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# Functional Processing Aspects of Working Memory: Capacity Limitations and Mechanisms of Forgetting

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FUNCTIONAL PROCESSING ASPECTS OF WORKING MEMORY: CAPACITY  
LIMITATIONS AND MECHANISMS OF FORGETTING

by

CHRISTOPHER L. BLUME

(Under the Direction of Lawrence Locker)

ABSTRACT

Previous working memory literature has considered the occurrence of an increase in reaction time following an object-switch as evidence supporting a single-item focus of attention. Much literature has also identified interference from other information as the principle cause of forgetting. These hypotheses are here challenged by (1) postulating reaction time differences are indicative of a multiple-item focus of attention that preferentially orders items based upon task-relevance, rather than a single preferred item and (2) presenting evidence of a decay process concurrently causing forgetting alongside interference. In Experiment 1 participants completed a task in which multiple repetitions of a single item resulted in inconsistent reaction times indicating this item was afforded more resources within a pool of multiple items as it became more task-relevant rather than the object switch cost indicating a single item focus of attention. Experiment 2 measured both interference and decay in a task with differential cognitive load and trial time, respectively. Each of these conditions resulted in forgetting from memory independent of one another. This is interpreted such that decay results in forgetting even in the presence of varying degrees of interference and is not affected by said interference.

INDEX WORDS: Working memory, Focus of attention, Decay

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LIMITATION AND MECHANISMS OF FORGETTING

by

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Bachelor of Arts, University of Missouri, 2010

A Thesis Submitted to the Graduate Faculty of Georgia Southern University in Partial  
Fulfillment of the Requirements for the Degree

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## TABLE OF CONTENTS

ACKNOWLEDGMENTS .....	5
LIST OF TABLES .....	8
LIST OF FIGURES .....	9
CHAPTER	
1 INTRODUCTION .....	10
Historical Background .....	11
The Structure of Memory.....	15
Recent Trends .....	22
Current Issues.....	30
Project Objectives .....	37
2 METHOD & RESULTS .....	39
Experiment 1 Method .....	39
Experiment 1 Results.....	45
Experiment 2 Method .....	49
Experiment 2 Results.....	52
3 DISCUSSION .....	54
Experiment 1 Discussion .....	54
Experiment 2 Discussion .....	57
General Discussion .....	60
Concluding Remarks.....	63
REFERENCES .....	64
APPENDICES	
A TABLES.....	72

B FIGURES .....	82
REFERENCES .....	64

## LIST OF TABLES

Table 1: Experiment 1 Primary ANOVAs .....	72
Table 2: Experiment 1 Means and Standard Errors .....	73
Table 3: Run Pairwise Comparisons .....	74
Table 4: RPS Pairwise Comparisons .....	75
Table 5: Margin of Error Means and Standard Errors for Load .....	76
Table 6: Margin of Error Means and Standard Errors for RI .....	77
Table 7: Experiment 2 3x3 ANOVA .....	78
Table 8: Load Pairwise Comparisons .....	79
Table 9: RI Pairwise Comparisons .....	80
Table 10: Load*RI Margin of Error Means and Standard Errors .....	81

## LIST OF FIGURES

Figure 1: Representations of Direct-Access Region and Proposed Preferential Order of Multiple Items.....	82
Figure 2: Example of Experiment 1 Procedure.....	83
Figure 3: Predicted Results of Experiment 1 .....	84
Figure 4: Observed Results of Experiment 1 .....	85
Figure 5: Example of Experiment 2 Procedure.....	86
Figure 6: Experiment 2 Decay-only Predictions.....	87
Figure 7: Experiment 2 Interference-only Predictions.....	88
Figure 8: Expected Results of Experiment 2 .....	89
Figure 9: Observed Results of Experiment 2.....	90

## CHAPTER 1

### INTRODUCTION

Working memory, or the small amount of information held in mind and able to be manipulated for a cognitive task, has a broad range of relevant applications. There is much research linking working memory abilities related to general fluid intelligence (Engle, Kane, & Tuholski, 1999; Conway, Kane, & Engle, 2003; Cowan et al., 2005; Jaeggi, Buschkuhl, Jonides, & Perrig, 2008), attention deficit hyper-activity disorder (ADHD; Klingberg, Forssberg, & Westerberg, 2002), emotion regulation (Schmeichel, Volokhov, & Demaree, 2008), and more. The nature of these links, however, is not well understood stemming, in part, from the plethora of working memory models used by researchers to determine what the implications of an effect are, as well as the genesis of the effect. Indeed, several of the above described linked cognitive abilities/detriments have been as equally disproven as supported (Ozonoff & Strayer, 2001; Redick et al., 2012). One subject of great current interest is the purported relationship between working memory and ADHD. The recent notion of some researchers (e.g., Klingberg, Forssberg, & Westerberg, 2002) that by training individuals on working memory tasks the symptoms of ADHD can wane is contended by other researchers who fail to find support for such an effect (Redick et al., 2012). Likewise, emotion regulation can be seen as affecting working memory abilities as well as being effected by them (i.e., greater working memory is associated with a greater ability to regulate emotions; Schmeichel, Volokhov, & Demaree, 2008). The current study will begin to address this disconcerting lack of consensus by assessing competing theories concerning the functional properties of one

proposed piece of the working memory puzzle, the focus of attention. The nature of the focus of attention, the most precise and absolute aspect of working memory, will be examined by both exploring how items are maintained within it, as well as what happens to those items when they are expelled from this focus attention

### Historical Background

**The Ebbinghaus tradition.** Memory research within the science of psychology is often dated back over a century to the initial work of Hermann von Ebbinghaus. Ebbinghaus developed a way to answer two basic questions: how *much* can be memorized and how *long* do those memories last. Ebbinghaus studied his own memory by memorizing lists of nonsense syllables devised as a series of consonant-vowel-consonant (CVC) trigrams over a short time period.

An important point of this work to Ebbinghaus (1913) was what he termed *savings*, or the difference in the number of trials it took to relearn a list of CVCs. Hence, if a list of 15 CVCs took 10 trials to learn (i.e., perfect serial recall) and only 4 trials to relearn an hour later, the memory savings of 15 CVCs over an hour was 6. Differences in savings dependent on the number of CVCs such that a list of 16 items took more trials to learn than did a list of 6 items, provided some evidence for a capacity limit in memory. Although this research did not set out with the declared goal of informing upon a limit to the amount of information that could be memorized, it is nonetheless an important base from which memory capacity research cites precedence.

Notably, direct evidence for a capacity limit comes from work predating Ebbinghaus by W. Stanley Jevons (1871). Jevons' procedure was to toss a handful of beans into the air above a box. He would then momentarily glance in the box, quickly

turn away, and attempt to enumerate the beans in the box. Upon measuring his error rate he found that when the true number surpassed five he began to produce a significant increase in total errors. Between Jevons' inability to enumerate more than five items and Ebbinghaus' decreasing savings for larger lists of CVCs, there was evidence in favor of the idea that a set capacity limit exists in a short duration memory later dubbed *immediate memory* by William James (1885).

**Miller's psychology of the processing mind.** Miller's contribution to memory research was instrumental regarding a definitive measure of capacity limits. The 'magical' number  $7 \pm 2$  postulated by Miller (1956) provided a quantifiable value to the idea of limited capacity memory. Although previous work assumed there was a limitation to the number of items that could be stored in immediate memory, there was now empirical evidence to support the notion. The idea of a defined capacity limit was so remarkable that to this day new parameters on capacity limits within psychology (e.g., Cowan, 2001; Lewis, 1996; Gobet & Clarkson, 2004) as well as other disciplines (e.g., Warfield, 1988) are referred to as 'magical' in direct reference to the original capacity limit estimation of Miller. The repeated use of the term 'magical', however, demonstrates a possible oversimplification and later misconstrued intention of Miller's span of seven. The number seven is described as magical due to the varying areas of study in which it can be observed, not because the number itself is a gold standard of how much the human mind can maintain. While  $7 \pm 2$  is described by most as the limit of short-term memory, this structural basis was not Miller's intent. Indeed, the term short-term memory is at no point mentioned in his quintessential paper. Rather, as was the case in the work of Jevons (1871), what Miller described was a *span of absolute judgment*. Similar to Jevons' early

work, this span refers to the number of items that can be perfectly recalled before increasing reliance on *estimations* (i.e., close to the accurate recall, but not perfect) of information must occur.

**Increasing capacity.** This span of absolute judgment is considered a limit on perfection (i.e., recall with perfect accuracy) in immediate memory recall in the same way that Jevons found an increasing error rate as the number of beans he was required to enumerate increased. However, Jevons' error rates remained within a close range of the correct judgment indicating one of the ways Miller described for increasing this capacity limit. The ability to come close to the actual judgment beyond seven items is what Miller termed *relative judgment*. By making relative judgments on a larger set of information we are able to adequately, if not perfectly, perceive a greater amount of information. This suggests that an absolute limit to perfect recall in memory may not be the best way to view the limitations. Further support for this idea comes from evidence showing the ability to increase capacity.

Miller's *span of perceptual dimensionality*, or the number of ways to perceive an object (e.g., color, shape, pitch, texture) is critical to understanding capacity limits. For example, we are able to perceive a blue square within an array of colored circles even if more than seven colors are present and one of those circles is blue. The shape of the blue square adds a perceptual dimension allowing for the magical number to be surpassed due to the ability to differentiate items by shape as well as color. The fact that memory span can be increased through perceptual tools outlines the earlier point that Miller's capacity limit was meant as a function of processing ability more than a structural component. A structural capacity limit describes a fixed boundary of capability whereas processing

capacity is dependent on the context or the necessary function of need. As an example, if Jevons' bean box were described as the structural boundary of a capacity of seven, no attempt to add an eighth bean would succeed. As a processing capacity though, the limit of seven is subject to adaptive considerations such as perception of attributes or dimensions. Here, the maximum of seven beans can be processed as a function of categories, each of which separately adheres to the magical number (e.g., six navy beans and seven kidney beans).

The final method Miller described for increasing capacity is the use of mnemonic devices. For example, arranging information into a sequence of absolute judgments (i.e., guesses and estimations are not made) comprises the method of loci in which a geographic pathway is used to make associations between items to be remembered and points along the path (e.g., building columns can be associated with paper towels). By organizing the items into a sequence of absolute judgments such as 'columns equal paper towels' the capacity limit of information can be greatly increased. The method of making a series of absolute judgments in a row also encompasses the notion of *chunking*. The limit of seven applies to the number of chunks, or meaningful units of information, as opposed to the number of individual bits of information, so by chunking bits together we can increase the capacity limit of memory (e.g., the bits FBICIAIRSNSA can be chunked into the series FBI-CIA-IRS-NSA). It is important to note that categorization and chunking are different processes as the four chunks above are made up of smaller items forming semantic associations. Categorization could then be utilized if the number of chunks you were required to memorize surpassed a capacity limit by grouping them into categories (e.g., the above chunks are categorized as government agencies, whereas other

chunks such as NFL-MLB-EPL would be categorized as athletic leagues). Chunking creates combinations of multiple items; categorization creates differences between items. What is made clear by the flexibility of immediate memory span and the nature of the ways to elicit this malleability is that Miller's capacity limit does not imply a structural memory system but an active functional process of "working memory" (Miller, Galanter, & Pribram, 1960).

#### The Structure of Memory.

Despite Miller's earlier ideas of memory processing, Atkinson and Shiffrin (1968) proposed a model for the structure of memory breaking it into the three temporal components of sensory, short-term, and long-term memory (LTM). This model has shown great pervasiveness in the impact of these terms to the extent that they are present in the vernacular of the non-scientific population and are even utilized in scientific papers that purport to disqualify the idea of a structural basis of memory (e.g., the *Temporal Distinctiveness* theory of Glenberg & Swanson, 1986).

Sensory memory, the first component of this standard model, is thought to be unlimited in capacity, and is considered to be a short-term store of raw sensory perceptions for later processing. LTM is likewise considered to be unlimited in capacity as it contains the total accumulation of all past memories. Notably, LTM information can contribute to processing of information in short-term memory. As will be discussed later, the contribution of LTM is critical to an understanding of active processing in short-term memory. Short-term memory is subject to a capacity and duration limit. As the available span of immediate memory had already been defined as  $7 \pm 2$ , the association of the magical number with the short-term storage component has become commonplace. The

short-term store of information is also inexorably linked with attention in that the items present in this store are the immediate perceptions from the sensory storage component deemed relevant. As shown by Miller's (1956) work on the fluctuating nature of capacity limits based on attentional aspects, a full understanding of the nature of short-term memory necessitates linking the memory system with attention.

**Baddeley's structure of working memory.** One of the most influential models of memory building upon the notion of short-term memory is the *multiple-component model of working memory* (Baddeley & Hitch, 1974) in which the capacity limitation applies to a resource capacity of a *central executive*. The central executive component of the working memory system is the residence of attentional attributes in Baddeley's (1986) model and is responsible for planning events, making decisions, and even allocating cognitive resources to two sub components. Each of the two subsystems in this model is responsible for a certain type of perceived information but does not control attention. The *visuo-spatial sketchpad* component is specially called upon for maintaining visual and spatial information. In the case of a mental rotation task (Shepard & Metzler, 1971) in which a person is required to determine if two figures are the same despite the different spatial orientation of the figures, the visuo-spatial sketchpad is responsible for generating and maintaining the two images for further processing (i.e., rotation).

The other subsystem in the multiple-component model of working memory, the *phonological loop*, has led to much debate and critique. Although it has been described as the best-developed component of the model (Baddeley, 2000) it is also the most common component unable to 'do its job' when attentional limitations of the central executive are

compromised. The phonological loop is responsible for maintaining auditory information in a passive phonological store. This passive store, however, contains a process for rehearsing verbal information in the 'articulatory loop'. The best evidence for a phonological component of working memory is the phonological similarity effect (Conrad & Hull, 1964) whereby similar acoustic features (e.g., e and v) are more difficult to accurately remember than are visually or semantically similar features (e.g., u and v). Evidence of the articulatory loop within this component is illustrated by inducing *articulatory suppression* of the 'loop' process (Murray, 1968). Articulatory suppression prevents rehearsal (i.e., the articulatory loop) of verbal information by requiring continuous recitation of irrelevant sound (e.g., "the, the, the, the..." spoken by a participant). This repetitive recitation presents little, if any, additional processing beyond the rehearsal process itself (Naveh-Benjamin & Jonides, 1984). The impaired memory for phonologically presented items when the articulatory loop's resources are consumed by articulatory suppression shows the articulatory loop as buoying items in the phonological store.

The Baddeley (1986) model places the determination of which items occupy attention on the central executive. The mental resource of attention affecting memory processes reverts the focus of memory research back upon Miller's original description of his processing capacity limit and away from the structural standard model of Atkinson and Shiffrin (1968). Whereas the standard model describes the memory system as a series of simple storage structures, each of the stores in Baddeley's model possess an active process; be it the allocation of attentional resources by the central executive, rotational

processing by the visuo-spatial sketchpad, or the articulatory loop by the phonological store.

**Processing within structures.** An assumption of the multiple component model is that cross-talk between the subsystems is possible (i.e., through processing, information can move from one component to another). However, the articulatory suppression technique described earlier has been used in many working memory studies to provide evidence against the notion of subsystems of working memory as separate components. Specifically, when articulatory suppression is utilized for visually presented verbal items, the inability to acoustically rehearse the information should preclude the possibility of transfer from the visual to phonological system (Baddeley, 2000). Although some level of decreased capacity is evident, it is still possible to recall most of these items (Baddeley, Lewis, & Vallar, 1984). The only explanation of this capability while maintaining separate components is the asserted notion that transferring information between subsystems is unnecessary, as the visual information could simply be recalled from the visuo-spatial sketchpad. This can not be the case, however, as the visuo-spatial sketchpad (i.e., visual information) is effective in storing complex visual patterns (e.g., Shepard & Metzler, 1971), but not well suited for serial recall (Phillips & Christie, 1977). The ability to recall visually stored information, therefore, necessitates that the visual information (seeing letters) be stored phonologically (sound of letters) if recall is to be achieved.

Furthermore, visual similarity effects are present in some tests of verbal information (e.g., hearing the letter 'u' and confusing it with the visual letter 'v') further indicating an exchange of information between the phonological and visual subsystems

(Logie, Del Sala, Wynn, & Baddeley, 2000). The subsystems are evidently linked in a manner inconsistent with describing them as fully separate components. Yet more evidence in contention of the separate components is presented in the observed increase in recall span for lists of words with a semantically meaningful relationship (i.e., a sentence). Recall of unrelated words generally declines around five words but when the words are organized into a sentence, a list more than three times as long can be accurately recalled. This requires semantic knowledge stored in LTM but the only part of the multiple-component model with access to LTM is the central executive, which lacks storage ability. In summation, the multiple-component model seemed unable to account for the sharing of information under certain conditions as well as the ability for semantic knowledge stored in LTM to affect phonological recall ability in its current form (Baddeley, 2000).

To account for these observed effects, Baddeley (2000) proposed a fourth component in the *episodic buffer*. The episodic buffer is able to temporarily store information from multiple sources (e.g., acoustic and visual), integrate multiple source codes into a single episodic memory (e.g., codes of bark, soft, and brown integrated as ‘dog’), and supply temporarily stored integrated information to the central executive when it is ‘requested’ (i.e., conscious awareness). Furthermore, the episodic buffer is instrumental in retrieving semantic knowledge from LTM providing the storage ability lacking in the central executive. Partially in light of this fourth ‘fix-all’ component, some researchers began more emphatically looking for a more parsimonious explanation for the cross-component communication.

**Loss of memory: Decay versus interference.** More recent working memory models will be discussed in detail later but an important point is as yet unresolved: what happens when items no longer occupy the scope of attention? On this point the multiple-component model utilizes the method of decay, or the loss of information from memory due solely to the passage of time. The job of the articulatory loop is explicitly stated as preventing decay of auditory memory in the phonological store after a few seconds through rehearsal (Baddeley, 2000). The simple reason for this is that decay is thought to be impossible while items remain in the focus of attention, which is where rehearsal keeps them. The idea of decay of memories is as old as the study of memory itself, as the first evidence for its existence comes from the work of Ebbinghaus (1913). Ebbinghaus charted his savings scores over time into what is known today as the *forgetting curve*. The forgetting curve shows that information is forgotten quickly after a short time interval and information that remains following this initial drop is less likely to be forgotten. The most impactful implication of this work in later years is that it introduced the idea of memory decay. The notion of decay was also present in Thorndike's (1913) 'law of disuse'. The idea that simply not making use of learned behaviors will effectively weaken the behavior bears striking resemblance to the account of memory that states shifting attention away from information will result in impaired memory of the information. Both cases conform to the account 'if you don't use it, you lose it'. The earliest empirical evidence of decay in immediate memory comes from what is now known as the 'Brown-Peterson Task' (Brown, 1958; Peterson & Peterson, 1959) in which a set of three letters is presented followed by a counting backward task (e.g., 309, 306, 303, etc.) before recalling the three letters. The counting backward task is of

variable length and this length between letter presentation and letter recall is referred to as a *retention interval*. With articulatory suppression from the counting backward task preventing rehearsal, a decreasing overall accuracy is shown as a function of the increasing retention interval presenting evidence that the passage of time leads to forgetting in memory (i.e., decay).

The obvious flaw in this methodology is the presence of an increasing amount of new information as the retention interval increases. In other words, as more time passed, more new information was processed (i.e., more counting). This issue brings to light the main competing theory of memory decay: *interference*. Interference can be broken down into the two possible temporal directions of retroactive and proactive. Retroactive interference refers to the loss of old information due to the presentation of new information and proactive interference is the instance of older information making it more difficult to learn new information. In the current context it is sufficient to view interference as the notion that other information, not the inherent passage of time, is responsible for memory loss.

In an effort to more elegantly investigate the competing roles of decay and interference Waugh and Norman (1965) developed a method known as the ‘probe-digit task’ for manipulating both interference and decay. This task consists of a series of 16 digits spoken at a rate of either one-per-second or four-per-second with the final digit invariably acting as the ‘probe-digit’. Upon hearing the final digit the participant was asked to determine what digit followed an earlier presentation of that digit (e.g., for the list ...4 5 6 3 8 2 6, the correct response is 3). As the one-item-per-second list required more time to complete (16s), a poorer performance on these trials than the quicker four-

per-second pace (4s) would indicate the presence of decay. On the other hand, if performance declined as the number of intervening items between the recall- and probe-digit increased, then interference is indicated. The latter was shown to be the case as the presentation rate showed little effect whereas the number of intervening items resulted in a steady decline in performance.

### Recent Trends

More recently, alternative views to the multiple-component model have led to a number of alternate explanations as well as a revisiting of some fundamental assumptions. For example, with the addition of the episodic buffer component to his model Baddeley had, it could be argued, made the phonological loop and visuo-spatial sketchpad redundant, as these components are responsible for jobs that can be accomplished solely by the episodic buffer. Essentially, attention is analogous to the central executive and memory to the episodic buffer. Issues are now being re-examined including capacity limits ('can we only retain a magical number of items and must this magical number be the same for everyone?'), the reason for forgetting ('decay or interference?'), as well as structural assumptions ('is working memory really a simple equitable trade-off of the classic short-term memory store?').

**The focus of attention.** Broadbent (1958) initially described attention as a filter that leads to the direct consequence of a capacity restricted storage faculty from the large amount of information perceived through the senses (i.e., a capacity limit). The central executive acts as this filter by controlling the process whereby the conscious intention of the mind is able to shift where and what is to be attended. The inherent need to shift attention toward or away from certain perceptions (i.e., not *everything* can occupy

attention) further demonstrates that the locus of the capacity for immediate memory is that of a *scope of attention* (Cowan et al., 2005). The scope of attention is derived from another of Broadbent's (1975) descriptions in which it is suggested there exists a limited form of attentional capacity that can maintain only a few items. Capacity limits placed upon attention as opposed to storage reveals the intriguing issues of how it is determined which items occupy the scope of attention and what happens when these items are no longer occupants. Recent research on capacity limitations tends to investigate the scope of attention in terms of how attentional resources devoted to a processing function, such as the central executive, determine how much information can be handled at any time, rather than as a limit in storage. As previously described in the work of Miller (1956), storage limitations can be circumvented by adding extra dimensions to the information being stored. Luck and Vogel (1997) had discounted the idea that feature-attributes play a role in capacity limit. However, recent study of this shows that the capacity of working memory *is* more dependent on *attributes* (modern vernacular for Miller's dimensions) than the quantifiable number of items. Specifically, Cowan, Blume, and Saults (2012) showed that when a task requires binding multiple attributes into one item (e.g., color and shape make up a 'blue circle') capacity is less than when memory for only one attribute of the items is necessary (e.g., 'blue' or 'circle'). Structurally, the same number of items is presented but how they are processed determines the capacity.

The ability to differentially attend to certain attributes or items as a whole (e.g., a bit or chunk) is described as a 'zoom-lens' model of attention (Eriksen & St. James, 1986). The items within a 'zoomed in' scope of attention are referred to as the *focus of attention*. The focus of attention is similar to Miller's (1956) span of absolute judgment in

that the items within the focus of attention are theorized to be held in a perfect state of memory and they are not susceptible to forgetting by decay (Cowan, 1999). Keeping items in the focus of attention requires one of two active processes in either articulatory rehearsal (Naveh-Benjamin & Jonides, 1986), described earlier, or attentional refreshing (Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007). Attentional refreshing is simply the active directing of attention toward an item to strengthen its memory trace, or the ability to retrieve the memory (Camos, Mora, & Oberauer, 2011). When these processes are compromised (e.g., articulatory suppression for rehearsal and a loud novel stimulus for refreshing) items can be knocked out of the focus of attention allowing for forgetting of those items (Barrouillet, Bernardin, & Camos, 2004). These points are the agreed upon functional limitations of the focus of attention. However, the capacity of the focus of attention is not yet considered conclusive (i.e., how far we must ‘zoom-in’ before we obtain items in a perfect state of memory).

This investigation is divided into camps that espouse either a multiple-item focus of attention (e.g., Cowan, 2001; Barrouillet et al., 2007) or a single-item focus (e.g., Oberauer, 2002; Lewandowsky, Oberauer, & Brown, 2009). These different notions will be discussed in greater detail later, but for the present it is important to know that a single-item focus states that only one item or chunk is selected to be attended to for an individual cognitive task, whereas a multiple-item focus regards the focus as able to equally maintain more than a single item or chunk within the focus of attention.

**Developmental and individual differences.** Differences between the relative working memory abilities of individuals returns the idea of structural limitations back to the forefront of important research topics. Developmental changes in working

memory abilities are one manner in which these differences are most evident. In the case of the previously mentioned attentional refreshing, age is shown to be important in determining how detrimentally the irrelevant speech effect (i.e., a distracting word deterring attentional control) can affect the focus of attention. For example, Elliot (2002) illustrated a decreasing irrelevant speech effect for recall of a series of numbers as participants' age increased (i.e., eight year olds are more affected than nine year olds, nine year olds are more affected than ten year olds, and ten year olds are more affected than adults). Developmental changes are here apparent in that younger age groups show a diminished ability to attend to and recall relevant items when irrelevant words are present due to interference with rehearsal. However, this effect declines in older age groups as it is theorized that either (if not both) (1) the focus of attention's capacity increases or (and) (2) the process of attentional refreshing becomes a part of an individual's cognitive repertoire (Elliot, 2002; Cowan, 1995). Each of these cognitive developments is important for considering working memory in terms of processing aspects rather than structural components as they, respectively, assume (1) capacity is dependent on an increasing inherent processing capability and (2) the introduction of a new process through development makes a previous estimation of capacity dependent on age.

Observed differences in working memory ability continue beyond cognitive development, however, as adult individual differences are also present in the relative susceptibility to irrelevant stimuli (Elliot & Cowan, 2005), as well as working memory span tasks. Working memory span tasks are considered either simple or complex depending on the nature of the task (Turner & Engle, 1989). Simple span tasks include the *digit-span* in which a series of numbers is quickly presented and a participant is asked

to serially recall (i.e., recall in order) as many digits as possible with the final digit recalled being the final digit presented. For example, for the digit list “4,6,3,5,7”, recall of “3,5,7” is a span of three whereas recall of “6,3,5” is a failed trial in that the final digit recalled was not the final digit presented. The most common complex span task of working memory is the *operation-span* (O-span). The general procedure of the O-span is to present a letter as memoranda followed by an arithmetic equation and repeat each step several times until the participant is asked to serially recall the letters presented in between the arithmetic equations (a widely utilized automated version is described in Unsworth, Heitz, Schrock, & Engle, 2005). Simple span tasks then, consist of a single task procedure that requires memory and attention, whereas complex span tasks consist of a dual task procedure with each task requiring working memory resources. In individual differences research of working memory these span tasks are used to distinguish between *high span* and *low span* individuals and these groups often demonstrate different abilities in working memory (e.g., ability to accurately switch between relevant information in the focus of attention, Unsworth & Engle, 2008; ability to tune out irrelevant information from the focus of attention in averting the cocktail-party phenomenon, Conway, Cowan, & Bunting, 2001). As with the development of new cognitive processes, inherently different processing capabilities of individuals are observed despite the assumption of identical working memory structures within all individuals.

**Modern models of working memory.** Current models of working memory differ in regard to both structure-versus-process as well as decay-versus-interference. The importance of processing in working memory has led some researchers to treat the

working memory system in terms of its processing mechanisms as opposed to attempting to lay out a definitive structure of how information is encoded from sensory input into memory. One such model that takes processing into account while still utilizing a storage nomenclature is the *dual-store model* of Unsworth and Engle (2007). This model is largely dependent on individual differences in working memory abilities in defining a *primary memory* and *secondary memory* and supports the notion that a high working memory span improves performance of both stores. Primary memory can be generally considered similar to the focus of attention previously mentioned in that it is a capacity limited store demanding attention. The secondary memory store is more analogous to a traditional LTM store such that it contains items displaced from primary memory either through interference from new incoming information or attentional drift (i.e., attentional resources devoted to a task to weaken with or without a second task demanding said resources).

It should be noted that a number of current models rely upon interference for loss of items from a capacity limited store without allowing for or considering the possibility of decay. Davelaar, Goshen-Gottstein, Ashkenazi, Haarman, and Usher (2005) present a two-store model in which items are displaced from an episodic-contextual buffer (again, equivalent to the capacity limited focus of attention) to a lexical-semantic LTM only by incoming items (i.e., interfering items). Davelaar et al. describe decay as being negated through a process similar to rehearsal or attentional refreshing (though termed self-recurrent excitatory input). Similarly, Oberauer and Kliegl (2001; 2006) outline an interference-based model in explaining limits on processing speed and accuracy. This model takes into account a greater amount of interference based on similarity of attributes

of items, whereas Davelaar et al. considered interference as a more general influence of displacement from attention.

Decay does, however, have a large influence in the *time-based resource-sharing model* of Barrouillet, Portrat, and Camos (2011). This model allows for interference but also includes mechanisms for a decline in recall of items from complex span tasks as *time passes* concurrent with a distractor task (recall that complex span tasks incorporate resource-sharing between dual-tasks). In opposition to Davelaar et al. (2005), in which decay is negated through self-recurrent excitatory input (i.e., attentional refreshing), this model illustrates decay for cases in which this process is not possible (e.g., distractor tasks comprising a cognitive load). Individual differences can be taken into account here insofar as a capacity limit is determined by attentional refreshing rate and rate of decay (i.e., faster refreshing affords greater capacity, Cowan, Rouder, Blume, & Saults, 2012).

**Embedded-Processes model.** A common theme throughout these models is a close relation to a LTM store. Indeed, some models of working memory go so far as to place the working memory system entirely within LTM (e.g., Cowan, 2001; Oberauer, 2002), whereas working memory had previously been generally associated with the short-term store of Atkinson and Shiffrin (1968). Cowan (2001) considers working memory as a system of three embedded-processes in (1) LTM, (2) the activated portion of LTM, and (3) the focus of attention. In this case then, working memory is not considered on a structural basis, but rather as a completely functional process. The LTM store of this *embedded-processes model* is identical to previous descriptions by Atkinson and Shiffrin, although the activated portion of LTM contains the previously acquired knowledge that is relevant to the task at hand. This activated portion of memory shares characteristics with

a spreading-activation account of information processing (Collins & Loftus, 1975) such that items (or nodes) related to a situation are in a state of activation preferentially to items with no direct relation to the current task requirements (e.g., a dinner party may activate semantic knowledge of etiquette but not internal combustion engines). The focus of attention here is the limited number of items ( $4\pm 1$ , Cowan, 2001) that can be attended to in a state of perfection (i.e., with no potential for memory loss). Items within the focus are not susceptible to forgetting unless/until they are removed to LTM (active or inactive). An item can enter the focus *voluntarily* if selected by a central executive (identical to Baddeley's [1986] definition) from the activated portion of LTM or from sensory inputs and *involuntarily* if it constitutes a novel sensory stimulus, especially if salient (e.g., a loud bang, bright color, or semantically relevant stimulus such as the irrelevant speech effect or the cocktail party phenomenon). An important point is these newer models tend to more heavily value the underlying processing that defines working memory rather than attempting to design a structure of discrete components. Another major shift is that these models allow for 'cross-talk' between the previously different components, as they are unimodal in their treatment of auditory and visual information.

Despite the greater reliance on processing over structure, models such as the embedded-processes model of Cowan (1999) are not immune to minor adjustments that limit processing aspects. In the same manner of the addition of the episodic buffer to the multiple-component model, Oberauer (2002) made the structural addition of a *direct-access region*, which attends to only a single item at a time, within Cowan's focus of attention (this model had previously espoused a multiple item focus). The remaining three-or-so items in the focus then constitute a second level of working memory. With

this structural addition, a formerly unitary component of working memory is pieced in two. This updated version of the model also posits that the process of decay is not a mechanism of forgetting. The current research intends to further investigate the nature of functional processing in regard to a single or multiple item focus of attention. It will be argued that a unitary focus of attention able to contain multiple items is the more parsimonious interpretation. A process of decay in working memory will also be investigated to demonstrate how items are maintained in working memory when outside of the focus of attention. This existence of such a process would be inconsistent with several of the previously described models that do not allow for such a process. Such models would require major changes if they are to remain valid.

#### Current Issues

**Processing aspects determining capacity.** Within working memory theory there is a lack of consensus as to whether multiple items can be maintained in the focus of attention or if a single item is the maximum capacity of our attention in an absolute state of perfection (as originally defined by Miller's span of absolute judgment, 1956; and later refined by Cowan, 2001). A simple method for determining if a multiple item focus is possible requires the concurrent use of multiple items without allowing an opportunity for active retrieval of those items over a series of trials. An example of this is the previously mentioned O-span task, which utilizes focus-switching (i.e., directing attention to a different object) within a trial. Participants are asked to retain an item (e.g., the letter B) followed by a secondary task constituting a *cognitive load*, or the simultaneous use of resources between multiple tasks (e.g., a simple arithmetic equation) before finally recalling the initial item (Turner & Engle, 1989). The important measure of

this process is reaction time (RT). When an object change (e.g., switching from the letter to the arithmetic) occurs in the above task, an increase in RT for recalling the letter is observed following this change. This *object switch cost*, or increase in RT as a result of switching from one object to another, has been interpreted as evidence for a single item focus. The notion here is that this additional time is required in order to move the new item into a singular focus of attention (Oberauer, 2002). This supports a single item absolute focus termed by Oberauer as the *direct-access region*. The recalled item is said to have returned to the pivotal absolute attentional state from another temporary storage in Oberauer's description of the focus as containing a second level process (Oberauer, 2002). This simple solution, however, is reminiscent of the addition of the episodic buffer component of Baddeley (2000), leading different researchers to different conclusions regarding the capacity of the focus of attention, as well as sometimes returning to a more structural description of memory.

Pashler (1992) notes that placing a standard limit on the capacity of attention can be misleading as a result of distinct cognitive processing limitations referred to as a 'cognitive bottleneck'. However, this very 'cognitive bottleneck' has been shown to disappear through extensive practice on a dual-task procedure suggesting a basic familiarity with a task can increase previously observed attentional limitations (Schumacher et al., 2001). Recent work with extensive practice has provided support for plasticity in the theorized structure of working memory. Oberauer and Bialkova (2011) showed that a single item focus *can* be expanded with practice when the items are from different modalities (e.g., a numerical digit and a spatial location) although items of the same type are processed sequentially to avoid cross-talk between the multiple, similar

items. These data demonstrate the type of processing taking place (parallel for dissimilar modalities and sequential for similar) can alter the capacity limits in working memory such that object switch costs may be nothing more than a by-product of sequentially processing certain types of information. Overall, literature on the nature of capacity limits suggests that when a single item focus is beneficial to task performance, a single item represents the capacity, as shown in switch cost data, but when a larger capacity is beneficial, the focus can expand (Eriksen & St. James, 1986). This can be understood by relating the focus of attention to a camera's zoom-lens inasmuch as for a picture of the grand canyon, the focus 'zooms out', whereas for a portrait, the focus 'zooms in'. This would indicate that evidence supporting a single-item direct-access region may be task-dependent. In other words, for a task that is more efficiently completed utilizing processing of more than a single item at once, responding may reflect a multiple-item focus in working memory.

This hypothesis was tested when Gilchrist and Cowan (2011) slightly modified a switch cost methodology that previously supported a single-item focus (Oberauer & Bialkova, 2009) to require the access of multiple items and found that the focus of attention was greater than one. Oberauer and Bialkova initially designed a procedure whereby colored circles were learned as representing numbers (e.g., blue equals five). Following a learning phase of these representations, participants were asked to solve a color equation (e.g., blue minus brown) followed by another trial that would change the equation in some way (e.g., blue becomes brown and brown becomes green for the equation 'brown minus green'). When this equation required two items updated in the focus of attention (i.e., both items changed) the reaction times were indistinguishable

from a single updated item. The explanation provided was that the two items had been combined to form a single chunk (i.e., still only a single item in the focus). The Gilchrist and Cowan procedure tested the presence of chunking in the two-item switch trials of the procedure by using multiple features (geometric shapes and color blobs), which would make chunking more difficult as object-features could not be inter-changed between trials. This procedure resulted in increased RT when both features changed compared to a single feature change showing that (a) the two-item update trials of Oberauer and Bialkova actually only required a single *feature* update (i.e., attribute or dimension) and (b) updating two features in the focus of attention takes longer than a one update. Therefore, the focus of attention can maintain more than one distinguishable feature, although at a cost with respect to RT.

**Forgetting by decay.** The plasticity of a formerly supposed structural model of working memory indicates that, as noted by Pashler (1992), additions to the structure of working memory (e.g., the direct-access region and episodic buffer) should be abandoned. Rather, a better understanding of the *functional processes* of working memory will provide a clearer picture of the concept. Processing aspects of working memory have not been entirely shunned, as previously discussed, but the nature of this process faces the difficulty of overcoming a long debate concerning decay versus interference. Interference is now widely accepted as evident from all sides of this research. However, while many researchers consider this debate to have been decisively ‘won’ in favor of interference (Lewandowsky, Oberauer, & Brown, 2009), support for decay is still evident.

Decay can be broken down into several theories but at the crux of the issue is that the simple passage of time results in memory loss independent of interference. The previously mentioned two classic methodologies that studied decay have important concerns still unresolved today. In the Brown-Peterson task (Brown, 1958; Peterson & Peterson, 1959) it is important to note the type of decay being tested is what is known as *trace decay*. Trace decay posits that the ability to retrieve a memory is impaired as time passes. The expectation of decay of this kind is for the RT for a response to increase as retention interval increases. In other words, the notion of trace decay is supported if there is a shorter RT when only three seconds pass between study and test than when 18 seconds pass. Effectively, trace decay *was* shown in this RT data. More time was spent reconstituting the memory trace as more time passed during the retention interval. Trace decay theory posits that the memory trace after only three seconds was readily available whereas the memory trace after 18 seconds had decayed and therefore produced the longer RT. A recent re-analysis of the original probe-digit task of Waugh and Norman (1965), likewise illustrates a result supporting decay theory. Recall the probe-digit task presented a sequence of digits with interference manipulated through examining the number of intervening digits between the probe and the to-be-recalled digit. As is the case in a number of more recent studies discussed below, decay is assessed by manipulating timing within the procedure. In this case, timing was manipulated by altering the presentation rate of the digits. Re-analysis of this quintessential evidence against decay using Bayesian modeling showed statistical evidence for a decay process when the level of interference was relatively high or low (Altmann & Schunn, 2012). That is, Waugh and Norman found no main effect of decay where one exists for

interference. This re-analysis showed a significant interaction suggesting decay may occur under certain conditions (i.e., in the case of either high or low interference).

More recent evidence from Towse and Hitch (1995) illustrates a decline of counting-span as counting *speed* was decreased whereas counting *difficulty* showed no effect on counting span. Increased difficulty would require greater *cognitive workspace*, or pre-determined resource availability, and can therefore be considered analogous to interference in its use of available resources. As noted, in this study it was not the difficulty that seemed to negatively impact memory, but simply allowing more time to pass (i.e., allowing for decay). A particular difficulty with showing the presence of decay, however, is that decay of memory is unlikely, if not inherently impossible, when rehearsal and attentional refreshing are allowed. However, methods that suppress these can be considered to be interference (e.g., Waugh & Norman, 1965). As time is the question for this process, however, time can be the answer. As noted above, the timing of participants' task demands in an experimental design embeds a possible functional means by which to assess the decay process. Typically, in memory research of all types, responses are provided as soon as possible with very little time in between responses. Presumably, this practice is the participant's way of 'getting information out' before it is lost from memory. Assuming then a presumed loss of memory 'not quickly gotten out', a procedural contingency in which a pre-determined interval is required between individual responses could provide a mechanism by which time is allowed to pass, but all interfering information has been presented prior to the memory test. To this end, Cowan and AuBuchon (2008) found evidence of decay by requiring memory responses in a predetermined time interval pattern as opposed to allowing participants to respond

immediately. That is, participants were not able to respond as quickly as possible and instead had to wait before providing each individual response. Using this paced-timing response procedure, recall became progressively worse toward the end of the list. Support for the conclusion of decay from this paced-timing procedure has been provided from multiple replications (Portrat, Barrouillet, & Camos, 2008; Barrouillet, De Paepe, & Langerck, 2012). All of these studies share the important point that in order to find decay, study *and* response timing within the memory task must be carefully controlled. That decay is observed only under very specific conditions, however, suggests that forgetting due to decay is minor compared to forgetting due to interference, and consequently, decay may lack external importance as it is overpowered by interference in real-world generalizations such that any potential effects are not present concurrently with interference.

Therefore, evidence must be presented that consistently shows decay is present even in the event of interference. This has been partially accomplished, but only under specific conditions. Ricker and Cowan (2010) showed evidence for time-based forgetting for unconventional (i.e., unrehearsable) visual items in working memory independent of interference but were unable to determine if the decay was gradual or ‘sudden-death’ (i.e., do memories slowly lose cohesion as time passes or is there a definitive time interval when they disappear entirely?). This procedure presented an array of symbols with no discernable common verbal titles (e.g., hieroglyphs) followed by a cognitive load task of either repeating a spoken digit or speaking the ‘spoken digit minus one’ (e.g., presented with ‘5’ participant says ‘4’). These low and high cognitive load conditions, respectively, along with a condition with no secondary task were presented for variable

retention intervals before a second array was presented to be determined as the same or different from the initial array. The results illustrated that both increases in cognitive load as well as increases in retention interval led to poorer accuracy such that high-load conditions were less accurate than low load conditions and, notably, within all conditions, longer retention intervals were less accurate than shorter retention intervals. The current experiments will expand on this in order to assess conventional verbal items, thereby expanding the specific conditional decay parameters (i.e., visual information) set by Ricker and Cowan (2010), as well as demonstrate that sequential processes of a multiple item focus of attention are susceptible to preferential degradation (loss of higher standing in the sequential order) mimicking the process of gradual time-based decay of memory.

#### Project Objectives

The current objectives are to further investigate the nature of processing effects on capacity limits and decay in the context of a functional rather than structural framework. It is hypothesized that (1) multiple items are held in the focus of attention and that object switch costs are not indicative of a single item focus and (2) processes in working memory are subject to decay. Experiment 1 will provide support for the notion that the focus of attention maintains items in multiple discrete slots based on *immediate task relevance* relative to other items within the same focus. That is, it is not the case (as in Oberauer, 2002) that the focus can be broken down into the structurally disparate components comprising a single preferred item (i.e., the direct-access region) and the remainder of attended items. Rather, preferential ordering of items occurs within a unitary system. In this way, the object switch cost effect, previously cited as evidence for a single item focus, is actually an artifact of measuring items as ‘single’ and ‘other’. If

this is the case, object switch costs between the items in the ‘other’ group should also be observed, as *all* items are preferentially ordered relative to task-demands. This would also account for large variances in the object switch costs for measurements based on ‘single’ and ‘other’ parameters (e.g., Oberauer, 2002). Further, evidence for decay would demonstrate a crucial shortcoming of many models of working memory (i.e., interference-only models) and help further develop those models that allow (or fail to disallow) decay. Experiment 2 will illustrate that, in the absence of rehearsal and attentional refreshing, requiring a response in less-than-adequate time to retrieve the memory leads to a gradual decay of retrieved memories as a function of increased retention time, independent of interference.

## CHAPTER 2

### METHOD & RESULTS

#### Experiment 1 Method

Oberauer (2005) demonstrated that when multiple individual numbers are presented as memoranda, requiring an arithmetic update to two *different* numbers results in a longer RT for the second update than if the second arithmetic update remains at the same number. The presence of these object switch costs (the observed increase in RT when directing attention away from one item and toward another) in working memory tasks has been suggested as evidence for a single item focus of attention. The proposed procedure will illustrate, however, that object switch costs are not consistent (i.e., magnitude of switch cost fluctuates) within a task trial utilizing repetition (utilizing the same item consecutively) or lag (*returning* to a previously utilized item after varying arithmetic updates to other items). Whereas Oberauer demonstrated simply that a switch increases RT, examining *types* of switches (i.e., not examining conditions as *switch* or *no-switch*) further informs upon the processing aspects of the focus of attention. Unsworth and Engle (2008) showed that RT is not consistent when the switch condition is analyzed based on smaller breakdowns of type in a simple counting span task. The lack of consistency in switch costs is key in terms of distinguishing between a single item focus of attention versus a multiple item focus. Using the approach of Unsworth and Engle within the context of Oberauer's methodology, it can be shown that a preferentially ordered multi-item focus of attention is observed in an updating task of verbal items. The task, to be described in greater detail later, presents several individual numbers to be remembered followed by a series of arithmetic updates to those numbers in a procedure

which manipulates (1) run (i.e., updating the same number consecutively) and (2) lag (i.e., returning to a previously updated item following updates to other items) while also keeping track of (3) runs-prior-to-switch (i.e., the 'run' count prior to arithmetically updating a new item). The implications of these three factors are described below.

(1) An item truly prioritized to sole possession of the focus of attention should not show changeable characteristics in RT with repeated repetition (run), as it cannot demand any more attention (i.e., all available attentional resources have already been devoted to it). Therefore, an RT continually decreasing as an item is repeatedly selected to be updated illustrates that it does not have sole placement in the focus of attention following the initial repetition, as has been previously postulated (Oberauer, 2005). The continually decreasing RT is instead showing the item is becoming increasingly preferential within the item-order of a multiple-item focus of attention as more attentional resources are devoted to it (e.g., if one repetition yields an RT of 2,500ms, a second repetition will result in a 2,000ms RT). That is, a single item focus would predict a floor on RT after a single repetition, whereas a process of ordering multiple items based on task relevance suggests increasing repetitions will allow for decreases in RT as attentional resources are updated.

(2) An unutilized item's RT (when ultimately utilized) will increase as a function of the number of consecutive instances the item goes unutilized. This can be inferred as diminished task relevance of the unutilized item resulting from a degradation of the value of that item. In order to keep other factors (e.g., repetition) constant, data will here be collected utilizing a *lag* methodology. Lag is defined as the number of intervening *unutilizations* between two utilizations of the same item (e.g., utilizing one item, utilizing a

different item, then utilizing the first item again places a lag value of one on the *return* to the first item). The RT to an item that was arithmetically updated two manipulations prior (i.e., lag=1) should be shorter than the RT to an item updated four manipulations prior (i.e., lag=3) (Unsworth & Engle, 2008). A multiple item focus of attention would suggest that differences in lag RT (shorter RT for shorter lag) indicate that the importance of items (i.e., attention allocation) is continuously updated, as opposed to the presence of a second store where items would presumably be held equally.

(3) Following a switch away from a repetitively utilized item, RT will increase as a function of the number of repetitions prior to the switch (e.g., a switch to a new item following a run of two might yield an RT of 3,000ms whereas a switch following a run of three will result in a 3,500ms RT). The increase in RT from one item to another is defined as the object switch cost, predicted by a single item focus to remain constant regardless of repetition on the initial item, as the item's focus within working memory has not changed. Alternatively, an ordered multiple item focus predicts increasing repetition places increasing relevance to the repeated item resulting in increasing switch cost (i.e., RT for a different item) as a function of repetition.

The procedural details of the current experiment are similar to work illustrating a single item focus of attention (Oberauer, 2002; Oberauer, 2005) demonstrating that the stable RTs predicted by a single item focus give way to RT fluctuations consistent with multiple items constantly jockeying for position within the focus. Indeed, depending on the processing aspects of any task, several different estimations of these RTs are possible but the heart of this experiment is to show that a multiple item focus is *possible*. Were this same procedure run with a greater number of individual items to be updated, task

completion would become impossible, as the attentional demands would then exceed the capacity of the focus of attention. The mere ability to accomplish the task suggests a multiple item focus of attention while the fluctuating nature of the RT fails to suggest a single item direct-access region within that focus. Therefore, a structural component for a single item focus that is only sometimes present is less parsimonious than a multiple item focus that can discretely order those multiple items when the situation calls for such order (for a representation of both the direct-access and discretely ordered focus of attention refer to Figure 1).

### *Participants*

Twenty-four undergraduate (19 female, 5 male, mean age 20.16 years) students from a southeastern university participated for course and/or extra credit.

### *Apparatus*

Standard QWERTY keyboards were used for responses and stimuli were displayed on a computer monitor. Auditory feedback was provided through single channel speakers at a sampling rate of 44.1 kHz. Auditory feedback was provided to ensure an adequate speed/accuracy relationship such that responding was as rapid and accurate as possible. The experiment was designed using E-Prime 1.0 Software (Schneider, Eschman, & Zuccolotto, 2002).

### *Procedure*

Participants engaged in a memory-updating task modeled after a task used by Oberauer and Kliegl (2006). This task began with the presentation of four boxes on the screen, each with a single digit number inside ranging from 1 through 9 (e.g., 

5
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4
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8
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2
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). The participant began a trial by memorizing these four ‘start’ digits for as long as was

needed before pressing the space bar. A series of arithmetic operations were then displayed one at a time within one box at a time, each to be responded to by the participant (see Figure 2). Each of these operations was to be responded to such that the box in which the operation is presented indicated which of the four individual ‘start’ digits is being manipulated. The four start digits provided participants with the first half of the equation for each individual box whereas the second half was provided through the series of operations within one of the single boxes (e.g., if *box 1* had a start number of 5 and an operation is presented in *box 1* as  $\boxed{+3}\boxed{\phantom{0}}\boxed{\phantom{0}}\boxed{\phantom{0}}$ , the full arithmetic equation to be solved is  $5+3$  and the participant was asked to respond with 8 as soon as possible after  $\boxed{+3}$  appears on screen). Participants were instructed to respond as quickly and accurately as possible using the top-row number keys as soon as each operation was presented (i.e., within each trial, several arithmetic responses are to be given). Following each correct response, a 50ms 700 Hz tone sounded whereas an incorrect response elicited a 100ms 300 Hz tone. This tone did not delay the presentation of the next operation and was intended to encourage an optimal response time/accuracy relationship. Information was also constantly updated within the task such that the correct response to each equation replaced the initial ‘start’ digit for the box in which the operation was conducted (e.g., the result to the equation above is 8, so the number to be remembered as the first half of *box 1* equations is now 8 instead of 5, so that the four boxes should now be thought of as  $\boxed{8}\boxed{4}\boxed{2}\boxed{1}$ ). Following the final successive operation, a new ‘start’ list was provided.

A total of 192 trials with a varying number of arithmetic operations each were presented to each participant (for a total of 863 possible responses) invariably including

exactly 24 trials of each of 12 run, lag, and RPS conditions. The design patterns are such that each condition occurs exactly 24 times with position counterbalanced so that 6 of each of the 24 trials took place in each horizontal position. Likewise, when a switch occurred, it was counterbalanced such that half of the switches moved from left-to-right and half moved from right-to-left. Selection patterns were designed allowing for repetition of box selection for up to four consecutive operations before switching to a new box (i.e., run=4 followed by RPS=4). Likewise, more selection patterns allowed for a lag of up to four between operations in the same box (e.g., for the selection sequence: *box 1, box 2, box 3, box 1*; the second *box 1* constitutes lag=2). All arithmetic operations were single-digit addition or subtraction problems with a result that was also single-digit to avoid math anxiety/ability differences. Notably, each of the greater run conditions would include the lesser conditions embedded within them such that, in order to reach run=4, the conditions for run=1, run=2, and run=3 would be met along the way. Therefore, an a priori decision was made to specifically regard trials designed as run=2, run=3, and run=4 as such in order that subject condition mean RTs would be composed of an equal number of responses. In other words, only the equation that satisfied the greater run was included in analyses. Participants completed all conditions in a within-participants design. The pattern selection was a blocked random-without-replacement design such that 12 blocks of 16 trials were presented, each block consisting of 8 lag trials and 8 run/RPS trials (the RPS manipulations must follow run manipulations so they are contained within the same trials). Additionally, though the four start numbers must be disparate, at any point throughout the updating task the updated numbers could be the same as in the example of  $\begin{bmatrix} 5 & 4 & 8 & 2 \end{bmatrix}$  becoming  $\begin{bmatrix} 8 & 4 & 8 & 2 \end{bmatrix}$ .

## Experiment 1 Results

Prior to analyses, reaction time (RT) data that fell beyond three standard deviations (SD) from the grand mean were excluded (< 2%) resulting in an overall mean RT of 2367.57ms across all conditions with a SD of 359.06ms. Likewise, overall accuracy was measured to check for poor accuracy as grounds for exclusion (below 70%), but all participants reached at least 75% overall accuracy.

### **Preliminary Analyses**

**Accuracy measures.** Conditional accuracy was analyzed across several factors in order to determine if difficulty level was equal within each factor. All reported Analyses of Variance (ANOVA) are one-way repeated measures. Some of the following analyses violated sphericity as determined by a Mauchly's test. All  $F$  values with decimal degrees of freedom used a Greenhouse-Geisser correction. No effect was found for experimental trial block order,  $F(6.17, 141.97) = .83, p = .55$ . Sequential equation order within a trial series, however, did have an effect,  $F(1.59, 36.55) = 54.09, p < .001$ . Fisher's Least Significant Difference (LSD) test confirmed significant ( $p < .05$ ) linearly descending differences in accuracy as a series of equations continued from the first ( $M = .94, SEM = .01$ ), to second ( $M = .90, SEM = .01$ ), to third ( $M = .85, SEM = .01$ ), to fourth ( $M = .80, SEM = .02$ ), to fifth ( $M = .75, SEM = .02$ ), to sixth equation ( $M = .68, SEM = .03$ ). Likewise, horizontal number position on which an equation was to be solved also showed an effect,  $F(3, 69) = 18.92, p < .001$ . An LSD test showed more accurate responses when the equation was on the number in the far left, or position one, ( $M = .89, SEM = .11$ ) than when on the far right ( $p < .01$ ), or position four, ( $M = .86, SEM = .14$ ). Position four was, in turn, more accurate ( $p < .05$ ) than positions two ( $M = .84, SEM = .13$ ) and three ( $M =$

.82, SEM = .13), which were not significantly different from one another. Finally, a paired samples *t*-test showed that an equation switching from right-to-left ( $M = .78$ , SEM = .02) was not significantly different from one switching from left-to-right ( $M = .79$ , SEM = .02),  $t(23) = .08$ ,  $p = .94$ .

**Reaction time measures.** All above accuracy checks were similarly analyzed for potential RT differences in milliseconds (ms). Again, all ANOVAs are one-way repeated measures and decimal degrees of freedom indicate Greenhouse-Geisser corrections for violated sphericity. No effect was found for experimental trial block order,  $F(11, 253) = .78$ ,  $p = .66$ . Sequential equation order within a trial series, however, did have an effect,  $F(2.49, 57.32) = 12.07$ ,  $p < .001$ . An LSD test (listed in descending order by mean RT) showed the sixth equation had a significantly longer RT ( $M = 2630.82$ , SEM = 78.52) than all others ( $p < .05$ ). The next longest RT was for the first equation ( $M = 2426.98$ , SEM = 96.33), which was significantly longer than the fourth ( $p < .05$ ) and marginally longer than the fifth ( $p = .067$ ). The second equation ( $M = 2353.33$ , SEM = 77.05) was different only from the previously mentioned sixth. The third equation ( $M = 2344.81$ , SEM = 72.20) was significantly different from the fourth ( $p < .05$ ). The fifth equation ( $M = 2302.98$ , SEM = 60.67) was significantly different only from the previously mentioned sixth and first (marginal for the latter). The shortest RT was for the fourth equation ( $M = 2302.51$ ), which was significantly different from third ( $p < .05$ ) and the previously mentioned first and sixth equations. Likewise, horizontal number position on which an equation was to be solved also showed an effect,  $F(3, 69) = 34.47$ ,  $p < .001$ . An LSD test showed significantly ( $p < .01$ ) longer RT for equations on position three ( $M = 2541.35$ , SEM = 72.01) than positions four ( $M = 2530.86$ , SEM = 76.94) and two ( $M = 2392.47$ ,

SEM = 73.72), which were not significantly different from one another. Position one (M = 2256.35, SEM = 72.23) was significantly different from all others ( $p < .001$ ). Finally, a paired samples  $t$ -test showed that an equation switching from right-to-left (M = 2579.03, SEM = 74.68) was significantly different from one switching from left-to-right (M = 2787.90, SEM = 77.63),  $t(23) = 5.85, p < .001$ .

### Primary Analyses

**Accuracy measures.** Accuracy was again measured prior to RT for experimental conditions in order to determine task difficulty level within each factor. All reported Analyses of Variance (ANOVA) are one-way repeated measures and decimal degrees of freedom indicate Greenhouse-Geisser corrections for violated sphericity. There was a significant effect for *lag*,  $F(3, 69) = 33.05, p < .001$ . An LSD test confirmed a linear significantly ( $p < .01$ ) decreasing accuracy as lag increased from one (M = .62, SEM = .04), to two (M = .49, SEM = .04) to three (M = .40, SEM = .04), but not four (M = .37, SEM = .04). Lag of two was likewise significantly different from all other conditions ( $p < .01$ ). Lag of three was not different from four. . There was also a significant effect for *run*,  $F(3, 69) = 16.89, p < .001$ . An LSD test showed that a run of one (M = .87, SEM = .02) was not different from a run of two (M = .84, SEM = .02), but a run of three (M = .78, SEM = .03) was significantly ( $p < .01$ ) less accurate, as was a run of four (M = .71, SEM = .03). A run of two was significantly different from both three ( $p < .01$ ) and four ( $p < .001$ ), which were likewise significantly different from all others ( $p < .01$ ). Finally, there was a significant effect for *run-prior-to-switch* (RPS),  $F(3, 69) = 14.72, p < .001$ . An LSD test showed that an RPS of one (M = .76, SEM = .02) was marginally ( $p = .057$ ) more accurate than an RPS of two (M = .71, SEM = .03) and significantly more accurate

than both ( $p < .001$ ) three ( $M = .62$ ,  $SEM = .04$ ) and ( $p < .001$ ) four ( $M = .60$ ,  $SEM = .04$ ). RPS of two was also significantly more accurate than both three ( $p < .01$ ) and four ( $p < .001$ ), which were not significantly different from one another.

**Reaction time measures.** Analyses included only data from trials with accurate responses on all arithmetic operations to account for any increased RT confounds following an error (Dudschig & Jentzsch, 2009). Predicted results for a single- or multi-item focus of attention can be seen in Figure 3. A single item focus predicts no differences within any of the primary analyses (e.g., a run of one equals a run of four). The proposed discretely ordered multi-item focus predicts descending RT for increasing run and ascending RT for both increasing lag and RPS. The following analyses can be observed in Tables 1-4 and Figure 4. Again, all ANOVAs are one-way repeated measures and decimal degrees of freedom indicate Greenhouse-Geisser corrections for violated sphericity. There was no effect of lag on RT,  $F(2.31, 53.19) = .30$ ,  $p = .78$ . There was, however, an effect for run,  $F(3, 69) = 3.67$ ,  $p < .05$ . An LSD test showed a significantly longer RT for a run of one ( $M = 2029.44$ ,  $SEM = 87.39$ ) than both a ( $p < .01$ ) run of two ( $M = 1861.32$ ,  $SEM = 70.49$ ) and a ( $p < .05$ ) run of four ( $M = 1869.53$ ,  $SEM = 78.20$ ). The RT difference between the run of one and run of three ( $M = 1931.44$ ,  $SEM = 81.08$ ) approached ( $p = .085$ ). There were no other significant differences for run on RT. There was a marginal effect for RPS,  $F(3, 69) = 2.39$ ,  $p = .076$ . However, an LSD test showed a significantly ( $p < .01$ ) longer RT for an RPS of one ( $M = 2742.08$ ,  $SEM = 98.94$ ) than an RPS of three ( $M = 2530.28$ ,  $SEM = 92.88$ ) as well as a marginal ( $p = .067$ ) difference from an RPS of four ( $M = 2555.44$ ,  $SEM = 117.56$ ). The difference between an RPS of one from that of an RPS of two ( $M = 2629.78$ ,  $SEM = 99.32$ ) was not significant, nor

were any other comparisons. As noted, the omnibus test did not reach significant at an alpha of .05. Therefore, the above post-hoc tests should be treated with caution and viewed as representing trends toward differences in RPS.

### Experiment 2 Method

Experiment 2 utilized varying retention intervals of similar materials from Experiment 1 with varying levels of cognitive load. The procedure examines the gradual decay of discrete ordinal information over time by examining the *magnitude* of incorrect responses. Zhang and Luck (2009) found evidence against such gradual decay in that memory for color over time remains fully present until it is lost in entirety (i.e., sudden death). The current experiment intends to show that the expected results of gradual decay are present when information is perfectly discrete and ordered (e.g., numbers) and must be retrieved prior to achievement of absolute memory trace, or completion of memory retrieval/reconstruction, therefore showing that trace decay of information leads to relative rather than absolute judgments that (Miller, 1956) can be defined as gradual loss of details. Data supporting this conclusion are expected here, although it was not present in Zhang and Luck's experiment, possibly due to their use of "noisy" (p. 3) visual memory for continuous variables (i.e., colors). In a single math-updating operation procedure similar to that described in Experiment 1, when participants are not able to engage in rehearsal or attentional refreshing, increasing retention intervals will increase the numerical degree to which incorrect memory trace recall differs from the correct response. In this way, a smaller retention interval should result in significantly greater instances of 'near-misses' (e.g., response given is off by only one or a couple of digits) whereas longer retention intervals will increasingly approach random chance responding

(e.g., given response being off by 1 is equally as likely as being off by 5 or 6).

Incorporating differing levels of cognitive load (described below) will further demonstrate that although interference influences overall accuracy it does not affect the proportional degree of inaccurate responses such that the defining factor between a near-miss and distant-miss will be a function of the retention interval, as well as cognitive load condition.

### *Participants*

Thirty-three undergraduate students (24 female, 9 male, mean age 19.18 years) from a southeastern university participated for course and/or extra credit.

### *Apparatus*

All materials were identical to Experiment 1 except that auditory feedback was not provided.

### *Procedure*

Prior to beginning the experimental trials, participants went through training for articulatory suppression to accustom themselves with the task of repeating the word 'the' at a constant rate of twice per second. Following this, as in Experiment 1, participants completed a memory-updating arithmetic task. Each trial began with the presentation of a fixation-cross for 1,000ms at which point the articulatory suppression was to begin (see Figure 5). Four boxes enclosing random single digits from 1 through 9 were then presented for 1,000ms to be remembered. Retention interval durations of 4,000, 7,000, or 10,000ms preceded a single arithmetic operation in one of the four boxes. During this retention interval, one of three possible cognitive load conditions occurred: high-load, low-load, or no-load. The high-load condition presented participants on screen with a

series of letters to be judged as a consonant or vowel by pressing the ‘C’ or ‘V’ keys, respectively. The low-load condition presented an ‘X’ on either side of the screen to be recognized as left or right using the same keys (‘C’ for left and ‘V’ for right). No secondary task was presented in the no-load condition, though articulatory suppression was still present. The load task was presented at intervals of 1,500ms during the retention interval. The retention interval durations, as well as the cognitive load presentation rate, allowed for equal differences between conditions as conditions changed in that there was an increase of three seconds between each retention interval, as well as two additional presentations of the load task. The participant must respond, following the retention interval, to a single arithmetic operation within 2,500ms. This response time limit was meant to prevent absolute memory trace retrieval by disallowing the participant sufficient time to bring the numbers back into the focus of attention and complete the equation (i.e., the allotted time for a response requires relative judgments to be made, as established in pilot testing as well as prior experiments, e.g., Oberauer, 2002). The four numbers to be remembered throughout the retention interval as well as the box selected for the equation were randomly selected on each trial. All participants completed all cognitive load and retention interval duration conditions in a within-participants design composed of a total of three blocks of trials separated by load. Load conditions were separated into blocks to decrease task difficulty. A Latin square design was used to determine the order of the cognitive load conditions. The retention interval durations were randomly selected without replacement for each trial to prevent participants anticipating the arithmetic operation (i.e., the prevent participants from predicting how long the retention interval would last). Ten practice trials preceded each change in cognitive load condition and

always used the middle interval duration of 7,000ms. Each trial block consisted of 30 experimental trials for a total of 90 experimental trials plus 30 practice trials.

### Experiment 2 Results

Prior to analyses, all response data for the final equation following an imperfect performance on the load tasks were excluded. Overall accuracy among all conditions was  $M = .55$ ,  $SD = .19$ . All responses were reconfigured into margin of error such that responses were not excluded based on inaccuracy, but were instead organized into interval categories of  $\pm 0$ ,  $\pm 1$ ,  $\pm 2$ ,  $\pm 3$ , etc. (e.g. if the participant responds “6” when the correct response is “3”, the trial will be coded as “ $\pm 3$ ”). These codes better allow for the ability to examine whether or not memory is *gradually* lost than would merely examining accuracy. Alternative predictions are represented in Figures 6 (decay-only), 7 (interference-only), and 8 (proposed independent effects or both decay and interference). Overall margin of error among all conditions was  $M = 1.02$ ,  $SD = .55$ . Mean margin of error for all individual conditions can be observed in Table 5. Random chance responding (i.e., memory ‘death’) was set at  $\pm 2.96$  ( $SEM = .23$ ), which is the grand mean of the average of all possible  $\pm$  designations for each participant response to each correct response (e.g., for a correct response of 1, codes of  $\pm 0$  through  $\pm 8$  [ $M = 4$ ] were possible, whereas a correct response of 5 could yield only the codes  $\pm 0$  through  $\pm 4$  [ $M = 2.22$ ]).

The following analyses can be observed in Tables 6-10. Again, decimal degrees of freedom indicate Greenhouse-Geisser corrections for violated sphericity. A 3x3 within-participants ANOVA (see Figure 9) of cognitive load and retention interval (RI) revealed a main effect of cognitive load,  $F(1.42, 43.87) = 17.07$ ,  $MSE = 12.17$ ,  $\eta_p^2 = .36$ ,  $p < .001$ . An LSD test indicated that performance in the no load condition ( $M = .78$ ,  $SEM$

= .10) was better than both the low ( $M = 1.18$ ,  $SEM = .11$ ) and high ( $M = 1.35$ ,  $SEM = .14$ ) load conditions ( $p < .001$ ). The high and low load conditions were not significantly different from one another. There was also a main effect of RI,  $F(2, 57.24) = 6.11$ ,  $MSE = 2.61$ ,  $\eta_p^2 = .17$ ,  $p < .01$ . An LSD test indicated worse performance for the 10s RI ( $M = 1.28$ ,  $SEM = .14$ ) than both the 7s RI ( $M = 1.05$ ,  $SEM = .10$ ) and the 4s RI ( $M = .96$ ,  $SEM = .08$ ). The 7s and 4s RIs were not significantly different from one another. There was, critically, no significant interaction,  $F(3.21, 99.42) = .92$ ,  $MSE = .40$ ,  $\eta_p^2 = .03$ ,  $p = .44$ .

## CHAPTER 3

### DISCUSSION

#### Experiment 1 Discussion

As is often the case with data utilizing a new analysis for a past methodological design, the data do not clearly support a simple prediction. Some aspects of Oberauer's (2002) direct-access region were supported foremost by the observed reaction time (RT) difference between the run trials from the RPS and lag trials (i.e., no-switch trials have longer RTs than do the switch trials across all levels indicating the expected object switch cost). Further support comes from the lack of any significant effects for the lag condition and only marginal effects for the RPS condition. However, in stark contrast to Oberauer's direct-access interpretation, the run trial's RT decreased upon reaching a run greater than one. This effect, however, also failed to continue linearly as the run increased in accordance with the current paper's prediction. Although the RPS factor was of marginal significance, an investigation of the trends revealed that the pattern of results was effectively opposite of the prediction of discretely ordered items in a multiple-item focus of attention.

One possibility is that these results are more indicative of a zoom-lens model (Eriksen & St. James, 1986) that off-loads the most recently used item once a switch away from that item has occurred. That is, the focus of attention, as each trial begins, contains all four items equally. Selecting an item prioritizes ('zooms-in') that item, selecting the item again (i.e., run of one) further prioritizes it, and upon a third consecutive selection (i.e., run of two) the item reaches the maximum possible priority within the focus of attention (i.e., only after three consecutive utilizations can an item be

said to be in direct-access) resulting in the shortest observed RTs. If this priority item is then discarded in a switch, it can then be off-loaded from the focus leaving only three items from which to select for the remaining trials leading to the paradoxical shorter RT for larger RPS trials. That is, as there are fewer items upon which to ‘zoom-in’ at this point, the switch actually becomes easier (i.e., now there are functionally three items upon which to ‘zoom-in’ as opposed to four as the priority item has been discarded). As noted, this would only be predicted after several consecutive selections leading to the rather counterintuitive RPS effect observed.

Further evidence contrary to a single-item direct access region is the box position significance, which indicates participants are serially maintaining and updating all four items on each trial as opposed to simply moving a new item in the direct access region. The trend toward a decrease in RT for the fourth horizontal position could be a result of the absence of the possibility of a left-to-right switch giving participants the added advantage of two, as opposed to three, potential options with which to concern themselves (i.e., stay, switch left, or switch right). Further evidence of the serial maintenance from position one can be observed by the shorter RT when a switch reverses horizontal position. A switch to the left is best explained as faster than a switch to the right as the items are being serially scanned from position one on each equation as opposed to the most recently utilized position, indicating that item is not maintained in ‘direct-access’.

While this explanation is consistent with the data there remains the possibility that participants simply respond more quickly to the greater RPS trials from a confound of equation order. The preliminary analyses indicated that the RT across all experimental

conditions decreased throughout a trials series. The higher levels of RPS required a greater number of equations before their conditions could be met so they invariably occurred on the tail-end of trials. Contrary to this explanation, however, is that the RPS of four trials *always* occurred on the sixth trial, which had the longest observed RT. This may be a simple matter of there *never* being a seventh equation within a trial, therefore participants may have expected the trial to be over upon presentation of the sixth. This possible confound of equation order is not a concern for the run effect as this effect appears early in the trial sequence and remains consistent as the trial length increases.

Accuracy was seen to decrease along with RT as a trial series continued. There is a single opportunity for an error on trial one, whereas trial six has the potential for six errors. Once a single error has occurred, participants are more likely to have lost all four items from the frustration of a mistake and therefore unlikely to overcome the earlier mistake (Dudschig & Jentsch, 2009). That is, once having made an error, participants are less likely to return to a high level of accuracy. This is more likely as the number of trials is longer and therefore may account for the drop in accuracy as trial series increases.

In sum, a zoom-lens conceptualization of the focus of attention is best supported by the present data. This conceptualization does not disqualify the capability of the focus of attention to discretely order all items or to maintain a single item to greater priority should task demands call for such. Instead it can be regarded as a compromise between any number of contingencies (including the two tested here) based on the specific cognitive task to be accomplished. The present data indicate the inner workings of the focus of attention are too dynamic a process to be bound by structural components.

## Experiment 2 Discussion

The data for Experiment 2 provide clear results in-line with the prediction of the gradual decay of memory independent of a concurrent resource-sharing interference. The main effect for cognitive load is one that would be expected by a consensus of researchers indicating that interfering items (Waugh & Norman, 1965; Oberauer & Kliegl, 2006) as well as attentional resource-sharing (Pashler, 1992; Towse & Hitch, 1995; Barrouillet, Bernardin, & Camos, 2004) between multiple tasks will result in the loss of memory (i.e., interference causes forgetting). The main effect of retention interval (RI), however, provides clear evidence that decay, the simple passage of time, likewise plays a role in forgetting. This effect replicates the results of Ricker and Cowan (2010) as well as expanding upon the specific conditions under which their data could indicate decay of memory.

In Ricker and Cowan (2010) the decay effect was observed for visual information in unconventional, and therefore unrehearsable, characters. The present data now indicates verbal information, when rehearsal is suppressed, is also susceptible to time-based forgetting. This effect has been long explored, but rarely found or quickly disproven in the past (Brown, 1958; Peterson & Peterson, 1959; Waugh & Norman, 1965). The current experimental evidence draws upon the wealth of more recent research that supports the existence of a decay process. Further, the current study takes into account differences in cognitive load, as opposed to simply implementing a locus of interference (Towse & Hitch, 1995; Barrouillet, Bernardin, & Camos, 2004; Barrouillet, et al., 2007), and manipulating the timing of response *and* study of the information

(Cowan & AuBuchon, 2008). These individual ideas, which the present work integrates into a single experiment, each demonstrate the conditions under which decay can occur.

The limited conditions under which decay has been observed introduce the second major expansion of past results from the present data: external relevance. Interference is an extremely easy effect to show. Decay effects have been historically easy to show when interference is not controlled and, contrarily, historically difficult to show when interference is present. The simplest explanation for this happenstance is that decay may well be overpowered by interference and effectually negligible. If this is the case, then decay would be externally irrelevant and not generalizable. The ever-expanding conditions under which decay has been observed begin to speak against this idea, but in the previously mentioned Bayesian analysis by Altmann and Schunn (2012) there remains the dependence of decay upon the level of interference. The current research, along with Ricker and Cowan (2010), however, shows some memory loss with the passage of time in the context of multiple levels of interference conditions. It is noteworthy that the current results, unlike Ricker and Cowan, were unable to show a significant effect between all levels of the retention interval. A likely explanation for this is that longer intervals may be required to see significantly diminished verbal memory using the current margin-of-error analysis technique. Critically, no interaction was observed between the cognitive load and RI conditions. Were the effects of decay dependent upon interference (i.e., presence of a ‘fanning out’ of data as load condition increased), the question of external relevance of decay would remain. The stability of the decay effects, however, indicates decay is always present when forgetting takes place

even in cases in which it cannot be observed due to more extreme detriments to forgetting from interference.

The final, and perhaps the most critical contribution of the current study is evidence that decay of memory is *gradual*. Zhang and Luck (2009) failed to show this effect when participants were asked to remember a color on a color wheel. This null effect may have been due to the use of visual information, which Zhang and Luck argued could be held in a noisy fashion. If the memory was noisy to begin with, any loss of that memory would then likely be too great to suffer gradual decay while still remaining at all intact. The current use of perfect discretely ordered information (i.e., numbers) more effectively allows for partial loss of information while maintaining some remnant of the initial memory. The main model for this study, Ricker and Cowan (2010), was unable to address the idea of gradual decay as it presented arrays of characters to be judged as ‘same’ or ‘different’, therefore allowing for analyses of only absolute accuracy and hits-false alarms. These analyses do not speak to the possibility of gradual loss of detail. By measuring margin of error, as opposed to accuracy, it could be determined if memory existed in an absolute, near relative, or distant relative state (continuously measured). Whereas decreasing accuracy would indicate only that memory was diminishing, increasing margin of error indicates whether the memory had diminished to a negligible level (i.e., sudden death) or was continuously degrading.

In sum, the present experiment presents evidence supporting the growing body of work that supports a time-based loss of memory independent of interference. The current study expands this literature by demonstrating that verbal items are indeed susceptible to

forgetting as a function of the passage of time and that this decay can be viewed as a gradual process.

### General Discussion

The current experiments provide new insight into the nature of working memory models. The focus of attention is a theoretical construct used to help understand observed effects from cognitive processes related to working memory. Contrary to predictions, Experiment 1 did not clearly show that serially presented arithmetic equations become discretely ordered based on task relevance (i.e., preferentially ordered in a multi-item focus of attention). Indeed, the serial presentation order itself had a greater effect. However, neither did it support the notion of a structurally valid single-item region of direct-access. The RT difference for the run trials was as predicted. However, this was not the case for the lag condition or the run-prior-to-switch. Undoubtedly, this direct-access region is present at times when an individual cognitive task is best accomplished by prioritizing one item over all other information, but I have argued that a more parsimonious account of the focus of attention would be a multiple-item focus with the ability to process this single item should the task call for such prioritization. The surprising results concerning switch costs might be suggestive of a process of prioritization in that a single-item may have, at times, been preferential to the other three during the task. However, there is also evidence that object switch costs are not indicative of this structure as maintaining the same item further shortened reaction times. Interestingly, the horizontal box position showed a serial navigation beginning at the number on the far left, *not* the most recently utilized item. Consequently, there is a serial processing component involving multiple items. Attention may have been influenced as

much by position as by the particular item in that position. It could be speculated that the finding that both accuracy and speed decreased with trial run may be due to a greater emphasis on position over the particular item. However, further studies would need to be conducted to assess this possibility. It may also be the case that, as accuracy decreased throughout a trial series, the RTs for latter updates within a series (i.e., *only* those responded to accurately) represent an improvement in fluidity of processing. That is, as participants progressed with perfect accuracy through a trials series, they were able to establish a better rhythm of responding leading to accurate trials later in a series having shorter RTs. This, though, is more speculation requiring further research. To experimentally determine if this speculative reasoning is true, a study could be designed that alters the point within a trial at which the manipulations of interest take place. By presenting manipulations satisfying conditions (e.g., run of one) at earlier and later points within a trial it could be determined if the independent variables are in fact independent, or if it is rather the manipulation order within a trial that determines the RT.

Experiment 2, alternatively, presents compelling evidence that interference is *not* the only forgetting process to which these expelled items are susceptible. When items are expelled from the focus they become theoretically susceptible to forgetting. The main model of working memory tested (Oberauer, 2002) does not allow for this forgetting by any means other than interference. However, the current study provides support for the notion that models of working memory should incorporate mechanisms to account for the effect of passage of time on memory (e.g., mechanism for the time effect in *attentional drift*, Unsworth & Engle, 2007; reducing the time-effect through *attentional refreshing*, Cowan, 1999).

In regard to limitations of the current study, these data do not provide a compelling picture of how the focus of attention in working memory is organized. Further research is required to resolve key limitations. Specifically, Experiment 1 presents trial sequences such that the final manipulation of each trial is the equation of interest. This becomes an issue when the equation order effect is taken into account. Larger levels of run, lag, and RPS invariably took place later in a series of equations than did smaller levels and could account for some reaction time and accuracy differences. This could be rectified by creating longer trial series in which larger run, lag, and RPS trials take place earlier in a series than do their smaller counterparts. Also, as discussed above, the focus of attention may be highly context dependent. Therefore, further research is needed in order to determine the extent to which the data in Experiment 1 reflect task demands specific to the methodology as opposed to reflecting attentional processes within working memory. Experiment 2 would likewise benefit from design refinement as the main effects were present, but not all condition levels significantly differed from one another as was expected. This issue may be resolved simply by incorporating more data (i.e., more participants) in order to increase power. Decreasing the allotted response time for the final equation (2.5s in Experiment 2) may also diminish variance. Participants achieved greater accuracy than expected within the 2.5s response time limit. Decreasing this time may provide more ‘near-miss’ data by forcing participants to rely more heavily on relative judgments. As indicated by the dashed line in Figure 9, responses at no level of any condition surpassed the threshold for random chance responding indicating that at no point did ‘death’ of memory occur (sudden or otherwise). Ideally, at least the longest retention interval of the highest load condition

should surpass this mark. The above suggestions for diminishing variance as well as longer retention intervals may accomplish this and, in the process, lead to significant differences between all condition levels.

### Concluding Remarks

The current data provide information that can help in refining our understanding of how working memory is organized as well as our ability to more adequately understand how these processes can affect other cognitive faculties such as ADHD, general fluid intelligence, and emotion regulation. Although, the particular nature of these relationships cannot be addressed based on the data presented here, they can help in organizing models to allow for a better understanding of how working memory processes in different situations work, or fail to work.

The two experiments evaluated together inform upon some aspects of current models of working memory. The results are suggestive that the focus of attention (or otherwise titled compatible concept) may be flexible in regard to its ability to accomplish varying tasks. The direct-access region, for one, presents a structural limitation for a process that is not always evident and should, as Pashler (1992) recommended of all structural components, be abandoned in favor of functional processes that can be utilized when required and discarded when unnecessary. Likewise, working memory models must include the possibility of memory loss due to the passage of time as well as interference. This does not necessarily require that models failing to adhere to these two functional processes be abandoned, but rather that the limiting structural components and forgetting processes be further explored to better refine current models and further our understanding of working memory.

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APPENDIX A

TABLES

Table 1.

*Experiment 1 Primary ANOVAs*

Conditions	<i>df</i>	<i>F</i>	<i>MSE</i>	<i>p</i>
Lag	2.31	0.30	48519.54	0.78
Run	3	3.67	144509.48	0.02*
RPS	3	2.39	216719.47	0.08

*Note: \*p < .05*

Table 2.

*Experiment 1 Means and Standard Errors*

Conditions	Mean	SEM
Lag1	2742.42	94.00
Lag2	2757.12	96.32
Lag3	2688.78	104.38
Lag4	2676.68	112.96
Run1	2029.44	87.39
Run2	1861.32	70.49
Run3	1931.44	81.08
Run4	1869.53	78.20
RPS1	2742.08	98.94
RPS2	2629.78	99.32
RPS3	2530.28	92.88
RPS4	2555.44	117.56

Table 3.

*Run Pairwise Comparisons*

Run		<i>Mean Difference</i>	<i>SEM</i>	<i>p</i>
Run1	Run2	168.12	52.66	0.00**
	Run3	98.00	54.51	0.09
	Run4	159.91	72.97	0.04*
Run2	Run1	-168.12	52.66	0.00**
	Run3	-70.12	48.13	0.16
	Run4	-8.21	53.06	0.88
Run3	Run1	-98.00	54.51	0.09
	Run2	70.12	48.13	0.16
	Run4	61.91	59.02	0.31
Run4	Run1	-159.91	72.97	0.04*
	Run2	8.21	53.06	0.88
	Run3	-61.91	59.02	0.31

*Note: \*p < .05, \*\*p < .01*

Table 4.

*RPS Pairwise Comparisons*

RPS		<i>Mean Difference</i>	<i>SEM</i>	<i>p</i>
RPS1	RPS2	112.30	84.32	0.20
	RPS3	211.80	74.06	0.01*
	RPS4	186.64	96.98	0.07
RPS2	RPS1	-112.30	84.32	0.20
	RPS3	99.49	68.00	0.16
	RPS4	74.34	99.34	0.46
RPS3	RPS1	-211.80	74.06	0.01*
	RPS2	-99.49	68.00	0.16
	RPS4	-25.16	94.19	0.79
RPS4	RPS1	-186.64	96.98	0.07
	RPS2	-74.34	99.34	0.46
	RPS3	25.16	94.19	0.79

*Note: \*p < .01*

Table 5.

*Margin of Error Means and Standard Errors for Load*

<i>Load</i>	<i>Mean</i>	<i>SEM</i>
None	0.77	0.10
Low	1.18	0.11
High	1.35	0.14

Table 6.

*Margin of Error Means and Standard Errors for RI*

<i>RI</i>	<i>Mean</i>	<i>SEM</i>
Four	0.96	0.09
Seven	1.05	0.10
Ten	1.28	0.14

Table 7.

*Experiment 2 3x3 ANOVA*

Conditions	<i>df</i>	<i>F</i>	<i>MSE</i>	<i>p</i>	$\eta_p^2$
Load	1.42	17.07	12.17	0.00**	0.36
RI	2	6.11	2.61	0.00*	0.17
Load*RI	3.21	0.92	0.40	0.44	0.03

*Note: \*  $p < .01$ , \*\*  $p < .001$*

Table 8.

*Load Pairwise Comparisons*

Load		<i>Mean Difference</i>	<i>SEM</i>	<i>p</i>
None	Low	-0.41	0.06	0.00*
	High	-0.58	0.12	0.00*
Low	None	0.41	0.06	0.00*
	High	-0.17	0.12	0.14
High	None	0.58	0.12	0.00*
	Low	0.17	0.12	0.14

*Note: \*p < .001*

Table 9.

*RI Pairwise Comparisons*

RI		<i>Mean Difference</i>	<i>SEM</i>	<i>p</i>
Four	Seven	-0.09	0.08	0.25
	Ten	-0.32	0.10	0.00**
Seven	Four	0.09	0.08	0.25
	Ten	-0.23	0.10	0.03*
Ten	Four	0.32	0.10	0.00**
	Seven	0.23	0.10	0.03*

*Note: \*p < .05, \*\*p < .01*

Table 10.

*Load\*RI Margin of Error Means and Standard Errors*

<i>Load</i>	<i>RI</i>	<i>Mean</i>	<i>SEM</i>
None	Four	0.61	0.11
	Seven	0.70	0.10
	Ten	0.99	0.15
Low	Four	1.05	0.12
	Seven	1.24	0.15
	Ten	1.25	0.14
High	Four	1.22	0.13
	Seven	1.22	0.13
	Ten	1.61	0.24

APPENDIX B

FIGURES

Figure 1.

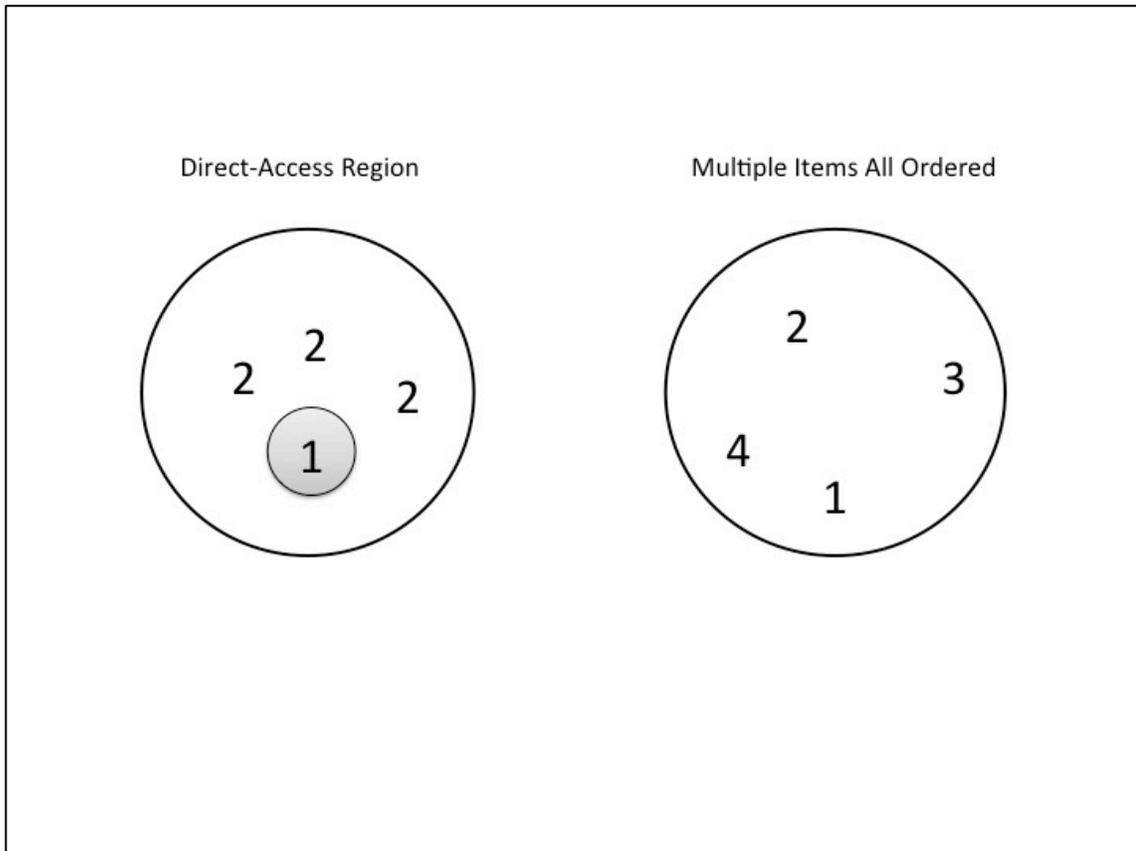


Figure 1. Representations of Direct-Access Region and Proposed Preferential Order of Multiple Items.

Figure 2.

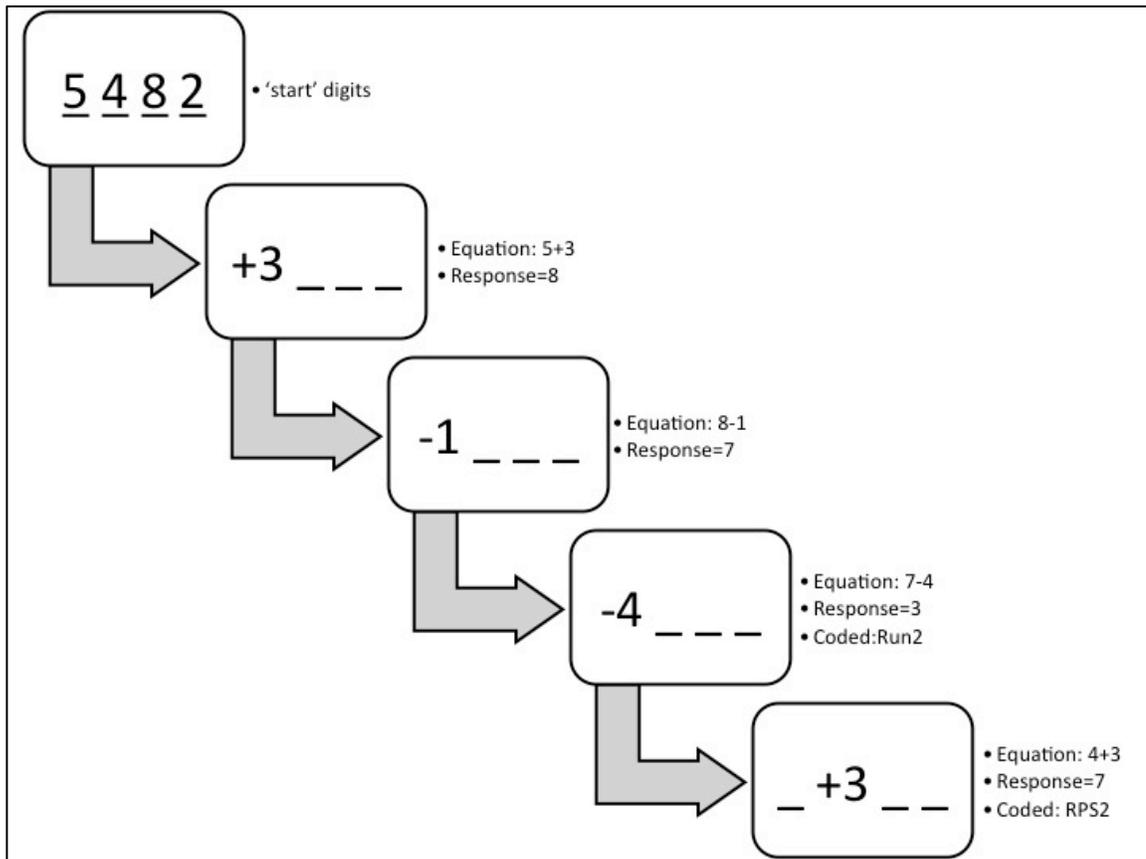


Figure 2. Example of Experiment 1 Procedure. Both run and RPS are represented in a single trial here where the first screen presents the 'start' list, the fourth screen presents a manipulation consistent with a run of two, and the fifth screen presents a manipulation consistent with an RPS (run-prior-to-switch) of two. This trial would here conclude and a new 'start' list would be presented indicating a new trial. At the conclusion of this figure the current 'start' digits for the four boxes are  $\boxed{3} \ \boxed{7} \ \boxed{8} \ \boxed{2}$ .

Figure 3.

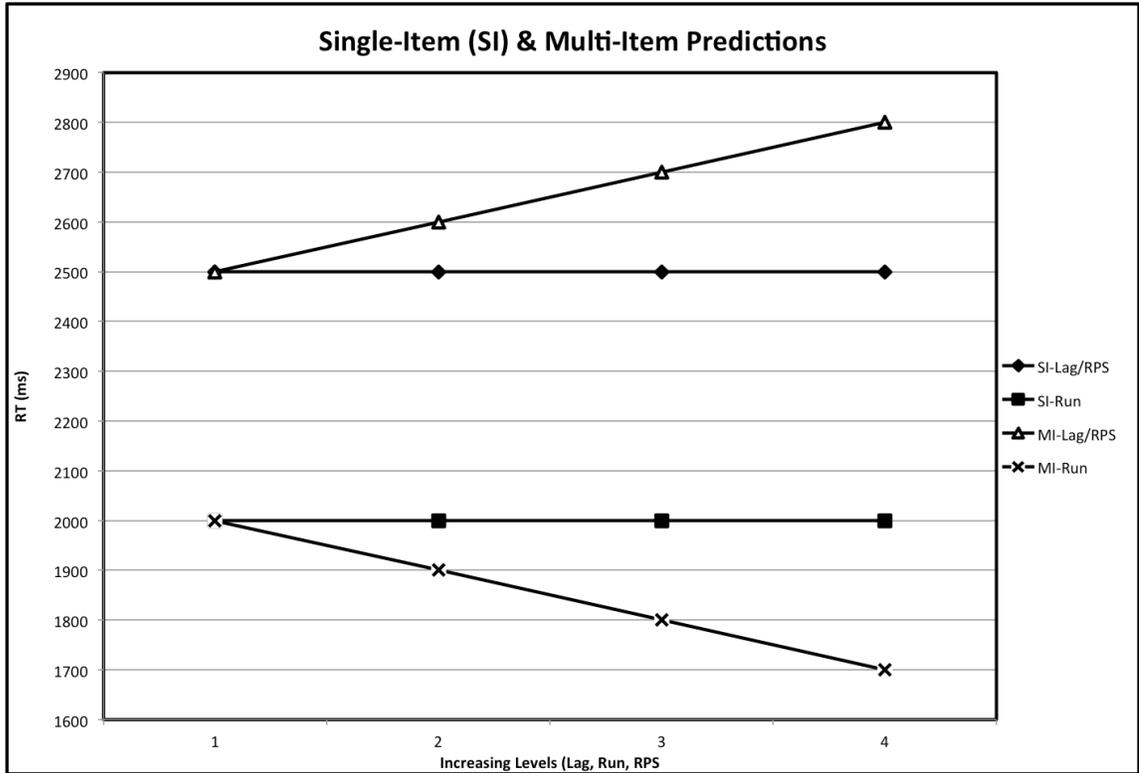


Figure 3. Predicted Results of Experiment 1. Single-Item predictions (diamond & square) remain consistent across levels. Multi-Item predicts decreasing Run RT (X) as level increases, and both Lag and RPS RT (triangle) RTs to increase as level increases.

Figure 4.

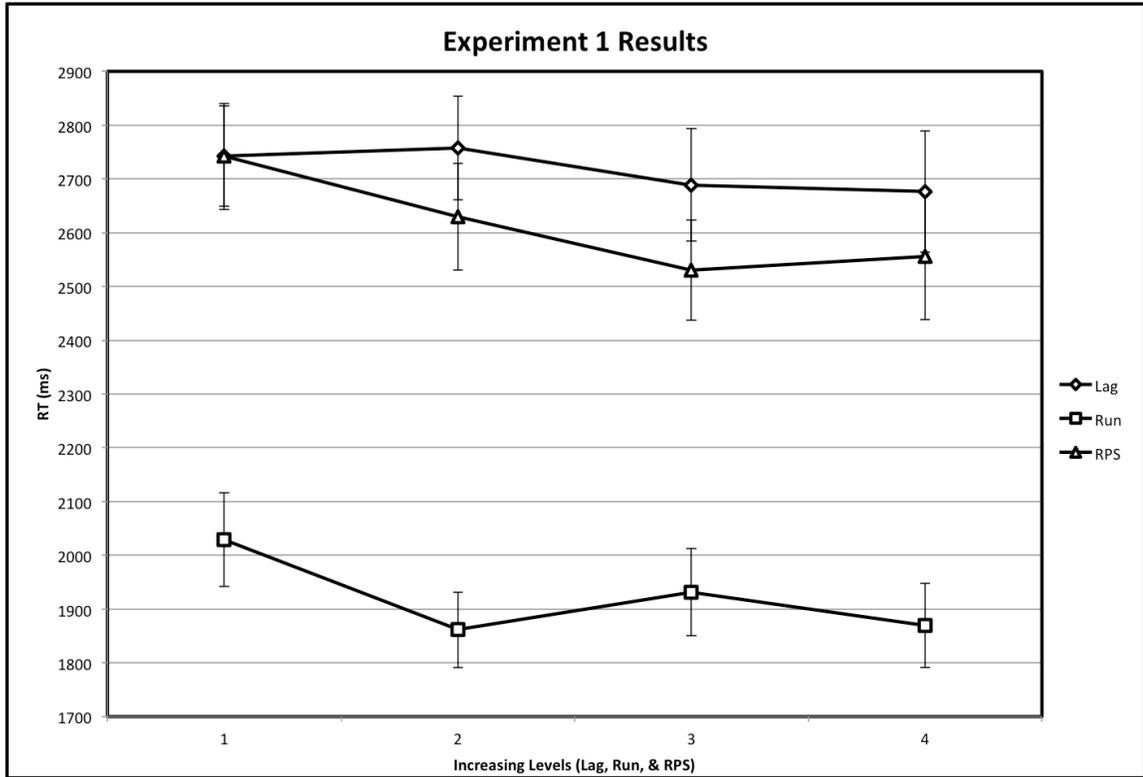


Figure 4. Observed Results of Experiment 1. Bars are standard errors.

Figure 5.

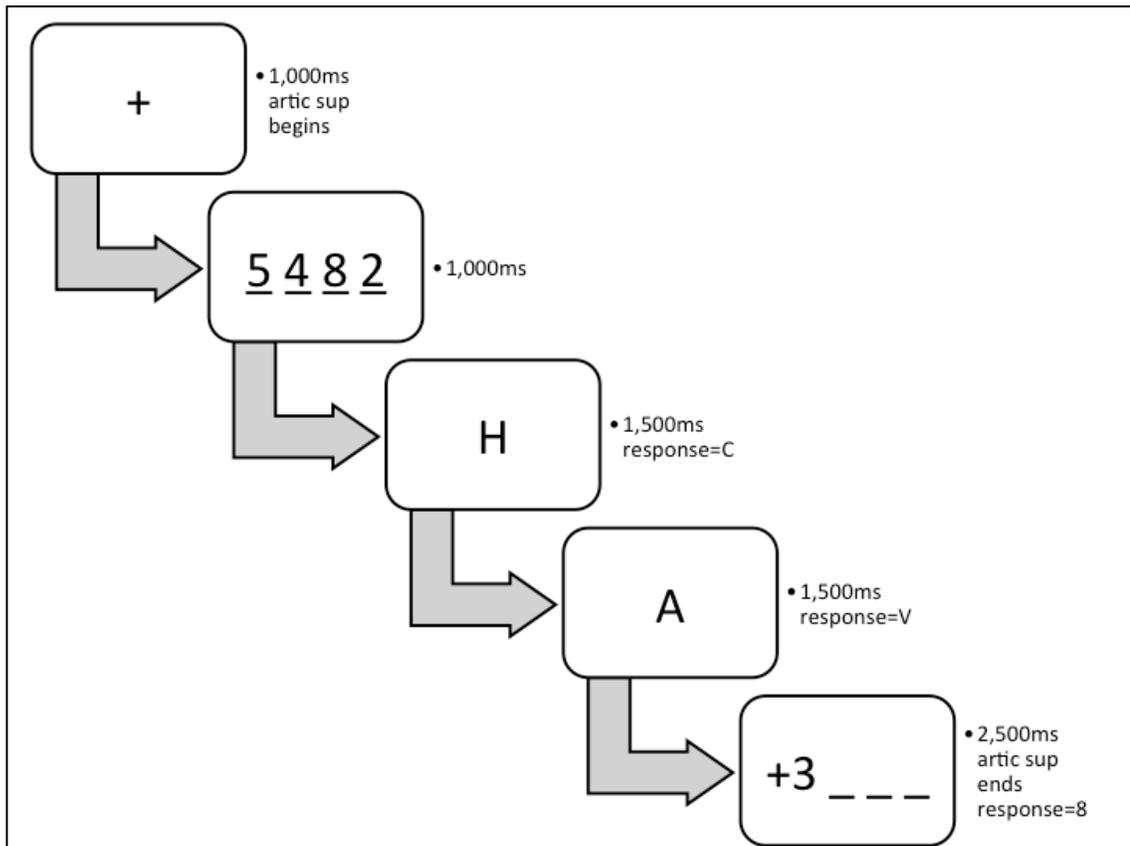


Figure 5. Example of Experiment 2 Procedure. Presentation is condition of a high-load, 4,000ms retention interval. First screen shows fixation cross for 1,000ms at which point participant is to begin articulatory suppression. Second screen provides list of numbers for 1,000ms to be remembered through the secondary task. Screens three and four provide high-load task of determining presented letter as a consonant (press C key) or a vowel (press V key). Final screen provides arithmetic operation to be solved. As soon as operation appears, articulatory suppression ceases and a response is given by participant.

Figure 6.

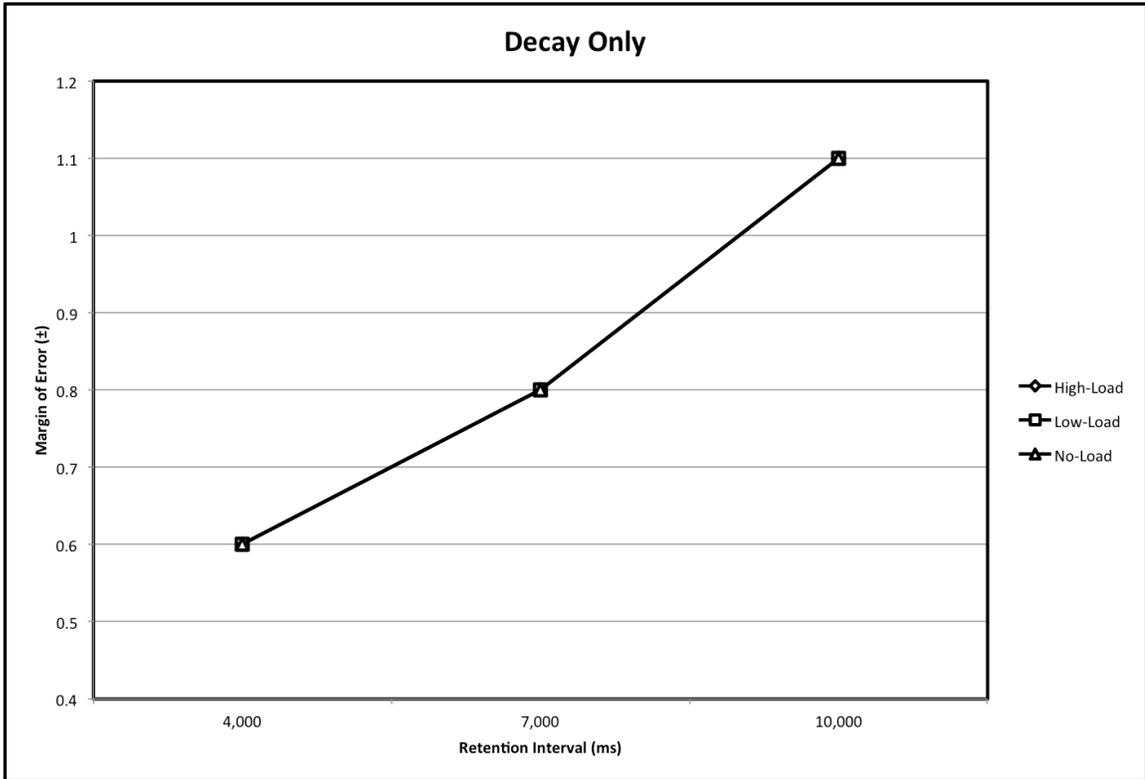


Figure 6. Experiment 2 Decay-only Predictions.

Figure 7.

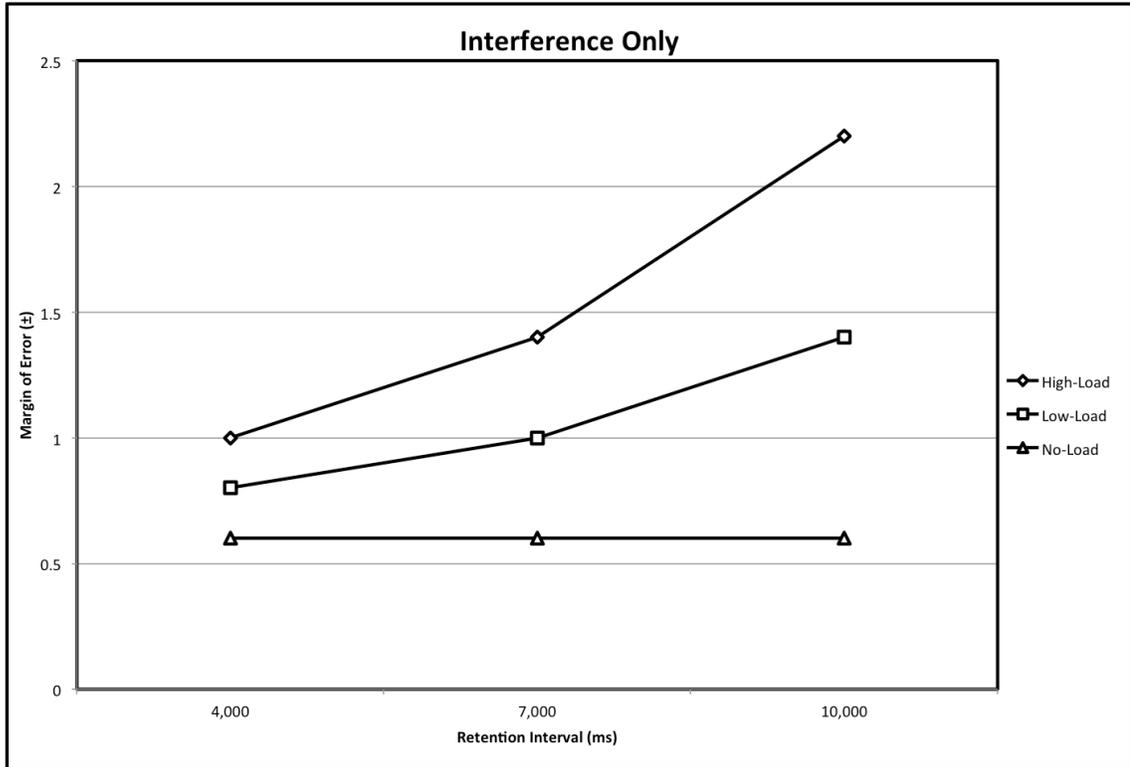


Figure 7. Experiment 2 Interference-only Predictions.

Figure 8.

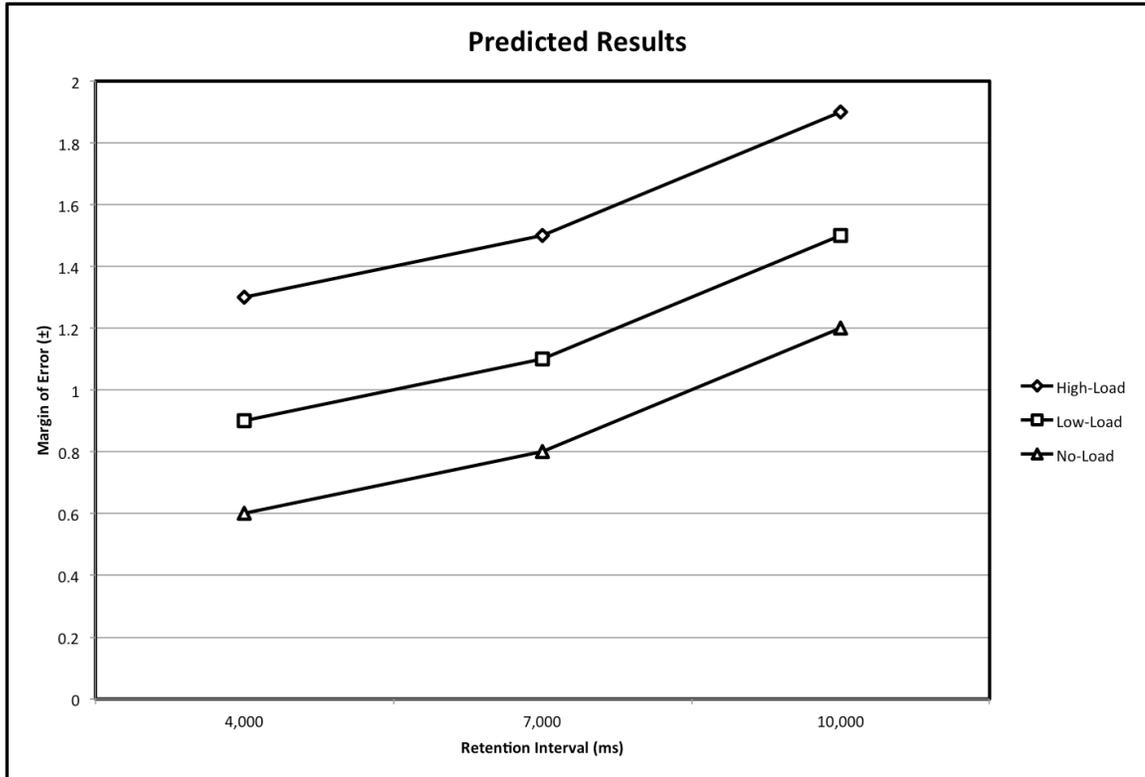


Figure 8. Expected Results of Experiment 2. Each load condition increases the overall magnitude of incorrect responses (individual lines), as does increasing retention interval duration (x-axis). The prior shows an effect of interference whereas the latter demonstrates gradual time-based decay.

Figure 9.

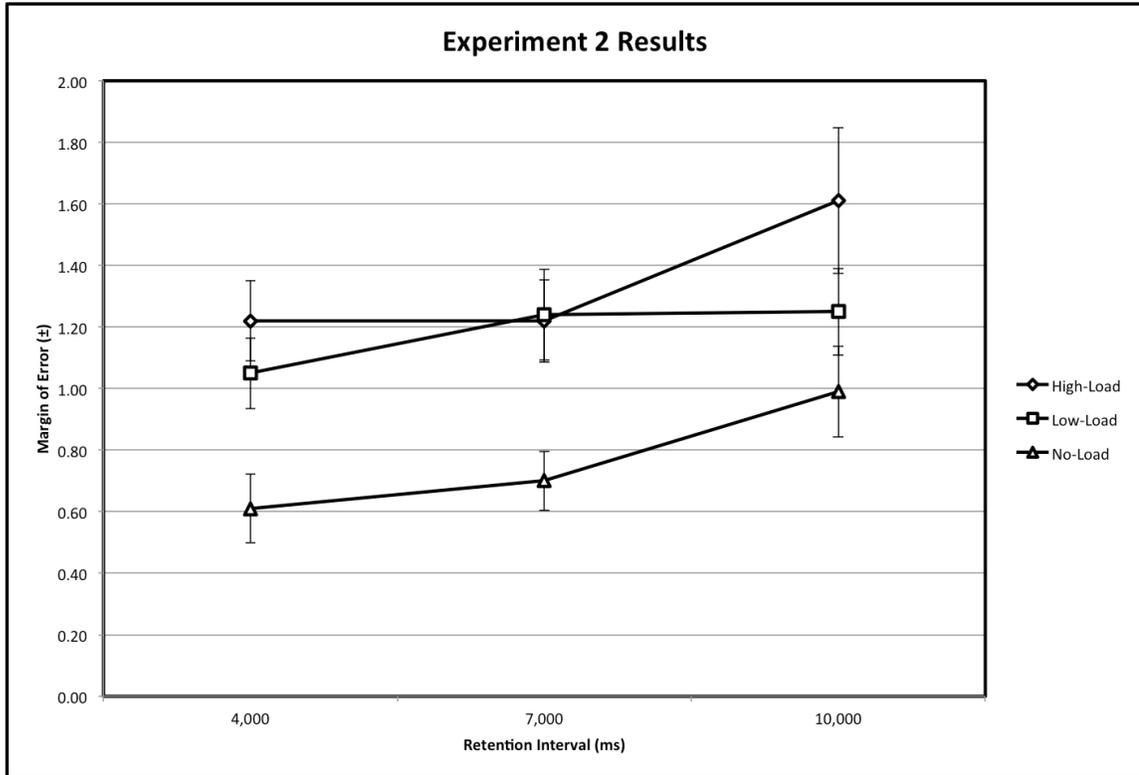


Figure 9. Observed Results of Experiment 2. Bars are standard error. All data fell well below random chance ( $\pm 2.96$ , SEM = .23).