REPETITION EFFECTS IN OBJECT SWITCH COSTS: AGAINST A SWITCH COST MEASURE OF A DISCRETE FOCUS OF ATTENTION

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ABSTRACT

Object switch costs have been taken to index items in the focus of attention (e.g., Oberauer, 2005). They refer to savings in reaction time (RT) when a target object to which a response must be made is the same as the target object in the previous trial, compared to trials in which there is a switch to a different target object. It has been presumed that switch costs occur because each target object remains in the focus until there is a need to switch to a different target. Here we show, however, that object switch costs can increase as the number of repetitions of a target object increase from 1 to 3 before a possible switch. If switch costs solely reflect presence of an object in the focus of attention, then presence in that focus would appear to be gradated rather than all-or-none. Additional interpretation of the data comes from a separate examination of switch and no-switch trials across different numbers of repetitions. These data are inconsistent with a single-item focus of attention because of two specific patterns of data: a shorter RT for non-switching trials when going from 1 to 2 repetitions, and a longer RT for switching trials going from 2 to 3 repetitions.

Chapter 1: Literature Review

This project re-examines evidence regarding the nature of the human focus of attention. In particular, does the focus of attention include a single item or several items? And if there are several items in focus at one time, are they of equal strength or magnitudes differing in a gradated manner? Below I outline an essential historical background of research on the focus of attention as well as how this construct has been measured. Different interpretations of these measures are then discussed from the theoretical standpoint of the capacity of the focus. These interpretations are most commonly divided into theories of a single-item capacity vs. the notion of a focus that can hold multiple items at any one time.

Historical Background of the Focus of Attention

Attention is a concept that has been closely linked to primary memory. James (1890) defined primary memory as the trailing edge of the conscious present. This trailing edge referred to all information held in mind that could prove relevant to an upcoming task. However, labeling an item as *primary* within the memory system may be a relative term based upon cognitive task demands on resources. This could be the case if not all items in the conscious present are considered equally relevant. For this reason, attention has long been considered from viewpoints that place divisions and limits on what is attended and how much can be attended. For example, Broadbent's (1958) *filter model* introduced the notion of levels of attentional processing as well as which items reach the higher levels. Similarly, Pashler (1992) has theorized about a *cognitive bottleneck* limiting the number of items that can be attended to at a high enough level to complete a cognitive task. These and other ideas about the limits of attention have led to the modern notion of a focus of attention. Within memory research, the focus of attention generally refers to those items held in mind at the greatest degree of accessibility. In other words, items in the focus are available at the highest level of attentional processing and could be maintained beyond any cognitive bottleneck. Theories that attempt to unify attentional processing with a memory system (i.e., *working memory*, Miller, Galanter, & Pribram, 1960; Baddeley & Hitch, 1974), would eventually need to operationalize the concept of the focus of attention.

Working memory refers to the small amount of information held in a highly accessible state in order to carry out cognitive tasks. Numerous processes have been theorized within the construct of working memory often describing varying levels of information accessibility. One of the more widely recognized of these processes is the focus of attention. The focus is said to hold the items in the highest state of accessibility because it pertains to the items presently in use for a cognitive task. Under this definition, the focus could be equated, at least partially, with Pashler's (1992) cognitive bottleneck in that it holds the items currently attended in order to carry out a cognitive task. However, a more recent controversy surrounds this definition as some researchers posit that the focus is actually better conceived as a sub-process within a broader cognitive bottleneck. At the heart of the matter is the capacity limit of the focus of attention. Some researchers support a definition encompassing multiple items (Cowan, 2001; Gilchrist & Cowan, 2011), whereas others maintain a single-item narrow focus is the greatest degree of item accessibility relative to items outside of the focus (Garavan, 1998; McElree,

1998) or to other items in a broad focus (Oberauer & Kliegl, 2006; Oberauer & Bialkova, 2009).

The theoretical limits and specific qualifications for what the focus of attention does and how it does it are important for practical application. This mechanism has implications for the larger concept of working memory (particularly working memory span), which has further implications for general fluid intelligence (Engle, Kane, & Tuholski, 1999; Conway, Kane, & Engle, 2003; Cowan et al., 2005; Jaeggi, Buschkuehl, Jonides, & Perrig, 2008), attention deficit hyper-activity disorder (ADHD; Klingberg, Forssberg, & Westerberg, 2002), and emotion regulation (Schmeichel, Volokhov, & Demaree, 2008) among others. Practical application of these relationships with working memory is difficult without a framework for understanding the underlying mechanisms of working memory (e.g., the focus of attention). Researchers, clinicians, and businesses have already begun to create brain training programs based on, as yet, the incompletely understood concept of working memory (e.g., Lumosity by Lumos Labs and BrainHQ by Posit Science). In essence, attempting to understand how working memory relates to ADHD without first understanding how the focus of attention works is akin to attempting to understand how photosynthesis relates to oxygen production without first understanding how chlorophyll works. The basics direct the larger issues.

Evidence of this need for understanding the most basic mechanisms prior to theorizing about the larger concepts abounds. The current controversy regarding working memory training and its supposed benefits, or lack thereof, is one example. Evidence supporting working memory training as a ‘cure’ for ADHD (among other purported benefits) has been shown by some (Klingberg, Forssberg, & Westerberg, 2002) and has even taken a hold in the popular media. Yet other researchers have attempted to cull the spread of this idea as they find very little benefit of working memory training outside of improvements on related working memory tasks (Melby-Lervåg, & Hulme, 2013; Shipstead, Redick, & Engle, 2012). A better understanding of underlying mechanisms, e.g., the focus of attention, would help inform views about practical applications of working memory techniques. To better understand working memory, it is necessary to understand the procedures used to measure the focus of attention.

Measuring the Focus of Attention

In the major line of cognitive research related to the focus of attention, various researchers have used access time (measured by reaction time) as an indicator of an item's presence in the focus of attention, or its absence from that focus (Garavan, 1998; Gilchrist & Cowan, 2011; McElree, 1998; Oberauer, 2002, 2005; Oberauer & Bialkova, 2009, 2011). In the research conclusions of the soon to be described updating task, access time is further utilized to dissociate information *within* the focus as opposed to the more classical interpretation, which considers access time only as a measure that differentiates items of different processes. Here, the interpretation of one measurement tool based on this retrieval-speed logic, object switch costs, is re-examined (Garavan, 1998; Oberauer, 2002). This project attempts to ascertain the most parsimonious interpretation of how object switch costs inform upon working memory organization. As such, it is necessary to review the measurement tool of interest, i.e., object switch costs.

Object Switch Costs

Within working memory theory, there is a theoretical debate concerning whether the focus of attention can hold multiple items, or if one of those items is more highly accessible than the rest (see Figure 1). The main method that has led to results supporting the latter assertion is the examination of object switch costs. Object switch costs occur when several objects must be held in mind concurrently while one of them is updated. It refers to the presence of a longer reaction time (RT) when a task's target object is different from the previous trial, compared to trials in which the same object is responded to again.

The type of switch cost examined here, modeled after Oberauer (2002), is illustrated in the left-hand column of Figure 2. The trials are presented in blocks. At the beginning of every block, the participant memorizes a set of digits at different box locations (either 2 or 3 locations, in different conditions). After that, several arithmetic updates are to be made one at a time to be applied to the digit that had appeared in a box. When the operation is presented in one box the others remain blank throughout a sequence until each is selected in turn for an arithmetic update. The answer is to be produced and the updated set is to be kept in mind for the subsequent trial. For example, in the right-hand column of Figure 1, the participant should remember *5, 3, 4*; then add 2 to the second object and consequently press the 5 key; then remember the result, *5, 5, 4*; then apply the next operation to whatever object is indicated, etc. The typical finding is that the RT to yield the next answer will be shorter on average if the same object in the set is updated again (e.g., in the illustration, an arithmetic change of the second box) than if a different object in the set is updated (an arithmetic change to the first or third box). That difference in RT is the object switch cost.

Object switch costs have implications for theories of the focus of attention, which are considered below. First, though, it is helpful to consider some of the desirable properties of tasks that examine object switch costs, such as the one used here. Methodology for object switch cost studies can require continuous updating of multiple items of information. This continuous and fast-paced updating impedes mechanisms that could provide a modus operandi of retaining the information outside of the focus of attention, e.g., a temporary long-term store such as an activated long-term mechanism. Updating accomplishes this by continuously changing the memoranda in order that mnemonics such as rehearsal and chunking of the items becomes impractical (Naveh-Benjamin & Jonides, 1986). A rapid pace of the task further impedes memory-improving mechanisms that would require assistance from a secondary mechanism (e.g., activated long-term memory). Simply put, updating tasks examining the switch costs of items are thought to be completed by participants without relying on secondary systems of working memory. This implies that the observed effects can be assumed to have to do only with the focus of attention.

Theories of the Focus of Attention

Single-Item Focus

The classic account for the additional time present in these object switch costs is that it indicates additional processing time needed for the focus of attention to replace its single-item with a new, different item (Garavan, 1998; Oberauer, 2002). Research investigating the possibility of a primary item in the focus of attention is generally set up within the framework of looking for one (i.e., methodology that investigates if *one* item is different from *others*). Pashler (1992) showed that when attempting to accomplish multiple tasks at once there arose a diminished ability to accomplish one or both of them. Object switch costs could be considered a replication of this effect at the more finite *item*-

level within a single task when more than a single item is held in mind during the lone task (Garavan, 1998; Oberauer, 2002). The predominant theoretical interpretation of object switch costs is that they indicate that a single item receives priority in the focus of attention (Oberauer & Hein, 2012).

The *three-embedded-components model* (Oberauer, 2002, 2009) posits three component systems of working memory, one within another, corresponding to three distinguishable levels of item-accessibility. The three components of this model (in ascending order of item-accessibility) are the activated part of long-term memory, the region of direct-access, and the focus of attention. The prior two components of this model correlate to two processes of a multiple-item model to be discussed later, whereas the final component posits a sub-process with a single-item capacity. However, this final component shares a name with a multiple-item process of the to-be-described model so here the latter two components will be described as the *broad focus* and the *narrow focus*, respectively, to simplify terminology for model comparison. These same terms were used by Oberauer and Hein (2012) for similar model comparison.

The activated part of long-term memory here describes a non-capacity limited 'stand-by' component for information that is not currently, but may become, task relevant. The broad focus serves a similar function with the added distinctions of greater accessibility of items and a capacity limitation of about four items. The narrow focus is the locus of the notion of a *primary* memory item held in greater accessibility than all *other* items. Perhaps the best-articulated support for a single-item narrow focus is that of Oberauer and Bialkova (2009) in which multiple items could only be incorporated into this component if they were chunked into a single unit (e.g., the three items F – B – I, can be held in the single chunk FBI). *Chunking*, in the models discussed here, is not considered a point of contention as it is accepted by both models (i.e., multiple-item focus models allow for chunks to be considered as types of items and the ability to retain a single chunk composed of multiple items is not taken as evidence for or against the capacity to hold multiple, separate items).

Oberauer and Bialkova (2009) found that when two items were processed on every trial (e.g., in that study, colors to be mentally converted to numbers in order to resolve an equation such as ‘brown plus blue’) the pattern of results suggested that switch cost was not diminished by updating only part of a chunk. Thus, the cost of one item switching to a different color was just as high as the cost of both items switching. Repetition of part of a chunk would not be helpful. This suggests the two items formed a single chunk indistinguishable from a single item. Furthermore, there is evidence that two items of similar kind (e.g., 2 digits or 2 spatial locations) cannot be maintained together in the focus of attention without resulting in cross-talk that interferes with memory for the items (Oberauer & Bialkova, 2011). This evidence is further explored in the next section.

Multiple-Item Focus

Alternative to the single-item focus account, another group of researchers has theorized that the focus of attention is able to accommodate multiple items. These multiple items, about 3 to 5, are suggested to simultaneously occupy the focus even when there is no reliance on supplementary mechanisms such as sensory memory or verbal rehearsal (Cowan, 2001; Gilchrist & Cowan, 2011; Bae & Flombaum, 2013). The theoretical viewpoint that there is a limited but plural capacity in memory is longstanding. Indeed, this same estimate was first numerated nearly a century and a half ago (Jevons, 1871) under a different term (i.e., immediate memory, James, 1885).

The *embedded-processes model* (Cowan, 1999) considers the memory system as a whole to contain long-term memory (LTM), an activated portion of long-term memory (aLTM), and the focus of attention(FoA). Processes in this model are referred to as embedded as the memory system is conceived as a unitary system with each process acting within a larger process (i.e., the FoA acts within aLTM, which acts within LTM). This is contrary to a model of multiple mechanisms that operate apart from one another, such as the Baddeley and Hitch (1974) *multiple-component model*.

The embedded-processes model does not posit the presence of a further sub-process in the narrow focus. Instead, in its simplest form, it considers the several items within the focus of attention to be relatively equally accessible. However, these items must be considered able to be somewhat differentially accessible given evidence from several sources (see Cowan, 2001). An important source of evidence in this regard is the presence of object switch costs in updating tasks (as well as incongruent data from some other tasks, e.g., visual search). The primary difference between single-item vs. multiple-item focus capacity is that the latter does not view the *one* item utilized to be functionally different from the *other* items, as does the single-item account. Instead, the multiple-item theory accounts for the observation of object switch costs as evidence that the multiple items can differ in strength or priority *within* the focus (Cowan, 2011).

For example, the previously described method of Oberauer and Bialkova (2009) that supported a single-item account has also been utilized to show support for a multiple-item focus given different functional task demands. Gilchrist & Cowan (2011), using a slightly modified procedure, obtained data that presented a pattern of object switch costs more compatible with a multiple-item account of the focus. Specifically, whereas Oberauer and Bialkova found no evidence for a difference in the object switch costs when a partial chunk update was made compared to a full chunk update (a result interpreted as evidence of two items chunked into one), Gilchrist and Cowan found such a difference in switch costs between a partial and full chunk update. While the initial study examined only a single attribute (i.e., color), the latter manipulated multiple attributes which could not be easily chunked together (i.e., color and shape). This multiple-attribute procedure required a learned association between a shape and letter (e.g., square and *W*) and a second learned association between a color and number (e.g., blue and *4*). At test, participants were then shown a shape and color (e.g., square and blue) and asked to identify the corresponding letter-number combination (e.g., *W4*). Identification was accomplished by a mouse-click on a grid of lettered rows and numbered columns. A second experiment confirmed alterations to the grid pattern did not affect results. Gilchrist and Cowan found that updating only one of two items in memory on a subsequent trial resulted in less of a switch cost than when both items were updated. Recall this was not the case in Oberauer and Bialkova. This suggests that, based on functional task demands, two items can be inextricably linked in the focus of attention as a single chunk (insofar as reaction time goes). When chunking is not possible, however, both items can still be held as separate individual items. Similarly, the previously mentioned Oberauer and Bialkova (2011) showed that the focus of attention can expand beyond a single item to accommodate two items provided sufficient task-fluency obtained through extensive practice (i.e., as task proficiency is achieved, theoretically diminishing the resources necessary per item, the focus can accommodate multiple items). This effect was only observed, however, if the two items were of a dissimilar kind (i.e., a digit and a spatial location, but not 2 digits or 2 spatial locations).

These many examples may make it difficult to determine just what it is about these two models that is different. After all, the most recently provided citation presents evidence of multiple items in the focus while concluding that multiple items can be held in the focus without violating the assumptions of the single-item position. To restate, the primary discrepancy between the alternate views of the focus is whether or not a functional difference exists between one primary item above all others. In this most recent case, that functional difference is item *kind*. For this case, the single-item account allows multiple items that are functionally different such that if required to maintain three items, one digit and two spatial items, only the single digit would be able to occupy the narrow focus. The multiple-item account does not preclude the possibility of the two spatial items, or even all three items, held in the focus concurrently.

Essentially, the three-embedded-components model (Oberauer, 2002) is derived from the embedded-processes model (Cowan, 1999). The single-item focus account reforms the traditional idea of the focus into a sub-process within a broader focus to account for the incongruent object switch cost data yielded from updating tasks (McElree & Dosher, 1989; Garavan, 1998; Oberauer, 2002; Oberauer & Kliegl, 2006). This sub-process then constitutes a *particularly* highly accessible primary item, the updated item, whereas the multiple-item focus is relegated to a level of working memory less active than the single-item focus but more active than the activated part of long-term memory (Figure 1).

There must be an explanation for how it is that functionally similar items can be said to occupy the same level of accessibility in a multiple-item focus despite RT differences observed in the object switch cost paradigm. This is the driving question of the present project. This project attempts to ascertain the most parsimonious interpretation of the working memory system's method of organizing items within a capacity limited focus of attention. Under investigation is if and how allotment of individual items' attentional resources is disparate. A single-item narrow focus account predicts a primary item can differ in attentional resources whereas the other items remain similar to one another. A multiple-item account could be supported by multiple results. In essence, there are two main multiple-item possibilities: all of the items are held with equal priority (contrary to common interpretation of object switch costs) or *all* of the items are held with unequal priority (as opposed to the single-item account that one item has priority over other items held equally to one another).

The Present Study

The present study uses an updating task (described in detail in the experiment methods) previously interpreted as evidence of a single-item focus of attention due to the presence of object switch costs. Multiple items are required to be held in mind with one item updated at a time. Past research (e.g., Oberauer, 2002) has determined that the RT provided for any particular object-update is greater when that update is to a different item (i.e., a switch) than on the previous trial compared to updating the same item as a previous trial. This study examines raw RT data from this task without changing the task itself. Therefore, through a more in-depth examination of data always there, yet not recorded, it is asserted an interpretation of object-switch costs as evidence of a single-item focus of attention is a result of examining only the surface of much deeper data source.

On the basis of equal priority, it would be difficult to explain why one item appears functionally different than the others with regard to the object switch cost effect. For the present study (refer back to Figure 2) an equal priority account would predict a difference between the object switch cost magnitude depending on the number of items (i.e., the 2-box trial would present smaller object switch costs than that of the 3-box trial). This contrasts the single-item position that a primary item is functionally different from the others. The only change between trial conditions is the primary item went from being regarded as ‘primary-of-two’ to ‘primary-of-three’. However, the single-item account could predict the greater switch cost magnitude based on item interference. While the single-item model necessitates a primary item, the specific benefit of this item could be diminished by 3 rather than 2 items jockeying for this position of greater accessibility.

Unequal priority is more likely to be a valid interpretation of object switch cost data. Possible theoretical interpretations for this prediction include a discrete-slot model of resource sharing in the focus of attention (Zhang & Luck, 2008; Anderson, Vogel, & Awh, 2011) or gradated representations (Bae & Flombaum, 2013). Organizing the focus of attention into multiple discrete slots may appear to be a similar account to a single-item focus as, viewed from an overarching level, these two accounts appear to be negligibly different in that each provides resources in some focus (broad and narrow, or sole) for several items. However, the multiple-item position allows for more flexibility in how the multiple items are maintained. Assume for the moment the focus has the resources to maintain up to 5 discrete slots. The single-item model would allow for resource division *only* into a primary item (the narrow focus) and secondary items, which *must* be allotted equal resources under this interpretation. The multiple-item discrete-slot account does not dismiss the possibility that a single item may be allotted the resources for all 5 slots, that 3 items may comprise all focus resources, or indeed that a single updated item can take up 2 slots while the remaining items each take up 1 slot. This last configuration would result in a shorter RT for the single updated item observationally identical to the single-item sub-process account.

Cowan (2001) assumed that there is a continuum of priorities, up to the capacity limit. For example, it has been suggested that items in a short list can share the focus of attention when the list must be scanned in memory to determine whether a probe item is present in the list (Sternberg, 1966). Under that assumption, however, it cannot be assumed that presence in the focus of attention is all-or-none with identical resource allotment between list items. There exists an RT dependence (when scanning for a probe item) on the number of items in a list (up to a capacity limit; see Burrows & Okada, 1975) such that there can be stronger representations of items when there are fewer items in the scanned list. Similarly, in research on visual array comparisons, Zhang and Luck (2008) were able to fit their data only with a model in which, when there are fewer items to be remembered than available slots in working memory, an item can be represented in greater precision by taking up more than one slot. In these theoretical views, there is a fixed capacity limit but, within the limit, it is possible for items to be represented at different levels of priority. Even when only one item is relevant, as in the present study, its level of activation or strength in the focus of attention could theoretically vary. Gradated representations can occur, even independent of discrete slots, so long as the number of items remains under the capacity limit (Bae & Flombaum, 2013). Strict capacity limits for multiple-item focus models drop as low as 3 (Anderson, Vogel, & Awh, 2001), therefore it is unlikely the present study will surpass the threshold for the possibility of obtaining gradated representations. Were a greater number of items used in the experiments described below, the possibility of obtaining data in-line with this possible explanation would diminish, if not disappear completely, thereby decreasing its predictive power.

Chapter 2: Experiment 1

In Experiment 1 of the present study, we created an opportunity for the priority of an item to change throughout 1 to 3 repetitions of the same target before a possible switch. If switch costs reflect the presence of an item in the focus of attention, and if only one level of strength of that presence is possible, then repeating multiple trials with the same object as the target should not change the magnitude of the switch cost. The target remains the solitary item in the focus of attention. It must be noted that motor or simple procedural knowledge cannot account for increased magnitude of switch costs in the experimental design shown in Figure 2, inasmuch as the response differs from trial to trial even when the object being updated remains the same. If, however, there are different levels of strength of an item's presence in the focus of attention, then repeating the same target multiple times might be expected to increase the resource allocation to that item within a multiple-item focus, thereby increasing the subsequent switch cost.

It was possible to find certain key sequences of trials within the results to be compared. With letters *A* and *B* representing specific object locations, the important comparisons included the final trial in each of the following trial sequences: *AA* versus *AB* (the object switch cost as traditionally measured); *AAA* versus *AAB*; and *AAAA* versus *AAAB*. If the source of object switch costs is the inclusion of *A* in an all-or-none, single-item focus of attention; all sequences should produce equivalent switch costs on RT. Switch costs of different magnitudes depending on pre-switch repetitions, however, indicate item *A* is being allotted additional resources as the repetition count increases. This cannot be explained with a single-item account as the updated item should have achieved presence in the narrow focus in the initial *AA* versus *AB* sequence (according to the classical single-item interpretation of object switch costs). A multiple-item account allows for the possibility of allotment of additional resources to an item as it becomes more task-relevant.

Method

Participants

Introductory psychology course credit was awarded to 41 participants (31 female, 11 male; mean age 18.75 years, SD=0.80). They were native speakers of English. Four additional participants were excluded because they did not make any correct responses in at least one condition.

Apparatus, Stimuli, and Procedure

The experiment was programmed in E-Prime (Psychology Software Tools, Pittsburgh, PA) and conducted on computers with one participant per sound-attenuated booth. Blocks of 12 trials were presented, each beginning with two or three locations marked with boxes, each filled with a digit to be remembered, as shown in Figure 2. Each trial block began with a screen informing the participant that a series was upcoming. The procedure included 5 practice blocks (two blocks with 2-box trials and three blocks with 3-box trials, in a random order) followed by 34 test blocks, with 12 trials per block. The order of 2- and 3-box test trial blocks was random, with 17 blocks of each type. The target location was randomly selected with replacement on each trial in each block, eliminating any possibility of using expectancy to prepare for the next trial. On each trial in a block, one digit was to be updated and the updating response RT was recorded.

Each box within the set of two or three (depending on the trial block) was 40 mm high and 60 mm wide, and pairs of boxes were laterally separated by 13 mm. Digits presented in the boxes were about 8 mm high and 5 mm wide. Participants had as long as they wanted to memorize the two or three digits presented at the beginning of each trial. When they pressed a key to continue, the digits disappeared and one randomly-selected box was filled with an arithmetic operation (e.g., *+2* or *-3*) such that the result remained in the range of 1 through 9. The required response was to press the appropriate number key from the line above the QWERTY keyboard, as quickly as possible without making an error. As in Oberauer (2005), feedback for a correct response was a 700-Hz tone for 50 ms followed by 50 ms of silence; feedback for an incorrect response was a 300-Hz tone for 100 ms. Participants had the chance for several breaks between trial blocks, with a screen indicating that they should press a key to continue when ready.

RT results were calculated only for trial sequences for which the responses had been correct since the beginning of the trial block. Individual trial RTs less than 0.5 s were excluded because they were thought to represent primarily guesses, and those longer than 10 s were excluded because they were thought to represent inattention to the task. The restrictions on RT eliminated only 0.3% of trials that otherwise would have been included.

Results

Proportions correct were fairly high, as shown in Table 1, and RTs were examined only up to the point preceding an error in the sequence. Given that there are no theoretical predictions for the pattern of proportions correct, they were not analyzed further.

The RTs and accuracies are shown in Table 1, and the calculated switch costs (switched- target RTs minus same-target RTs) are depicted in Figure 3. The switch costs were entered into an ANOVA with two within-participant factors: the number of boxes in each trial in the block, and the number of repetitions of the pre-switch target location (1, 2, or 3). The latter factor was not patterned into the experiment (in order to avoid predictability of the targets) but occurred by chance, and was measured wherever it happened to occur.

As shown in Figure 3, there was a main effect of the number of repetitions on switch costs, $F(2,80)=4.16$, $p<.05$, $\eta_p^2=.09$. Newman-Keuls tests indicated that the 1- and 3-repetition trials differed from one another at $p<.05$. There was also a large effect of the number of boxes, $F(1,40)=22.58$; switch costs were much smaller for 2-box trials ($M=375$ ms, $SEM=52$) than for 3-box trials ($M=817$ ms, $SEM=103$). Thus, the effect of repetitions of the target location on the switch cost increased monotonically. The lack of a significant interaction (η_p^2=.01) between these two factors will become a main focus of Experiment 2, which examines an unexpected trend in the data of Experiment 1.

Chapter 3: Discussion

Presence of an item in the focus of attention serves as a good explanation for why there is an RT savings when a target location is used repeatedly across trials, despite the fact that the updated response still differs from one trial to the next (Oberauer, 2002, 2005). Yet, the present findings show that there must be more subtlety to that argument. We found multiple-repetition effects on RT, with a switch cost that increases following more repetitions with the same object, at least up to three such repetitions (Figure 3). Of particular interest, contrary to previous accounts of switch costs obtained from updating tasks, is when the definitive cost of switching actually occurs. As noted earlier, the traditional measure of switch cost utilizes only the *AA* versus *AB* trials. A cursory glance at the Experiment 1 RT data in Table 1 shows a flaw in this interpretation. Though an increase in RT on switch trials can be seen solely within these trials, the more intriguing effect can be seen when comparing these trials to the *AAA* and *AAB* trials (column 2 in Table 1). The switch trials for these two conditions remain similar to each other whereas the non-switch trials show a decrease in RT. Therefore, there is technically not a greater switch cost here but a repetition benefit. When subtracting out the difference between RT for non-switch and switch trials this effect is lost and interpreted as an increased switch cost (see Figure 3). A 'true' object switch cost does, however, turn up in the remaining 3-repetition trials (i.e., *AAAA* and *AAAB*). For these trials no further repetition benefit is observed and a pure increase in the RT for switch trials is observed for the first time. Two separate mechanisms appear to be at work within what has previously been considered a unitary effect defined as object switch costs. The observed increase in magnitude of switch cost from multiple repetitions was expected and serves as evidence for a multiple-item account of the focus of attention. The presence of multiple mechanisms apparently at work resulting in a fundamental change in the genesis of the RT differences was not predicted. More research specifically designed to investigate these effects, including Experiment 2 presented here, is necessary to identify what change in the theoretical account best explains this finding. Several possibilities are as follows.

Multi-slot Focus Account

Cowan (2001) and others have proposed that the focus of attention might hold more than one item at a time (cf. Gilchrist & Cowan, 2011; Oberauer & Bialkova, 2011). If so, then the focus of attention might also be capable of including a varying amount of resources for a single relevant item, perhaps by using more than one slot for the same item (Zhang & Luck, 2008). The application to the present data would be that the focus of attention becomes more committed to the target item as it is repeated in multiple trials, until some maximal gradation point is reached (i.e., no further resources are available to be allotted). Presumably this point would occur with 3 to 5 slots committed to the same item (Cowan, 2001). Each slot committed to the target object would contribute neural activation that would converge on a rapid and high-fidelity use of the item in the focus of attention, increasingly so as more slots are committed to the target object.

Only at the point of maximal gradation could the single-item focus account of Oberauer (2002) explain these data, thereby rendering this interpretation incomplete. At the maximal gradation point the single updated item has been allotted all of the resources available and while further repetitions do not further diminish RT, a switch to a new item requires additional time relative to both an additional repetition and a switch with fewer repetitions. This is the object switch cost traditionally viewed as evidence for a single-item focus account. Essentially then, the narrow focus within a broad focus account would be a functional process rather than an ever-present structural component. This arrangement would be supported within the framework of Oberauer and Hein (2012).

This interpretation, however, still requires a mechanism to explain the repetition benefit effect. One possible interpretation is that an episodic buffer (Baddeley, 2000) is able to buoy the single-item on the initial trials by incorporating cognitive input (i.e., resources to be allocated) from multiple systems of memory. This episodic buffer, here, would have exhausted its potential benefit by the 3-repetition trials resulting in no further RT benefit observed after this point. Taken together, this process of multiple mechanisms could be viewed as beginning with a multiple-item focus (Cowan, 2001), followed by resource-sharing (Anderson, Vogel, & Awh, 2011; Zhang & Luck, 2008) accomplished through an episodic buffer (Baddeley, 2000) until one slot in a multiple-item focus becomes functionally unique at a point of maximal gradation resulting in the necessity of additional processing time to reintegrate the items maintained in a broad focus to again be utilized (Oberauer & Hein, 2012).

Proactive Interference Account

Another possibility is that the switch costs occur because recently used targets vie for attentional resources. Indeed, there is some evidence that there are lasting effects of recent targets, or lag effects (Oberauer, 2006). In the present study, the more times the same target location is presented in a row, the less recent and hence less interfering the competing target locations would become.

In one possible variant of this explanation, the last few target objects would stay within the focus of attention with the prior objects interfering with the current object within that focus. Among researchers who appear to accept that there is a multiple-item, capacity-limited region of working memory associated with the focus of attention (either directly in that focus or just surrounding it), most have found little or no proactive interference among items (Cowan, Johnson, & Saults, 2005; Halford, Maybery, & Bain, 1988; Oberauer & Vockenberg, 2009). There is, however, a recent exception in which a higher amount of repetition of materials was used (Carroll et al., 2010), and that high amount of repetition of items does seem applicable to the present study, in which the responses always were single digits 1-9.

Long-term Memory Representations

Last, it may be theoretically possible that RT switch costs do not reflect the presence of an item in the focus of attention after all. Instead, for example, it is possible that a long-term memory representation of the target item is built up, binding its location to its successive history of digits, and that long-term representation becomes stronger or more accessible in the immediate task with more successive repetitions of the same target object (cf. Cowan, 1995, 1999; Ericsson & Kintsch, 1995; Unsworth & Engle, 2007). It is hard to understand how this might work in the present context, however. As the repetitions progress, the number of digits associated with the current target increase, presumably causing more proactive interference, making responding more difficult, not easier.

Chapter 4: Experiment 2

Given that several possible explanations of these results are viable, a second experiment was run to confirm the results of Experiment 1. The main inadequacy from analyses based solely on the results of Experiment 1 is the apparent interplay between multiple underlying mechanisms. The effects of an object switch cost are as expected for a gradated focus of attention when measured by the traditional RTn^2 - RTn^1 equation (see Figure 3). However, examining RT without subtracting out the object switch cost shows two separate effects (see Table 1). From pre-switch repetition 1 to 2 there is a *decrease* in overall RT when the object does not switch (for both 2 and 3 box trials), whereas switching has no effect. Conversely, from pre-switch repetition 2 to 3 there is an *increase* in overall RT on switch trials (for both 2 and 3 box trials), whereas further repetition has no effect. These two separate effects converge when using the traditional object switch cost analysis.

Experiment 2 further examines the locus of this difference with one minor methodological adjustment. It is impossible to control every factor at once and the second experiment controls a slightly different factor than the first experiment. In the first experiment, the randomization scheme resulted in the equal likelihood of operating on *each box*. For the three-box case, this meant that two thirds of the trials were switch trials. In the second experiment, in contrast, the randomization scheme resulted in the equal likelihood of *switch and no-switch* trials (see Figure 2).

Additionally, the observed dual nature of the genesis of the switch cost was not predicted for Experiment 1 (i.e., in the raw RT data, the repetition benefit followed by a true switch cost as repetition count increased). As such, the amount of viable data to support these effects is limited, particularly for the latter repetition trials. An error on a trial terminated data collection for the remainder of each block, therefore the number of data points for each increasing repetition case was diminished given the increased likelihood of errors occurring later in a block. Therefore, Experiment 2 slightly alters the conditions to test generalizability of the effect as well as adds more data to provide more robust results to confirm Experiment 1 had not merely been an effect of noise in limited data. The latter purpose was accomplished by increasing the number of trial blocks from 34 to 50.

Similar results for the 2-box condition would act as a pure replication of Experiment 1 and results of the 3-box condition will provide greater depth for analysis of the individual effects of repetition and switch. In making one box more task-relevant it can be inferred whether the repetition effect disappears for pre-switch repetition trials 2 to 3 because (1) that item has reached the maximal gradation point and can be afforded no further resources by the focus of attention, or (2) that the cognitive demands are such that it is beneficial to allocate resource slots of the other two boxes to the one in use (thereby pushing an item out of the focus and into a less accessible area). A replication of the results from Experiment 1 are conducive to the former whereas the latter would predict even greater resource allocation to the repetition box in 3-box trials as this box is now more likely to be further selected than in Experiment 1. The presence of a longer RT only on switch trials following multiple (two to three) repetitions would provide support for a gradated multiple-item focus. Conventional object switch costs (e.g., Oberauer, 2002; Oberauer & Kliegl, 2006) could be described as an effect of additional resource allotment within the focus, whereas the true switch cost is present only when an item deemed comparably task-irrelevant to other items must be accessed from a less highly accessible area of working memory (e.g., activated long-term memory). Were the direct-access region (i.e., the broad focus) of Oberauer (2002) truly a separate capacity limited mechanism within the focus of attention, it too should show a true switch cost, rather than apparent switch cost artifacts from repetition effects.

Participants

Introductory psychology course credit was awarded to 40 naïve participants (26 female, 14 male; mean age 19.21 years, SD=1.80). They were native speakers of English.

Apparatus, Stimuli, and Procedure

The procedure for Experiment 2 was identical to that of Experiment 1 with two exceptions. Selection for 3-box trials was based on a 50% likelihood of each trial to switch to a new box. Therefore, the repetition box was 50% likely to be selected again and each of the unutilized boxes had a 25% chance of selection. Additionally, the total number of trial blocks was increased from 34 to 50 to reduce the chance that observed effects were due merely to noise in a limited data set.

Results

A 2x2x3ANOVA confirmed that Experiment condition (i.e., the different switch probability for each experiment) did not have an interacting effect on Switch/NoSwitch condition, $F(1,480)=.13$, *ns*, nor on number of repetitions, $F(2,480)=.42$, *ns*. Likewise, there was no three-way interaction, $F(2,480)=.32$, *ns*. Therefore, all data from both experiments was combined for all further analyses to provide a more robust data set from which any effects could be examined.

The RTs and accuracies are shown in Table 2, and the calculated switch costs are depicted in Figure 4. As with Experiment 1 results alone, the switch costs from the complete data set, N=81, were entered into an ANOVA with two within-participant factors: number of boxes in a trial and number of pre-switch repetitions. The expanded data set confirmed the main effect of number of repetitions on switch costs, $F(2,480)=5.82$, $p<.01$, $\eta_p^2=.02$. Newman-Keuls tests indicated that the 1- repetition condition differed from both the 2- ($p<.05$) and 3- ($p<.01$) repetition conditions. There was also a large main effect of number of boxes, $F(1,480)=39.18$, $p<.001$, $\eta_p^2=.08$; switch costs were much smaller for 2-box trials (M=391.18ms, SEM=29.15) than for 3-box trials (M=746.42ms, SEM=49.39).

However, when the box number conditions were analyzed in separate ANOVAs, the effect of repetitions on switch cost was only significant for the 3-box condition, $F(2,240)=4.31$, $p<.05$, $\eta_p^2=.03$. Newman-Keuls test indicated that the 1- repetition condition was marginally different from the 2- repetition condition ($p=.053$) and significantly different from the 3- repetition condition ($p<.05$). There was not a significant effect of repetition on switch cost for the 2-box condition, $F(2,240)=1.56$, *ns*.

Further examination of the overall RTs (i.e., mean RT prior to subtracting out the switch costs) is intended to examine the previously noted apparent dual underlying effects (i.e., a repetition benefit from 1- repetition to 2- repetitions and a ‘true’ switch cost from 2- repetitions to 3- repetitions) driving the presence of the object switch cost effect. A 2x2x3 ANOVA was run on number of boxes, Switch/NoSwitch condition, and number of repetitions, respectively. Overall mean RT is depicted in Figure 5. There was a main effect of box condition, $F(1,960)=58.58, p<001$, $\eta_p^2=.06$, and Switch/NoSwitch condition, $F(1,960)=217.06, p<001$, $\eta_p^2=.18$. Interactions were present for box condition by Switch/NoSwitch condition, $F(1,960)=21.17$, $p<.001$, and, crucially, for Switch/NoSwitch by repetitions, $F(2,960)=3.14$, $p<.05$. The latter interaction is indicative of the predicted dual pattern of the repetition effect on RT dependent on whether a particular trial is a switch or no-switch.

As with the switch cost analyses, separate ANOVAs were run for the box number conditions. The 2-box condition failed to obtain a significant interaction effect of Switch/NoSwitch by repetition on RT, $F(2,480)=.58$, *ns*. The 3-box condition obtained only a marginally significant interaction of Switch/NoSwitch by repetition on RT, $F(2,480)=2.76$, $p=.06$.

Chapter 5: General Discussion

The data presented in this paper have implications for determining the most parsimonious theoretical organization of working memory. The two main theoretical accounts discussed have only one key difference up for debate: the focus of attention. In the past, the mere existence of an object switch cost effect in RT data has been inferred as evidence for a focus of attention that is able to maintain only a single item (or chunk) at any moment. This is a logical and perfectly reasonable interpretation of the aforementioned effect. An accepted definition of the term *focus of attention* under the similar theoretical accounts of Cowan (2001) and Oberauer (2002) is information maintained in the highest possible state of accessibility. It follows from this that a cost of switching between multiple items indicates that a single item is always more accessible than other items, which must be peripheral in some way.

Oberauer (2002) accounts for this seemingly peripheral aspect with the inclusion of a region of direct access (i.e., a broad focus) in a minor alteration of Cowan’s (2001) embedded-processes model of working memory. Essentially, Oberauer’s embedded-components model accounts for a hitherto unexplainable phenomenon with one minor addition to the overall structure in a similar vein to the addition of the episodic buffer to Baddeley’s (2000) multiple-component model. The data presented here, however, provide some initial indication that this minor addition does not account for the full breadth of possible switch cost effects.

A clear trend of increasing switch costs as number of pre-switch repetitions increased was found in both the 2-box and 3-box trial conditions (see Figure 4). This trend was shown to be significant for the 3-box condition but not the 2-box condition. The lack of a significant increasing switch cost effect in the 2-box condition cannot be explained solely with the present data set but several possibilities could be investigated in the future. One such explanation is that with only two items to be remembered, the difference between a single-item focus and a multiple-item focus that can gradate items is functionally indistinct as measured by object switch costs. This explanation is unlikely given the clear trend in the data which shows that an item in use can be afforded additional resources following multiple repetitions. Another possible explanation is that variability from individual differences is superseding the effect. This hypothesis could be easily tested by separating participants into groups based on some individual difference in common (e.g., working memory span). Multiple groups based on common working memory span could reduce within-group variability providing a significantly increasing switch cost separately for high-span participants and low-span participants, but not for both groups together.

The results of the 3-box condition are much less ambiguous. These data give clear initial evidence that switch costs effects are better explained by a multiple-item account of the focus of attention than a single-item account. Object switch costs are almost uniformly interpreted as evidence for a single-item capacity of the focus of attention (e.g., Oberauer, 2002; Oberauer & Bialkova, 2009). Even past interpretation of switch costs as evidence of a multiple-item focus has required some addition to a methodology that had previously shown no such evidence. The addition of a second attribute by Gilchrist and Cowan (2011) to the method of Oberauer and Bialkova (2009) described earlier is one such example of this practice. In review, Oberauer and Bialkova found that updating one part of a chunk (i.e., two colors chunked together) resulted in the same switch cost as updating both parts, indicating multiple-items could only co-occupy the focus of attention when chunked together. Gilchrist and Cowan used multiple attributes (i.e., color and shape), which could not be easily chunked together, to show that multiple items that could not be chunked can both occupy the focus as interpreted by a larger switch cost when both items were updated rather than just one of the items.

Oberauer and Bialkova (2011) have since supported this effect allowing that, after practice, the focus of attention can expand to accommodate multiple, separate items. This has by no means settled the debate, however. The need to make conditional changes in order to show evidence for one theory or the other changes the debate from which one better describes the organization of working memory, to when does each theory apply. Under certain conditions, one theory works, under a different set the other works better. The question of functional dependence is an important one, but a more important question is which idea works in most cases? Working memory is a conceptual construct used as a model for understanding how memory and attention interact. As such, it is at its most useful when it can be applied to a multitude of different situation and conditions. To this end, the current results were obtained with no specific alteration to past methodology that showed evidence of a single-item account. These data were obtained only with a deeper analysis of the switch costs without additions to the method of Oberauer and Kliegl (2006). In doing this, the current data shows that even though a surface examination of object switch costs may indicate a single item as functionally distinct and requiring its own component in working memory, a closer examination shows this to be an oversimplified interpretation.

The present study supports the predictions of a multiple-item focus of attention that can appropriate disparate resources to these multiple items. This resource allotment may be accomplished through a continuous gradation or by appropriating multiple discrete slots to some items. This particular debate is not one that can be answered thoroughly enough by the present data. Furthermore, this question may itself be functionally different than the question of multiple- versus single-item capacity. Whereas a multiple-item account is described here as more useful than its counterpart for its theoretical stability across conditional changes, the manner of resource allotment may be more a question of placement on a spectrum between the two, rather than wholly one or the other (Suchow, Foughnie, Brady, & Alvarez, 2014). For this reason, this debate is left for future research better suited to pinpoint this spectral placement.

A representation of the manner in which a multiple-item, but not a single-item focus of attention is supported (for the 3-box condition) is shown in Figure 6. Figure 6a presents a representation of a single-item focus being switched from item-to-item with each individual trial, while Figure 6b represents gradated resource allotment to all three items on each trial. This particular figure provides a representation of a switch trial, but can easily be used to imagine repetition trials (as is done below). A repetition cannot be explained in the Figure 6a representation while a further increase in level of activation (i.e., in Figure 6b, an increase in font size) of a repeated item would account for an increase in the cost of switching away from this repeated item.

This repetition explanation may also account for the greater observed effect for the 3-box trials over the 2-box trials. With only two items, the representational difference in Figure 6 would show that the single- and multiple-item accounts are functionally identical (i.e., each would merely provide a different representation of the same thing happening: one item given more attention while the other loses attention). Therefore, both a single- and multiple-item account would predict a lesser effect for 2-box trials. However, expanding beyond a 2-trial representation would show further possible gradation for a multiple-item focus (i.e., in Figure 6b, the repeated item is represented with a continually increasing font size as the non-utilized item is continually minimized), whereas a single-item focus would be unable to account for further differences in accessibility between the two items. The current study showed only a trend approaching this 2-item gradation process (see Figure 4), but future research examining more than three repetitions or using different memoranda could present this as another significant limitation for a single-item focus of attention.

The representation in Figure 6 can also be used to provide a possible locus for the dual effects in the overall RT data. These effects are best observed in the 3-box panel of Figure 5. The no-switch trials show a repetition benefit from 1-repetition to 2-repetitions with no further benefit at 3-repetitions. Conversely, the switch trials show no ‘true’ switch cost from 1-repetition to 2-repetitions, but do show such an effect at 3-repetitions. One possible interpretation of the dual effects is that, following 1-repetition, as yet unassigned resources are being allotted to the item (i.e., here imagined as an increase in font size of the repeated item) while the ‘true’ switch cost following a 2^{nd} repetition could be from re-allocation of resources from the unutilized items to the repeated item (i.e., here imagined as a decrease in the font size of one or both of the unutilized items).This interpretation asserts that all items are allotted equal resources until one is selected to be updated; after which, that item is then allotted all spare attentional resources. Further repetition of that item then requires re-allocation of already assigned resources. The initial allocation of spare resources would explain why there is a benefit for that item with no cost to the others, whereas the re-allocation of resources would explain the cost to the unutilized items. A problem with this interpretation is that the repeated item is given more resources following each repetition, yet there is no further benefit to that item at 3-repetitions. It is possible that, despite being allotted further attention resources, no further benefit is possible due to a floor in RT before this point. If this were true it would mean the cognitive process of re-allotment of attention resources is flawed, at least in this one instance. However, this is by no means a conclusive interpretation, but rather one possibility assumed from a single data set. This is another promising potential line of future research.

The classic interpretation of switch costs is that they indicate a single-item being moved into the focus of attention, replacing a previously focused item. An alternative view of switch costs, which requires more than just an item's presence versus absence in the focus of attention, is partially supported here. Specifically, an item that remains currently relevant over several trials becomes higher in priority than an item that has only been currently relevant for one trial. This interpretation is supported by trends for either 2 or 3 items, though significantly so only for 3 items. Further evidence against the use of object switch costs as evidence of a discrete, single-item focus of attention is the presence of an interaction effect between the Switch/NoSwitch and repetition conditions. This interaction is revealed through an examination of the overall RT data from which the switch cost manipulation of data (i.e., RTn^2 - RTn^1) to be driven by the presence of two different effects underlying the switch cost. This effect is washed out using the subtraction equation used to obtain the object switch costs further diminishing the interpretive power of this particular data manipulation.

It should also be noted that these data cannot conclusively be said to confirm the necessity of a focus of attention. It is possible that an organization of working memory could work with the items described here as those in the focus are merely a subset of long term memory representations (see Figure 7). This account would attribute the repetition benefit as a consequence of learning which strengthens the object locations in long term memory. Any switch cost present could then be considered an effect of a learned expected update not occurring. This is an important possibility to note as the switch cost paradigm is used to argue different organizational arrangements of the focus of attention even though switch costs cannot be said to confirm even the existence of a focus, let alone how it is arranged.

Chapter 6: Conclusion

No matter which explanation of the multiple target-object repetitions causing increased switch costs is correct, the present result places an important and strong constraint on an often-studied phenomenon. Here it is shown that an effect previously thought to be indicative of a single mechanism, object switch costs, has potentially neglected to find a second underlying mechanism, repetition benefits, due to its being subtracted out by examining only the difference in RT between conditions of switch and no-switch. Any adequate theory of how attention is used in working memory must accommodate these results. There are certainly occasions in which a single-item account of the focus of attention better conceptualizes the organization of working memory. However, these occasions would then presumably have a superfluous component in the region of direct access (Oberauer, 2002). The multiple-item focus of attention of the embedded-processes model (Cowan, 2001) is able to accomplish the most important goal of a conceptualization: it works across many functional conditions and task demands. Minor methodological adjustments to past data (Oberauer & Bialkova, 2009) in-line with a single-item focus have provided data better interpreted when allowing multiple-items in the focus (Gilchrist & Cowan, 2011; Oberauer & Bialkova, 2011). The present data further expand the interpretive range of a multiple-item focus without relying on methodological changes and instead simply delving deeper into data from a method previously interpreted superficially as evidence of a single-item focus (Oberauer & Kliegl, 2006).

Several future avenues of research can commence stemming from this initial line of work. An investigation of the significance of the repetition effect for three but not two items is one such possibility. Whether or not there is even any functional difference between a single-item focus and a multi-item focus with only two items remains an open question. A few possible research directions follow. Simply adding further repetitions into the design of the experiment may show that greater repetition would lead to a repeatedly probed item becoming more highly accessible after the 3-repetition cut-off point of the present study. Similarly, use of a design in which an item is repeatedly probed without update (i.e., without changing the item's identity each trial) may show a significant trend showing two items can become more accessible. This would indicate the lack of significance for the current study was due to the updating procedure and not because only one item of in the focus of attention. Another possibility is that individual differences are negating a 2-box effect present only in some participants. One way to test this would be to separate participants into high working memory span and low working memory span groups. It could be that only one of these groups shows the effect and, for the current study, the other group is negating the effect in the data. This study proposes a flaw in the use of the switch cost measure to answer the question of focus capacity, therefore future research would benefit from a different measure to investigate open questions about the focus and working memory in general. No definitive conclusion is reached in this discussion about where on a spectrum of continuous gradation of memoranda and discrete slots for individual items the focus of attention falls. This question could be answered with a better understanding of the separate, dual effect seen in the raw RT data. Why don't these effects (the repetition benefit and 'true' switch cost) happen in tandem? Why does the benefit precede the cost? Why is the benefit a larger effect than the cost? Why is there a benefit for two or three items, but no cost for two items (see Figure 5)? Answering these and other questions will lead to a better overall understanding of the processes of working memory.

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Table 1

Reaction Time and Proportion Correct Means (with SEM), Experiment 1

		Pre-Switch Repetitions					
		1		2		3	
Items	Box Type	Mean	SEM	Mean	SEM	Mean	SEM
		Reaction Time (RT) in ms					
2	Same	2140	71	2001	71	1994	89
2	Switched	2409	65	2371	66	2479	114
3	Same	2310	63	2080	79	2095	127
3	Switched	2919	96	2927	118	3091	152
		Proportion Correct					
2	Same	0.97	0.00	0.97	0.01	0.97	0.01
2	Switched	0.90	0.01	0.92	0.01	0.88	0.02
3	Same	0.96	0.01	0.98	0.01	0.96	0.02
3	Switched	0.86	0.02	0.86	0.02	0.86	0.03

Note. RT included only trials with correct responding preceded by 100% correct responding in that trial block. Participants without data for every cell were omitted.

Table 2

Reaction Time and Proportion Correct Means (with SEM), Experiments 1 & 2

		Pre-Switch Repetitions					
		1		2		3	
Items	Box Type	Mean	SEM	Mean	SEM	Mean	SEM
		Reaction Time (RT) in ms					
2	Same	1996	51	1898	49	1864	66
2	Switched	2325	50	2287	51	2319	75
3	Same	2166	54	1962	53	1983	75
3	Switched	2721	70	2748	81	2882	103
		Proportion Correct					
2	Same	0.93	0.01	0.93	0.01	0.94	0.01
2	Switched	0.88	0.01	0.86	0.01	0.86	0.02
3	Same	0.91	0.01	0.93	0.01	0.93	0.02
3	Switched	0.83	0.02	0.83	0.02	0.84	0.02

Note. RT included only trials with correct responding preceded by 100% correct responding in that trial block. Participants without data for every cell were omitted.

Figure 1

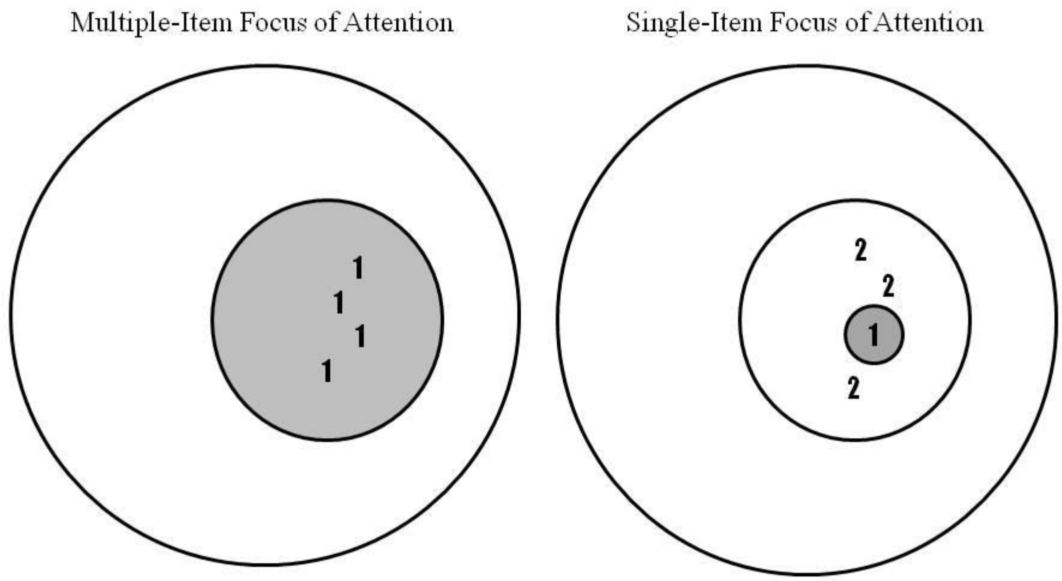

Multiple-Item Focus of Attention
1
1
1
1
Single-Item Focus of Attention
2
2
1
2

Figure 2

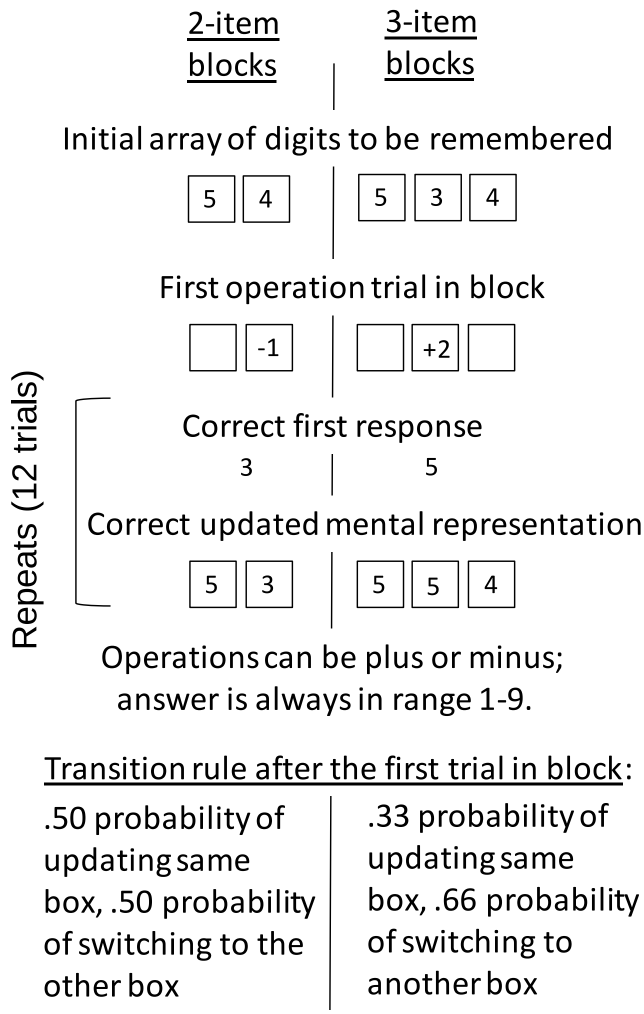
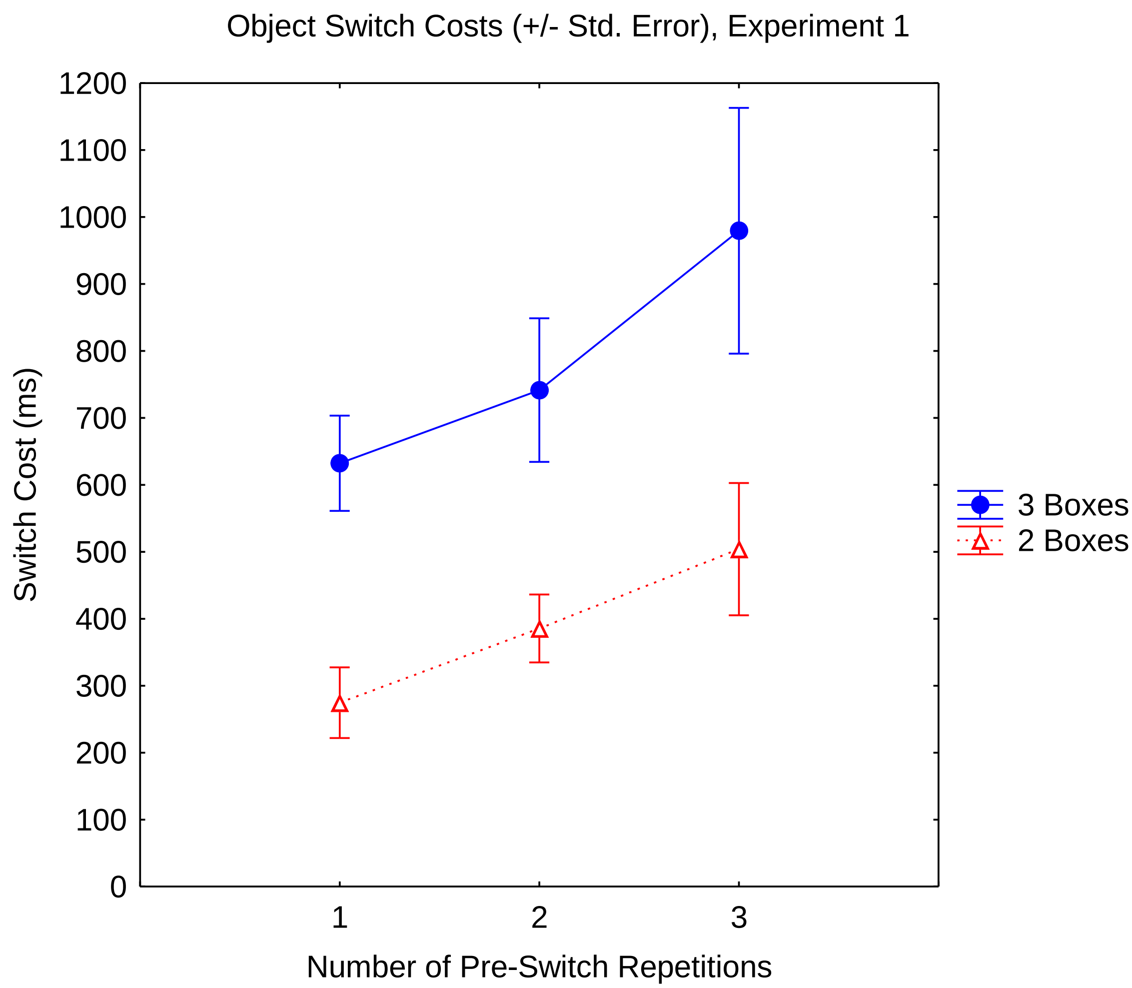
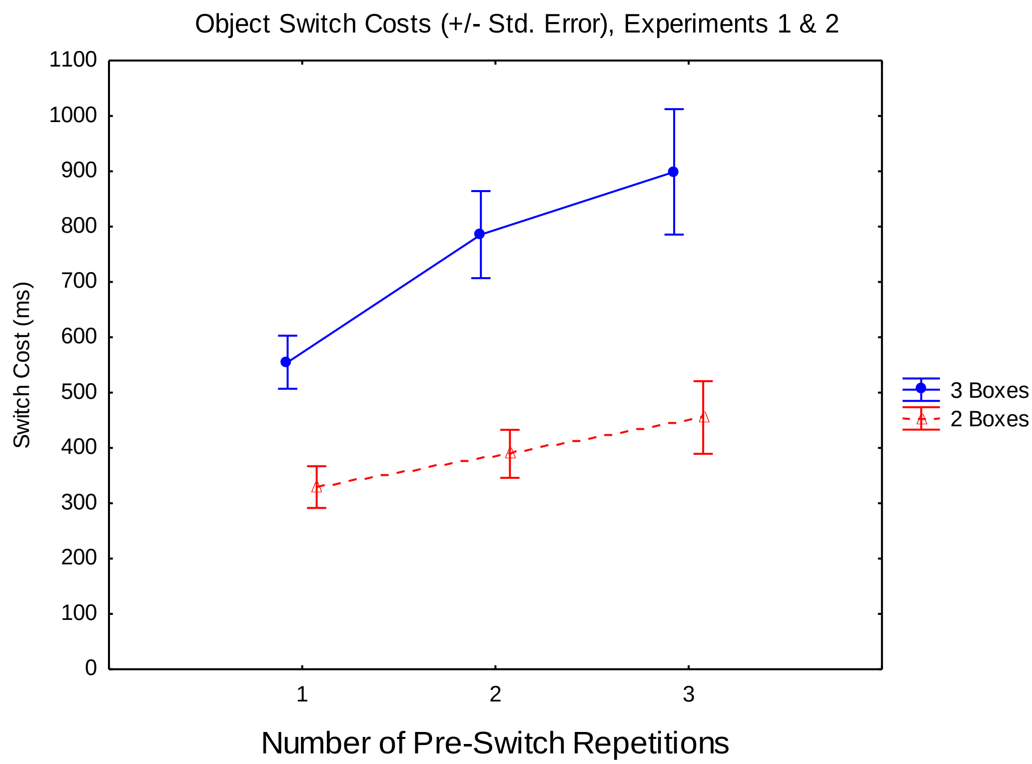

2-item blocks
3-item blocks
Initial array of digits to be remembered
5 4
5 3 4
First operation trial in block
-1
+2
Repeats (12 trials)
Correct first response
3
5
Correct updated mental representation
5 3
5 5 4
Operations can be plus or minus; answer is always in range 1-9.
Transition rule after the first trial in block:
.50 probability of updating same box, .50 probability of switching to the other box
.33 probability of updating same box, .66 probability of switching to another box

Figure 3



Object Switch Costs (+/- Std. Error), Experiment 1
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
Switch Cost (ms)
1
2
3
Number of Pre-Switch Repetitions
3 Boxes
2 Boxes

Figure 4



Object Switch Costs (+/- Std. Error), Experiments 1 & 2
Switch Cost (ms)
1100
1000
900
800
700
600
500
400
300
200
100
0
1
2
3
Number of Pre-Switch Repetitions
3 Boxes
2 Boxes

Figure 5

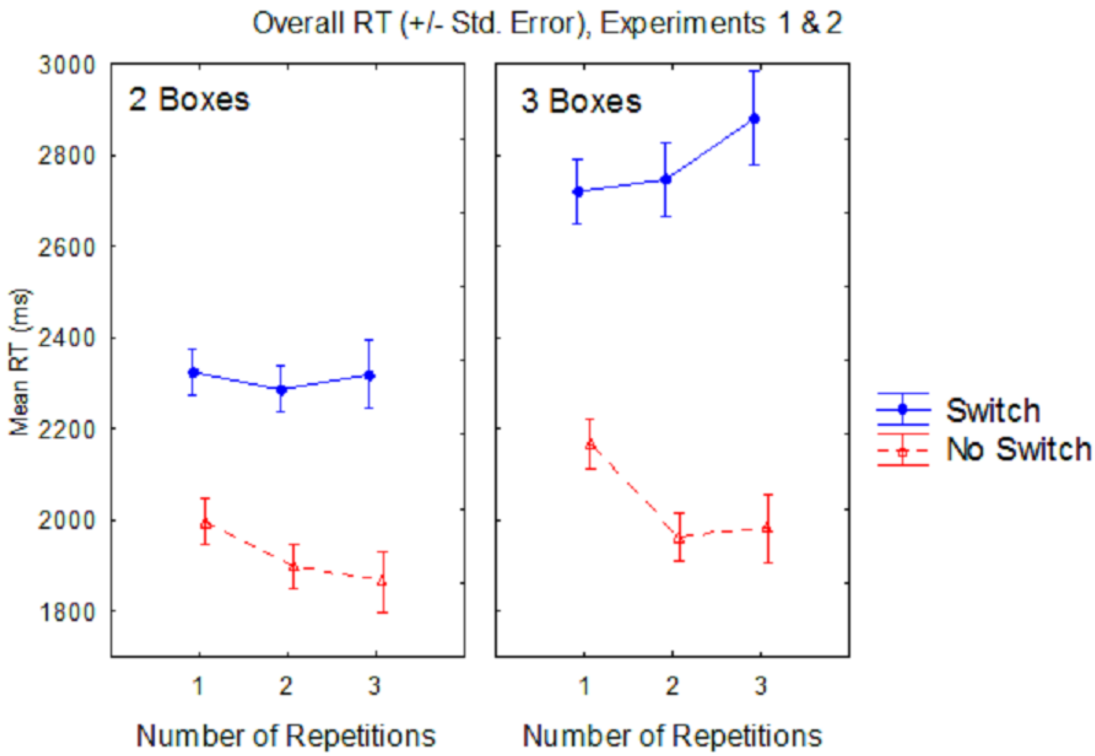

Overall RT (+/- Std. Error), Experiments 1 & 2
2 Boxes
3 Boxes
Mean RT (ms)
3000
2800
2600
2400
2200
2000
1800
1
2
3
Number of Repetitions
Switch
No Switch

Figure 6

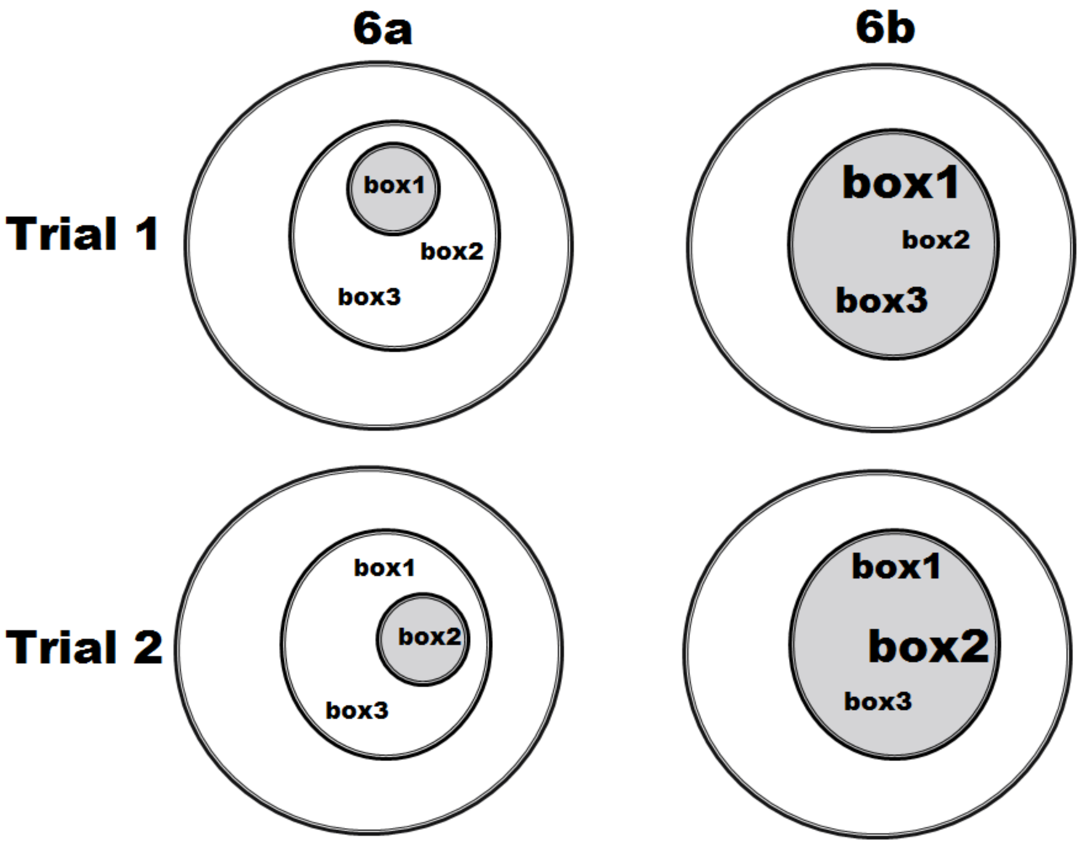

6a
6b
Trial 1
box1
box2
box3
box1
box2
box3
Trial 2
box1
box2
box3
box1
box2
box3

Figure 7