IS LUMOSITY AN EFFECTIVE BRAIN TRAINING PROGRAM?: A META-ANALYSIS OF THE EXISTING RESEARCH

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ABSTRACT

IS LUMOSITY AN EFFECTIVE BRAIN TRAINING PROGRAM?: A META-ANALYSIS OF THE EXISTING RESEARCH

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Working memory allows individuals to temporarily hold and manipulate information in their mind to complete tasks. It is a critical aspect of an individual's cognitive functioning as it impacts their ability to reason, solve problems, carry out multi-step directions, and perform academic task. Research has recently shown promising results for increasing working memory and other cognitive skills with computerized brain training. Lumosity is a computerized brain-training program that claimed to improve different aspects of cognitive functioning including working memory, attention, cognitive flexibility, and processing speed. It also claimed that individuals with specific health conditions could benefit from training with the program. Research examining the efficacy of the program has produced limited and inconsistent results. Lumos Labs, the parent company of Lumosity, was sued for making unsubstantiated claims about the program's effectiveness and benefits. The current study utilized a meta-analytical approach to examine four published, peer-reviewed articles that analyzed the effects of Lumosity on working memory, attention, cognitive flexibility, and processing speed. The results of the meta-analysis revealed a small effect on attention. There was no significant impact on working memory. A meta-analysis could not be conducted on cognitive flexibility and processing speed as there was only one study that examined each of these constructs.

CHAPTER ONE: INTRODUCTION

Working memory (WM) is a mental workspace where goal relevant information is temporarily stored and manipulated (Baddeley & Hitch, 1974; Morrison & Chien, 2010). The construct is fundamental to higher cognitive thinking and is an indicator of our potential or ability to learn (Alloway & Copello, 2013; Morrison & Chien, 2010). Research has shown individual differences in executive functioning and fluid intelligence are strongly predicted by the amount of information WM can hold (Engle, Tuholski, Laughlin & Conway, 1999).

The importance of working memory has been emphasized in previous research as it relates to certain reading and mathematics skills (Alloway & Copello, 2013). It also plays a critical role in one's daily functioning as it is essential to problem solving, following multistep directions, and reasoning (Alloway & Copello, 2013; Baddeley & Hitch, 1974; Just & Carpenter, 1992). Many individuals with health conditions experience deficient working memory skills, such as those Mild Cognitive Impairment *(*Aurtenetxe et al., 2016*),* Attention Deficit/Hyperactivity Disorder (ADHD) (Dovis, Oord, Wiers, & Prins, 2013), and Alzheimer's disease (Stopford, Snowden, Thompson & Neary, 2007) to name a few.

Because working memory is activated during a wide array of activities, the malleability of this construct with regard to interventions is of great importance. There are many programs that have been marketed as being able to improve working memory and related functions. However, research examining and confirming the efficacy of these programs is limited despite their claims. The purpose of this study is to investigate the validity of claims made by a computerized brain-training program by looking at the effects its has on working memory and related skills across studies.

CHAPTER TWO: LITERATURE REVIEW

Definition of Working Memory

There is not a clear-cut definition of working memory, but most researchers think of it as a limited capacity storage system, where goal-relevant information is preserved and manipulated (Baddeley & Hitch, 1974; Just & Carpenter, 1992; Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005). An individuals working memory can only hold a certain amount of information for a small amount of time, and the information that it stores is manipulated to help complete the task at hand. Working memory is essential when performing complex tasks such as problem solving, reasoning, and learning (Baddeley & Hitch, 1974; Just & Carpenter, 1992). For example, when we are completing a problem-solving task like trying to solve a mathematical word problem, we use our working memory to hold key pieces of information from the problem we will need. Then, we pull skills that we have already learned about how to solve the problem from long-term memory and apply them. Likewise, when we are given a task requiring us to reason, like solving a puzzle, we use our working memory to compare and contrast information from the puzzle to find the piece that is missing. To help complete a task, we utilize our working memory when we manipulate and apply information we are given or we already have in memory (Alloway & Copello, 2013). For example, when following a map, we take the information from the map and manipulate it to fit the environment around us in order to get to the destination.

Although there is a relationship between them, working memory is different from short-term memory and long-term memory. Short-term memory is a storage system that temporarily holds small amounts of information for a brief period of time (Baddeley, 2010). We use our short-term memory when we remember a phone number or someone's name (Alloway &

Copello, 2013). Long-term memory is a storage system that holds memories from the past but also knowledge that an individual has accumulated over his or her lifetime. The concept of working memory was derived from the shortcomings of understanding cognitive processes with only short term and long-term memory.

The multi-store model of memory proposed by Atkinson and Shriffin (1968) was a unidimensional model that suggested short-term memory system acted as a working memory. However, this model was plagued with problems. While this model assumed the simple conservation of material in short term memory would ensure long term learning, we now know the degree of learning depends more on how we process information (Baddeley, 2010). For example, we know that when we are trying to learn or remember a certain word, it is much more efficient to encode the word based on it's meaning rather than process it through the mere repetition (Craik & Lockhart, 1972). Another problem for this unidimensional conceptualization of working memory arose after a study was conducted on an individual with a very specific short-term memory deficit (Shallice & Warrington, 1970; Baddeley, 2010). This individual only had a digit and letter span of two items or less. Although this patient presented with this deficit, he appeared to show normal, long-term learning. This finding went against the assumption that without an adequate short-term memory, information should be lost, and the ability to learn would be inhibited (Shallice & Warrington, 1970; Baddeley, 2010).

The limitations of earlier models prompted the introduction of a new model that abandoned idea of a unitary system and replaced it with a system comprised of three interacting subsystems or "slave systems" (Baddeley & Hitch, 1974). The first subsystem was the central executive. This system was considered to be an attentional controller and one we employ when we attend to information being processed and stored (Baddley, 2000). For example, when listening to someone speak, we are attending to the words he or she is saying so we can remember them, all while organizing them in a way that makes sense. Assisting this subsystem, were two short-term storage systems: the visuo-spatial sketchpad and the phonological loop. The visuospatial sketchpad is responsible for holding visual material and the phonological loop is responsible for holding verbal-acoustic material. For example, when an individual is completing a puzzle, the visuospatial sketchpad collects the information about the shape and size of the puzzle piece and uses working memory to figure out where it belongs in the puzzle. Likewise, when an individual encounters someone reading to him or her, the phonological loop collects and stores the information being spoken and uses working memory to make sense of what is being said. Not only was it assumed that these subsystems interacted, but that they did so by processing in a parallel fashion instead of a sequence of consecutive stages (Baddeley, 2010). This means that the individual must be attending to the visual or auditory information while the information is being simultaneously stored and processed.

The three-component model eventually developed into the multicomponent model, which offered a broader theoretical framework (Baddeley, 2010). This multicomponent model included links to long-term memory and a fourth component called the episodic buffer (Baddeley, 2010). Since long-term memory is comprised of knowledge and memories that has been accumulated over the years, we can use this component of our working memory to form associations between information that is already stored and new information that is being processed (Alloway & Copello, 2013). The episodic buffer provides a temporary store where chucks of information from the various components of working memory can interact with each other in a multidimensional code (Baddeley, 2010). For example, when someone is reading a passage out loud while you are following along in a book, the episodic buffer would combine both the auditory and visual information to make sense of the of the material to the reader.

Other models, such as Cowen's (2005) embedded processes model, have been offered as theoretical frameworks for working memory. However, the original model proposed by Baddeley and Hitch (1974) has been widely embraced in other research studies and has been considered the most accepted model over time (Asselen et al., 2006; Dovis et al., 2013; Egeland, Aarlien, & Saunes, 2013, Huntley & Howard, 2010).

Development of Working Memory

It has been well established that over the lifespan, the brain changes considerably. This is especially evident during childhood and adolescence, when the brain is growing and maturing rapidly (Tamnes et al., 2013). Research looking at the developmental trajectories of the brain has indicated the development of grey matter follows an inverted U-shaped trajectory over the lifespan (Goldstein, Allen, Thaler & Luther, 2014). This means, as we age, grey matter as a whole increases to a peak, and then steadily declines over time. However, grey matter density in various regions of the brain peaks at different rates. Grey matter density does not peak until later in adolescence for regions of the brain implicated during working memory-laden tasks, indicative that our working memory is not fully developed until around this time (Goldstein et al., 2014; Tamnes et al., 2013).

Behavioral studies of working memory development have reported that working memory increases from childhood to adulthood (Thomason et al., 2009). A study looking at the individual components of the Baddeley and Hitch (1974) model of working memory examined whether these components changed in capacity over childhood (Gathercole, Pickering, Ambridge & Wearing, 2004). Linear increases in performance for each component of the model, which includes the phonological loop, a central executive, and the visuospatial sketchpad, were apparent from 4 years of age to adolescence. This means as we age, the amount of information we can hold and process increases.

In addition to behavioral studies, neurological studies have also examined the development of working memory. One study looked at the variations in brain activity as working memory capacity develops in individuals ages 9 through 18 (Klingberg, Forssberg, & Westerberg, 2002). Brain activity was measured using functional magnetic resonance imaging during a visuospatial working memory task and a baseline task. During the visuospatial working memory task, individuals were presented with a sequence of 4x4 grids and asked to remember the location of a red circle that appeared on each grid. After a delay, the individuals were presented with another grid and asked to press a button if the circle was in the same location as any of the circles presented before the delay. During the baseline task, subjects were presented with a sequence of 4x4 grids and watched as a green circle appeared in any of the four corners of the grid. After a delay, subjects would press a button after the green circle appeared in the middle of the grid. The older children showed higher activation of certain brain regions that were used during the working memory task compared to the younger children (Klingberg et al., 2002). Brain activity in these brain regions was also significantly correlated to working memory capacity. This finding suggests as we age, increases in brain activity are due to the increases in working memory capacity.

Another study looked at the changes in functional brain circuitry that are associated with developmental improvements in visuospatial working memory in individuals 8 through 47 years of age (Scherf, Sweeney, & Luna, 2006). Results of the study showed that from childhood through adulthood, regions of the brain associated with visuospatial working memory change in the amount and location of activation (Scherf et al, 2006). In children, activity occurred primarily in ventromedial regions of the brain, whereas adolescence recruited activation from a more extensive network including the dorsal lateral prefrontal cortex, anterior cingulate, posterior parietal lobe, and anterior insula. In adulthood, activation became more localized and lateralized. Activation occurred in the left dorsal lateral prefrontal cortex, ventrolateral prefrontal cortex, and supramarginal gyrus. These findings suggest that as we get older, the brain regions implicated during working memory become more refined.

Neurological Basis of Working Memory

Multiple brain regions have been associated with the construct of working memory (Fletcher & Henson, 2001) although the level of activation in these areas may change from childhood to adulthood (Scherf et al., 2006). Two different theories that include domain specific and domain general functional networks, attempt to explain the patterns of brain activity related to working memory maintenance (Li, Christ, & Cowan, 2014).

The domain specific view of working memory anticipates that distinctive regions of the brain are implicated in the maintenance of stimuli from different domains of working memory (Li et al., 2014). Results of a study revealed that left hemisphere speech areas were activated during maintenance of verbal information and the right premotor cortex was activated during maintenance of spatial information (Smith & Jonides, 1999). This was evident on a verbal item recognition task, a verbal 2-back task, and a spatial-item recognition task. Maintenance of object information activated more ventral regions of the prefrontal cortex. This was evident on an object-item recognition task. Additional evidence to support the domain specific view comes from a study looking at the neural systems of spatial and object working memory maintenance (Courtney, Ungerleider, Keil, & Haxby, 1996). These neural systems were examined using positron emission tomography (PET) to measure regional cerebral blood flow. Significant increases in regional cerebral bloodflow to various regions of the brain including the fusiform, parahippocampal, inferior frontal, anterior cingulate cortices, the right thalamus, and midline cerebellum were more active during object working memory when compared to spatial working memory. This was evident during a face memory task. Regions of the brain that were implicated for spatial working memory included the superior and inferior parietal cortex and the superior frontal sulcus. This was evident during a location memory task (Courtney, et al., 1996).

In comparison to the domain specific view, the domain general view of working memory anticipates a common brain region(s) is consistently active during maintenance of stimuli regardless of the stimuli's domain, in addition to brain regions specific for individual domains. This means while certain regions of our brain are activated during specific types of task, other regions of our brain are activated regardless of the type of task. One study found that a region in the left intraparietal sulcus was activated during the maintenance of both visual and auditory stimuli in working memory (Cowan et al., 2011). A second study also provided evidence for common regions of the brain being activated during spatial and verbal working memory tasks (Chein, Moore, & Conway, 2011). Results showed that activity increased in the lateral prefrontal, anterior cingulate, and parietal cortices during verbal and spatial versions of a complex working memory span task. These increases in performance were evident during the encoding, maintenance, and coordination phase of the task. Furthermore, verbal and spatial recall was associated with activation of the anterior prefrontal and medial temporal regions of the brain (Chein et al., 2001). In summary, it makes sense that both the domain-specific and domain-general theories can both be true. These two different approaches suggest that although certain brain regions may only be implicated when maintaining specific types of information (domain-specific), many regions of the brain are connected through complex neural systems and share a common maintenance mechanism.

The modulatory effects of dopamine on working memory, specifically D1 and D2 receptors, have been studied extensively in humans; however, results have yielded inconsistent findings (Liggins, 2009). Some research has shown working memory was facilitated after D2 receptor agonists were administered (Luciana, Collins, & Depue, 1998; Luciana, Depue, & Arbisi, 1992). This means when a substance was injected that activated the D2 receptors, working memory was enabled. A different study found that working memory was impaired after D2 receptor antagonists were administered (Luciana & Collins, 1997). This means when a substance was injected that inhibited D2 from binding to its receptors, working memory was compromised. These finding suggests D2 plays an important role in facilitating working memory. Another study found that working memory was not affected at all by D2 receptor modulation (Muller, Cramon, & Pollmann, 1998). This finding suggests D2 plays a less important role in facilitating working memory. Overall, the evidence from the literature suggests the specific effects on working memory by D1 and D2 receptors remains debatable (Liggins, 2009).

Malleability of Working Memory

For many years it was believed that after a brief period in early development, our brain was a hard-wired machine with a fixed working memory capacity (Hardy, Drescher, Sarkar, Kellett, & Scanlon, 2011; Kelly, Foxe, & Garavan, 2006). Although the adult brain was thought to be resistant to change, research has shown that the organ is malleable and capable of improving its efficiency (Bryck & Fisher, 2012). Different interventions, including targeted training exercises, have been found to improve different aspects of cognitive functioning (Hardy et al., 2011).

Multiple studies have looked at the effects of interventions on improving working memory capacity (Blum, Jawad, Clarke & Power, 2011; Gray et al., 2012; Finn & McDonald, 2011; Gropper, Gotlieb, Kronitz, & Tannock, 2014; Kesler, Lacayo, & Jo, 2011; Mehta, Goodyer, & Sahakian, 2004; Mehta et al., 2000). Interventions involving medication and computerized brain training have been the primary areas investigated in the literature. Working memory training has been associated with improved performance on trained and non-trained tasks and on tasks considered complex (Klingberg, 2010). Neuroimaging studies have also supported the notion of brain training programs improving working memory capacity (Olesen, Westerberg, & Klingberg, 2004). Additional evidence regarding the effectiveness of these interventions will be discussed in the remainder of this paper.

Interventions for Deficits in Working Memory

Psychopharmacology

Attention Deficit/Hyperactivity Disorder (ADHD) is characterized by deficits in working memory, as well as other executive functions (Klingberg et al., 2005). Stimulant medication is often prescribed to treat individuals with this disorder. Of the children diagnosed with ADHD, it is estimated that at least 85% of these individuals are medicated with stimulants (Olfson, Gameroff, Marcus, & Jenson, 2003). Although stimulant medication has been shown to be an effective treatment for some of the symptoms of ADHD, findings are inconsistent regarding its effects on working memory (Egeland et al., 2013).

Methylphenidate, or MPH, is a common stimulant medication used to treat individuals with ADHD (Safer & Malever, 2000). One study looking at the effects of methylphenidate on working memory found the drug improved ADHD individuals' performance on a spatial working memory task. During this task, participants were asked to search through different colored boxes on a computer screen in order to find blue tokens. During the first trial of the test, participants were presented with three different colored boxes. Tokens were hidden one at a time behind the boxes and the participants were instructed once a token had been found behind a particular box, that box could not be used again to hide a token. Tokens that were found were placed in a designated column on the right side of the screen. This task was performed three more times using three colored boxes. The number of boxes increased to four, six and eight boxes throughout this test. The number of tokens hidden for each problem was equal to the number of boxes shown. Errors were documented when the participant returned to a box in which they had previously found a token. (Mehta et al., 2004). Other research utilizing this same type of task has found similar results (Mehta et al., 2000). Furthermore, this research showed that individuals with a lower working memory capacity benefitted more from medication than individuals with the best working memory.

In contrast, a study examining the effects of MPH on unmedicated boys with ADHD found that MPH did not improve performance on that type of working memory task. In this study, seventy-three boys were randomly assigned to either a placebo group or two different treatment groups. Spatial working memory was assessed at baseline and two weeks later. Each treatment group received a different dose of MPH at the second time of testing, which proved to have no effect on their working memory performance. (Rhodes, Coghill & Matthews, 2006). An additional study found similar results (Blum et al., 2011). The reason for the inconsistency between these findings is unclear, but one study found "MPH effects on working memory are selective and that they vary as a function of working memory component and measurement" (Bedard, Jain, Johnson, & Tannock, 2007, p. 872). Different aspects of working memory respond differently to this type of stimulant medication and the measures used to assess working memory performance vary in their responsiveness to this drug.

Although stimulant medication has been proven to be a beneficial treatment for the symptoms of ADHD, more specifically the ability to sustain attention (Turner, Blackwell, Dowson, McLean & Sahakian, 2005; Blum et al., 2011), not all parents want their children to be medicated. Due to a host of side effects (Pelham et al., 1990), a pharmacological approach may not be the best intervention for some children.

Computer-based Interventions

In the past few years, computerized brain training programs have become a popular tool for improving different cognitive abilities (Shipstead, Hicks & Engle, 2012). Programs such as *Cogmed* and *Lumosity* market their programs to a wide variety of people with the intention of improving executive functioning skills and preventing cognitive decline (Pearson Education, Inc., 2014; Lumos Labs, n.d.).

Cogmed working memory training. Cogmed working memory training program is marketed as a tool that can be used to improve attention, behavior, and the capacity to learn by increasing working memory capacity (Pearson Education, 2016). The rationale behind working memory training is that working memory is the fundamental function by which other cognitive abilities are driven (Shipstead et al., 2012). By improving working memory capacity, you are ultimately going to improve other executive functions (Pearson Education, Inc., 2014).

This program was designed by leading neuroscientist to be used by individual's ages 4 through 80 who are hindered by their poor working memory capacity. This can include individuals that suffer from variety of maladies such as attention deficits, learning disorders, brain injuries, strokes, and natural aging (Pearson Education, Inc., 2016). The intervention is completed online, five days a week, for five weeks. It includes 25 training sessions, with each session consisting of eight exercises and lasting around 30-45 minutes. A Cogmed Qualified Coach works with the user throughout the process and helps to ensure the trainings completion. The training can be completed at home, work, or in school and is offered in various regions around the world. Although Cogmed claims its intervention is “evidenced based”, findings on whether working memory capacity is improved, generalized, and then sustained over time after the implementation of the program are inconsistent.

One study by Dunning, Holmes, and Gathercole (2013) investigated whether children with low working memory would benefit from Cogmed and if the benefits would extend beyond standard working memory task. The study explored the effects of the program on working memory related classroom activities, other cognitive skills, and developing academic abilities (Dunning et al., 2013). Results showed an increase in performance on untrained verbal and visuospatial working memory tasks after the intervention was implemented. These tasks included the counting recall, listening recall, backward digit recall, Mr. X, spatial span, and odd-one-out subtests from the Automated Working Memory Assessment. The boost in performance was still partially evident after 12 months for verbal working memory. In contrast, there were no significant improvements in performance on working memory related classroom tasks or academic tasks. There was also no significant impact on visual scanning or the ability to sustain attention, which was measured by the Continuous Performance Test and the Visual Scanning subtest on the Delis-Kaplan Executive Function System.

Another study looked at the effects of Cogmed working memory training on children with ADHD (Klingberg et al., 2005). The results were similar to the aforementioned study in that treatment effects were apparent on measures of visuospatial working memory and verbal working memory post intervention. These measures included the span-board task from the

WAIS-RNI and Digit-span from the WISC-III. The beneficial effect the training had on visuospatial working memory remained at a follow-up assessment 3 months later. Additional treatment effects were observed for response inhibition, complex reasoning, and parent ratings of ADHD symptoms.

Shavelson (2008) examined the effects of the program on a group of middle school children in Northern California. Working memory was measured using two types of tasks: simple span task and dual task. Results showed that compared to the control group, performance of the participants in the experimental group significantly improved on the simple span tasks but not on the dual tasks. The experimental groups improvement on a measure of fluid intelligence was also not statistically significant when compared to the control group.

The effects of this brain-training program were also assessed in adolescents with learning disabilities and co-occuring ADHD (Gray et al., 2012). Significant improvements in working memory were made between pretest and posttest on measures that resembled the training activity. These criterion measures included a digit span task and a spatial span task. No transfer effects to other measures of working memory or attention were evidenced. These near and far transfer effects were assessed using multiple different measures including a CANTAB Spatial Working Memory task, The Working Memory Rating Scale, The D2 test of Attention, the Wide Range Achievement Test-4-Progress Monitoring Version, the Strengths and Weaknesses of ADHD-symptoms and Normal-behavior scale, and the IOWA Conners scale.

One study, looking at the effects of this training program on college students with ADHD or LD, showed promising results. Training effects were evident on a test of auditory-verbal working memory and a short-term visual spatial measure (Gropper et al., 2014). These test included the Digit Span subtest on the WAIS-IV and the Spatial Span task on the CANTAB.

After a two-month follow up, the effects on these aspects of working memory were still apparent. On self-report measures, including the Cognitive Failures Questionnaire and the Adult ADHD Self-Report Scale, participants in the working memory-training group reported fewer symptoms of ADHD and a decrease in cognitive failures in their everyday lives after they completed the program. Furthermore, the group continued to report fewer cognitive failures at follow- up. In contrast, results of this study failed to show near transfer effects to other measures of working memory, or far transfer effects to other aspects of cognitive functioning and academic performance.

Lumosity. Lumosity is another a computerized brain-training program where users play a variety of different games to exercise their brain. A team of scientists created Lumosity by taking multiple different neuropsychological tasks and converting them into games (Lumos Labs, n.d.). Unlike Cogmed, Lumosity is marketed to the lay-public and does not require a trained professional to supervise the administration of the program. The program offers over 40 games that aim to exercise and improve different areas of cognitive functioning including memory, attention, processing speed, mental flexibility, and problem solving. The program can be tailored to meet the needs of the user by allowing them to select which areas of functioning they desire to progress. Within each area, the user can then choose which aspects of that function they wish to target.

Lumosity is listed as one of "America's Most Promising Companies (2013)" by Forbes magazine (Forbes, 2013), has over 50 million users (Schatz, 2013), and had revenue of over $23 million in 2012. Although Lumosity has experienced great financial success, the Federal Trade Commission (FTC) recently filed a complaint against Lumos Labs, the parent company of Lumosity, for making unsupported claims about the efficacy of the program (Federal Trade

Commission [FTC], 2016). Lumos Lab allegedly claimed that scientific studies proved that training with the program would provide the following benefits: "(1) improve performance on everyday tasks, in school, at work, and in athletics; 2) delay age-related cognitive decline and protect against mild cognitive impairment, dementia, and Alzheimer's disease; and 3) reduce cognitive impairment associated with health conditions including stroke, traumatic brain injury, PTSD, ADHD, the side effects of chemotherapy, and Turner Syndrome" (FTC, 2016, para. 6). Lumos Labs was allowed to settle the deceptive advertising charges by paying $2 million dollars in redress and allowing subscribers to cancel their auto-renewal.

In comparison to Cogmed, research on this computerized cognitive training program is extremely limited. One study looked at the effects of Lumosity in fourteen healthy, middle-aged adults (Hardy et al., 2011). Before and after the training was implemented, participants in the training group and the waitlist control group completed the following tasks: divided visual attention, forward/backward spatial working memory, and letter memory. These task were deployed in the context of the Lumosity website and completed at home by the participants. The divided visual attention task required participates to identify and fixate on a stimulus in the center of a computer screen. While fixating on the center stimuli, participates were asked to click on small solid black circles that would appear in varied locations around the central stimulus. The distance between the location of the mouse click and each black circle was recorded and used as a measure of accuracy. The forward and backward spatial working memory task required the participant to watch the computer screen as several light blue squares were presented. During this task, the squares would change from light blue to dark blue one at a time and in a random pattern. In the forward spatial working memory task, participants were asked to repeat back the order in which the squares changed color by clicking on each square.

During the backwards spatial working memory task, participants were asked to repeat back the squares that changed color in the opposite order of how they were presented. After each correct trial, the number of squares presented increased by one. The task ended once the participant failed to successfully complete two trails with the same number of squares. During the letter memory task, participants were presented with a random string of letters on the computer screen and asked to remember as many of the letters as possible. Afterwards, the participants had to type in the string of letters they observed. Each time the participant typed in the letters correctly, the span was increased by one. The task ended once the participant missed two consecutive trials. For this study, participants trained on Lumosity for an average of twenty-nine sessions over a five-week period. Each of the sessions took around twenty minutes to complete. Results showed that participants in the training intervention group improved significantly more on untrained measures of visual attention and spatial working memory compared to the wait-list control group after completing the training.

Another study looked at the effects of Lumosity on adults aged sixty year or older with a current diagnosis of Mild Cognitive Impairment (Finn & McDonald, 2011). During this study, participants completed pre- and post- test measures of cognitive functioning from the Cambridge Automated Neuropsychological Test Battery (CANTAB). These measures included the paired-associates learning task, the intra-/extra dimensional set shifting task, the spatial working memory task, and the rapid visual information processing task. Perceived control over memory was measured using the Memory Controllability Inventory. Participants were required to complete thirty sessions of the training program, with each session containing four to five exercises. On average, it took participates around eleven weeks to complete the training program. Results showed, when compared to the waitlist control group, participants in the training group made significant improvements on a measure of visual sustained attention. However, there were no significant changes on other measures of processing speed, visual memory, and cognitive control.

Another study, looking at the effects of Lumosity on improving cognitive skills of breast cancer survivors, returned less than hopeful results for increasing working memory capacity (Kesler, et al., 2013). During this study, participants were required to participate in the training program four times per week for twelve weeks. Each session included various combinations of thirteen different exercises and took around twenty to thirty minutes to complete. Five exercises were completed during each session. Although, many of the exercises in this program focused specifically on training working memory, no significant improvements were made between a pre- and post- test measure of this construct when compared to the waitlist control group. This measure included the digit span task on the Wechsler Adult Intelligence Scale 4th Edition (WAIS-IV). Increased performance was evident for other measures of executive functioning including cognitive flexibility, processing speed, and verbal fluency. These measures included the symbol search task on the WAIS-IV, the Wisconsin Card Sorting Test (WCST), and the letter fluency task on the Delis-Kaplan Executive Function System (D-KEFS). Other research has found similar results to the aforementioned study in participants with cancer-related brain injuries (Kesler, et al., 2011). The training program did not improve visual attention or working memory, however it was effective at increasing performance on measures of processing speed, cognitive flexibility, and visual and verbal declarative memory.

Statement of the Problem

Working memory enables individuals to temporarily preserve and manipulate information to assist in performing simple and complex tasks (Baddeley & Hitch, 1974; Just &

Carpenter, 1992.) During childhood and adolescence, working memory increases to a peak, and begins to decrease in later adulthood. This is supported by changes in grey matter and brain activity (Goldstein et al., 2014; Klingberg et al., 2002; Tamnes et al., 2013). Interactions between multiple brain regions within the frontal and parietal lobes have been associated with working memory (Fletcher & Henson, 2001; Chein et al., 2001; Courtney et al., 1996; Cowan et al., 2011; Li et al., 2014; Smith & Jonides, 1999). The brain, including the regions indicated for working memory, was once thought to be fixed and unalterable (Hardy et al., 2011; Kelly et al., 2006). However, research investigating the ability to improve working memory and other aspects of cognitive functioning has produced encouraging results.

Some studies have demonstrated increases in working memory after the administration of MPH and dopamine receptor agonist (Luciana et al., 1992; Luciana et al., 1998; Mehta et al., 2000; Mehta et al., 2004). A newer area of research has investigated the efficacy of computerized brain training programs to improve working memory and related functions. Two training programs that have been studied extensively are Cogmed and Lumosity. There have been mixed results as to whether these programs are effective, as studies have evidenced both positive and negative outcomes for improving cognitive skills (Hardy et al., 2011, Kesler et al., 2011; Kesler et al., 2013; Gropper et al., 2014; Gray et al., 2012; Shavelson, 2008; Klingberg et al., 2005; Dunning et al., 2013)

After an extensive review of published and unpublished research, it was determined that are no meta-analysis documented in the literature examining the effectiveness of Lumosity. This could be due to the fact that there has been less research conducted using this brain-training program compared to other programs like Cog-Med. In addition, Lumosity has recently been sued for making unsubstantiated claims about what the program can do (FTC, 2016). Therefore the current study utilized a meta-analytical approach to determine the efficacy of Lumosity for improving working memory and various cognitive functions. Aggregating the research findings allowed the researchers to examine if the claims made by Lumos Labs had any validity.

After reviewing the current body of research on the malleability of working memory with regard to interventions, the following research questions have been generated: (1) Is there a significant impact on working memory after using Lumosity? (2) Is there a significant impact on attention after using Lumosity? (3) Is there a significant impact on cognitive flexibility after using Lumosity? and (4) Is there as significant impact on processing speed after using Lumosity?

CHAPTER THREE: METHODS

To best determine the overall effect of a program, a researcher can conduct a meta-analysis. This approach allows a researcher to quantitatively synthesize the results of multiple studies to determine if the results are statistically significant or if a program is effective. In the present study, the goal was to examine the efficacy of Lumosity as a means for improving various cognitive functions including working memory, attention, cognitive flexibility, and processing speed. To conduct a meta-analysis, a researcher must complete the following steps: (1) locate studies for the analysis, (2) select relevant studies to include, (3) extract data from the studies, and (4) analyze and interpret the results.

Inclusion Criteria

To be considered eligible for inclusion in the present meta-analysis, studies were required to meet the following criteria: (1) The full text article or manuscript was available in English, (2) The study was published in a peer-reviewed journal or an unpublished dissertation/thesis, (3) A control group was used for comparison results, (4) Standardized assessments and rating scales were used to measure relevant dependent variables during pre- and post- test, and (5) Essential data needed to calculate effect size was included in the original study.

Search Strategy

Multiple searches were conducted using two electronic databases (Google Scholar, EBSCO host) to locate studies to be included in the present analysis. These databases were searched using combinations of the following key works: attention, brain, computerized, computer based, cognitive, intervention, Lumosity, memory, program, training, and working memory. A bibliography that contained article citations from Lumosity's Human Cognition

Project was also utilized. This resource provided the names of studies that had implemented Lumosity as the intervention tool in their research. Two individuals independently reviewed the titles and abstracts of the indicated studies and 14 articles were identified as potentially eligible. Of these, 4 met the inclusion criteria. (See Figure 1 for Study Selection; See Table 1 for Summary of Characteristics of Included Studies).

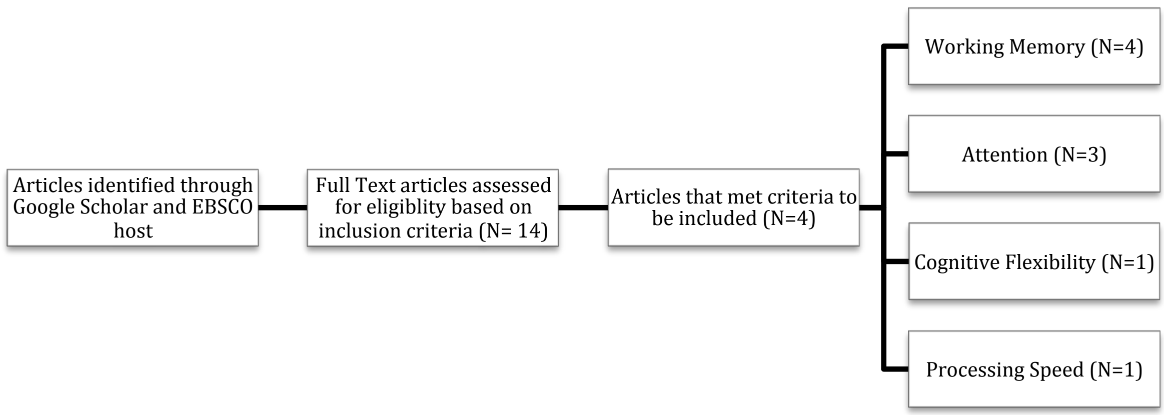

Figure 1. Study Selection Diagram

Table 1. Summary of Characteristics of Included Studies

Authors	Treatment N	Control N	Age Range	Diagnoses	Domains Measured
Ballesteros, Prieto, Mayas, Toril, Pita, Ponce de Leon, Reales, Waterworth	17	13	57-80 years	None	Visuospatial working memory, Attention, Speed of processing, Cognitive flexibility
Charvet, Haider, Melville, Krupp	11	9	18-70 years	Relapsing Remitting Multiple Sclerosis (RRMS)	Working memory, Attention
Finn & McDonald	8	8	> 60 years	Mild Cognitive Impairment	Visual recognition, Visual sustained attention
Shute, Ventura and Ke	35	42	18-22 years	None	Working memory

Data Extraction

The RevMan 5.0 program (RevMan, 2014) was used to extract data from included studies. The data was organized by outcome measure for analysis.

Outcome Measures

An evaluation of the outcome measures was conducted by examining the difference between the Lumosity intervention group and a control group over four different domains. The most proximal assessment information was used as the score for comparison in cases where there were multiple measures for a domain.

Working Memory

Working memory is an individual's ability to temporarily store and manipulate auditory or visual spatial information (Baddeley, 2012). All four studies that met inclusion criteria measured working memory. A few different measures were used to measure working memory including the Wechsler Memory Scale III, Corsi blocks tapping test, a CANTAB task, and Raven's Progressive Matrices.

Attention

Attention is an individual's ability to focus during a rote task or activity and consciously inhibit irrelevant stimuli. (Korkman, Kirk, & Kemp, 2007). Of the four studies that met inclusion criteria, three measured attention. The studies measured attention using a 5 serial position Corsi Blocks task, a CANTAB task, and DKEFS Trail 5 task.

Cognitive Flexibility

Cognitive flexibility is an individual's ability to alter their strategy or approach when problem solving or completing a task (Korkman et al., 2007). Of the studies that met inclusion criteria, one measured cognitive flexibility. The tool used to measure cognitive flexibility was the Wisconsin Card Sorting Task.

Processing Speed

Processing speed is an individual's ability to process information quickly and efficiently. Of the studies that met inclusion criteria, one measured processing speed. The tool used to measure processing speed was a computerized speed of processing task.

CHAPTER FOUR: DATA ANALYSIS

For each domain, individual effect sizes (the standardized mean difference) were calculated based on post-test comparisons between the intervention group (Lumosity) and the control group. The individual effects sizes within each domain were combined using the inverse-variance method. In this approach, individual effect sizes in each study were weighted by their inverse variance, before being combined to form an overall estimate. A random-effects model was selected because of the heterogeneity across studies, as suggested by meta-analytic technique experts (Borenstein, Hedges, Higgins, & Rothstein, 2009; Field & Gillet, 2010). The studies in our meta-analysis used different assessments to measure variables and the demographics of the samples varied. The amount of variability among a set of effect sizes that is a function of heterogeneity is represented as I^2. Larger I^2 values suggest greater heterogeneity rather than chance. Effect sizes for each domain will be interpreted using Cohen's "Rule of Thumb". A result of .20 reflects a small effect size; a result of .50 reflects a medium effect size; and a result of .80 reflects a large effect size.

Working Memory

There were four studies that met inclusion criteria, and that examined the differences in working memory between the individuals in the Lumosity intervention group and the control group. The overall standard difference effect was small and not statistically significant (.07 95% CI -.45-.59, z=. 26, p=.79). Heterogeneity across studies was substantial (I^2 =68%, X^2 =9.25, df=3, p =.03). See Figure 2 for the Forest Plot of Working Memory.

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Mean Difference IV, Fixed, 95% CI
Ballesteros et al	35.5	8.1	17	29.2	9.6	13	0.6%	6.30 [−0.19, 12.79]
Charvet, Shaw, Haider	−0.26	0.68	11	−0.52	0.67	9	77.2%	0.26 [−0.33, 0.85]
Finn & McDonald	90.62	9.39	8	80.22	15.39	8	0.2%	10.40 [−2.09, 22.89]
Kesler, Hosseini, Heckler,	12	0	21	13	0	20		Not estimable
Kesler, Lacayo, & Jo	0	0	0	0	0	0		Not estimable
Shute, Ventura and Ke	7.65	2.6	35	8.51	2.33	42	22.0%	−0.86 [−1.97, 0.25]
Total (95% CI)			**92**			**92**	**100.0%**	**0.07 [−0.45, 0.59]**

Heterogeneity: $Chi^2 = 9.25$, df = 3 (P = 0.03); $I^2 = 68\%$
Test for overall effect: Z = 0.26 (P = 0.79)

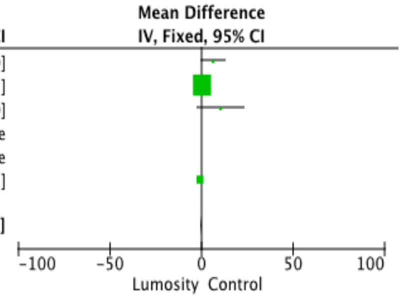

Figure 2. Forest Plot of Working Memory

Attention

There were three studies that met inclusion criteria, and that examined the differences in attention between the individuals in the Lumosity intervention group and the control group. The overall standard difference effect was small but statistically significant (.11 95% CI .03-.19, z=2.84, *p*=.004). Heterogeneity across studies was small (I^2 = 0%, X^2 =.58, df=2, *p* =.004). See Figure 3 for the Forest Plot of Attention.

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Mean Difference IV, Fixed, 95% CI
Ballesteros et al	0.36	0.23	17	0.22	0.17	13	29.2%	0.14 [−0.00, 0.28]
Charvet, Shaw, Haider	0.64	0.43	11	0.63	0.26	9	6.4%	0.01 [−0.30, 0.32]
Finn & McDonald	0.9	0.05	8	0.79	0.13	8	64.3%	0.11 [0.01, 0.21]
Kesler, Hosseini, Heckler,	14	0	21	12	0	20		Not estimable
Total (95% CI)			**57**			**50**	**100.0%**	**0.11 [0.03, 0.19]**

Heterogeneity: $Chi^2 = 0.58$, df = 2 (P = 0.75); $I^2 = 0\%$
Test for overall effect: Z = 2.84 (P = 0.004)

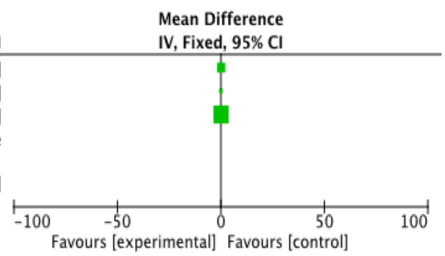

Figure 3. Forest Plot of Attention

Cognitive Flexibility

A meta-analysis on cognitive flexibility could not be conducted, as there was only one study that met the inclusion criteria that was also measuring this domain.

Processing Speed

A meta-analysis on processing speed could not be conducted, as there was only one study that met the inclusion criteria that was also measuring this domain.

CHAPTER FIVE: DISSCUSION

Lumosity is a computer based brain-training program that claimed to improve different cognitive skills like working memory, attention, cognitive flexibility, and processing speed (Lumos Labs, n.d.). The program also declared that users with health conditions like Alzheimer's, dementia, Mild Cognitive Impairment, traumatic brain injury, stroke, Turner's syndrome, ADHD, and PTSD would benefit from participating in the program (FTC, 2016). Lumos Labs marketed Lumosity under these assumptions although the existing research examining the effectiveness of the program was limited and the results were inconclusive. As a result, the multi million-dollar company was sued by the IFC after it was determined there was insufficient evidence to support the proclamations. Lumos Labs agreed to settle the lawsuit and Lumosity has since then removed the deceptive statements from it's website. However, they continue to operate and sell subscriptions. In addition to having a limited research base, no meta-analyses have been conducted synthesizing the research that is available. The purpose of this study was to conduct a meta-analytical review on the impact of Lumosity on specific cognitive skills to see if the claims made by Lumos Labs really do have some validity.

Before discussing the results, it is important note that at the time of the analysis, only fourteen studies were found that used Lumosity to improve cognitive functioning. Just four of those fourteen studies met inclusion criteria. A large number of the excluded studies lacked an appropriate control group. A control group is important as it allow researchers to compare an experimental group to a control group to see if an independent variable, or treatment, has an effect. Without a control group, researchers are unable to isolate an independent variable to determine its impact. In addition, many studies omitted essential data needed to calculate effect size. The aforementioned issues prevented us from being able to conduct a meta-analysis on the cognitive flexibility and processing speed domains.

Our meta-analysis found that Lumosity had no significant impact on working memory skills when examined across studies. These results could be due to the fact that the measures used to measure working memory were not sensitive enough to detect changes in the construct, or because Lumosity simply did not impact working memory skills. In contrast, our results showed that Lumosity did have a small effect on attention. The difference between Lumosity's impacts on attention and working memory are somewhat surprising considering the role of attention in working memory. An individual must attend to information that is important and suppress information that is irrelevant during working memory tasks (Palladino & Ferrari, 2013). Previous research has shown that children with more attention problems were less efficient at suppressing irrelevant information and displayed poorer performance on working tasks compered to children that were able to suppress irrelevant information (Palladino & Ferrari, 2013). Considering this, one may expect to see increased performance on working memory tasks from improved attention.

A meta-analysis on the cognitive flexibility domain could not be conducted, as the domain was measured using a single study. However, the included study showed that Lumosity had no significant effect on the construct (Ballesteros, et al., 2014) Cognitive flexibility, which is a component of executive functioning, shares many of the same of the same subprocesses as attention and both require self-regulatory skills (Korkman, Kirk, & Kemp, 2007). If Lumosity trains the underlying processes needed for attention, one would think the training could have some effect on cognitive flexibility. Likewise, a meta-analysis on the processing speed domain could not be conducted, as the domain was measured using a single study. The included study showed significant effects from Lumosity on processing speed (Ballesteros, et al., 2014).

Limitations of Study

Our meta-analysis was not without limitations. As previously discussed, the most obvious limitation was the small number of studies that met eligibility criteria for inclusion. However, this was unavoidable due to the small number of research studies that have been conducted using Lumosity in general. Many of the studies considered for inclusion lacked an appropriate control group or failed to include essential data needed to calculate an effect size. This is a major limitation because it is difficult to get a comprehensive look at the efficacy of a program with such a limited research base. Our meta-analysis was also unable to examine subgroups, as the number of studies was limited for specific demographics. This was of particular importance since Lumos Labs claimed its program could benefit certain subgroups of individuals with disabilities and health conditions. In addition, a considerable amount of research conducted has not been done independently of the company itself. This could confound the results of those studies as the researchers may feel obligated to attain certain outcomes or may be biased in their opinions of the program.

An additional limitation we experienced was the heterogeneity of the populations in the studies. The demographics of included studies differed by age and health condition. For example, one studies population included healthy individuals between the ages of 18-22, while another studies population included individuals with Mild Cognitive Impairment whose age was >60. The amount of variability that was attributable to study heterogeneity for the working memory domain was substantial. This was problematic as the heterogeneity across studies made us less confident in our prediction about the overall effect of Lumosity on this construct.

Suggestions for Future Research

The current body of research regarding the effectiveness of Lumosity is lacking. Since our meta-analysis, along with other studies, show that Lumosity has little to no effect on some of the cognitive skills it claims to train, more research in this area would be greatly beneficial. An increase in research regarding Lumosity's effects on healthy individuals and specific subgroups would also be useful. This would allow researchers to examine differences between age groups and individuals with health conditions like ADHD, TBI, Alzheimers, dementia, etc. Many people pay to use this program in hopes to benefit from it. It is imperative that researchers add to the literature base so that consumers aren't blindly purchasing a product that is ineffective.

Another area that should be investigated more thoroughly is the duration of the training. Unlike Cogmed, Lumosity does not provide specific guidelines on how many sessions a user needs to train or how long the training should last. Inconsistencies in the duration of training between studies could be a reason why some studies evidence positive effects from the training while others do not. These inconsistencies are not surprising considering there is no research establishing the minimum number of training sessions needed in order to successfully train executive functions (Kesler, et al., 2013). It is also possible that the duration of training may be unique to the cognitive ability being trained. For example, the amount of time it takes to train working memory could be double the time it takes to train attention. Research in this area will be valuable to all computerized brain training programs, not just Lumosity.

Lastly, many studies have not examined if training with Lumosity has any effect on academic performance or behavioral functioning. Since Lumosity is a cheaper alternative to programs like Cogmed, it's impact on behavior and reading and mathematics achievement could be of great importance to school systems. If Lumosity's impact on these things were positive, children with ADHD or specific learning disabilities could possibly benefit from using the program.

CHAPTER SIX: SUMMARY

The results of the current meta-analysis indicated that training with Lumosity had a small effect on attention, but no impact on working memory. A meta-analysis could not be conducted on the cognitive flexibility or processing speed domains due to them being measured by a single study. Additional research is necessary to better determine the efficacy of this program, which represents a limitation of the present study. That being said, Lumosity's positive impact on at least one of the constructs is encouraging. Since working memory affects many areas of individual's life and is associated with multiple health conditions, it would be beneficial for future research to delve deeper into examining this construct with regards to Lumosity.

Recent research examining the efficacy of Cogmed Working Memory Training (CMWT) also produced encouraging results. A meta-analysis of the research on CMWT showed that the program had a moderate impact on auditory and visual-spatial working memory but no statistically significant impact on attention (McLaughlin, B.E., 2016). Although Cogmed and Lumosity have evidenced increased performance on clinical measures, there is little to no research examining generalization of skills and long-term effects. Both products are mass marketed as an "easy fix" for improving cognitive functioning, but evidence of real-world application is lacking.

Considering Lumosity's vast number of users and recent legal issues, it is important for the company to provide evidence that it is a scientifically valid and useful tool for consumers. Future research examining the program needs to include control groups for comparison, so that effects can be attributed to the program, instead of other variables. Furthermore, studies that produce positive outcomes need to be replicated to verify the results. It may be that Lumosity needs to change or improve the program in order to positively affect cognitive functioning.

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