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Dual Task Interference in Low-Level Abilities: The Role of Working Memory and Effects of Mathematics Anxiety

Alex Michael Moore
University of Nevada, Las Vegas

DUAL TASK INTERFERENCE IN LOW-LEVEL ABILITIES: THE ROLE OF WORKING MEMORY AND EFFECTS OF MATHEMATICS ANXIETY

By

Alex Michael Moore

Bachelor of Arts - Psychology
Southern Illinois University Edwardsville
2007

Master of Arts - Psychology
University of Nevada, Las Vegas
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Alex Michael Moore

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Department of Psychology

Mark Ashcraft, Ph.D., Committee Chair

Joel Snyder, Ph.D., Committee Member

David Copeland, Ph.D., Committee Member

Carryn Bellomo Warren, Ph.D., Graduate College Representative

Kathryn Hausbeck Korgan, Ph.D., Interim Dean of the Graduate College

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ABSTRACT

Mathematics anxiety is a negative affective reaction to situations involving mathematical thought and is commonly believed to reduce cognitive functioning by impairing the efficient use of working memory resources. The conventional theory describes that the processing disadvantage associated with high levels of math anxiety increasingly impairs performance as working memory demands increase in a math task. Despite this convention, recent reports demonstrate that the high math anxious disadvantage can be measured in tasks that are relatively free of working memory assistance (Maloney, Ansari, & Fugelang, 2011; Maloney, Risko, Ansari, & Fugelsang, 2010). The present study examines these relatively low level effects in college adults. A dual task paradigm was designed to test the engagement of different processing faculties in number comparison (Experiment 1) and enumeration (Experiment 2). The results of the present study mostly replicated the math anxiety effects reported in the literature; however, the dual task settings provide key insight into their interpretation. The results obtained are explained in the context of the Attentional Control Theory (Eysenck, Derakshan, Santos, & Calvo, 2007), and reasoning is provided for the extension of the math anxiety construct to include components related to attentional control. Finally, implications drawn from this extension are used to explore the interaction between math anxiety and achievement for future research.

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CHAPTER 1

INTRODUCTION

In the early 1990's, toy producer Mattel introduced a new line to its popular Barbie doll franchise called the "Teen Talk Barbie". Designed to speak to an older generation of Barbie enthusiasts, the doll was built to play scripted recordings like, "Let's go shopping!" or "Want to have a pizza party?" However one line in particular, "Math class is tough!" enraged women's advocacy groups, firmly placing the doll in infamy. The controversy behind this phrase came with allegations that it promoted negative stereotypes regarding women's roles in the science, technology, engineering, and mathematics (STEM) fields. Mattel promptly replaced the dolls with ones that did not mention mathematics (New York Times, 1992).

Note that this is not the only instance of businesses selling products displaying this negative stereotype. Retailer Forever 21 and department store JC Penny have stocked their shelves with products reading, "I'm too pretty to do math!" and similar messages. Importantly, these seemingly innocuous phrases were said to promote an apathetic disposition toward mathematics to young women.

So how influential are these instances of "math bashing"? The relevant literature is split on this topic. For example, recent work investigating the "gender gap" in mathematics shows negligible differences in math performance between boys and girls (Hyde, Lindberg, Linn, Ellis, & Williams, 2008); however other research has shown that if you prime women with the negative stereotype that men perform better in math than women, then women tend to perform worse in math tests compared to their male peers (Beilock, Rydell, & McConnell, 2007; Krendl, Richeson, Kelley, & Heatherton, 2008).

Regardless of the actual impact these messages may have on our youth, female or otherwise, it is important to note that the domain of mathematics is the true target of this "math bashing", a sentiment rarely expressed for other educational realms in our culture. In fact, if any well-adjusted adult in our society would express the equivalent phrase, "Reading is tough!", we might pass negative judgment on that individual. Nevertheless, even with basic mathematical skills contributing to the foundations of literacy in our society, individuals freely admit to having less than adequate skill in the domain, admitting to be unable to calculate a tip on a bill, for example, and receiving positive feedback from peers about this inadequacy.

One potential reason for this free and even boastful negative sentiment towards mathematics is that, as Barbie herself claimed, "Math class is tough!" Geary (1995; 2000) published an interesting comment on the domain, making a distinction between biologically primary and secondary competencies. As a way to illustrate this distinction, Geary describes that a biologically primary capacity for human language learning does not simply transfer to the abilities of writing or reading, two biologically secondary abilities. According to Geary, among other implicit abilities, the basic mathematical principles of recognizing the numerosity of sets, small number counting, and even basic arithmetical relations like addition and subtraction are biologically primary. That is, regardless of culture or level of education, these basic competencies are demonstrated without significant variation in expression, and are found quite early in development. Conversely, biologically secondary competencies, including larger number computation, and more complex arithmetical operations such as multiplication or division, are learned only through explicit instruction, and require significant effort on the part of the individual to practice and ascertain the principles involved. Note that the implication here is that any biologically secondary competency would require significant effort to master. So, with regard to the "math bashing" just described, it is easy to see why Barbie would hold the opinion she does about the domain. Simply put, math takes effort.

Another plausible reason for this blatantly negative outlook towards mathematics is the fact that math requires a significant degree of mental effort to achieve proficiency in its concepts, even if the process is sufficiently practiced. As we will discuss throughout this work, the procedures inherent in mathematical processing have been shown to be heavily reliant on a limited-capacity mental mechanism known as working memory (DeStefano & LeFevre, 2004; Raghubar, Barnes, & Hecht, 2010). Interestingly, this mechanism has been implicated at almost any level of math computation, regardless of the complexity of the problem. Put in another way, Barbie is warranted in believing that math is tough because, regardless of the kind of mathematical task she needs to complete, the processing required is most likely to be mentally taxing. It is this topic, the level of cognitive strain experienced while performing mathematical tasks that I will be exploring in the present study.

The purpose of the present experiments is to examine the contribution of the working memory system in mathematical tasks thought to be free of its assistance during calculation. Recent work has been published with this critical assumption at the heart of its arguments, and has exploited a large and long-standing gap in the literature. Briefly, the developing literature has shown that mathematics anxiety, an aversive and potentially debilitating reaction to mathematical problem solving, influences reaction time (RT) and accuracy in two relatively simple numerical tasks: enumeration and magnitude comparison (Maloney, Ansari, & Fugelsang, 2011; Maloney, Risko, Ansari, & Fugelsang, 2010). The authors' conclusions regarding their results rest on two robust associations with mathematics anxiety in the extant literature. One of these relates to the literature suggesting that math anxiety serves to undermine otherwise normal working memory function (Ashcraft & Moore, 2009). As we will discuss shortly, it has been suggested that math anxiety results in a transitory depletion of working memory resources when participants engage with mathematical problem solving. The other potential conclusion appealed to the association between math anxiety and overall poorer mathematical achievement (Hembree, 1990; Ma, 1999).

The purpose of this study, then, is to examine these two possible explanations for the worse performance of high math anxious individuals in relatively simple mathematical tasks. More specifically, the present study examines the interrelations of working memory, mathematics anxiety, and mathematical achievement in pursuit of explaining the high math anxiety disadvantage just described. As such, reviews relevant to these three constructs are presented prior to the descriptions of the two experiments reported here.

Working Memory

Imagine the following scenario:

> After completing his chores, George's mother gave him a 5 dollar bill that he could use at the local grocery store to buy candy. George decides that he wants to

buy as many jaw breakers as he can without exceeding his $5 limit. If each jaw breaker costs 38 cents, how many jaw breakers can George buy?

How should George go about finding the number of jaw breakers he can purchase? Assuming George is advanced enough in math education, and calculation can be made manually, then he could quickly divide 5.0 by .38 and find the solution to the problem. Assuming this problem becomes apparent at the store, however, and manual calculation is not possible, then George is forced to compute the division mentally, which is no small task to complete. Another strategy could be to add the price of each jaw breaker repeatedly until the running total reaches the $5 dollar limit. Although not as complex as the division, this mental calculation is still slow, error-prone, and mentally taxing (Logie, Gilhooly, & Wynn, 1994)

This example illustrates the idea that throughout an average day, an individual can encounter numerous situations that require quick, decisive, and accurate mental calculation. This skill is commonly called upon—calculating the tip on a restaurant bill or calculating the cost difference between sale and non-sale items at a store, for example. Inherent in these scenarios is the need to maintain many pieces of information in memory while performing multi-step procedures to reach a final solution. These acts of maintenance, integration, and storage of information are vitally reliant on a mental mechanism known as working memory.

At the surface of the construct, working memory is thought to be a limited-capacity mechanism that manipulates, integrates, and temporarily stores information at the forefront of an individual's attention (Engle, 2002; Miyake & Shah, 1999; Raghubar et al., 2010; DeStefano & LeFevre, 2004). It has been implicated in a wide array of cognitive domains including learning and memory, and has been implicated as contributing to fluid intelligence (Engle, 2002; Miyake & Shah, 1999). More recently, the field of mathematical cognition has also come to appreciate its importance (DeStefano & LeFevre, 2004; Raghubar et al., 2010). The field has learned that whether engaged in rather simple activities such as basic counting (Hecht, 2002) or in more complex procedures such as addition (Ashcraft & Kirk, 2001) or multiplication (Imbo & Vandierendonck, 2007b), working memory plays an important role in math-related tasks.

Many models describing the function of this mechanism exist, ranging from domain-general capacities of attention (Engle, 2002) to domain-specific, multicomponent accounts (Baddeley & Hitch, 1974; Baddeley & Logie, 1999). The largest distinction between most models involves the nature of the resources utilized when performing complex mental procedures—either that these resources are found in an unspecified pool of resources, or that the resources are contained within domain specific modules of the mechanism. Researchers in math cognition have primarily focused on the multicomponent model and more specifically through the lens of the specific model proposed by Baddeley and colleagues (Baddeley & Hitch, 1974; Baddeley & Logie, 1999).

The Baddeley multicomponent model specifies the network of three main subcomponents: the central executive, the phonological loop, and the visuospatial sketchpad (VSSP). The employment of these subcomponents is somewhat hierarchical in responsibility. The central executive is thought to manage the system, actuating processes like basic attention, task-switching, and integrating the information temporarily stored by the two “slave” systems, the phonological loop and VSSP. The phonological loop is specifically responsible for language based information and processes like active rehearsal and storage of such information. The VSSP plays a similar role, however exclusively for visual or imagery-based information (Baddeley & Logie, 1999; see Baddeley, 2000 for a recent extension of this model).

To examine the role of working memory, two experimental approaches are commonly adopted. In the individual differences approach, participants’ behavior is measured in the task of interest and performance is analyzed between groups of participants that vary by their working memory capacities. Essentially, the participants are also tested in an independent task measuring working memory to determine the functional upper limit of individuals’ working memory capacity. The reason for this is to assess the maximum amount of processing that can occur with each individual’s limited availability of cognitive resources. The participants are then grouped by their capacity into low, medium, and high capacity groups, and it is these three categories that are compared. Typical results from this type of investigation show less efficient and more error prone performance on a math test, for example, in the low compared to high capacity groups. To be sure, the low capacity group is already hindered by a small capacity limit, so the heavy demands of complex cognitive processing are dealt with less proficiently than those with larger capacities (Seyler, Kirk, & Ashcraft, 2003).

Instead of relying on two separate measures to examine the role of working memory in complex cognitive tasks, the second paradigm integrates the two into a “dual task” procedure. Basically, behavior is measured in the task of interest (primary task) while the participant concurrently meets the demands of another, unrelated task assumed to tax working memory (secondary task). Importantly, each task is also completed in isolation to ensure a measure of baseline performance without additional cognitive load. The rationale for this paradigm is to introduce processing interference such that impaired performance on either task with concurrent processing, but not in the control trials, indicates mutual reliance on the same working memory resources. Of course, the observation of little to no impairment under concurrent processing indicates independent processes that are not in competition for working memory. Because researchers can pair primary and secondary tasks that employ working memory resources from the same subcomponent, the field can assess the specific role of each working memory domain in mathematical processing.

Importantly, both of these approaches have been tested in the same study, and results obtained from both procedures yielded similar patterns of behavior. For example, Seyler, Kirk, and Ashcraft (2003) tested performance in a simple subtraction task. Participants demonstrated the expected results, strong problem size effects in Experiment 1; that is, participants showed pronounced spikes in reaction time when calculating subtractions with a double-digit minuend than single-digit minuends (e.g. 11-4, 11 is the minuend). This large problem impairment suggested that calculation relied on slower, and perhaps more demanding processes in this type of problem. To test this hypothesis, Seyler et al. first recorded the participants' working memory capacities individually to form the low, medium, and high capacity groups, and then tested the simple subtraction facts in a dual task setting (Experiment 4). Here, the secondary task required holding 2, 4, or 6 randomly sequenced letters in memory for later recall after completion of the primary task.

The results were quite transparent. First, letter recall performance degraded in the dual task trials compared to control trials. These results suggested that mental subtraction does, indeed, rely on working memory resources. The second set of results demonstrated individual differences in working memory capacity and performance in the dual task setting. That is, the spike in errors from control to dual task trials was much larger in the low capacity group than the high capacity group, showing particular disadvantage of the low capacity group to perform even simple subtraction problems in the presence of additional yet irrelevant cognitive processing. Crucially, the extent to which this low capacity disadvantage affected performance depended on how much additional processing was introduced by the secondary task. When the additional load was light (2 letter load), capacity groups did not differ. By comparison, the low capacity group made almost twice as many errors in letter recall (56%) as the high span group (31%) when the secondary load was heaviest (6 letter load). These differences showed that it is not the simple case that the low capacity group was just worse at subtraction, but that the low capacity disadvantage was exacerbated in situations of heavy and complex cognitive processing.

The results from Seyler et al. (2003) serve to establish the importance of the working memory mechanism in mental arithmetic while also illustrating the two most common techniques for demonstrating its involvement. Because the secondary task involved the simple memorization of letters, the assumption can be made that the phonological loop carried the majority of the processing burden in this last example. Of course, this would lead to the conclusion that phonological resources are needed while completing subtraction problems. With this example in mind, we now turn to a discussion of the literature exploring the exact use of resources specific to each individual sub-component of the Baddeley working memory model.

Subcomponents

As stated previously, the attraction of the multicomponent model is the ability to isolate the different subcomponents' processing. This method is fruitful; not only can we better understand the use of working memory resources within mathematical processes, but we can also take a closer look at the specific kind of processing used in different mathematical capacities. We will revisit this point throughout this work, as its implications have fueled the development of the present study. Before delving into the intricacies of these relationships, however, I will describe the responsibilities of the subcomponents in mental arithmetic. First I will describe the literature implicating the two slave system components, followed by a description of the role of the central executive.

Slave Systems

The slave systems, phonological loop and visuospatial sketchpad (VSSP), are thought to be independent subcomponents whose resources are employed by the central executive. Because of this independence, the field has sought to explore their unique responsibilities in mental arithmetic. At first glance, the evidence supporting the responsibilities of each slave system seems inconsistent or convoluted (DeStefano & LeFevre, 2004; Raghubar et al., 2010). However, as noted by DeStefano and LeFevre, the results obtained in these investigations often rely on many methodological factors that are not held standard from one experiment to the next. For example, the horizontal or vertical orientation of the problem (Imbo & LeFevre, 2010; Trbovich & LeFevre, 2003), the modality of problem presentation (Heathcote, 1994; Logie et al., 1994), and even the mathematical operation tested (Lee & Kang, 2002; Seyler et al., 2003) can determine which, and to what extent, slave system resources are engaged. Despite these idiosyncrasies in the literature, the over-arching roles of these subcomponents are apparent, and it is these qualities we will review in this section.

Phonological Loop

Of the two slave systems, the majority of research has been conducted to investigate the role of the phonological loop in mental arithmetic. Generally speaking, this subcomponent is thought to be responsible for the manipulation and temporary storage of verbal qualities of information. To load the processing capacity of this mechanism, researchers have commonly chosen to ask participants to memorize strings of information, typically letters, to be recalled after completion of the primary task (Seyler et al., 2003). Furthermore, the act of repeated verbalization of letters (Hecht, 2002), or memorization of non-words (Trbovich & LeFevre, 2003) have also been used. Essentially, the secondary task has been designed to tax the component's capacity for storage or active rehearsal.

Most commonly, the consequence of a concurrent phonological load is associated with detriments in procedure execution during calculation, for example, when using counting procedures to solve arithmetic problems if direct retrieval is not used (Hecht, 2002; Imbo & Vandierendonck, 2007a; Seyler et al., 2003), transformation strategies in addition and subtraction (Imbo & Vandierendonck, 2007a) or having to maintain intermediate values of complex problems, as in multi-digit addition or multiplication

(Ashcraft, 1995; Heathcote, 1994; Imbo & Vandierendonck, 2007b; Logie et al., 1994; Seitz & Schumann-Hengsteler, 2002). The common thread of these studies is degraded performance in strategy use during calculation if the phonological loop is taxed. For example, when in a task that requires a running total of additions, concurrent letter memorization results in poorer performance than when the secondary task demands are not present (Logie et al., 1994).

Visuospatial Sketchpad

The established role of the VSSP is similar to that of the phonological loop, however the VSSP is thought to manipulate and temporarily store visual or imagery based information. Common techniques for loading this component include asking participants to remember the visual attributes of objects in arrays (Fougnie & Marios, 2009), or a sequence of target locations on a computer screen (Corsi block test: Geary, Hoard, Byrd-Craven, & DeSoto, 2004).

The noted confusion in subcomponent involvement in arithmetic is most likely attributable to the results obtained while examining the VSSP. On the whole, it appears that its most obvious role is manipulation and storage of numerical information in problems where procedure execution relies on the physical arrangement of the problem. To illustrate this point, researchers have found involvement of the VSSP in the subtraction operation, especially in borrow procedures, presumably because of the visual nature of physically borrowing from the tens to the ones column (Imbo & LeFevre, 2010; Lee & Kang, 2002). In contrast, such involvement of the component is absent in multiplication, which is consistent with the idea that multiplication facts are stored in verbal, not visual, neural codes—therefore not requiring visual resources (Campbell, 1997).

Interestingly, some of the strongest support for these claims comes from developmental investigations. Throughout development, children are continually confronted with new mathematical operations or procedures, and the common trajectory of gaining proficiency in these operations is to commit the basic "facts" of each number pair to memory. This process, then, involves permanent storage of verbal relationships between the digits. So, when younger children are tested in a multiplication primary task, for example, more interference is observed with concurrent VSSP load than a phonological load, due to the fact that these children have not yet committed the facts to memory, and rely on the physical components of the task to reach a solution. As children age, however, both VSSP and phonological loads degrade performance, as the strategies used to find a solution rely on the visual nature of calculation, as well as verbal retrieval from long-term memory (McKenzie, Bull, & Gray, 2003; see Siegler, 1996 for an account of developmental shifts in calculation strategies).

Central Executive

Although the roles of the two slave systems may be less than clear, evidence supporting the responsibilities of the central executive is quite cohesive. The umbrella role of the central executive is to coordinate, manipulate, and integrate information stored by the two slave systems. These duties seem to reflect the system's capability to inhibit irrelevant information, task switch, and follow problem solving algorithms through to their completion (Baddeley & Logie, 1999).

To tax this component's processing, two common methods are used; both requiring active processing while the primary task is being completed. The first technique is random letter generation (speaking strings of letters in a random order; Hecht, 2002). The second technique, the continuous choice reaction time task, requires the participant to indicate, via button press, if a sound presented during the primary task was a high or low tone (Imbo & Vandierendonck, 2007b; Szmalec, Vandierendonck, & Kemps, 2005). Essentially, the tasks attempt to burden limited capacity resources without loading the slave systems' temporary storage capacities.

Perhaps one of the reasons the evidence regarding the central executive seems so clear-cut is that loading this component interferes with almost any level of calculation, for example, being implicated in single fact calculation, regardless of operation scrutinized (DeRammelaere, Stuyven, & Vandierendonck, 1999; Hecht, 2002; Imbo & Vandierendonck, 2007a, 2007b; Lemaire, Abdi, & Fayol, 1996; Seitz & Schumann-Hengsteler, 2000). Interestingly, this component's widespread involvement in low-level calculation is even found in simple counting strategies in coordination with the phonological loop (Camos & Barrouillet, 2004; Hecht, 2002).

As an example, Hecht (2002) examined the role of working memory resources in the selection and execution of calculation strategies in addition verification (deciding if the fully provided addition equation is correctly stated or not). Of course, the primary task was the verification; however two different secondary tasks were administered. The first, taxing phonological processing, required the repeated verbalization of one letter of the alphabet, also known as articulatory suppression. The other secondary task, taxing central executive processing, required participants to verbalize a self-created random sequence of letters while verifying the addition equations. At the end of each trial, participants indicated the calculation strategy used during completion of the primary task.

Importantly, working memory load did not influence the selection of strategies used by the participant; however it did affect the efficiency of the strategy used. Essentially, the presence of either secondary task impaired accurate responding, however only the concurrent central executive load caused slower RT in the verification process when simple counting strategies were selected for calculation (Hecht, 2002).

In terms of its more complicated duties, the central executive has been implicated in strategies involving the transformation of digits (e.g. transforming 7 + 9 to 7 + 10 – 1), as well as any calculation requiring the carry operation, as in addition (Fürst & Hitch, 2000; Imbo, Vandierendonck, & De Rammelaere, 2007; Seitz & Schumann-Hengsteler, 2000, 2002). Furthermore, executive resources are increasingly involved in situations where calculation requires increasing numbers of carries (Imbo, Vandierendonck, & Verguewe, 2007), and also in situations requiring maintenance and updating of cumulative sums (Fürst & Hitch, 2000).

In sum, the literature indicates two crucial aspects of the working memory system. One of these is that the processing capacity of an individual can be measured, creating an individual difference variable that is meaningful for mathematical problem solving. The second, and perhaps the most fruitful for the field, is that working memory resource employment in mathematical tasks can be manipulated in the dual task paradigm. Moreover, researchers can manipulate specific domains of processing in these tasks, in accord with the multicomponent model of working memory. This experimental technique allows for well specified and theoretically relevant processing competition to take place, with results speaking to the nature of mental calculation. It also allows for analysis of the processing domains of certain mathematical procedures.

This final point brings us to one of the goals of current investigation, that is, a dual task experimental setting that investigates the need for working memory involvement in basic mathematical procedures. More specifically, the processing employed when comparing symbolic magnitudes and object enumeration were investigated along-side secondary tasks taxing the three subcomponents of the multicomponent model individually. To make the impetus of this experiment transparent, however, two almost seemingly unrelated topics must first be examined—the first of these topics is the role mathematics anxiety is believed to play in mathematical tasks.

Math Anxiety and the Triple Task Effect

As illustrated in the previous section, mathematical processing is a complex, and potentially fragile mental capacity (see Moore, McAuley, Allred, & Ashcraft, in press for further review). Again, the dual task paradigm allows the field to manipulate, with a high degree of specificity, the efficiency and accuracy of this capacity. Another dimension of this capability we will consider is the role of an affective reaction to the domain of mathematics, mathematics anxiety, and how its presence is believed to alter the relationship between math processing and working memory. Before exploring this dimension, however, I will first describe the research establishing math anxiety's influence in math problem solving and the route through which this condition is thought to operate.

In an attempt to characterize math anxiety, Richardson and Suinn (1972) originally defined the construct as, “a feeling of tension and anxiety that interferes with the manipulation of numbers and the solving of mathematical problems in a wide variety of ordinary life and academic situations” (p. 551). Indeed, the effects associated with math anxiety can be observed in such commonplace situations such as calculating a tip on a restaurant bill, through more complex situations such as completing standardized math exams. In the laboratory, the associated effects of math anxiety have been observed in low-level activities such as simple counting (Maloney et al. 2010) or number comparison (Maloney et al. 2011), with increasing influence as computation complexity increases (Ashcraft, 1995; Moore et al., in press). Perhaps surprisingly, it is this pervasive influence that has led some to characterize mathematics anxiety as a phobic disorder (Faust, 1988), with support of this characterization coming from Ashcraft (2002), who described a testing session in which a participant burst into tears reportedly because of the anxiety experienced in a simple subtraction task.

Early research on the construct established many important relationships between math anxiety, and personal as well as educational factors. These relationships, reported in two meta-analyses on the topic (Hembree, 1990; Ma, 1999), further demonstrate the breadth of this condition. For example, mathematics anxiety is correlated -.82 with mathematics self-efficacy (belief in one’s own abilities), -.64 with the motivation to excel or pursue more advanced mathematical topics, and, not surprisingly, -.75 with enjoyment of math in pre-college samples (-.47 in college samples). These relationships clearly communicate the idea that an individual who experiences math anxiety does not habitually approach situations involving mathematics. For this reason, we have begun characterizing math anxiety as an emotional avoidance of mathematics (Ashcraft & Moore, 2009), correlating -.32 with intent to enroll in future math courses in college samples. Because these conclusions are drawn from correlational research, we cannot comment on the causality of these relationships, however, we do see disturbing relationships between math anxiety and overall math performance. Pre-college math achievement correlates -.34 with math anxiety (-.31 in college), and high school grades correlate -.30 (-.27 in college).

These results represent the traditional method for studying math anxiety, to establish meaningful relationships between important and relevant educational constructs. More recently, the area has turned to the laboratory to investigate the potential routes of influence this affective reaction has on mental processes. In brief, the field has found strong evidence of impairment of the working memory mechanism in association with high levels of math anxiety (see Moore & Ashcraft, 2012; 2013). This connection between the affective state and working memory function has been shown to be quite strong, with associated impairments found from low-level capacities to complex operations.

Early math anxiety research was rather straight-forward, and paralleled the rationale of early working memory research. More specifically, participants were asked to complete standard math tasks after the completion of math anxiety self-report scales. Then, the subsequent analyses explored performance in relation to low, medium, and high math anxious participant groups (Ashcraft & Faust, 1994; Faust, 1988; Faust, Ashcraft, & Fleck, 1996; see Ashcraft, 1995; 2002 for reviews). Briefly, these early examinations established some of the hallmarks of this condition.

In verification tasks of addition, subtraction, multiplication, and division, Ashcraft and colleagues noted that math anxiety did not have a strong effect on retrieval processes, due to the notion that the retrieval of math facts required little to no working memory capacity. Additionally, in more difficult math problems like two column addition, low math anxious participants typically completed the tasks more quickly and accurately than the high math anxious. Moreover, if the high anxious did complete the task as quickly as the low anxious, they were often much less accurate. This behavior, a speed/accuracy trade-off, suggested in-task avoidance in the high anxious individuals—it is as if they were responding as quickly as they could to simply end their participation requirements without much care for the accuracy of their responses.

Another hallmark observed in these exploratory studies was the level of impairment in those who rated themselves as high math anxious compared to those who reported low levels of anxiety. For example, in more complex, and thus more working memory demanding situations such as two column addition, high math anxious participants demonstrated difficulty in arriving at the solution of each problem—larger latencies and more errors. Importantly, this trend was exaggerated in situations where calculation required the carry operation. This last finding was instrumental in creating the hypothesis that math anxiety operated through the working memory mechanism, interrupting the normal, albeit restricted, online function of this mechanism (Eysenck, & Calvo, 1992; Eysenck, Derakshan, Santos, & Calvo, 2007). As we will discuss shortly, it is this comment, that mathematical anxiety is likely compromising available working memory resources and leading to an exaggerated deficit not experienced by low anxious participants that influenced researchers to investigate math anxiety in the dual task paradigm.

The triple task effect

The literature regarding working memory demonstrates that mathematical processing is complex and requires working memory resources, and that if another task is to be completed concurrently, then the working memory resources fall under competition from the two procedures. Now that research hypothesizes that mathematics anxiety exhausts working memory resources, then those high in math anxiety should perform especially worse in a dual task procedure compared to the low anxious. Essentially, math anxiety is creating an online disadvantage for high math anxious because it would diminish the total number of available resources.

Ashcraft and Kirk (2001) set out to investigate this hypothesis in a dual task setting with one- and two-digit addition, and letter string memorization as the secondary task. Trial procedure was such that a string of letters (2 or 6 letters in length) was presented until the participant was confident of their memory. Then, the addition problem was presented, and once a solution was vocalized, a prompt for letter recall appeared. Predicted results were as follows. All participants, regardless of math anxiety level, would show difficulty in problems requiring a carry, especially if concurrently loaded with a six letter memorization. Furthermore, this difficulty would be exaggerated in those who are high math anxious, due to an anxiety-restricted working memory capacity.

In short, this is exactly what Ashcraft and Kirk found. That is, all participants encountered interference in trials requiring carrying, and the interference was stronger if the secondary task required a six letter load. Crucially, the math anxiety groups' behavior demonstrated the predicted results—high math anxious participants, in conditions of carry and a six letter load, performed significantly worse (39% errors) than their low math anxious counterparts (20% errors).

The fact that the high math anxious experienced more difficulty in the most challenging condition compared to the low math anxious clearly demonstrates the role of math anxiety in the working memory mechanism. It is as if the high math anxious must perform in situations where a three-way competition for mental resources is present, effectively creating a triple task condition to complete. Equivalent evidence has been found in two-column subtraction with borrowing (Krause, Rudig, & Ashcraft, 2009). We simply refer to this three-way competition for resources as a qualitative "affective drop" in performance, referring to the debilitating effect emotion is thought to introduce to cognitive processing that is only experienced in the high math anxious (Ashcraft & Moore, 2009; Eysenck & Calvo, 1992; Eysenck et al., 2007).

The Current Investigation

The review presented here focuses on three crucial aspects of mathematical processing. First, working memory resources have been shown to be an integral component of problem solving, with observed contributions ranging from complex calculation such as addition (Ashcraft & Kirk, 2001) and multiplication (Imbo & Vandierendonck, 2007b) to simple processing such as counting (Camos & Barrouillet, 2004; Hecht, 2002). Second is the idea that mathematics anxiety is associated with an affective reaction to mathematical problem solving, and is believed to consume working memory resources in math tasks specifically. Related to these points is the third aspect of problem solving, that those with high math anxiety are thought to encounter an affective drop in performance, or a three way competition for working memory resources in the most challenging conditions of a mathematical task (Moore et al., in press). As described, however, this affective drop in performance seems to only occur in problem types that are heavily demanding of working memory resources. For example, this processing disadvantage is almost always absent in the small problems of studies investigating mental arithmetic for the solution of familiar or novel math procedures (e.g., Ashcraft & Kirk, 2001; Mattarella-Micke, Mateo, Kozak, Foster, & Beilock, 2011).

Despite these characteristics, two recent investigations of math anxiety demonstrate performance differences between high and low math anxious individuals in math tasks believed to be relatively low in working memory demand, namely numerical magnitude comparison and enumeration. To investigate the role of mathematics anxiety in number comparison, Maloney, Ansari, and Fugelsang (2011) administered two variants of the number comparison task to participants that reported having either high or low mathematics anxiety. One version required the comparison of two simultaneously presented single-digit Arabic digits presented on a computer screen (e.g. which is larger: 7 or 4?). The other version required comparison of one digit on the screen to a fixed standard magnitude of 5. In both experiments, Maloney et al found a math anxiety x numerical distance interaction such that both groups demonstrated the classic inverse relationship between the numerical distance of the digits compared and reaction time (as distance increases, RT decreases), but also that the high math anxious demonstrated more difficulty in comparing the digits as the magnitude difference became less distant (e.g. the RT difference between a comparison of 2 and 3 and a comparison of 2 and 8 was larger for the high, compared to low math anxious participants). In a similar way, Maloney, Risko, Ansari, and Fugelsang (2010) showed that, in a typical enumeration task, that counting, but not subitizing (rapid appreciation of small sets of objects; Kaufman, Lord, Reese, & Volkman, 1949; Trick & Pylyshyn, 1993; 1994a; 1994b) was slower in high compared to low math anxious participants, suggesting more interference in basic counting if anxiety was present.

Two considerations were offered regarding the math anxiety effects obtained in these low-level tasks. The first possibility reported was that the theorized transitory working memory deficit experienced by high math anxious individuals was the source of the group differences. The results from Maloney and colleagues' reports partially support this explanation. For example, the enumeration profiles of the anxiety groups diverged when working memory is implicated in processing (counting range), but not when enumeration is thought to proceed without assistance from the working memory mechanism (subitizing range). The difficulty with this interpretation, though, comes from the math anxiety differences in number comparison profiles where little evidence implicating working memory reliance exists. The authors note the difficulty in this conclusion because the extant literature does not address the exact working memory requirements of comparison processes.

The second explanation offered for the low-level math anxiety effects appeals to the numerical competency of low versus high math anxious individuals. The results of a steeper numerical distance effect and counting function in the high math anxious suggests that a process fundamental to numerical understanding is at play, although the authors provide little in the way of theory to describe what the nature of the deficits may be.

The purpose of the present study, then, is to replicate the math anxiety effects reported in Maloney et al. (2010; 2011) as well as to examine the two potential explanations offered by the authors. The method chosen for this investigation was the dual-task paradigm, which was selected for the following important reasons. First, as already discussed, the dual-task paradigm is a common and fruitful method for testing constructs in mathematical cognition. As stated by Maloney et al. (2010) the working memory impairment associated with math anxiety is assumed to be transitory, meaning that high and low math anxious individuals are not believed to fundamentally differ in working memory function (but see Maloney, 2011). Instead, the associated impairment is assumed to be a response to mathematical problem solving in the high math anxious, creating an acute processing disadvantage for this group which would be absent if other domains were tested. Thus, testing high and low math anxious participants in a dual-task setting allows for the direct manipulation of working memory resource availability. Further, even if fundamental differences do exist between groups, the increase of processing load within the dual-task setting should only serve to make the math anxiety group disparity even more apparent (Maloney et al., 2011).

The second reason for employing the dual-task paradigm was to address the point raised by Maloney et al. (2011); that the extant literature does not address the working memory requirements of numerical magnitude comparison. In response to this claim, the current study aims to examine the employment of working memory resources during the successful completion of number comparison and enumeration. To this end, participants completed either number comparison (Experiment 1) or enumeration (Experiment 2) as the primary task in a dual-task design in three separate blocks. Importantly, each block represented the unique pairing of the relevant primary task with one of three secondary tasks designed to tax the components of Baddeley and colleagues' working memory model. As such, this study serves as the first to identify which components of working memory are implicated in number comparison processing, as well as to extend the enumeration literature by taxing each component of the working memory system in one sample (see Camos & Barrouillet, 2004).

The final reason for employing the dual-task paradigm is to assess the possibility that mathematics anxiety is associated with different working memory components in different ways. Indeed, frameworks created to describe the negative effects of general anxiety in cognitive processing assert that the worry associated with anxiety should impair central executive mechanisms more strongly than the phonological loop which should be impaired more than the visuospatial sketchpad (Eysenck & Calvo, 1992; Eysenck et al., 2007; see also Derakshan & Eysenck, 2009). As the ideas within these frameworks have formed the basis for mathematics anxiety understanding today (Ashcraft & Kirk, 2001; Moore et al., in press), their implications will be examined in the present study as well.

With these ideas in mind, the present study has three goals in mind. The first goal is to establish the working memory requirements of comparison processes in adults. As stated, the extant literature is relatively quiet with regard to this topic, which is an important gap to fill in our understanding of the domain. The second goal is to thoroughly investigate the math anxiety construct. By examining task performance in relation to all three of Baddeley and colleagues' working memory components, the present study aims to examine which specific components are associated with the math anxiety disadvantage described. The final goal of this study was to explore the possibility raised by Maloney and colleagues that performance differences observed between math anxiety groups may be attributable to the mathematical competency of the participants. Because of this goal, participants completed a measure of mathematical achievement, and the data obtained from this assessment was considered as a potential mediating variable explaining math anxiety differences.

CHAPTER 2

EXPERIMENT 1

Experiment 1 was designed in an attempt to replicate the math anxiety effects reported in the higher/lower than 5 task variant (H/L 5; see Method) of Maloney et al. (2011); participants that reported higher levels of math anxiety were found to exhibit a steeper numerical distance effect (described below) than were their low math anxious counterparts. Furthermore, the goal of the experiment was to thoroughly examine the working memory demands of number magnitude comparison processes to assess the plausibility that the working memory impairment experienced by the high math anxious participants could be driving the effects reported. The final goal of the experiment was to assess the contribution of the mathematical competency to the performance obtained.

Of interest in a comparison study is the presence and magnitude of the numerical distance effect, whereby individuals' reaction times increase as a function of reduced numerical distance separating the magnitudes being compared (Moyer & Landauer, 1967). This inverse relationship has been theorized to reflect the organization of numerical magnitude representations in the brain, and is believed to either reflect noise inherent in the representations themselves, or the mental "space" between each representation. Thus, the numerical distance effect is thought to indicate the extent to which the activation of one representation overlaps or interferes with the activation of another during the comparison process—the closer (or noisier) the relationship between the magnitudes is, the more difficult it is for the individual to separate their unique activations in order to choose which is larger or smaller. These notions are supported with developmental evidence indicating that, with increasing age and numerical competency, the slope of the numerical distance effect is reduced (De Smedt, Verschaffel, & Ghesquière, 2009; Sekuler & Mierkiewicz, 1977). This development is presumed to indicate less representational overlap with greater mathematical competency, either because of greater distancing of representations in the mind or reduced noise of the representations (Sekuler & Mierkiewicz, 1977; see also Holloway and Ansari, 2009).

Maloney and colleagues showed that high math anxious individuals were characterized as having a steeper numerical distance effect than the low math anxious in their samples. Given the prevailing notion that the effect indexes the organization and precision with which magnitudes are represented, the authors favored the conclusion that the math anxiety effect might reflect the mathematical competency of the high math anxious in comparison to their low anxious peers. Importantly, however, the working memory deficit hypothesis was mostly discarded due to the lack of evidence in the literature indicating the working memory demands of magnitude comparisons.

Thus, the results of Experiment 1 were expected to establish the working memory demands of number comparison. In doing so, the working memory deficit hypothesis of math anxiety can be properly evaluated as a potential explanation of the math anxiety effects reported by Maloney et al. (2011). Further, mathematical achievement scores were collected from each participant in order to evaluate the preferred conclusion that numerical competency was driving the math anxiety differences in the numerical distance effect. By using these scores as covariates in the analyses, the results should be able to address if math achievement mediates the math anxiety effects observed.

Method

Participants

A total of 51 individuals (31 females) were recruited from the University of Nevada Las Vegas subject pool to participate in this experiment and were granted course credit upon providing consent for testing. The mean age of the sample was 20.4 years old.

Materials

Demographic Information. Each participant completed a short demographic questionnaire asking for information relating to the individual's age, gender, year in school, math courses taken and grades earned, as well as two items asking for a rating of the individual's enjoyment of math and mathematics anxiety.

Abbreviated Math Anxiety Scale (AMAS). The AMAS is a 9-item questionnaire asking various questions regarding hypothetical ratings of experienced mathematics anxiety in a variety of scenarios (e.g., "Thinking about an upcoming math test one day before.", "Listening to a lecture in math class.": Hopko, Mahadevan, Bare, & Hunt, 2003). The scale of response ranged from "1" indicating the feeling of "Low Anxiety" to "5" indicating the feeling "High Anxiety". Responses to all items are summed to yield the participant's mathematics anxiety score.

Wide-Range Achievement Test 3—Arithmetic Subscale. The Wide-Range Achievement Test—Arithmetic Subscale (WRAT-3) is a test of mathematical achievement consisting of 40 problems requiring calculation. The problems range from simple calculation such as simple addition through more difficult problems such as simplifying algebraic expressions. Participants were given 20 minutes to complete the measure. Total correct is used as an indication of achievement.

Procedure

Participants completed three blocks of dual-task trials that tested comparison performance as the primary task. Each block differed by the secondary task completed (phonological loop, visuospatial sketchpad (VSSP), and central executive). The trials began with a 500ms fixation point, after which the information to be remembered within the respective secondary task was presented (described below). After another 500ms fixation slide, one digit was presented on the screen that was to be used as a comparison to a fixed standard of the magnitude 5 (primary task). The task of the participant was to verbally indicate if the digit presented was “higher” or “lower” than the standard. This response was spoken into a microphone which acted as a voice key and stopped reaction time recording for this phase of the trial. The experimenter manually recorded each response of the primary task phase in a research journal. Digits presented were 1-4 and 6-9, corresponding to numerical distances of 1 through 4. Each numerical distance was sampled 24 times in each block, yielding 96 trials total. Once a response was recorded, the recall phase of the trial began which differed by secondary task. Below is the description for the secondary tasks utilized in this study.

The secondary tasks chosen for this experiment are a suite of tasks tested in the working memory literature to tease apart the unique functions of the central executive, phonological loop, and visuospatial sketchpad. These specific dual task settings were chosen because of their similarity in procedure. The central executive and phonological loop secondary tasks were adapted from Fougnie and Marios (2007), and the visuospatial sketchpad secondary task was adapted from Fougnie and Marios (2009).

Phonological Loop and Central Executive. The procedures for the central executive and phonological loop were the same, but each task required unique processing of the information presented. In the initial phase of the task, participants saw a screen with the word "LISTEN" centered, at which point either four or six randomly spoken letters were presented aurally through headphones, at an interstimulus interval of 500ms. The letters presented were randomly selected from the following 10 letters: FGKNQPRSTX. In the phonological loop setting, participants were told to simply commit the letters heard to memory in the order they were presented. In the central executive setting, participants were told to commit the letters heard to memory after arranging them in alphabetical order.

After completion of the primary task, a retention period of 2500ms was followed by a single probe memory test. On the screen were identical horizontal place-holders matching in number to the number of letters heard in the initial phase of the trial. The memory probe was one of the memorized letters above one of the place-holders. In the phonological loop setting, the participant decided if the probe's position matched that of the order initially spoken in the beginning of the trial. In the central executive setting, the participant decided if the position of the probe matched the correct position given the alphabetized arrangement of the letters heard. The probe's location was determined randomly on each trial and an equal number of match/no match trials were presented. In the case of control trials, participants initially heard a series of the letter "Y" (series lengths of four or six). This trial acted as a control as the position of the letter in the probe phase was always correct.

Visuospatial Sketchpad. A similar procedure was used as described for the other secondary tasks, but instead of memorizing letters for later recall, the participant was asked to memorize displays of object arrays. After the initial fixation slide, a display containing either four or six objects appeared for 500ms. The array consisted of two sets of circles and triangles and each object was randomly filled with different colors such that no color was repeated in any one trial. The colors of the circles were red, brown, blue, yellow, and purple. The colors that filled the triangles were light blue, green, pink, orange, and white. The participant was told to commit the locations of the colors to memory for later recall.

Following the primary task was a 1000ms single object cue (displaying either a black circle or triangle), a 1000ms retention period, followed by a memory test. The cue screen indicated which set of objects the participant would recall within a single change detection procedure (Irwin, 1992; Vogel, Woodman, & Luck, 2001; Wheeler & Triesman, 2002). That is, if the cue indicated a memory test for circles, then the task was to decide if the circle presented (in the specific position) matched in color to that of the original stimulus. For example, the participant decided if a red circle appearing on the screen had appeared in that position in the initial display.

The arrangement of the objects was such that, in the six object display, circles were placed in the bottom corners of the display and above the fixation point, while triangles were placed in the upper corners of the display and below the fixation point. In the four object condition, circles were placed to the left and right of the fixation, while triangles were placed above and below the fixation point (Fougnie & Marios, 2009). Note that these structural configurations of the shapes did not change, however the color of these shapes did. Thus, the behavior measured is the participant's ability to detect a change in color at specific shape locations. The cue presented was determined randomly on each trial and an equal number of match/no match trials were presented. In control trials, the initial display and memory phase consisted of shapes that were all black. Thus, the response phase should have always elicited a "match" response as the color of the objects was not subject to change.

Participants completed the informed consent and AMAS prior to the completion of the experimental trials. The WRAT-3 was administered after the experimental tasks were completed. Subsequently, participants were notified that their research credits were granted and were debriefed before leaving the laboratory. The experimental task was administered using Eprime 2.0 experimental software (Schneider, Eschman, & Zuccolotto, 2002). Each session lasted approximately 80 minutes.

Results

Analyses

The following results were drawn from the same mixed factor analysis of variance (ANOVA) design including numerical distance (distances 1-4), secondary task (central executive, phonological loop, VSSP), working memory load (zero, four, and six load), and math anxiety (low and high math anxious) as the independent variables. Reaction times (RTs) and percent error analyses were computed independently, once for the behavior recorded during the completion of the primary task (number comparison) and once for the behavior recorded during the secondary task (recall) phases of the trials.

Primary Task Reaction Time

The results of the comparison analysis revealed that the main effect of numerical distance was significant, indicating the typical decline in RT as the distance between the numerical magnitudes of the presented digit and the standard increased, F (3,123) = 3.27, $p < .05$, $\eta_p^2 = .07$. Further, RT was slowest in the VSSP secondary task (M=1067ms), followed with increasing speed in the central executive (M=937ms) and phonological loop tasks (M=843ms) respectively, F (2, 82) = 34.37, $p < .01$, $\eta_p^2 = .46$. The main effect of memory load was also obtained, indicating that the additional working memory load of maintaining four (M=969ms) and six (M=977ms) items in memory resulted in significantly longer RTs than observed in the zero load trials (M=901ms), F (2, 82) = 14.03, $p < .01$, $\eta_p^2 = .26$. Note that the four and six load conditions did not differ significantly.

Importantly, the two-way interaction between secondary task and load was significant [F (4,164) = 2.91, $p < .05$, $\eta_p^2 = .07$], as was the three-way interaction including these factors and math anxiety, F (4,164) = 3.41, $p < .01$, $\eta_p^2 = .08$. *Figure 1* and *Figure 2* illustrate the data from the two- and three-way interactions respectively. *Figure 1* reflects the overall slower performance under VSSP load. Surprisingly, this was even true of the zero load conditions. Further, within each secondary task setting, the zero load conditions were significantly faster than the four load conditions. Finally, the zero load conditions were significantly faster than the six load conditions within the central executive and VSSP settings but not in the phonological loop setting.

As seen in *Figure 2*, the overall greater interference in the VSSP setting was observed for both anxiety groups; however the interference experienced was especially large for the high math anxious participants. Post-hoc analyses indicated that the four and six load conditions were significantly slower for this group in comparison to the low anxious participants, and that these differences were the only ones to reach significance between the two anxiety groups. Importantly, the three-way interaction remained significant after including math achievement scores as a covariate in the analysis, F (4, 160) = 4.33, $p < .01$, $\eta_p^2 = .10$.

Primary Task Percent Error

Including percent error as the dependent measure resulted in a main effect of secondary task, F (2, 84) = 3.41, $p < .05$, $\eta_p^2 = .08$; however, this effect may be spurious and of little meaning. The post-hoc comparisons indicated that the overall percent error committed in the central executive task (M = 1%), phonological loop (M = 2.1%) and VSSP (M = .6%), did not statistically differ.

In a similar fashion, the numerical distance x math anxiety interaction was significant, F (3, 126) = 2.81, $p < .05$, $\eta_p^2 = .06$. The post-hoc comparisons for this effect revealed that the high and low math anxious participants did not differ at any numerical distance. Further, the within group comparisons showed that the errors committed by the low math anxious did not vary as a function of numerical distance, while the high math anxious participants committed a significantly larger percent of error in comparisons of digits 1 away in magnitude (M = 1.8%) than comparisons of digits 3 away in magnitude (M = .4%). Despite the correct direction of the high math anxious differences, the results are treated with caution, as it appears that all participants were at ceiling in terms of accuracy in the comparison phase of the task (all cells' percent error scores were less than 5% error overall). Moreover, both the main effect of secondary task and the interaction between distance and math anxiety were no longer significant after controlling for achievement scores [$F < 1.0$ for the main effect; F (3, 123) = 2.23, $p > .05$, for the interaction]. No interpretation is attempted for these effects, given the almost perfect performance recorded for all of the participants (see Risko, Maloney, & Fugelsang, 2013 for similar results concerning the size congruity effect in magnitude comparison).

Taken together, the primary task results suggest that magnitude comparison within the H/L 5 task variant relies on resources employed by the central executive and visuospatial sketchpad; however, little evidence was found demonstrating the involvement of the phonological loop in comparison processing. The associated impairments were reflected in RTs only. Additionally, it appears that the math anxiety groups differentially relied on the two relevant working memory components; the low and high math anxious participants demonstrated equivalent dual-task interference in the central executive task whereas the high math anxious participants were especially affected by concurrent visuospatial processing in comparison to the low math anxious participants. Finally, these math anxiety differences in RT do not seem to be associated with the mathematical achievement of the participants.

Secondary Task Reaction Time

The equivalent analysis including the RTs from the recall phase revealed that the central executive (M=2147ms), phonological loop (M=1233ms), and VSSP (M=941ms) processing times were significantly different from each other, F (2, 82) = 133.46, $p < .01$, $\eta_p^2 = .77$. Additionally, the main effect of memory load revealed that the zero load (M =

765ms), four load (M = 1664ms), and six load (M = 1893ms) conditions also differed significantly, F (2, 82) = 254.85, p < .01, η_p^2 = .86.

Finally the load x secondary task interaction was significant (see *Figure 3*), F (4, 164) = 94.25, p < .01, η_p^2 = .70. The post-hoc analyses for this effect showed that the zero load trials did not differ between secondary tasks, although the four and six load conditions did. Further, the RTs of each load were significantly different from each other within each secondary task. As seen in the figure, it is clear that additional processing slowed responding most in the central executive secondary task followed by the phonological loop. Importantly, no effects of math anxiety were obtained.

Secondary Task Percent Error

The percent error analysis revealed that a larger percent error was committed overall in the central executive (M = 20.4%) and VSSP (M = 22.0%) secondary tasks as compared to the phonological loop task (M = 12.7%), F (2, 84) = 20.34, p < .01, η_p^2 = .33. Also, the main effect of memory load was significant, F (2, 84) = 345.82, p < .01, η_p^2 = .89. The percent error committed was significantly different between all three levels, with 30.5% error in the six load trials, 21.6% error in the four load conditions, and 3% error in the zero load trials.

Finally, the secondary task x load interaction was obtained (see *Figure 4*), F (4, 168) = 12.83, p < .01, η_p^2 = .23. The figure shows that percent error was lowest in the phonological loop dual task setting and that percent error of the VSSP and central executive settings were equivalent in the four and six load conditions. Also shown is an increase in percent error with each addition of memory load in the phonological loop and

VSSP, while percent error in the central executive setting did not significantly differ from four to six load conditions. Interestingly, the between task comparisons by memory load revealed that the percent error in the zero load VSSP secondary task (M = 7.1%) was significantly larger than the percents recorded in the central executive (M = 1.0%) and phonological loop (M = 0.9%) secondary tasks.

Taken together, the results discussed so far lead to the possibility that, although not substantially working memory demanding, number comparison processes were differentially affected by the dual task settings administered. That is, both the central executive and visuospatial sketchpad were implicated in poorer comparison performance as compared to the phonological loop. Importantly, the worse performance in the VSSP task seemed to be due to impaired efficiency of the high math anxious participants specifically. The secondary task results indicate that memory recall was most difficult in the central executive setting, and least difficult in the phonological loop. Importantly, interactions including neither numerical distance nor math anxiety factors were obtained in the secondary task results, suggesting that the effects reported reflect the difficulty of the secondary tasks independent from the primary task.

One problem with the interpretation of the primary task results is that the RTs recorded varied across working memory load within their own time-scales; interpreting such results is difficult given the difference in absolute RT between each secondary task setting. To examine the relative interference associated with additional memory load within each secondary task, dual-task cost (DTC) scores were computed on the RTs for each participant's performance separately for the primary and secondary tasks. That is, a DTC score was computed for each distance presented within the levels of load of each dual-task setting per participant. The costs are calculated by taking the difference between the zero load condition RT (control condition) and the RT associated with the four and six load conditions independently (experimental conditions). That difference is then divided by the zero load condition RT and multiplied by 100. The cost scores represent a percentage of change from the baseline RT of the zero trials to the respective experimental trial condition (four or six load).

In the present study, the results of a DTC analysis allow for interpretations related to the exact nature of working memory employment during magnitude comparison (comparing the three dual-task settings to each other), as well as the nature of the interference that is most strongly associated with varying levels of math anxiety (being able to examine the absolute differences in impairment between high and low math anxious individuals). These interpretations are allowed due to the fact that the dual-task cost formula creates scores across the tasks and groups that are of a similar metric in percent change between zero load trials and those of additional load.

Primary Task DTC Analysis

Dual-task cost scores were input as the dependent measure in a 4 (distances 1-4) x 3 (central executive, phonological loop, VSSP) x 2 (four and six working memory load) x 2 (low and high math anxiety) ANOVA. Note that a more negative value indicates larger impairment because additional load resulted in larger RTs compared to the zero load trials. Stated another way, more negative DTC scores indicate greater decreases in processing efficiency.

The results of this analysis are illustrated in *Figure 5*. First, note the strong cost associated with the central executive setting. The impairment associated with this setting was significantly different from both the costs associated with VSSP and phonological loop, F (2, 82) = 6.0, $p < .01$, $\eta_p^2 = .13$. The latter two did not differ from each other. Importantly, the math anxiety x secondary task interaction was also obtained, F (2, 82) = 5.16, $p < .01$, $\eta_p^2 = .11$. The post-hoc analyses revealed that only the VSSP dual-task setting was found to incur differential costs between the math anxiety groups. Further, comparisons within the math anxiety groups revealed that the low math anxious participants demonstrated more cost in the central executive secondary task than in the other two settings. By contrast, the high math anxiety group only showed significant cost differences between the phonological loop and VSSP secondary tasks. Including achievement as a covariate did not eliminate the secondary task x math anxiety interaction, F (2, 80) = 6.52, $p < .01$, $\eta_p^2 = .14$.

Secondary Task DTC Analysis

When considering the costs associated with the secondary task performance, the main effects of secondary task [F (2, 84) = 91.65, $p < .01$, $\eta_p^2 = .69$] and memory load were obtained, F (1, 42) = 42.57, $p < .01$, $\eta_p^2 = .50$. The interaction of these two factors was also significant and is illustrated in *Figure 6*, F (2, 84) = 6.36, $p < .01$, $\eta_p^2 = .13$.

The figure clearly shows the two main effects: the central executive secondary task led to the greatest cost, followed by the phonological loop and VSSP tasks respectively. Further, the six-load trials led to more processing impairment than did the four-load trials. The interaction reflects that the discrepancy between the two memory load conditions was more substantial in the central executive and phonological loop tasks than in the VSSP task.

Note that the lack of math anxiety effects in the secondary task results support the idea that differences in dual-task performance between the high and low math anxious cannot be immediately attributed to overall differences in working memory capacity. That is, if the high math anxious did have lower overall working memory capacities, then the dual task cost analysis for recall performance would be expected to reveal a working memory load x math anxiety interaction, whereby the high math anxious would be associated with higher costs with increased memory load as compared to the low math anxious. This possibility was not confirmed in the present results, however.

The DTC analyses showed that comparison efficiency was impaired with additional central executive load for both groups, but also that the high math anxious in the sample exhibited impaired performance in the VSSP dual task setting. Importantly, the high and low math anxious group differences in the VSSP dual-task setting were only found in the primary task performance; no math anxiety group differences were obtained in the recall portion of the task. Because primary task completion was not found to influence performance in the secondary task, it appears possible that the high math anxiety group may have faced impairment in a process unrelated to the effective maintenance of visual information.

Experiment 1 Discussion

In sum, it appears that comparison processes (at least in the H/L 5 task variant) require central executive processing. Future studies need to examine this conclusion in the context of comparison of simultaneously presented digits, as the central executive demands demonstrated here may simply be related to the repeated retrieval of the standard magnitude needed for each trial (see Maloney, Risko, Preston, Ansari, & Fugelsang, 2010). Interestingly, however, the reliance on this component was not related to the numerical distance of each comparison completed. That is, additional working memory load did not influence the numerical distance effect, nor did the numerical distance of comparisons influence the performance within the secondary task.

One potential explanation for not finding differences in numerical distance effects as a function of math anxiety (as found in Maloney et al., 2011) could simply be that the variance associated with the dual-task paradigm may have overwhelmed the variance of the distance effects. Additionally, note that the sample tested by Maloney and colleagues was comprised of high and low math anxious individuals that were drawn from extreme ends of the distribution, while this study employed a median split procedure. Because of these differences between reports, future studies should attempt to replicate these effects in new samples. In the present study, however, the lack of differences in numerical distance suggests that the math anxiety differences are not related to the representation of numerical magnitude.

Importantly, the performance within the central executive task did not reveal math anxiety group differences. Instead, dual-task cost analyses suggest that group differences were observed only in concurrent VSSP dual-task demands; the high math anxious participants exhibited more cost than the low math anxious participants. The inclusion of the math achievement covariate did not account for this interaction. A potential explanation for this result is that the high math anxious individuals may suffer from visual working memory deficits, which could be used as support for conventional understandings of the mathematics anxiety construct. To the contrary, however, this same math anxiety deficit was not observed in the secondary task phase of the experiment or with the increase from a four to six working memory load. This is an important point because working memory deficits within a specific component should be present in the situations that are most difficult in a task, as is shown in numerous math anxiety investigations testing arithmetic performance (e.g., Ashcraft & Kirk, 2001; Mattarella-Micke et al., 2011).

The explanation considered here is focused on attentional resource efficiency related to the presence of high levels of mathematics anxiety (Eysenck et al., 2007). Critically, Eysenck and colleagues assert that the experience of anxiety during cognitive processing results in a shift away from goal-directed attentional systems in favor of stimulus-driven systems (i.e., Corbetta & Schulman, 2002), causing impaired performance in cognitive tasks relying on central executive resources. Recent work has shown that attentional processing is important for numerical magnitude comparison, and that factors affecting the allocation of attention to the task can alter comparison performance (Goldfarb & Tzelgov, 2005; see also Risko, Maloney, and Fugelsang, 2013). The full reasoning for this explanation will be provided in the General Discussion of this paper. To follow is an explanation of Experiment 2, which investigated math anxiety, math achievement, and working memory demands in a simple enumeration task.

CHAPTER 3

EXPERIMENT 2

Experiment 2 examines the association between mathematics anxiety and simple enumeration processes. Enumeration processes have been well studied in the field of mathematical cognition and visual attention (Ansari, Lyons, van Eimeren, & Xu, 2007; Balakrishnan & Ashby, 1992; Feigenson & Carey, 2005; Kaufman, Lord, Reese, & Volkman, 1949; Mandler & Shebo, 1982; Pagano, Lombardi, & Mazza, 2014; Trick & Pylyshyn, 1994). Of interest to the present investigation are results demonstrating less efficient enumeration of set sizes that require explicit counting procedures in individuals who are highly math anxious as compared to their low math anxious peers (Maloney et al., 2010). Importantly, these math anxiety differences were not observed in set sizes that are thought to require little (if any) working memory assistance. Before describing the conclusions offered by the authors, a brief description of the enumeration task and published interpretations are provided.

Enumeration is a process of updating a serial count of objects until the total of a collective set is known. There is a large and long-lasting debate in the literature regarding the mechanisms underlying these processes (Dehaene, 1997; Gallistel & Gelman, 1992; Le Corre & Carey, 2007; Wynn, 1992; 1995). The reason for this debate is centered on the well-researched construct of subitizing (Kaufman et al., 1949), or the rapid and accurate appreciation of the total enumerated in set sizes around 3 or 4 items in total. Beyond this range, explicit and more effortful counting procedures are needed to arrive at the set's total. The principle debate surrounding these characteristics is whether one or more enumeration mechanisms exist to accommodate the two ranges. Although the present experiment is not designed to make a determination regarding this debate, the ranges will be treated (at least qualitatively) as originating from two separate mechanisms, as suggested by the results of Maloney et al. (2010), which will be described shortly (see also Vuokko, Niemivirta, & Helenius, 2013). For the sake of clarity, enumeration in the present study will refer to the processes involved with identifying the total of set sizes (regardless of the actual size of that set), subitizing will refer to the enumeration of set sizes specifically in the range of 1-3 objects in total, and counting will refer to enumeration of set sizes larger than 3 in total.

The two processes described here tend to elicit drastically different performance profiles. The subitizing range often elicits RT profiles that are fast and vary little as a function of set size. That is, the RTs associated with the identification of the totals of set sizes in the range of 1-3 or 4 form a rather shallow slope with regard to increases in set size, and are characterized by relatively fast absolute RTs. By contrast, RTs in the counting range form a consistently increasing positive slope with each increase in set size. These profiles are found across the life-span (Chi & Klahr, 1975; Starkey & Cooper, 1995), and serve as a cornerstone set of phenomena in the math cognition literature.

These classic enumeration patterns are of interest in the present study due to a recent report implicating math anxiety as a factor that modulates the efficiency with which set sizes are enumerated. More specifically, Maloney and colleagues found a significant interaction between the number of items to be enumerated and math anxiety; high math anxious participants were found to have slower counting than the low math anxious, but RTs between the groups were similar in the subitizing range. The authors drew two possible conclusions regarding their results. The first was that this pattern of behavior supported the conventional math anxiety construct, with high math anxious individuals experiencing interference in the more working memory dependent counting range, but not in the relatively resource independent subitizing range. Importantly, the authors' conclusions also appealed to the notion that poorer counting skills may be related to deficient mathematical competency in the high math anxious individuals. To examine these trends further, the same method from Experiment 1 was employed here, but with enumeration serving as the primary task. The goals of Experiment 2 were to examine both the working memory deficit and mathematical achievement hypotheses under dual task settings. As in Experiment 1, math anxiety self-report and mathematical achievement scores of the participants were recorded to examine the relationships between both constructs and performance in an enumeration task.

Method

Participants

A total of 58 participants (37 females) were recruited for this experiment. The mean age of the sample was 20.3 years old. As in Experiment 1, course relevant research credits were granted in exchange for participation.

Procedure

The procedure for Experiment 2 is identical to that of Experiment 1 with the exception of the primary task. The enumeration task administered here consisted of trials in which participants viewed a screen with black squares (ranging from 1 to 8 in total) displayed on a white background. Upon stimulus onset, the goal of the participant was to count the number of squares as quickly and accurately as possible. Once the set size was known, the participant was instructed to speak the total into the microphone which acted as a voice key to stop recording the RT of the trial. Experimenters manually recorded the spoken response of the participants into a research journal. The set sizes were sampled 12 times each per block, yielding 96 trials per block. Each presentation of set size was a unique stimulus with pseudorandom arrangement of the squares controlling for stereotypical configurations of quantity (i.e. dice patterns). The experimental task was administered using Eprime 2.0 experimental software (Schneider, Eschman, & Zuccolotto, 2002). Each session lasted approximately 80 minutes.

Results

Analyses

The data recorded in Experiment 2 were input into ANOVAs designed with set size (1-8 in total), secondary task (phonological loop, central executive, and VSSP), working memory load (zero, four, and six loads), and math anxiety (high and low math anxiety) as the independent factors. Math anxiety was the only between-subjects factor. In the case of significant math anxiety effects, the analysis was re-visited with mathematical achievement input as a possible covariate. Dependent variables were the RTs and percent error within the primary and secondary tasks separately.

Primary Task Reaction Time

The ANOVA results showed that counting was slowest overall in the VSSP secondary-task condition (M = 1469ms), which was significantly slower than the RTs recorded in the central executive (M = 1380ms) and phonological loop dual-task setting

(M = 1352ms), F (2, 80) = 11.58, $p < .01$, $\eta_p^2 = .23$. The RTs of the latter two settings did not differ statistically from each other. Further, RTs were significantly slower in the four load (M = 1410ms) and six load conditions (M = 1451ms) as compared to the zero load conditions (M = 1339ms), F (2, 80) = 18.25, $p < .01$, $\eta_p^2 = .31$.

Importantly, the typical subitizing effect was obtained, F (7, 280) = 338.36, $p < .01$, $\eta_p^2 = .89$. The main effect of set size shows a shallow slope and relatively fast absolute RTs in the enumeration of the first 3 sets of objects, and a steeper slope with progressively slower absolute RTs as set size increased. As found in the literature, the set size x math anxiety interaction was obtained [F (7, 280) = 3.48, $p < .01$, $\eta_p^2 = .08$], and this effect was augmented with the inclusion of secondary task, F (14, 560) = 2.93, $p < .01$, $\eta_p^2 = .07$. *Figure 7* illustrates this three-way effect. The figure shows that the math anxiety x set size interaction can be described as growing discrepancy in the RTs of high and low math anxious individuals as the set size of the enumerated displays increased, and that this discrepancy is driven by slower RTs exhibited by the high math anxious individuals. This effect replicates the math anxiety effect found in Maloney et al. (2010). The contribution of the secondary task factor in the three-way interaction reveals two important patterns. First, it appears that the high math anxious experienced more interference due to concurrent VSSP processing than did the low math anxious participants. Second, note that the separation between the math anxiety groups begins earlier in the count sequence (with smaller set sizes) when the participants were under concurrent VSSP task demands. These patterns will be further explored later in the results.

The secondary task x memory load interaction was significant, and shows that the zero load trials of the VSSP task were significantly slower than the other two dual-task settings, as were the RTs associated with the six-load trials, F (4, 160) = 2.53, $p < .05$, $\eta_p^2 = .06$. The four load trials were only different between the VSSP task and the phonological loop task. As for the within task comparisons across memory load, the post-hoc comparisons revealed that the zero load trials were significantly slower than the four and six load trials (the four and six load conditions did not differ significantly). In the phonological loop task, only the zero and six load conditions differed. Finally, the VSSP zero load trials were significantly faster than the four and six load conditions, while the four and six load conditions were only marginally different ($p = .08$).

The working memory load x set size interaction was also obtained, F (14, 560) = 3.45, $p < .01$, $\eta_p^2 = .08$. From *Figure 8*, it appears that the zero load trials resulted in faster enumeration along with entire continuum. Within the range of smaller set sizes (1-3 in total), it appears that any additional load was associated with larger RTs, whereas only the six load conditions seemed to appreciably increase RTs in the counting range, but only in set sizes larger than 5 in total. To examine these patterns in greater detail, the subitizing and counting ranges were examined independent of each other.

Primary Task Reaction Time: Subitizing Range

The equivalent analysis including only set sizes ranging from 1 to 3 in total was conducted to examine the influence of secondary task, working memory load, and mathematics anxiety on enumeration RTs. The results indicate that secondary task did influence performance, revealing that RTs were slowest under concurrent VSSP load (M=975ms) as compared to the central executive (M = 883ms) and phonological loop (M

= 842ms) working memory loads, F (2, 80) = 12.11, $p < .01$, $\eta_p^2 = .23$. The VSSP task elicited significantly longer RTs than the other two secondary tasks, which did not differ from each other. Further, although not different from each other, the four and six load conditions (Ms = 936ms and 925ms respectively) were significantly slower than the zero load conditions (M = 838ms), F (2, 80) = 10.20, $p < .01$, $\eta_p^2 = .20$. Interestingly, the main effect of set size was significant, F (2, 80) = 7.62, $p < .01$, $\eta_p^2 = .16$. Upon further inspection, however, it appears that the difference in RTs may simply reflect the characteristics of recording voice key activation. That is, the means show significantly faster responses to the set size of 2 (M = 862ms) than 1 (M = 916ms) or 3 (M = 921ms). These results are thought to reflect the more prominent initial phoneme of the number word "two" than the other two set sizes in the this analysis (Rastle & Davis, 2002). No other effects were obtained in this analysis.

Primary Task Reaction Time: Counting Range

The main effect of secondary task within the counting range mirrored that of the subitizing range, F (2, 80) = 7.16, $p < .01$, $\eta_p^2 = .15$. That is, the VSSP secondary task (M = 1765ms) elicited significantly longer RTs than both the central executive (M = 1678ms) and phonological loop (M = 1659ms). Additionally, the RTs associated with six (M = 1767ms), four (M = 1695ms), and zero load conditions (M = 1640ms) were all significantly different from each other [F (2, 80) = 15.67, $p < .01$, $\eta_p^2 = .28$], and RTs increased as set size increased, F (4, 160) = 227.98, $p < .01$, $\eta_p^2 = .85$.

Figure 9 illustrates the significant working memory load x set size interaction, F (8, 320) = 3.86, $p < .01$, $\eta_p^2 = .09$. The figure shows that responses were slower as both set size and working memory load increased. Interestingly, it can be seen that the separation of RTs between memory loads did not become apparent until a set size of six items, and then persists throughout the rest of the enumeration continuum.

Importantly, the main effect of math anxiety was obtained [F (1, 40) = 4.48, p < .05, $\eta_p^2 = .10$], and contributed to a three-way interaction also including secondary task and set size, F (8, 320) = 3.72, p < .01, $\eta_p^2 = .09$. *Figure 10* illustrates the interaction, paneled by math anxiety group. First note the main effect of math anxiety, whereby the high math anxious were routinely slower in enumeration (M = 1809ms) than were the low math anxious individuals (M = 1592ms). Also, it appears that the high math anxious participants experienced much greater impairment due to concurrent VSSP processing along the entire continuum than the low anxious participants did. Importantly, including math achievement as a covariate resulted in the elimination of these two math anxiety effects [F < 1.0 for the main effect and F (8, 312) = 1.07 for the interaction, both ps > 1.0]. The contribution of math achievement will be addressed in the general discussion.

Primary Task Percent Error

The 3 (secondary task) x 3 (memory load) x 8 (number) x 2 (math anxiety) ANOVA with percent error as the dependent variable revealed a main effect of number such that percent error increased as the number of total objects counted increased, F (7, 280) = 15.54, p < .01, $\eta_p^2 = .28$. The post-hoc comparisons showed that, interestingly, the increase in error began at 6 objects (M = 6.3%) and was maintained through 7 (M = 5.4%) and 8 objects (M = 6.3%). All mean percents of set sizes below 6 elicited very few errors overall (all cell means < 1% error). Also significant was the number x load interaction, which shows the general trend of percent error after set sizes 5 in total growing more quickly specifically in the presence of a six item memory load. No other effects were obtained.

Primary Task Percent Error: Subitizing Range

The only effect to reach significance in the analysis including only the subitizing range of objects was the secondary task x math anxiety interaction, F (2, 80) = 3.39, $p <$ .05, $\eta_p^2 = .08$. Upon further inspection, however, it was determined that this effect is most likely spurious, given that all cells' values indicated performance that was at ceiling. To be sure, the largest mean percent error was 0.7% error, followed by a mean percent error of 0.4%. Beyond these two cells, the means were 0.1% or smaller. Moreover, the inclusion of the math achievement covariate eliminated the interaction, F (2, 78) = 1.95, $p > .10$. Given these effects, the trends will not be discussed further.

Primary Task Percent Error: Counting Range

As with the analysis including all set sizes, the counting range analysis revealed a significant main effect of number [F (4, 160) = 11.54, $p < .01$, $\eta_p^2 = .22$] and a significant number x load interaction, F (8, 320) = 2.31, $p < .05$, $\eta_p^2 = .06$. The same interpretations offered for the overall analysis hold for these results as well, and need not be discussed further.

The results from the primary task analyses revealed that, overall, additional processing of visuospatial information interfered most with enumeration performance. Furthermore, this effect was most prominent within the high math anxious participants, although mathematical achievement appears to mediate this characteristic of the data. Interestingly, performance in the subitizing range revealed that any amount of additional load led to equivalent impairment in enumeration, while the impairment observed in the counting range increased with each additional increase in working memory load. Finally it is important to note that observed impairments were most prominent in the extreme ends of the enumeration continuum (subitizing range and counting set sizes of 6 or greater).

Secondary Task Reaction Time

The RTs recorded within the information recall phase of the trials varied by the secondary task tested [F (2, 80) = 85.60, $p < .01$, $\eta_p^2 = .68$] and by the working memory load encountered, F (2, 80) = 256.80, $p < .01$, $\eta_p^2 = .87$. Further, the interaction of these factors is illustrated in *Figure 11*, which shows relatively small RT differences between the dual-task settings in the zero-load conditions, and with increasing differences between the secondary tasks as memory load increased. More specifically, it can be seen that additional working memory load resulted in the slowest RTs in the central executive dual task setting, followed by the phonological loop and VSSP, respectively.

Additionally, the RTs associated with recall increased as the set size enumerated increased [F (7, 280) = 3.41, $p < .01$, $\eta_p^2 = .08$], and this pattern varied as a function of working memory load, F (14, 560) = 2.86, $p < .01$, $\eta_p^2 = .07$ (See *Figure 12*). The most apparent trend of the figure shows a rather large separation in RTs between the zero load condition and the trials associated with additional load. Within each load condition, the effect of set size varied as well, with only a minor increase in RT with increasing set size in the zero load condition, a slightly larger increase in the four load condition, and the largest increase in the six-load condition. Note also the much more variable RTs in the six load condition than the other two loads.

Finally, the analysis revealed a four-way interaction including all of the factors of the ANOVA design, F (28, 1120) = 1.96, $p < .01$, $\eta_p^2 = .05$. Before attempting to explain this effect, however, the two enumeration ranges are considered separately for analysis.

Secondary Task Reaction Time: Subitizing Range

The analysis considering secondary task performance associated with the enumeration of set sizes in the subitizing range showed that responses were slowest under central executive load (M = 1911ms) which was significantly slower than those RTs in the phonological loop (M = 1335ms), which were in turn slower than the RTs in the VSSP setting (M = 991ms), F (2, 80) = 70.79, $p < .01$, $\eta_p^2 = .64$. Also, RTs increased as memory load increased, F (2, 80) = 174.75, $p < .01$, $\eta_p^2 = .81$. The six (M = 1783ms), four (M = 1609ms), and zero load conditions (M = 844ms) were all significantly different. Finally, the secondary task x working memory load interaction was significant and consistent with the pattern observed in the omnibus test; the four and six load conditions were associated with the largest RTs within the central executive dual task setting, followed by the phonological loop and VSSP settings respectively, F (4, 160) = 49.79, $p < .01$, $\eta_p^2 = .56$.

Secondary Task Reaction Time: Counting Range

Recall RTs associated with counting range trials were largest in the central executive secondary task (M = 1885ms), and were faster in the phonological loop (M = 1322ms) and VSSP (M = 1122ms) secondary tasks respectively, F (2, 80) = 75.81, $p < .01$, $\eta_p^2 = .66$. As described already, the six load trials (M = 1782ms), four load trials (M = 1661ms), and zero load trials (M = 887ms) were all significantly different from each other, F (2, 80) = 210.62, $p < .01$, $\eta_p^2 = .84$. Also, the time taken to respond in the recall phase increased as the number of items counted increased, F (4, 160) = 5.65, $p < .01$, $\eta_p^2 = .12$.

Interestingly, the secondary task x working memory load x set size interaction was obtained, and is presented in *Figure 13*, F (16, 640) = 2.10, $p < .01$, $\eta_p^2 = .05$. The patterns across the secondary tasks shows that the differences between additional load trials and the zero load trials is largest in the central executive dual-task setting, and that this difference is reduced in the phonological loop and VSSP tasks respectively. Further, the influence of set size reflects the steeper slope in the four and six load conditions as compared to the zero load condition. These patterns were supported by the secondary task x working memory load interaction [F (4, 160) = 74.83, $p < .01$, $\eta_p^2 = .65$] as well as the working memory load x set size interaction, F (8, 320) = 4.10, $p < .01$, $\eta_p^2 = .09$.

Finally, the four- way interaction including all of the design's factors was obtained [F (16, 640) = 2.35, $p < .01$, $\eta_p^2 = .06$], and was supported by the three-way interaction already described as well as the secondary task x number x math anxiety interaction, F (8, 320) = 2.42, $p < .05$, $\eta_p^2 = .06$. Importantly, with math achievement as a covariate in the follow-up analysis, the secondary task x working memory load x set size interaction, as well as the other supporting interaction of secondary task, set size, and math anxiety were eliminated (ps > .10). Although the four-way interaction remained significant after controlling for math achievement scores [F (16, 624) = 1.93, $p < .05$, $\eta_p^2 = .05$], its interpretation is not attempted given the loss of supporting effects and strong likelihood that the effect is spurious in the present data.

Secondary Task Percent Error

With the percent error of responses input as the dependent measure, the ANOVA results revealed the significant main effects of secondary task [F (2, 80) = 22.60, p < .01, η_p^2 = .36], working memory load [F(2, 80) = 161.63, p < .01, η_p^2 = .80], as well as their interaction, F (4, 160) = 12.30, p < .01, η_p^2 = .24. The main effect of secondary task showed that the percent error of responses within the central executive (M = 24%) and VSSP (M = 26%) were significantly larger than compared to the percent recorded within the phonological loop (M = 15%), although the former two did not differ from each other. The effect of memory load revealed that the percent error in the six load trials (M = 33%) was significantly larger than that within the four load trials (M = 25%), which, in turn, was larger than the percent error in the zero load trials (M = 7%). *Figure 14* illustrates the secondary task x working memory load interaction and reveals that, in general, the percent error within the phonological loop was lowest regardless of load. Further, the VSSP tended to elicit larger percents of error across all memory loads, and even elicited significantly more error in the zero load trials than either of the other two secondary tasks. Also, secondary task means differed in the four load conditions, while only the VSSP and phonological loop dual-task settings differed in the six load conditions.

The analysis also indicated that the number of objects counted influenced the percent error in the secondary task such that percent error in recall increased as the set size counted just previous to this phase of the trial increased, F (7, 280) = 3.85, p < .01, η_p^2 = .09. Importantly, the main effect of math anxiety was obtained such that the high math anxious committed a larger percentage of error overall (M = 24%) than did the low math anxious participants (M = 20%), and will be re-evaluated further in the results, F (1, 40) = 4.58, $p < .05$, $\eta_p^2 = .10$.

Secondary Task Percent Error: Subitizing Range

The analysis of the subitizing range indicated that the percent error in recall within the central executive (M = 23%) and VSSP (M = 22%) were significantly larger than in the phonological loop (M = 15%), F (2, 80) = 8.56, $p < .01$, $\eta_p^2 = .18$. Further, the main effect of memory load was obtained, revealing that the six load trials (M = 32%), four load trials (M = 23%), and zero load trials (M = 5.8%) all significantly differed, F (2, 80) = 103.93, $p < .01$, $\eta_p^2 = .72$. Finally, the interaction between these factors was obtained, and largely reflects the patterns described for the full analysis, F (4, 160) = 5.24, $p < .01$, $\eta_p^2 = .12$.

Secondary Task Percent Error: Counting Range

The analysis including the data associated with the counting range confirmed that the results obtained in the full analysis were the products of behavior within the counting range of set sizes. That is, the main effects of secondary task [F (2, 80) = 22.51, $p < .01$, $\eta_p^2 = .36$], memory load [F (2, 80) = 116.76, $p < .01$, $\eta_p^2 = .75$], set size [F (4, 160) = 3.95, $p < .01$, $\eta_p^2 = .09$], and math anxiety [F (1, 40) = 5.73, $p < .05$, $\eta_p^2 = .13$] were obtained. Further, the secondary task x memory load interaction was obtained and was consistent with the description provided for the full analysis, F (4, 160) = 9.91, $p < .01$, $\eta_p^2 = .20$. Including the covariate of math achievement in the analysis eliminated the main effect of math anxiety, F (1, 39) = 1.07, $p > .10$.

The results obtained in the secondary task portion of the experiment largely mirrored those obtained in Experiment 1. That is, the effects are indicative of secondary task difficulty as opposed to interference caused by the primary task. To be sure, the central executive setting appeared to be most difficult overall, while the phonological loop appeared to be the least difficult. Importantly, as observed in Experiment 1, participants appeared to exhibit a speed/accuracy trade off in secondary task performance when confronted with the VSSP secondary task setting.

Unlike the results from Experiment 1, the secondary task results did seem to be influenced by the demands of the primary task. That is, both the RT and error data reflected more difficult processing overall in the secondary task phase as the number of objects in the enumerated set sizes increased. With regard to RT, the effect of set size seems to reflect differences between the relatively shallow slope of the zero load conditions as compared to the four and six load conditions. Most importantly, the main effect of math anxiety in the percent error results was found to be mediated by the math achievement of the individuals.

Primary Task DTC Analysis

Because the results of Experiment 2 revealed that the subitizing and counting ranges of the enumeration largely differed in their susceptibility to interference within the task, dual task cost analyses were computed in an ANOVA evaluating the factors of secondary task (3 levels), working memory load (2 levels), math anxiety (2 levels), and enumeration range (2 levels: subitizing and counting range). The range factor was employed here to examine the relative costs incurred within each range, without the difficulty of interpreting differences between the set sizes enumerated.

The analysis showed a significant main effect of range [F (1, 38) = 4.69, p < .05, η_p^2 = .11] and a significant range x load interaction, F (1, 38) = 9.16, p < .01, η_p^2 = .19. The main effect reveals that the largest DTC scores were incurred in the subitizing range (M = -10.57%) as compared to the counting range (M = -5.46%). The interaction shows that the costs incurred within the subitizing range did not differ based on the memory load of each trial, but that load did influence the costs within the counting range. The four load conditions resulted in significantly less cost (M = -2.79%) than did the six load condition (M = -8.13%). No other effects were significant in the comparison phase dual task cost analyses.

Secondary Task DTC Analysis

The equivalent DTC analysis for the secondary task RTs indicated that the costs was greatest overall in the central executive (M = -216.66%), with less cost in the phonological loop (M = -117.0%), and VSSP (M = -23.58%) respectively, F (2, 76) = 72.52, p < .01, η_p^2 = .66. Also, the six load conditions led to a greater cost to efficiency (M = -127.29%) than did the four load conditions (M = -110.87%), F (1, 38) = 19.56, p < .01, η_p^2 = .34. Finally, these two factors interacted, and the effect is illustrated in *Figure 15*, F (2, 76) = 17.30, p < .01, η_p^2 = .31. The post-hoc analyses for this effect revealed that the four and six load costs were different between the three secondary tasks. Further, the comparisons revealed that the six load costs were significantly greater than the four load costs for the VSSP and phonological loop tasks, but were not different within the central executive dual task setting.

The dual task costs analyses are interesting because neither the primary nor secondary task results indicated significant differences between the math anxiety groups.

This may not be expected, as participants with higher levels of mathematics anxiety are assumed to perform less efficiently in conditions that demand substantial working memory involvement. Given the results of Maloney et al. (2010) and the working memory literature indicating that both central executive and phonological loop resources are utilized in counting procedures within arithmetic strategy completion (Hecht, 2002; see also Camos & Barrouillet, 2004), the typical high math anxious disadvantage would have been expected to be revealed in the high working memory load conditions. Recall, however, that the influence of working memory load had minimal effects within the enumeration range, and that the primary interference experienced originated from additional visuospatial processing as opposed to loading the central executive.

Experiment 2 Discussion

Experiment 2 was designed to examine the mental processing employed in a simple enumeration task, and to examine the possibilities that individual differences in mathematics anxiety and mathematical achievement would be associated with moderated task performance. To this end, participants completed an enumeration task in the context of three separate dual task settings, each tapping into one of the working memory components described by Baddeley and colleagues (Baddeley & Hitch, 1974; Baddeley & Logie, 1999). The goals of the experiment were to replicate the high math anxious disadvantage as reported by Maloney and colleagues (Maloney et al., 2010), to examine the specific type of cognitive processing utilized in enumeration, and to test the possibility that the math achievement of participants would be associated with task performance.

With regard to the first goal, Experiment 2 did replicate the math anxiety differences reported in Maloney et al., (2010). More specifically, it was found that those participants who reported higher levels of math anxiety were slower to enumerate within the counting range of set sizes than were the self-reported low math anxious. As found in the literature, this difference was not obtained in the subitizing range of set sizes.

Further, it was found that enumeration mechanisms were predominately reliant on visuospatial processing; enumeration performance was most impaired in the presence of concurrent visuospatial working memory load. These results were not surprising, as the extant literature is in large agreement that visual processing is essential to both the subitizing and counting ranges (Ansari, Lyons, van Eimeren, & Xu, 2007; Vuokko et al., 2013). By contrast, a couple of the enumeration results were surprising. First, the DTC analyses within the primary task revealed that additional cognitive load was related more strongly to the subitizing range as opposed to the counting range, which is counterintuitive based on the belief that the counting range is the more working memory demanding (e.g., Maloney et al., 2010). Finally, the results from Experiment 2 revealed that mathematical achievement was associated with performance in the enumeration task. Indeed, the use of math achievement scores as a covariate eliminated the mathematics anxiety group differences obtained. This achievement mediation indicates that some characteristic of low achieving individuals was related to enumeration above and beyond that of math anxiety. The explanation offered for this involvement will be outlined in the following section of this work.

CHAPTER 4

GENERAL DISCUSSION

The purpose of the present study was to examine the relationships between mathematics anxiety, mathematical achievement, and working memory function in the contexts of simple numerical magnitude comparison (Experiment 1) and enumeration (Experiment 2). More specifically, the present investigation sought to explore the surprising results reported by Maloney and colleagues which showed that mathematics anxiety was associated with a steeper numerical distance effect in comparison (Maloney et al., 2011) and steeper counting functions in enumeration (Maloney et al., 2010). These results are surprising because they fall outside the conventional purview of the mathematics anxiety construct which describes that math anxiety disrupts crucial working memory function needed to complete the most mentally taxing aspects of a task. The point of contention with respect to the conventional theory is that number comparison and enumeration processes are presumed to proceed with little need for working memory assistance. Thus, alternative explanations were considered for the individual difference effects observed. Here, I review the results found in the present investigation, and explain their relationships with the theory guiding the development of the math anxiety construct (the Processing Efficiency Theory, Eysenck & Calvo, 1992), and how important extensions of this theory are believed to relate to the results obtained (i.e., Eysenck et al., 2007).

The results from the present study can be described as follows. First, the primary task results provide evidence that the dual task settings differentially influenced performance in number comparison and enumeration. The setting most disruptive to comparison processes was the central executive dual task, while more nuanced influence of the VSSP was also found. By contrast, the VSSP dual task setting was found to be the principle source of influence on enumeration processes. Further, the influence of secondary task completion was limited to the RT data; accuracy in both primary tasks well exceeded 95% overall.

Importantly, although the completion of secondary task demands influenced primary task performance in meaningful ways, little evidence was found supporting a conclusion that primary task completion influenced performance in the secondary task recall portion of the experiments. A comparison of the figures related to secondary task RTs between experiments (*Figures 3* and *11*) as well as percent error (*Figures 4* and *14*) supports this claim; the secondary task x working memory load interactions were close reflections of one another. The exception to this claim was the finding that the number of objects enumerated did influence secondary task performance if the set sizes belonged to the counting range. Importantly, however, the secondary task x working memory load x set size interaction does not reveal differential influence of set size between secondary tasks. Instead, it appears that set size most strongly interacted with working memory load, which was influenced differentially by the secondary task. Thus, the results obtained support the idea that the mechanisms employed during the completion of the primary tasks are not crucially dependent on the resources of the working memory system unless explicit counting procedures are employed. Even with this exception, the influence of the primary task demands on the secondary task performance was minimal.

The performance associated with individual differences of the samples revealed that math anxiety was associated with differences in comparison and enumeration performance. That is, those who reported higher levels of math anxiety were found to incur larger dual task costs associated with concurrent visuospatial processing during comparison than were the low math anxious of the sample in Experiment 1. In Experiment 2, the high math anxious participants' performance showed steeper counting functions than their low math anxious peers. Importantly, Experiment 1 did not fully replicate previous work; a significant math anxiety x numerical distance interaction was not found as shown in Maloney et al. (2010). In contrast, Experiment 2 did replicate the math anxiety x set size interaction within the counting range of the enumeration continuum (Maloney et al., 2010); however, these effects were eliminated after including the math achievement scores of the individuals as a covariate in follow-up analyses. This latter result suggests that the relationship between math anxiety and explicit counting procedures was fully mediated by a characteristic associated with the mathematical competency of the participants.

Despite some inconsistencies between the results presented here and those reported by Maloney and colleagues, the two lines of research do agree on the idea that the present understanding of mathematics anxiety does not fully account for the effects obtained. In the next section, I will describe the founding principles of the math anxiety construct and how the present results are in conflict with their implications. Importantly, to follow is a description of the extensions applied to the base theory (extension: Attentional Control Theory; Eysenck et al., 2007) and an explanation of the current results in the context of this extended theory. As a preview, it will be argued here that both the present and previously published results pertaining to low level processing are well described by principles concerning attentional resource allocation. Further, it is believed that this approach is favorable to those in the literature due to the new avenues of research to be pursued following this novel interpretation.

Mathematics Anxiety and the Processing Efficiency Theory

The current theory describing math anxiety specifies that the worry, stress, and negative ruminations experienced in a math task serve to reduce the amount of working memory resources that are available to be utilized for the completion of a mentally challenging task (Ashcraft & Moore, 2009). As such, we have argued that this "affective drop" in working memory function leads to poorer performance in math tasks requiring substantial working memory assistance (Moore & Ashcraft, 2013). In essence, the demands present in a dual task procedure are augmented by additional resource competition brought on by anxiety, thus creating a triple task scenario.

The primary implications of the affective drop is that math anxiety should be related to increasing deficits in performance as the task being completed becomes more working memory intensive. As Maloney and colleagues report, however, neither number comparison nor enumeration fit the bill for such a description of working memory dependence. Indeed, the literature supporting the affective drop comes from reports demonstrating the high math anxious disadvantage in arithmetic calculation of large numbers and the carry operation (e.g. Ashcraft & Kirk, 2001), or in tasks utilizing an unpracticed novel procedure (modular arithmetic; Mattarella-Micke et al., 2011). Because of the relative ease of comparison and enumeration, Maloney et al. suggested that the typical working memory deficit hypothesis was not the appropriate conclusion to be applied to the differences obtained between high and low math anxious participants.

Instead, the authors drew the conclusion that perhaps a fundamental difference in numerical competency was driving their effects.

The major theoretical position of the math anxiety construct is based on the application of Eysenck and Calvo's (1992) Processing Efficiency Theory, as applied by Ashcraft and colleagues (e.g., Ashcraft & Kirk, 2001). The theory was easily adaptable for use in math anxiety, as it described potential routes through which generalized anxiety impaired cognitive task performance (although related, math anxiety is thought to be a separate construct from other forms of anxiety: Hembree, 1990). Two main assumptions were asserted by the Processing Efficiency Theory. First, anxiety was assumed to affect the efficiency (RT) of processing as opposed to its effectiveness (accuracy). The idea was that the worry associated with anxiety (e.g. negative ruminations, distressing thoughts) consumed crucial working memory resources by way of compensatory strategies employed by the individual to cope with the troublesome cognitions. Assuming the individual is able to utilize resources to accommodate this compensation, the speed of task-relevant processing will be slowed, as if the participant's anxiety serves to create a dual task testing environment (Ashcraft & Kirk, 2001; Eysenk & Calvo, 1992, see also Lyons & Beilock, 2012b). Processing effectiveness was thought to be diminished if the individual is unable to sufficiently engage in these strategies; the participant is not able to employ the requisite cognitive resources to cope with the anxiety and task demands. The second major assumption of the Processing Efficiency Theory identifies the central executive of working memory as being the component most susceptible to the negative effects of worry; the claim was that the central executive would be unable to inhibit the worrying thoughts (e.g., Hopko, Ashcraft, & Gute, Ruggiero, & Lewis, 1998).

Until most recently, Eysenck and Calvo's theory served the math anxiety literature well. As described, math anxiety investigations have routinely found that the high math anxious disadvantage is most apparent in situations that place a large amount of processing demand on the working memory system (Ashcraft & Kirk, 2001; Lyons & Beilock, 2012; Mattarella-Micke et al., 2011). Further, although the math cognition literature has yet to tie these deficits specifically to the central executive, the sound assumption can be made given the working memory review provided in the introduction of this work; the central executive is widely implicated in the completion of the arithmetic tasks utilized in the literature (for in-depth reviews see DeStefano & LeFevre, 2004; Raghubar et al., 2010).

Importantly, however, the Processing Efficiency Theory can only be loosely applied to the anxiety differences found in number comparison and enumeration. The difficulty is that (until the present study) the field has not established the exact processing demands of number comparison processing and enumeration processes are not considered to be heavily reliant on the working memory system (Maloney et al., 2010; 2011). Even if the counting range is specifically considered, intuition alone is enough to reason that the task's working memory demands pale in comparison to those of two-column addition with the carry operation. These ideas are supported in the present experiments, as comparison processes were not found to influence secondary task performance, and the little influence enumeration did have was not attributable to individual differences in the sample. This latter point is important because other tasks known to tax the working memory system tend to elicit impaired performance in secondary task completion (e.g., Ashcraft & Kirk, 2001).

As such, these results provide patterns for which the conventional theory of math anxiety cannot be applied to differential performance attributed to the math anxiety of the individuals tested. If the theory is to explain the low level differences obtained, then it will need to be updated to describe how such effects should be expected. Fortunately, such an updated perspective is offered in the recent extension of Eysenck and Calvo's (1992) model: the Attentional Control Theory (Eysenck et al., 2007). While overlap between the perspectives exists, the inclusion of attentional control in particular is quite helpful for the explanation of the present study's results as well as those in the extant literature.

Attentional Control Theory

At the surface level, the Attentional Control Theory maintains the two assumptions that processing efficiency is the component of performance primarily affected by anxiety (as opposed to processing effectiveness) and that the central executive is the component most affected by anxious interference. The important extension of the theory is that it provides thorough and empirically supported claims regarding the mechanisms by which anxiety (and associated worry) disrupts the functioning of the central executive in cognitive tasks. The basis for the updated account comes from the implications of the two major attentional systems outlined by Corbetta and Schulman (2002): the top-down, goal-oriented system and the bottom-up, stimulus-driven system. Importantly, the goal-oriented system is characterized by activations in prefrontal areas thought to reflect executive function (e.g. task switching and inhibition), while the stimulus-driven system is described as reflecting the activation of key temporo-parietal areas that are associated with the filtering and detection of salient stimuli relevant to the goals of the current task.

Eysenck and colleagues assert that the presence of anxiety creates an imbalance between these attentional systems in favor of the stimulus-driven system. Critically, this imbalance in the highly anxious individual is thought to result in heightened focus on the source of the anxiety. This principle is supported by research indicating that highly anxious individuals preferentially engage in threat-related stimuli as compared to their low anxious peers (Williams, Mathews, & MacLeod, 1996). Importantly, the theory claims that this bottom-up attentional preference for threat can be focused on either internal (negative ruminations) or external (fear-inducing stimuli) sources of threat. Further, the imbalance of attentional resource allocation leads to reduced attentional priority on the goal-relevant aspects of the task (attentional set: Corbetta & Schulman, 2002), thus starving the central executive of resources needed for crucial activities such as task switching or inhibition of irrelevant stimuli. More broadly, the heightened priority on the source of threat serves to reduce attentional control.

To connect these ideas to the experience of mathematics anxiety, the field must substantiate the idea that highly math anxious individuals view components of mathematical thought as being threatening. Reports in the literature support this claim. For example, Mattarella-Micke et al. (2011) found that increases in cortisol levels, a physiological marker for stressful arousal in humans (Elzinga & Roelofs, 2005), during math problem solving in a novel task was related to worse performance in high math anxious participants compared to their low anxious peers. Further, the first fMRI study in developmental math anxiety showed that the children with higher levels of math anxiety were recorded as having greater activation in the basolateral nucleus of the left amygdala during problem solving than their low math anxious counterparts (Young, Wu, & Menon, 2012). Importantly, this site of activation has previously been linked to learned fear response in human adults (Phelps, Delgado, Nearing, & LeDoux, 2004), and the authors showed that functional connectivity between this region and the ventromedial prefrontal cortex was stronger in the high math anxious children, suggesting the activation of a network believed to be implicated in the regulation of negative emotion (Phelps et al., 2004). In further support of the Attentional Control Theory, Young and colleagues found lower activation in parietal areas thought to be responsible for mathematical thought within the high than low math anxious children, which supports the theory's claim that anxiety reduces attentional control in favor of the threat (anxiety) than task demands (manipulating number). Perhaps most convincingly, Lyons & Beilock (2012a) found that the simple anticipation of mathematical calculation is enough to engage neural networks related to the expectation of physical harm.

Because worry impairs executive processing (Eysenck, 1992; Morris, Davis, & Hutchings, 1981), the theory claims that anxiety should be most disruptive in tasks requiring the central executive's assistance. This claim seems to be supported by the present investigation; suggesting reason for why both the high and low math anxious individuals were found to incur significant dual task costs while under concurrent central executive load, but only the high anxious exhibited costs during concurrent visuospatial load. Recall that the task variant administered in this study required participants to compare one digit presented on the screen with the magnitude of the standard that was continually held in working memory. The dual task cost analysis of comparison RT indicated that both the low and high math anxious participants experienced similar levels of processing interference when confronted with a central executive dual task setting. This result is interpreted to reflect the interference experienced in switching the focus of attention between the stored magnitude representation and the digit presented on the screen. Importantly, Eysenck et al., (2007) describes that a task does not need to be overwhelmingly working memory intensive to observe anxiety group differences.

Given the demonstration of executive attention requirements in comparison processes, it stands to reason that high math anxious individuals may still suffer from executive impairments due to worry associated with anxiety even when the central executive is not extrinsically taxed. With this assumption in mind, the high math anxious would still experience the imbalance in attentional system prioritization that favors the bottom-up processing of threat, which would neglect the task demands of communication between the stored magnitude and stimulus magnitude for comparison. Given frameworks within math cognition that describe the storage of magnitude in visual mental codes (e.g., Walsh, 2003), it appears that the high math anxious disadvantage in the VSSP dual task setting would reflect, on top of attentional system impairments, the inability to efficiently manipulate the standard's maintained magnitude for use in each trial's comparison. Note that this would not occur for the low math anxious participants because the task is not appreciably working memory demanding, and concurrent visuospatial processing would not interrupt the crucial function of controlling processing to favor the attentional set of the task (comparison). This interpretation further suggests that the magnitudes compared may not be relevant in the high math anxious participants' impaired performance, which is further reflected in the present study with the absence of the math anxiety x numerical distance interaction. Importantly, this stands in contradiction to the effect reported by Maloney et al. (2011). This discrepancy will be further explored later in the discussion.

Importantly, the Attentional Control Theory does appear to (at least partially) accommodate the effects obtained in the enumeration task as well. Recall that the results obtained revealed that mathematics anxiety was related to the performance recorded, however the effect was isolated to the counting range of the task. Similar results were found by Maloney et al. (2010).

Enumeration processes, especially those of subitizing, are reliant on stimulus-driven attention (Ansari et al., 2007; Egeth, Leonard, & Palomares, 2008; Olivers & Watson, 2008; Pincham & Szűcs, 2012; Poiese, Spalek, & Di Lollo, 2008; Vuokko, Niemivirta, & Helenius, 2013; Xu & Liu, 2008). Importantly, neurological evidence suggests that the attentional systems outlined by Corbetta and Schulman (2002) and utilized in the Attentional Control Theory are also implicated in the completion of enumeration tasks. For example, Ansari et al. (2007) had participants compare the magnitudes of either symbolic (Arabic digits) or non-symbolic (collections of objects) stimuli whose values were either subitized (1-4 in total) or estimated (stimuli of 10, 20, 30, and 40 in total). Importantly, brain scans were recorded during task completion to allow for an examination of the neural correlates associated with the processes of subitization and estimation. The results obtained from functional magnetic resonance imaging (fMRI) revealed that the right temporo-parietal junction (rTPJ) was more strongly engaged during the comparison of two subitizeable displays of non-symbolic magnitude than in the comparison of estimated quantities. Importantly, the TPJ is implicated in the bottom-up attentional system described here (Corbetta & Schulman, 2002). Most interesting was that this region was actually suppressed during the comparison of estimated quantities, and the authors found that the rate of suppression observed correlated with the speed of the comparison of the two stimuli.

Ansari et al. reasoned that the activation and suppression of the rTPJ suggest the efficient employment of the stimulus-driven and goal-oriented systems of attention. The explanation offered was that stimulus-driven attention (rTPJ) is needed in the evaluation of subitizeable sets, as the exact quantity must be known for accurate comparison. By contrast, this region is not needed in the comparison of estimated sets because the identification of precise stimulus features does not efficiently contribute to the accurate comparison of uncounted sets of objects. The correlation between the RT of comparison and the suppression of this area further supported these claims. The authors reasoned that suppression of the rTPJ would be beneficial to the participants in estimation and that more efficient suppression of the stimulus-driven attentional system would help to maximally engage the top-down processing of the large sets of objects to guide accurate comparisons. Of note were results showing that these patterns were not implicated in the comparison of symbolic magnitudes, suggesting that the activations described did not reflect the appreciation of the numerical qualities of the task or comparison processing.

With regard to the relationship between subitizing and counting mechanisms as tested in the present study, Vuokko et al. (2013) tested participants in a magnetoencephylography (MEG) study investigating the processes employed during enumeration. Their results demonstrated that posterior temporo-parietal areas reached peak activation during subitizing. By contrast, they also found that activation in frontal regions presumed to be related to attentional control grew as enumeration extended beyond the subitizing range.

These two neurological studies suggest that the two attentional systems of interest are intimately linked to the processes employed by enumeration mechanisms. As such, the implications of the Attentional Control Theory can be applied to the present study's results. Recall that differences in math anxiety groups were obtained within the counting range of the task. Given the evidence that attentional control is more strongly implicated in set sizes that extend beyond the subitizing range, it is offered here that the high math anxious disadvantage is the result of the imbalance of attentional systems described by Eysenck et al. (2007). That is, highly math anxious participants were likely unable to disengage focus of bottom-up attention as efficiently as their low anxious peers, thus impairing the attentional control needed to switch attentional focus for efficient enumeration.

With these ideas in mind, it is important to identify a need or use of top-down processing within the counting range to help substantiate this proposed impairment in the high math anxious participants. Such evidence is potentially provided in what is known as the end effect (e.g., Trick, 2008). Essentially, the end effect is reflected in the latencies of participants' performance within the counting range, which is characterized by a steadily increasing RT slope as the number of enumerated items increases. This characterization, however, does not typically hold for the final and largest set size sampled; instead, latencies for this largest quantity are typically as fast, if not slightly faster than the set size just prior in total. Trick (2008) described the effect as reflecting participants' ability to infer the numerical scope of the task and form accurate guessing strategies of response when large numbers of items are to be enumerated (Mandler & Shebo, 1982). Thus, the participant can merely infer that the largest set to be enumerated is nine, for example, and can accurately guess that a large set consists of nine objects once enumeration of seven or eight is accomplished with more objects remaining. Because this effect implies the use of a cognitive strategy in place of explicit enumeration, researchers commonly exclude the largest set size in analysis of performance (e.g., Trick & Pylyshyn, 1993).

The reasoning from the Attentional Control Theory would suggest that, if highly math anxious participants suffer from an imbalance of attentional system engagement that favors focus on the anxiety experienced (as opposed to goal-directed attention), then the end effect should be absent in their latencies, as explicit counting requires the use of efficient attentional control (e.g., Vuokko et al., 2013). Indeed, inspection of *Figure 10* from this study shows just that. Recall that the secondary task x set size x math anxiety interaction revealed overall slower enumeration in the high math anxious participants as compared to the low math anxious, and that the high math anxious individuals were especially impaired in the VSSP dual task setting. In comparison to the low math anxious, it can now be seen that the latency associated with eight objects (the largest in the task) in the VSSP task is substantially larger than those in the other secondary task settings, as well as in comparison to the latencies corresponding to the set size of seven recorded in all settings. From these results, it would appear that the heightened priority placed on the stimulus-driven attentional system impaired the use of the top-down end effect strategy when additional visuospatial resources were in demand.

These results are promising and suggest the appropriateness of interpreting low level differences between math anxiety groups in the context of the Attentional Control Theory (Eysenck et al., 2007). To summarize, the theory asserts that the presence of anxiety during cognitive testing results in a misallocation of attentional resources that favor focus on the source of threat and experience of worry and reduces attentional focus on goal-oriented attentional mechanisms. These findings are substantiated by reports indicating that highly anxious individuals demonstrate preferential engagement in threat-inducing stimuli (e.g., Williams, Mathews, & MacLeod, 1996) and lack the ability to efficiently inhibit distracting information (Hopko et al., 1998). Importantly, the Attentional Control Theory is an extension of the Processing Efficiency Theory (Eysenck & Calvo, 1992) that served as the basis for the development of mathematics anxiety theory. The present work applied these extended ideas to the construct of mathematics anxiety to support results indicating that high math anxious individuals were impaired in tasks that are not particularly working memory demanding, but still require efficient attentional processing.

Despite these important extensions of the math anxiety construct, however, important concerns in the present experiments have not yet been resolved. More specifically, the finding that the difference between high and low math anxious participants in the counting range of enumeration was mediated by mathematical achievement needs to be addressed. As will be described in the following section, the implications of the present discussion provide for future directions to be explored within the proposed framework.

Future Directions

The discussion provided here presents a convincing account that the math anxiety differences found in the number comparison and enumeration tasks are related to the interaction between attentional systems during problem solving. Future studies should continue to replicate these effects, and explore the breadth of the implications drawn here. Of interest is the larger possibility that attentional mechanisms may underlie the development of mathematics anxiety in the first place, as the mathematical mechanisms tested here are honed early in development and are thought to form the basis for later mathematical achievement and success (Anobile, Stievano, & Burr, 2013; DeSmedt, Verschaffel, & Ghesquière, 2009; Landerl, Bevan, & Butterworth, 2004).

In a related idea for future research, the field needs to explore the possibility that such low level attentional deficits are in any way related to similar effects observed in developmental studies investigating the relationship between mathematical competency and attentional function (Anobile et al., 2013; Steele, Karmiloff-Smith, Cornish, & Scerif, 2012). As an example, Steele et al., (2012) tested children's ability to complete three tasks tapping into different aspects of attentional processing. Their results showed that tests of sustained and selective attention produced behavior that was predictive of math achievement one year later, whereas a test of executive attention (spatial conflict) only predicted concurrent achievement. Further, Anobile et al., (2013) found that the relationship between sustained attention and mathematical achievement were maintained after controlling for variables such as the child's age, gender, and non-verbal ability. Importantly, the performance in the object tracking task did not relate to the reading ability of the same children. These ideas were considered in the present experiment with the finding that differences between the high and low math anxious in the counting range of enumeration were found to be mediated by the mathematical achievement of the participants. Below is a discussion of this result in the context of the attentional mechanisms explained here.

Recall that the math cognition literature reports robust negative relationships between math anxiety and achievement in both children (Ma, 1999) and adults (Hebree, 1990). Despite this important relationship, however, the field has taken few steps to examine the mechanisms underlying this connection. What is known is that those individuals who report high levels of math anxiety tend to perform worse in standardized exams and laboratory tasks testing mathematical competency. Further, high math anxious students report lower self-efficacy in the domain, express lower motivation to excel in its principles, and tend to avoid advanced math courses in their educational career.

As stated previously, enumeration, especially subitizing, has recently been established to primarily rely on visual attention (Egeth et al., 2008; Olivers & Watson, 2008; Pincham & Szűcs, 2012; Poiese et al., 2008; Xu & Liu, 2008). For example, Egeth et al. (2008) found that the ability to correctly identify the total of a subitizeable set size was greatly impaired if the set size was presented within the attentional blink. The attentional blink is a phenomenon whereby visual attention is exhausted after the identification of one target in a stream of visual information, leaving the individual with little attentional resources to identify a second target if it is presented within a small time frame subsequent to the first target (Broadbent & Broadbent, 1987).

These points are important to consider in the context of the present enumeration experiment results, as high anxious individuals are believed to be biased toward the stimulus-driven attentional system and engage in threat. More importantly, however, is developmental math cognition literature implicating efficient visual attention in concurrent and longitudinal success in mathematics (Anobile et al., 2013; Steele et al, 2012). These results suggest that maintaining and selectively allocating attentional resources are fundamental processes supporting growth in mathematical understanding. Because early math competency is believed to strongly predict future math achievement, it stands to reason that early deficits in attentional processing (and its connection to math achievement) would persist into adulthood, and may influence adults' performance in low-level tasks such as those administered in the present study. Thus, it is plausible that those who reported higher levels of math anxiety and also exhibited poor mathematical achievement may suffer from the over prioritization of stimulus-driven attention which may be faulty to begin with in those who are low achieving.

In an attempt to further substantiate the need to explore the relationships between math achievement, math anxiety, and attention, the subitizing results from Experiment 2 were revisited to examine the possibility that math achievement, which mediated the relationship between math anxiety and counting performance, would also relate to the fast and accurate enumeration of small set sizes. Recall that the DTC analyses from this experiment showed larger costs to processing in the subitizing range as compared to the counting range, suggesting that the attentional resources were taxed in the context of dual task processing. Thus, it was predicted that the low achieving participants would be slower than their more highly achieving peers to subitize in a 3 (secondary task) x 3 (working memory load) x 3 (set sizes 1-3) x 2 (math achievement group) ANOVA. Critically, the results revealed that the low achieving individuals in the sample (M = 996ms) were significantly slower to subitize than their more highly achieving peers (M = 821ms), F (1, 46) = 7.20, p = .01, η_p^2 = .14. Math achievement did not interact with the other factors in the design. Thus, this result supports the possibility that the math anxiety x math achievement interaction is a critical factor in the performance profiles obtained in this task, and that it is potentially the altered attentional prioritization of high math anxiety and attentional deficits of the low math ability that explains the effects reported here and in the literature (Maloney, 2010).

The implication from this result is that the math anxiety x numerical distance interactions reported in Maloney et al. that were not found in the present study might be due to the sampling method differences between the two studies. To be sure, the authors report recruiting participants from the top and bottom 25% of the math anxiety population. By contrast, the present study recruited participants without prior knowledge of the individuals' math anxiety scores and anxiety groups were determined by sample median split. It is argued that, given the math anxiety/math achievement relationships outlined here and elsewhere (Hembree, 1990; Ma, 1999), that the steeper numerical distance effect observed in the high math anxious participants may relate more strongly to the poorer numerical competency of their high math anxiety group than effects related to the attentional concerns raised in this work. Further, it is suggested that extreme sampling of individual difference groups may be misleading and should be avoided in future research addressing the relationships between math anxiety and math achievement in low level tasks.

APPENDIX: FIGURES

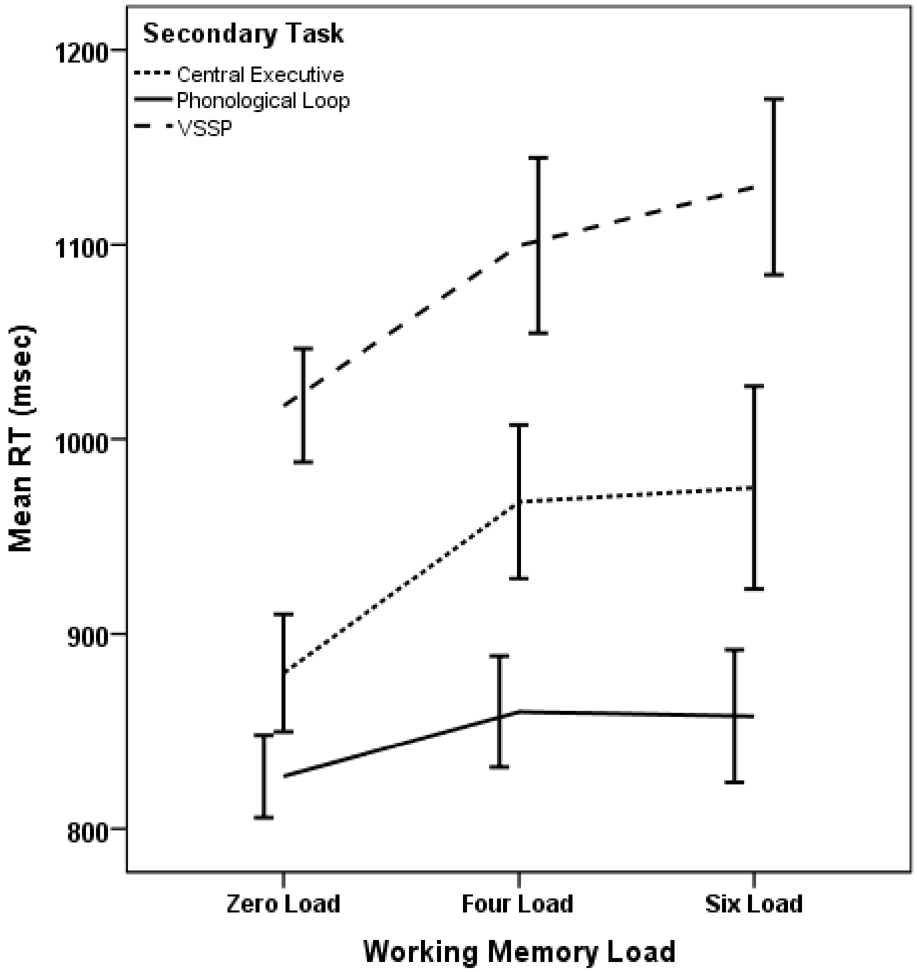

Figure 1. Secondary task x working memory load interaction obtained in the primary task RT analysis of Experiment 1. Error bars represent 95% confidence intervals.

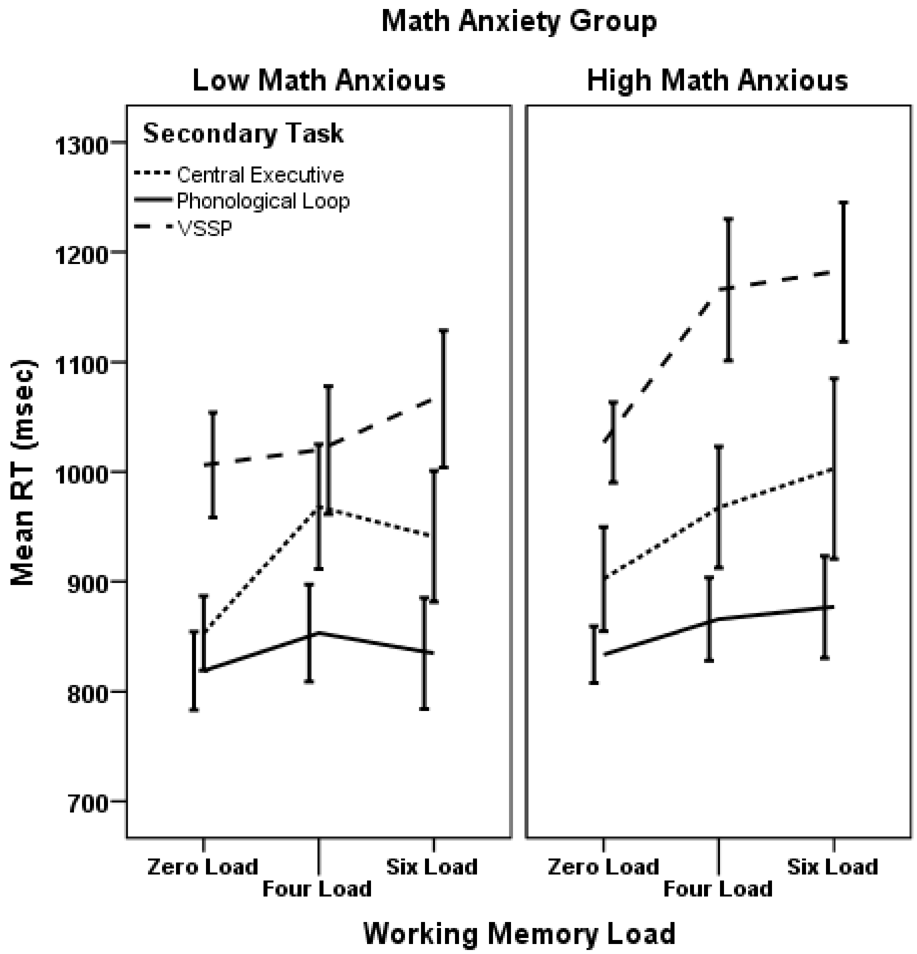

Figure 2. Secondary task x working memory load x math anxiety group interaction from the primary task RT analyses in Experiment 1. The figure is paneled by math anxiety group. Error bars represent 95% confidence intervals.

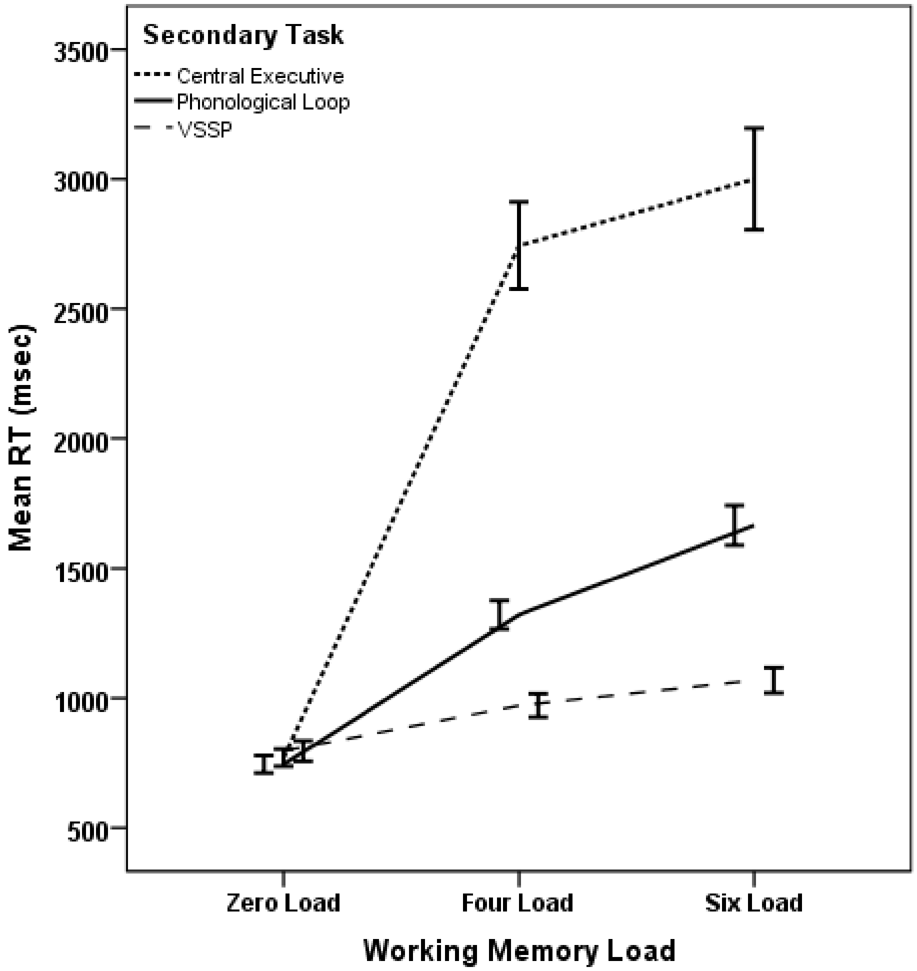

Figure 3. Secondary task x working memory load interaction from the secondary task RT analyses in Experiment 1. Error bars represent 95% confidence intervals.

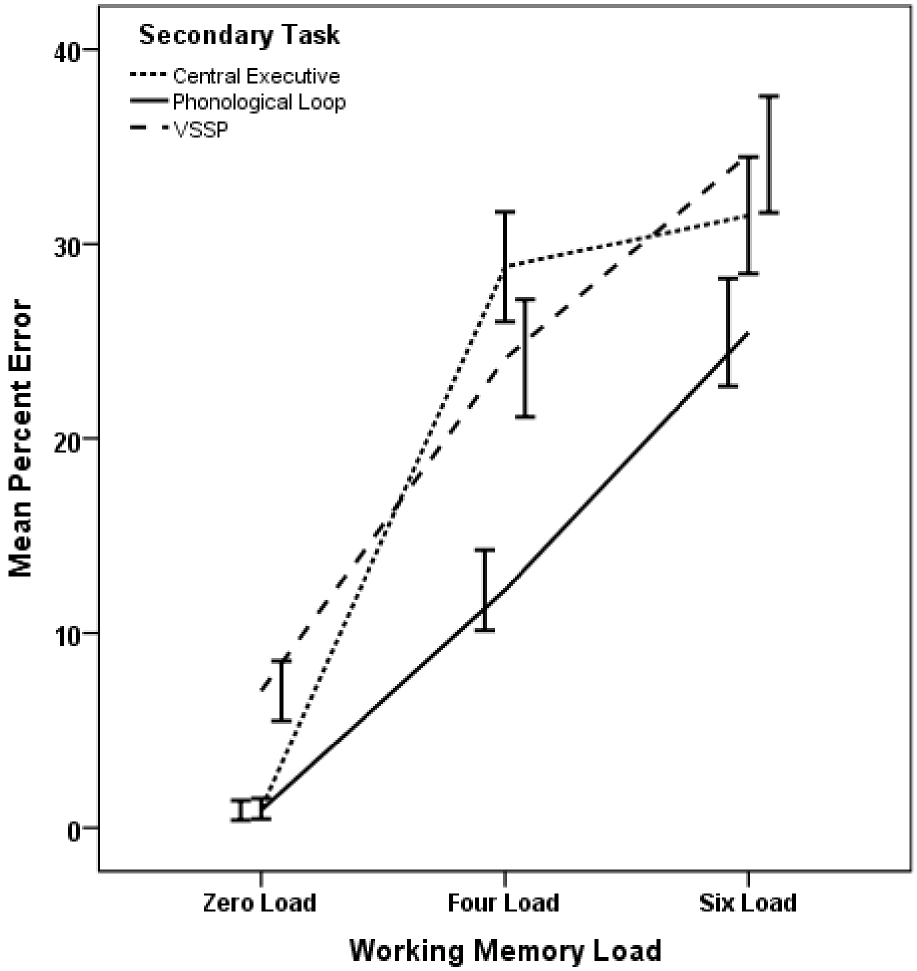

Figure 4. The Secondary task x working memory load interaction from the secondary task percent error analyses in Experiment 1. Error bars represent 95% confidence intervals.

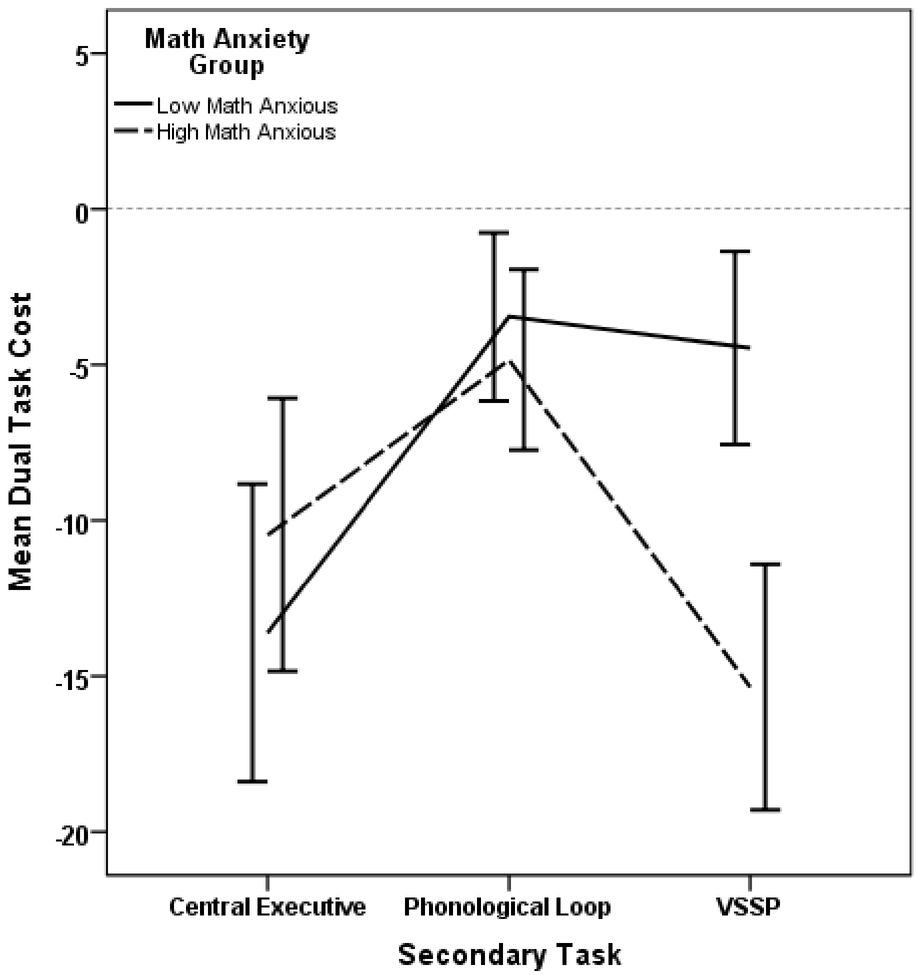

Figure 5. Secondary task x math anxiety group interaction from the primary task dual task cost analyses in Experiment 1. Error bars represent 95% confidence intervals.

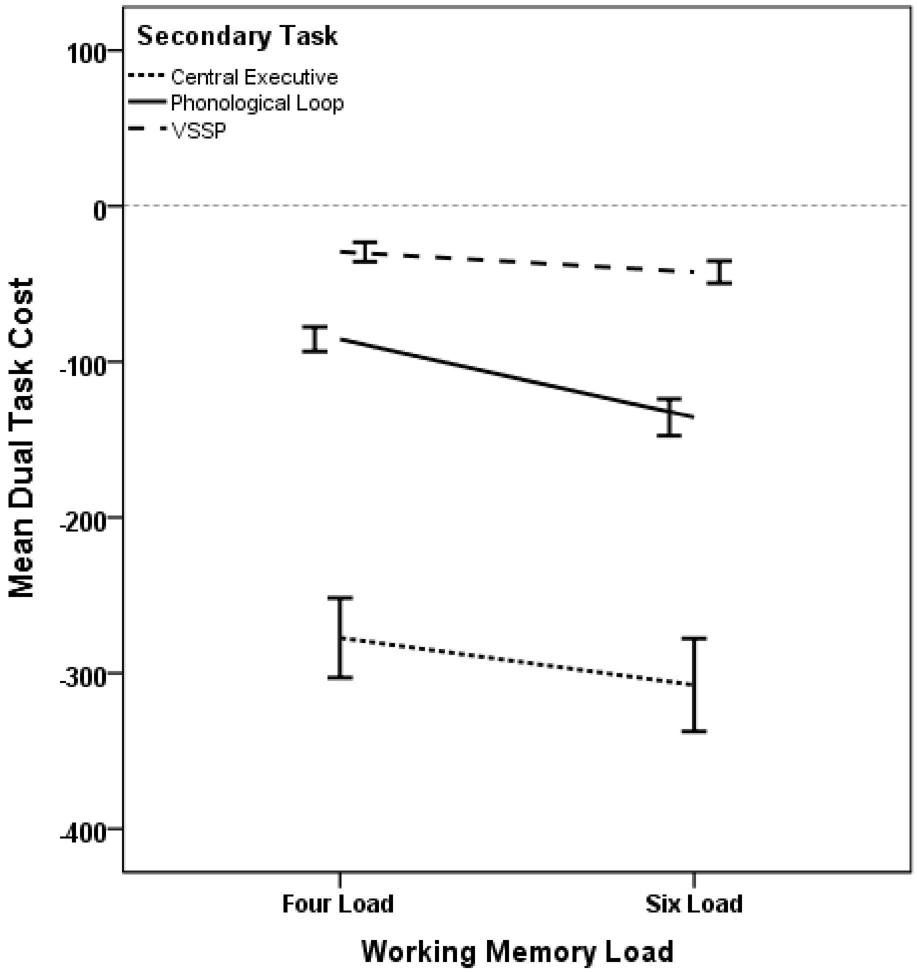

Figure 6. Secondary task x working memory load interaction from the secondary task dual task cost analyses in Experiment 1. Error bars represent 95% confidence intervals.

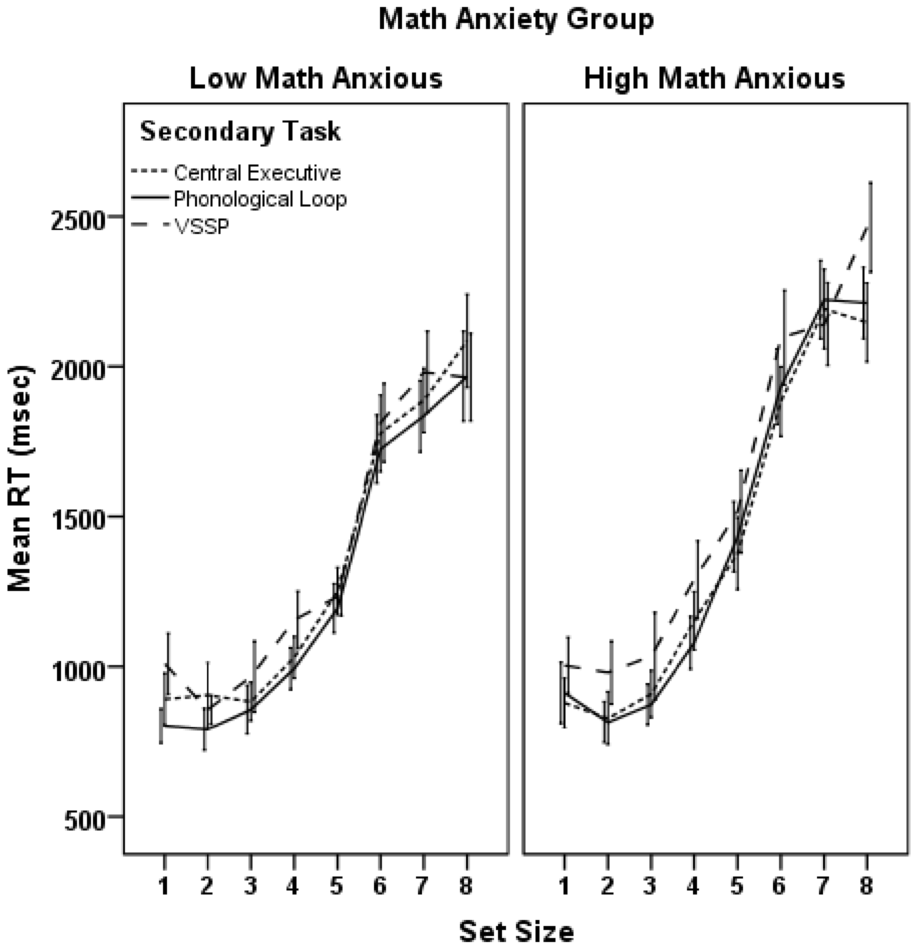

Figure 7. Secondary task x set size x math anxiety group interaction from the primary task RT analyses in Experiment 2. The figure is paneled by math anxiety group. Error bars represent 95% confidence intervals.

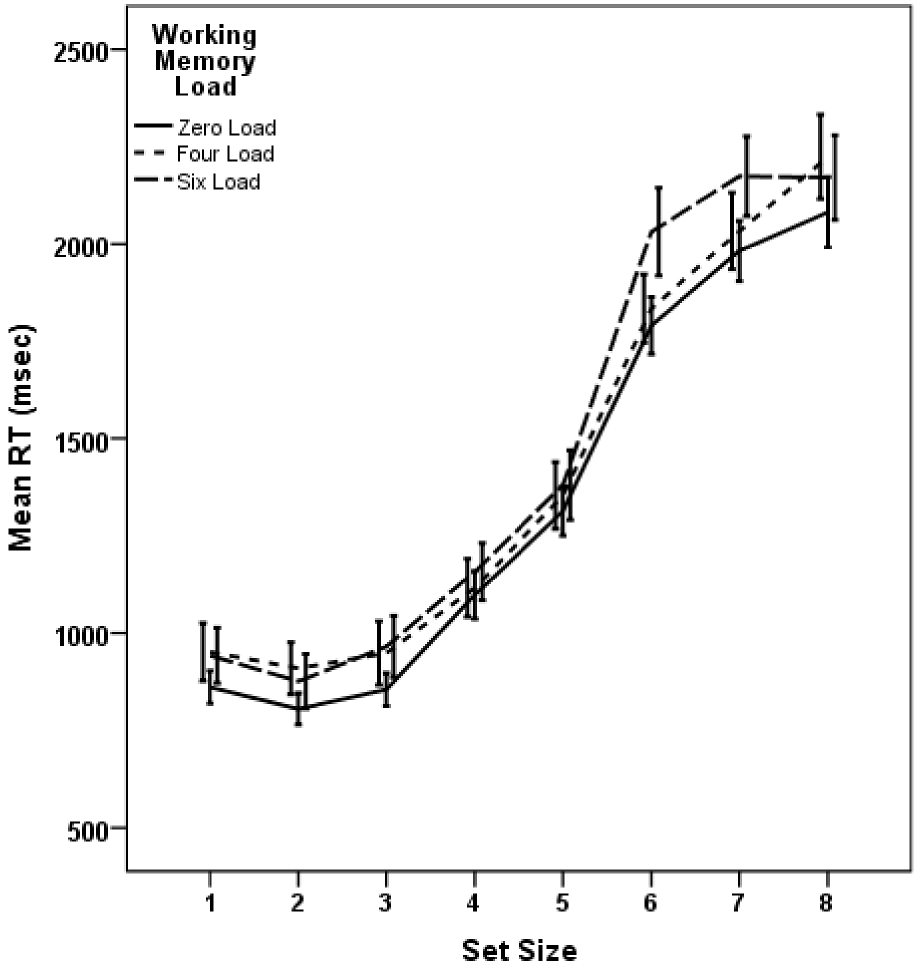

Figure 8. Working memory load x set size interaction from the primary task RT analyses in Experiment 2. Error bars represent 95% confidence intervals.

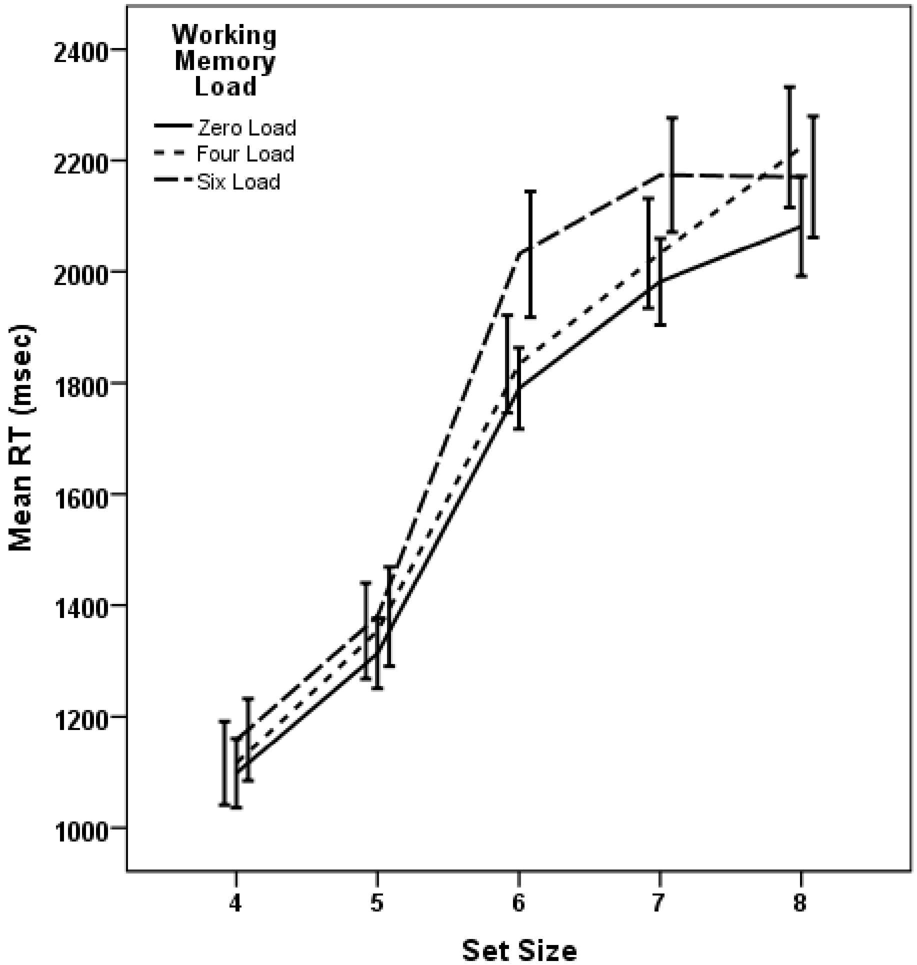

Figure 9. Working memory load x set size interaction from the primary task RT analyses within the counting range of enumeration in Experiment 2. Error bars represent 95% confidence intervals.

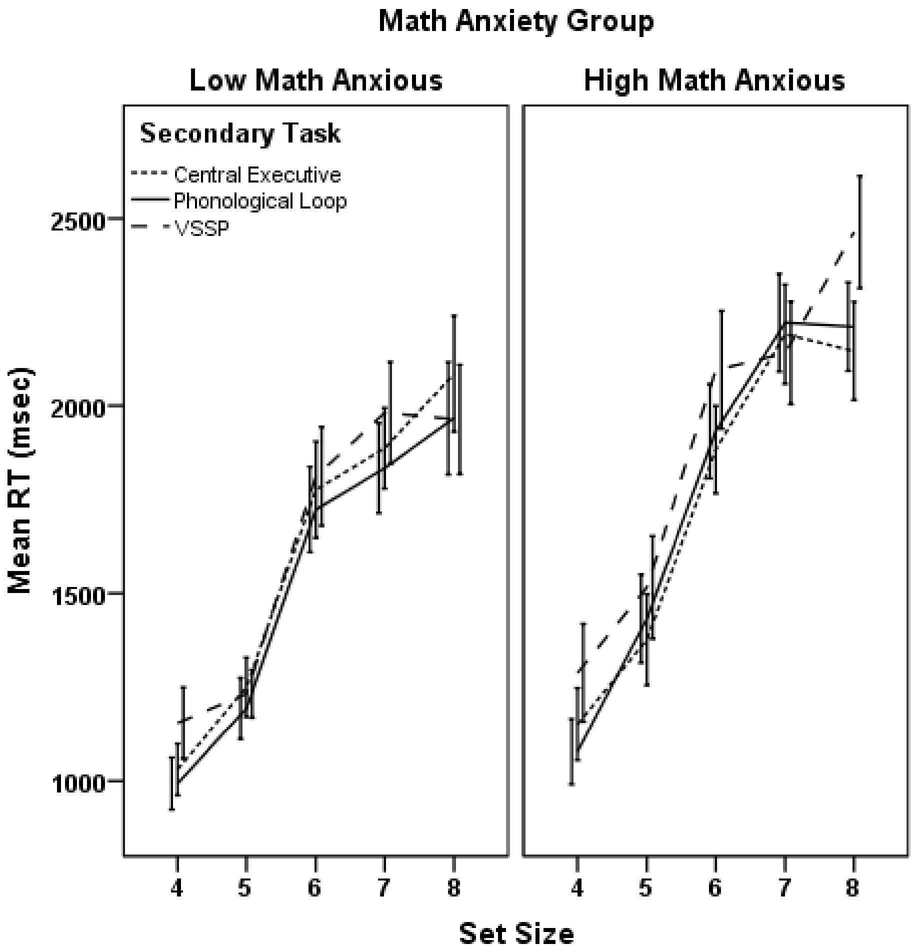

Figure 10. Secondary task x set size x math anxiety group interaction from the primary task RT analyses within the counting range in Experiment 2. The figure is paneled by math anxiety group. Error bars represent 95% confidence intervals.

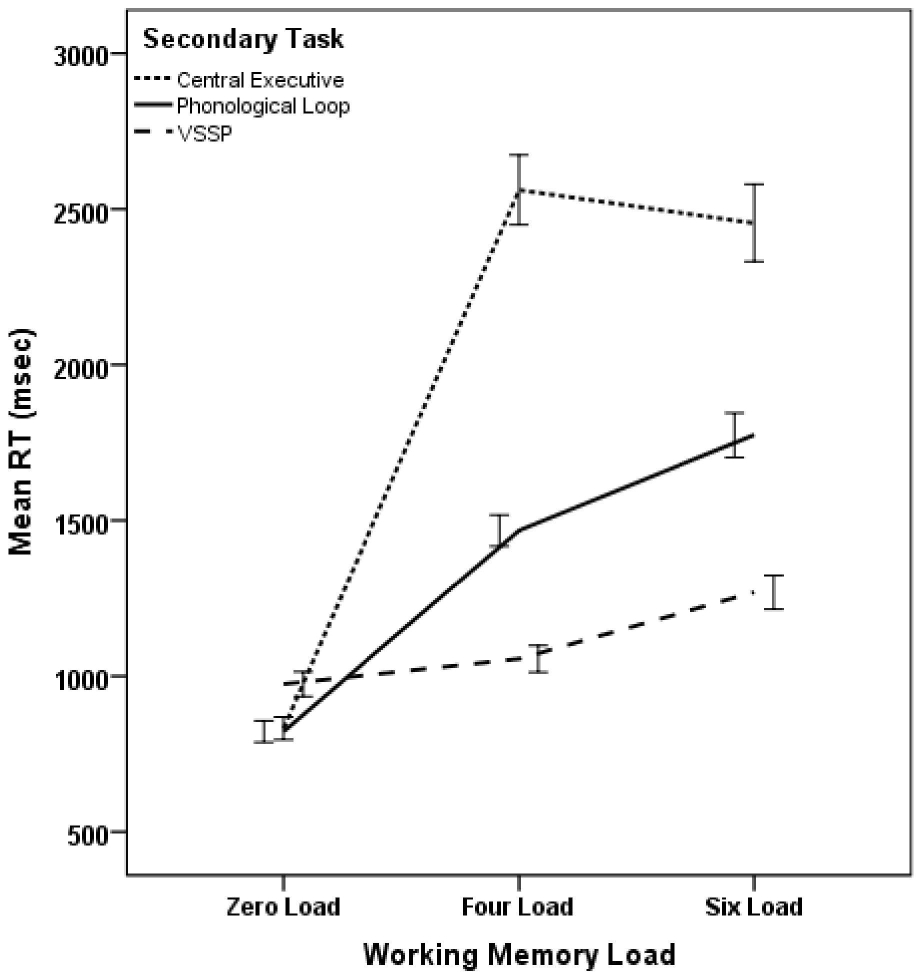

Figure 11. Secondary task x working memory load interaction from the secondary task RT analyses in Experiment 2. Error bars represent 95% confidence intervals.

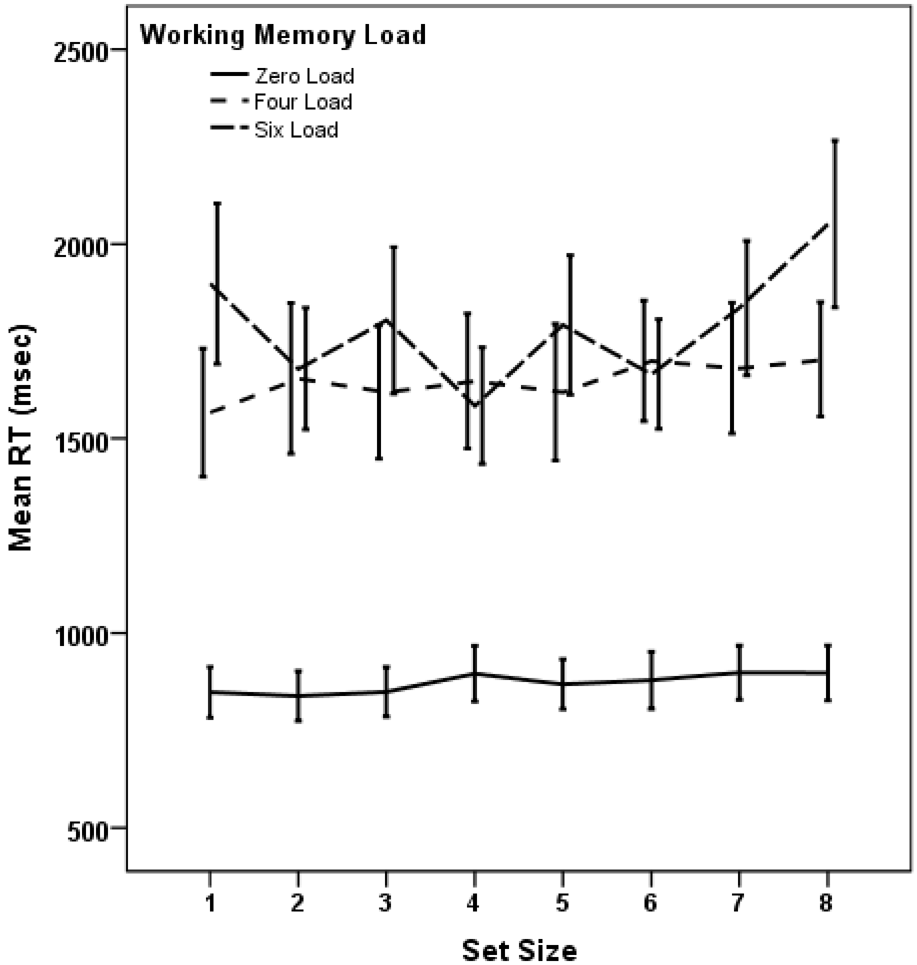

Figure 12. Working memory load x set size interaction from the secondary task RT analyses in Experiment 2. Error bars represent 95% confidence intervals.

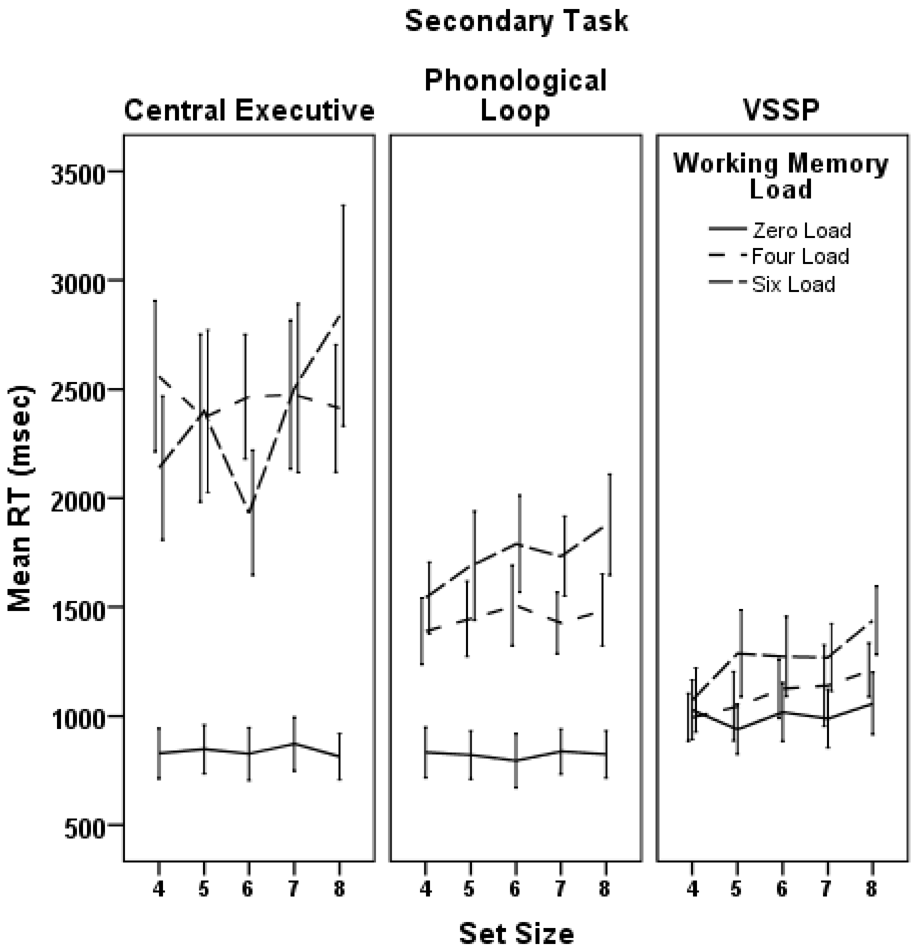

Figure 13. Secondary task x working memory load x set size interaction from the secondary task RT analyses in Experiment 2. The figure is paneled by secondary task. Error bars represent 95% confidence intervals.

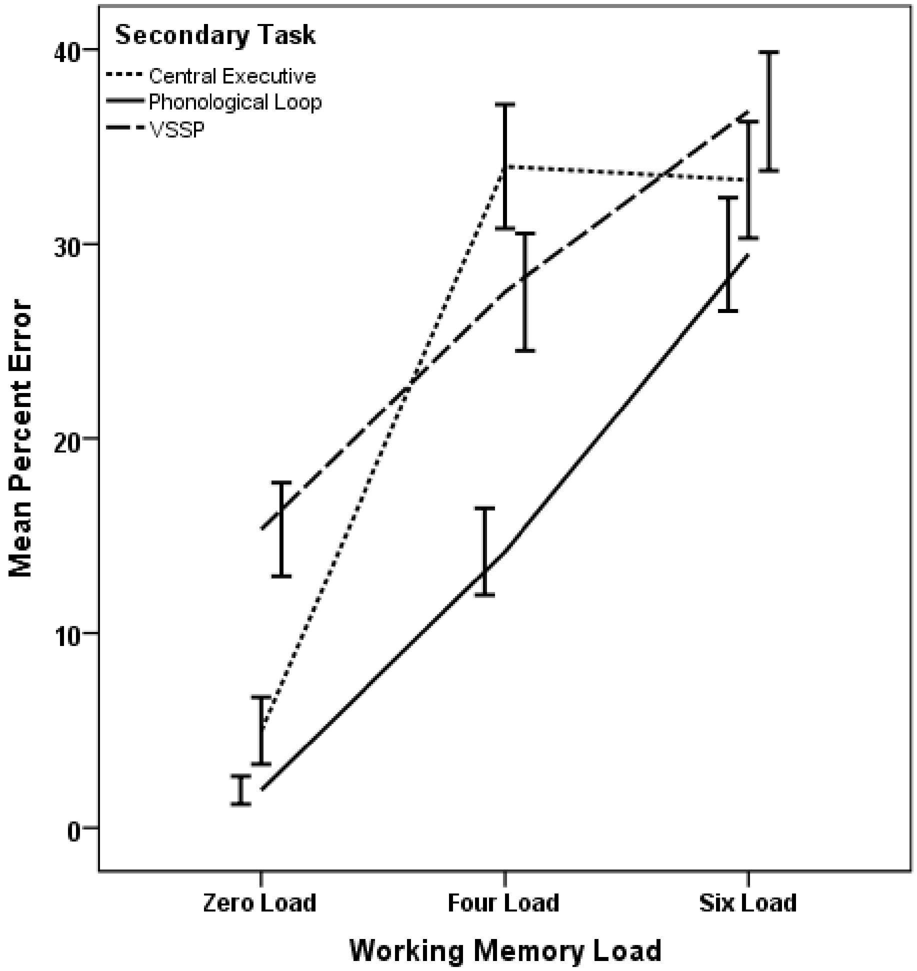

Figure 14. Secondary task x working memory load interaction from the secondary task percent error analyses in Experiment 2. Error bars represent 95% confidence intervals.

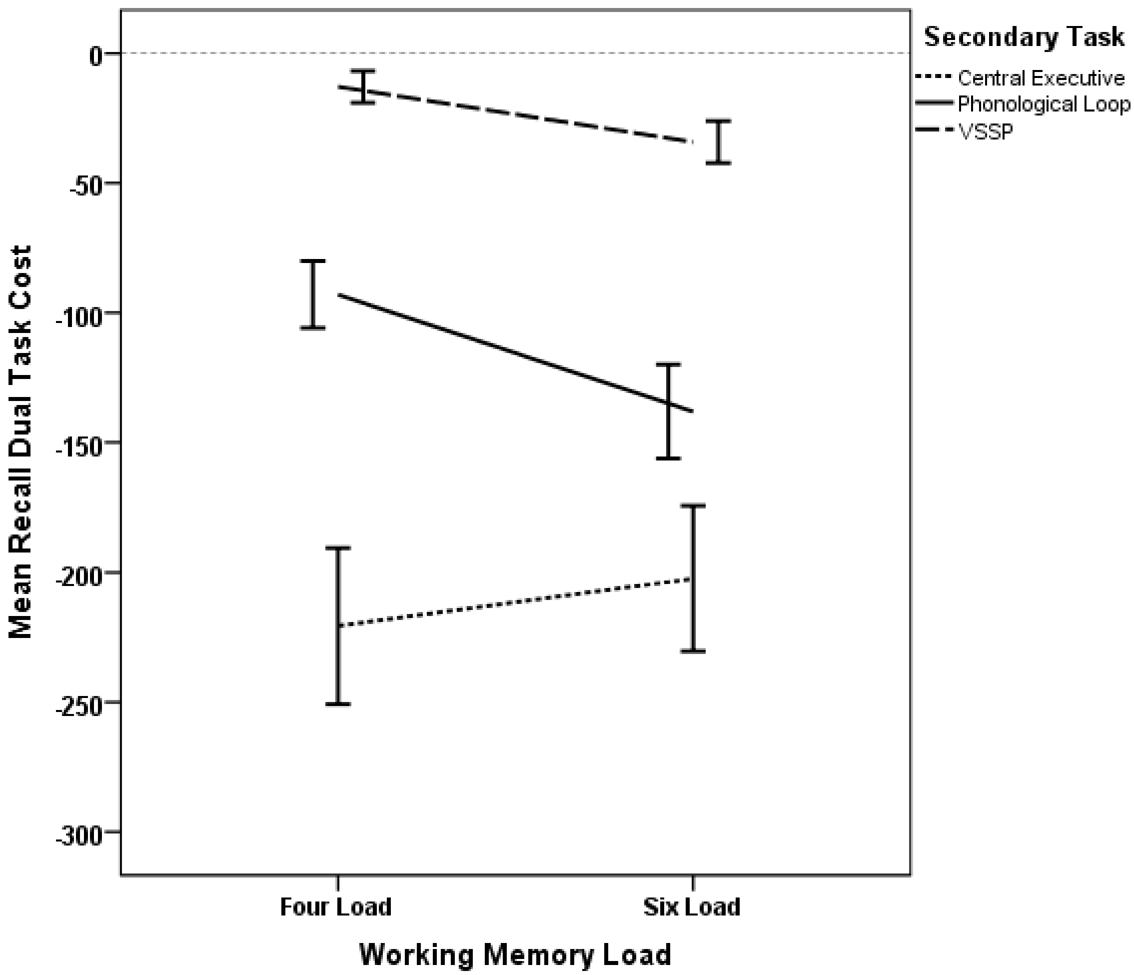

Figure 15. Secondary task x working memory load interaction from the secondary task dual task cost analyses in Experiment 2. Error bars represent 95% confidence intervals.

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CURRICULUM VITAE

Alex M. Moore

Department of Psychology

University of Nevada, Las Vegas

4505 S. Maryland Pkwy, Box 455030

Las Vegas, NV 89154-5030

Email: moore.alex85@gmail.com

Education

B.A. (May, 2007), Southern Illinois University Edwardsville.

Majors: Psychology and Spanish Language.

M.A. (August, 2011), University of Nevada Las Vegas, Experimental Psychology, Cognitive Emphasis.

Ph.D. (May, 2014) University of Nevada Las Vegas, Experimental Psychology, Cognitive Emphasis.

Positions Held

(Pre-doctoral)

Math Cognition Laboratory Manager, August 2007-August 2008 (Under Dr. Mark Ashcraft). Worked as the manager for the FRIAS Project—a longitudinal study examining the number sense and mathematical proficiency of children 1st through 5th grades. Duties included traveling to a local elementary school for data collection, managing research assistants in their work, contacting and managing correspondence with school faculty, data entry and analysis. Subsequent duties include write-up for publication.

(During doctoral studies)

Graduate Assistant and Doctoral Student, 2008-2014

Doctoral Project: Dual task interference in low-level abilities: The role of working memory and effects of mathematics anxiety.

President, Experimental Student Committee, Fall 2010-Spring 2011.

Cognitive Emphasis Representative, Experimental Student Committee, Fall 2011-Spring 2012

Publications

Ashcraft, M. H. & **Moore, A. M.** (2009)*. Mathematics anxiety and the affective drop in performance. *Journal of Psychoeducational Assessment*, *27*, 197-205.

*Awarded the Sage 2010 Most-Downloaded Article Achievement (from the Journal of Psychoeducational Assessment).

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Moore, A.M., McAuley, A.J., Allred, G.A., & Ashcraft, M.H. (in press). Mathematics Anxiety, Working Memory, and Mathematical Performance: The Triple Task Effect and the Affective Drop in Performance. To appear in S. Chinn (Ed.), *The International Handbook for Mathematical Difficulties and Dyscalculia*. Routledge.

Refereed Conference Presentations

Sturm, A., Galvin, K., **Moore, A.M.**, & Snead, M. (2007, May) Is it really just a game? Problem gambling, poker experience, poker skill, and anxiety during poker play. Poster presented at the Midwestern Psychological Association Conference, Chicago, IL.

Ashcraft, M.H. & **Moore, A.M.** (2009, April). Mathematical cognition in elementary children. Poster presented at the meetings of the Western Psychological Association, Portland, OR.

Children's and adults' number line estimates (with M.H. Ashcraft & R.T. Durette). Symposium presentation at the meetings of the Psychonomic Society, Boston, November, 2009.

Moore, A.M. & Ashcraft, M.H. (2010, May). Investigating the developmental math proficiency of children in a battery of math tasks. Poster presented at the meetings of the Association of Psychological Science, Boston, MA.

Moore, A.M. & Ashcraft, M.H. (2010, November) Number comparison in elementary students. Poster presented at the meetings of the Psychonomic Society, St. Louis, MO.

Moore, A.M. & Ashcraft, M.H. (2011, May) Influence of endpoint knowledge in dot enumeration. Poster presented at the meetings of the Association of Psychological Science, Washington, D.C.

Moore, A.M., Rudig, N.O., & Ashcraft, M.H. (2011, November). Calibrating adults' estimates in dot enumeration. Poster presented at The Psychonomic Society Conference, Seattle, WA.

Moore, A.M., & Ashcraft, M.H. (2012, June) Predicting the development of children's math performance. Poster presented at the Canadian Society for Brain, Behaviour, and Cognitive Science Conference, Kingston, ON, Canada.

Bies-Hernandez, N.J., Copeland, D.E., Rudig, N.O., **Moore, A.M.**, & Ashcraft, M.H. (2012, November). Examining the benefits of testing with mathematical learning. Poster presented at the meetings of the Psychonomic Society, Minneapolis, MN.

Ashcraft, M.H., Rudig, N.O., **Moore, A.M.**, & Carr, T.H. (2012, November). Attitudes about math and writing: Were you just "born" that way? Poster presented at the meetings of the Psychonomic Society, Minneapolis, MN.

Math anxiety, attitudes, beliefs, and performance (with M.H. Ashcraft & N.O. Rudig). Symposium presentation at the meetings of the Psychonomic Society, Minneapolis, November, 2012.

Teaching Experience

Course

Introductory Psychology	Fall 2010-Spring 2011
Research Methods in Psychology	Fall 2011-2014
Introduction to the Psychology Major	Fall 2013-2014

Clark County Public School System Professional Development Enrichment (March, 2012).

Selected among teaching graduate students to provide Psychology content enrichment to county high school teachers in the area of memory and cognition.

Professional Awards

Research Forum Outstanding Presentation Award ($160). Poster Presentation: **Moore, A. M.** & Ashcraft, M. H. (2011, May) Influence of endpoint knowledge in dot enumeration. UNLV Graduate and Professional Student Association Research Forum.

Research Forum Outstanding Presentation Award ($125). Poster Presentation: Ashcraft, M.H., Rudig, N.O., **Moore, A. M.**, Carr, T.H. (2013, March). Attitudes about math and writing: Were you just "born" that way? UNLV Graduate and Professional Student Association Research Forum.

UNLV Summer Session Scholarship ($2,000). 2013, May

Sterling Scholarship ($5,000). 2013, May

Ad-Hoc Reviews

Irish Journal of Psychology, 2012

Sage Open, 2012

Journal of Experimental Child Psychology, 2013

Professional References

Dr. Mark H. Ashcraft

Chair, Department of Psychology

University of Nevada Las Vegas

Phone: (702) 859-0175

Dr. David E. Copeland

Associate Professor of Psychology

University of Nevada Las Vegas

Phone: (702) 895-5213

Dr. Colleen M. Parks

Assistant Professor of Psychology

University of Nevada Las Vegas

Phone: (702) 895-0139