (Hasher & Zacks, 1988).

Aging Theories

Within attention and aging research, there is an ongoing debate about the cause of age-related differences. One hypothesis is that there is a general slowing of nervous system activity (Salthouse, 1996). The alternative is a modular approach. In the case of the latter, declines in specific functions (e.g., response selection) are the root cause of many age-related performance differences between younger and older adults. For instance, several researchers have suggested that older adults have more difficulty than

younger adults in selecting the proper task set when stimuli are associated two competing tasks (Kray & Lindenberger, 2000; Mayr, 2001). Also within the modular approach is a hypothesized deficit in inhibitory control (Hasher & Zacks, 1988). The inhibitory control hypothesis also predicts selection difficulty in the presence of distracting or competing information.

Inhibition and Aging

In the Hasher and Zacks (1988) model of working memory, general decline in the ability to inhibit, or control inhibition, was hypothesized to be an underlying cause in age-related deficits. Seemingly, a large portion of aging research has obtained results that appear to be consistent with general declines in the ability to control inhibition. Hasher and Zacks hypothesized the inefficient use of inhibition would lead to increased activation of information in working memory and increased spreading of activation. Both the increased activation and spread of activation would lead to increased competition between information and difficulty in processing. Evidence supporting general decline in inhibitory control has been obtained for a negative priming tasks (Hasher, Stoltzfus, Zacks, & Rypma, 1991). In this task, the lack of inhibition is observed when a distractor that must be ignored on one trial becomes the target on the subsequent trial. Younger adults were found to be slow in this instance because of carry over inhibition (i.e., the negative priming effect). The older adults, however, did not show the negative priming effect. These findings led Hasher et al. to conclude that the inhibitory control declines with age.

Age-related slowing in the Stroop task is also consistent with the theory of inefficient inhibition described above. Using electrophysiological and behavioral

measures, West (2004) observed slower RT for older adults in the Stroop task and decreased amplitude in brain activity over the frontal-central-parietal region, which has been associated with conflict processing during interference (e.g., distracting information).

Inhibition Is Modular

Although there is a large body of evidence consistent with general declines in inhibitory control with age, it can logically be reasoned that any evidence of preservation of inhibitory function could be seen as evidence in support of specific declines in inhibitory. To this end, Kramer, Humphrey, Larish, Logan, and Strayer (1994) had participants perform a battery of cognitive tests hypothesized to require separate control mechanisms. They observed that older adults had difficulties on some tasks, but did not show age-related differences on other tasks. Furthermore, the performance between these tasks was not highly correlated, suggesting separate forms of inhibition independently affected by age. Among the tasks that older adults completed, they showed increased rates of perseverative errors on the Wisconsin Card Sorting Task, but they did not show evidence of difficulty in the negative priming tasks. Kramer et al. concluded that inhibition is sensitive to the difficulty of the tasks.

Aging and Task-Switching

The task-switching paradigm provides an elegantly simple method for assessing which inhibitory functions are associated with age-related declines. Because of its utility for elucidating control functions, the task-switching paradigms are also a useful tool for investigating age differences between younger and older adults (e.g., Kray & Lindenberger, 2000; Mayr, 2001). Additive increases in the length of RT, rates of errors,

and increases in the switch cost on RT and error rates are indicators of task difficulty and the difficulty of control, respectively (e.g., Allport, Styles, & Hsieh, 1994). Differences in the ability to meet cognitive control demands can be understood by manipulating the difficulty of target discrimination during the perceptual stages (e.g., target ambiguity) or during the selection stage (e.g., response selection). The performance cost associated with switching is theorized to be caused by both interference between task sets and the time required to mentally reconfigure a new task set once a switch has been made (Meiran, 1996).

Aging and Task-Set Inhibition

Mayr and Keele (2000) provided compelling evidence that inhibition is necessary for task switching. Moreover, they demonstrated that the inhibitory processes that were observed in their paradigm could not be explained by negative priming. In the context of aging literature, this is very interesting because of the large amount of research have used negative priming paradigms to investigate age-related changes in inhibitory control (e.g., Connolly & Hasher, 1993; Hasher et al, 1991; Kramer et al, 1994). Mayr and Keele hypothesized the role of, and mechanism behind, the task-set inhibition was distinct from the type of inhibition used for selective attention during perceptual processing (e.g., Stroop or flanker task). Theoretically, if task-set inhibition is different from the inhibition used to block out distracting information, then it suggests that age-related difference in negative priming would not predict age differences in task-set inhibition. Negative priming, by nature, is the result of carry-over inhibition from inhibiting a distractor. Thus, negative priming would reflect inhibition during perceptual processing

stages as in Hasher et al. (1991), but not during the selection of response sets that task-set inhibition is hypothesized to do (Mayr, 2002; Schuch & Koch, 2003).

In the backward inhibition paradigm, it is not possible to distinguish between perceptual inhibition and selection inhibition. To disambiguate these two forms of inhibition in younger adults, Kuhns, Lien, and Ruthruff (in press) used a combination of backward inhibition and flanker paradigms. Kuhns et al. used what could be described as reverse negative priming to demonstrate that task-set inhibition can transfer to aid in the suppression of distracting information (see also Hübner, Haider, Dreisbach, & Kluwe, 2003). Thus, there is evidence, at least in younger adults, that task-set inhibition and the inhibition observed in the negative priming literature are unique, but not entirely independent from one another.

Age-related differences in switch costs are not always present (e.g., Kray & Lindenberger, 2000). The fact that age does not interact with switch costs is not surprising if the problem arises from inefficient inhibition and the declines in inhibitory control that are purely perceptual. Given that task-set inhibition is not a form of negative priming, it is unclear whether or not task-set inhibition would reveal a clear source of age-related differences. Although there were no age-related differences when switch costs were measured within blocks (known as the local switch cost), there was age-related difference when switch costs were measured between the pure blocks and the alternating blocks (known as the global switch cost; e.g., Kray & Lindenberger, 2000). These findings suggest that there are some age-related differences in the ability to maintain two different task sets in memory. Mayr (2001) hypothesized that task-set inhibition could possibly provide an explanation for global switch cost. This is a logical

assumption based on the fact that task-set inhibition has been shown not to be due to negative priming and does not predict local switch costs (Mayr & Keele, 2000). When the task-set inhibition hypothesis was tested, it turned out that global switch costs were not predicted by age-related differences. The global switch costs were, however, predicted by a combination of age, ambiguity of target stimuli (i.e., distractors) and response-set overlap (i.e., response selection difficulty). The task-set inhibition for older adults was significantly larger than younger adults (55 ms vs. 15ms). In spite of the difference, the results were not consistent with age-related changes in task-set inhibition.

It is possible both the changes in inhibitory control and cognitive control share a common origin. An interesting similarity in the studies by Kramer et al. (1994) and Mayr (2001) is the persistent activation and persistent deactivation (i.e., inhibition) of task sets, respectively. In Kramer et al., older adults showed high rates of preservative errors on the Wisconsin Card Sorting Task (WCST). In contrast, Mayr observed that older adults had no difficulty inhibiting tasks-sets. In fact, the N-2 repetition cost was larger for older adults than younger adults. At first blush these findings appear contradictory, but these processes are hypothesized to both take place at the task-set level and they both are the result of persistent activation or suppression of activation (i.e., inhibition). In the WCST, preservative errors are hypothesized to arise from a difficulty to inhibit the just abandoned sorting rule when a new to-be performed sorting rule is introduced. On the other hand, task-set inhibition is hypothesized to suppress competing activation from a just abandoned set in order to perform a new task-set. Given that Mayr observed a larger N-2 repetition cost for older adults, one possible explanation for these findings is that both the N-2 repetition cost and perseverative errors are a consequence from difficulty re-

activating a task-set. Depending on the lifespan of task-set inhibition, the perseverative errors could result from the difficulty undoing the inhibition previously applied. To test this hypothesis, one would manipulate the onset of the task cue for the upcoming task. The interval between the response of the previous task and the presentation of the task cue (RCI) allows a participant to switch away from the previous task. In the case of task-set inhibition, increasing the RCI should allow more time for the inhibition to dissipate. In contrast, the interval between the task-cue and stimulus presentation (CSI) is time to prepare for the upcoming task. If the difficulty in undoing task-set inhibition is the cause of perseverative errors, then increasing the RCI will reduce the number of errors. On the other hand, if perseveration stems from difficulty preparing then increasing the CSI will be more effective in reducing perseveration. A third possibility is that perseveration is not caused by either a difficulty in undoing inhibition or the difficulty in preparation. If perseveration stems from generalized slowing, manipulating RCI and CSI would have no effect. However, if the total interval time between tasks (i.e., RSI) was increased, there should be significant impact on RT and accuracy.

Indirect support for difficulties during task-set reconfiguration is supported by findings that cue processing in the Stroop task takes more effort for older adults (West, 2004). Older adults showed prolonged positive electrical brain activity around 300 (P300) ms post task cue onset. The P300 wave has been associated with, among other things, attention allocation and effortful processing. West concluded that the longer duration of the P300 in older adults was indicative of greater difficulty in processing the task cue. It is possible, however, that the longer duration was the result of more difficulty either undoing overcoming task-set inhibition or activating the new task set. Because

inhibition is applied during the application stage of task-set reconfiguration, cue processing should lead to larger switch costs and/or response time, but should not affect the perceptual inhibition of the irrelevant dimension in a Stroop task on a subsequent trial.

An additional question that still remains is whether task-set inhibition from one trial can be transferred to suppress a distractor on a subsequent trial. Traditionally in the WCST only two card-sorting rules are used. If three card-sorting rules were used, then the level of task-set inhibition could be assessed. From Mayr's (2001) results, older adults should be expected to show no difficulty applying task-set inhibition. Given that no studies to date have investigated this question, it remains unclear if older adults will have difficulty transferring inhibition or not. Difficulties in the coordination of processes despite stability of the processes themselves might lead toward supporting the internal control deficit hypothesis.

Consideration in any investigation should be given to the role of strategy differences between younger and older adults. It is quite possible that age-related differences are not the result of structural limitations, physical changes in sensory processing, or changes in the brain, but rather strategic changes in processing and responding. In Mayr and Liebscher's (2001) investigation of selection difficulties with old age, they found that older adults were slower, but that the relatively slower performance was amenable. When the presentation of task cues changed so that both the task and cue were removed from the screen performance after the fade out was not significantly different from the pre-fade out performance. In their Experiment 2, tasks were performed concurrently, one primary and one secondary. Over time the secondary

tasks cue was obscured with an “X” to indicate that it should not longer be performed. Older adults continued to visually fixate on the secondary task cue, which slowed performance. When Mayr and Liebscher removed the cue all together, older adults’ performance was no different from that of the younger adults. Moreover, in simple task switching experiments, a significant amount of the variance for age-related differences can be explained by conservative response biases. Physiological measures in this respect would not shed any additional light on the matter either. If the strategy differences result in different patterns of activation, the only difference detected would be in the pattern of activation and not the strategy. Clearly, a new line of methodology needs to be developed to tease apart physical and structural changes from age-related strategy changes. Task-set inhibition is one small step in this direction. It is a new indicator of cognitive processes in addition to RT and switch costs. Creating novel paradigms and combining existing paradigms in novel ways will produce unique sets of predictions that may elucidate the underlying changes and limitations that are characteristic of older adult performance. Magnetic resonance imaging (MRI) also has the potential to reveal structural changes.

Inhibition and aging research clearly shows that the inhibition of older adults is not universally affected by age. The increased distractibility and decrease in negative priming suggest there is a deterioration of these types of inhibition is negatively affected by age. However, careful consideration of age-related differences must take into account the possibility of alternative explanations other than age. Differences in expertise and strategy may influence how a task is performed. These differences may not represent physical limitations in cognitive processing. On the other hand, the differences may

represent strategic compensation for neurological limitations that are present. Task-set inhibition seems to not have the same age associated declines that other forms of inhibition do. The findings of Kuhns, Lien, and Ruthruff (2006) show that younger adults can transfer task-set inhibition on one trial to reduce the interference of a distractor from the same task-set on a subsequent trial. The question that remains unanswered is can task-set inhibition in older adults be used to block out distracting information after a task-set is inhibited.

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