A META-ANALYSIS ON THE EFFICACY OF COGMED WORKING MEMORY TRAINING.

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By

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ABSTRACT

A META-ANALYSIS ON THE EFFICACY OF COGMED WORKING MEMORY TRAINING

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Working memory is the ability to temporarily hold information in one's mind, manipulate this information and then use it. Working memory is a critical skill in one's daily functioning as it impacts our ability to carry out multi-step directions, apply reading skills, solve complex mathematic problems, and perform many other academic tasks. Research has recently found that working memory skills can be increased with proper training. Cogmed Working Memory Training (CWMT) is an online training program that is said to increase working memory and related skills in different populations of participants. Previous meta-analyses have analyzed the efficacy of CWMT and found no impact on reasoning ability, symptoms of ADHD, transfer effects on WM capacity, verbal ability, word reading, or arithmetic (Melby-Lervag & Hulme, 2013; Shipstead, Hick, & Engle, 2012). They did find immediate gains on verbal working memory and visual-spatial working memory, which did not maintain at follow up. The current study involved a meta-analysis of 13 recent (since 2011), published peer-reviewed articles or dissertations examining the effects of CWMT on auditory working memory, visual-spatial working memory, attention, parent and teacher ratings of inattention hyperactivity, self-ratings of ADHD symptoms and executive functions, reading skills, and math skills. The results of the meta-analysis only revealed a small impact on auditory working memory and a small to moderate effect on visual-spatial working memory. There was no impact on clinical measures of attention, self-rating of ADHD symptoms, teacher rating of inattention, nor parent rating of inattention. There were significant impacts on parent rating of inattention and teacher rating of hyperactivity. There was a small effect on self-rating of executive functions. In regards to academic skills, there were no statistical impacts on reading or math skills

INTRODUCTION

Working memory (WM) is an executive function used for temporary storage and manipulation of information (Baddeley, 2013; Baddeley & Hitch, 1974). The amount of information that an individual can hold in his or her WM is called working memory capacity (Olesen, Westerberg, & Klingberg, 2004). WM is an important construct for both cognitive and academic functioning of children and adolescents.

There are many populations, such as individuals with Attention Deficit/Hyperactivity Disorder (ADHD) (Wong & Stevens, 2013), individuals with an autism spectrum disorder (Russell, Jarrold, & Henry, 1996), individuals with schizophrenia (Tek et al., 2002), and older adults with dementia (Stopford, Thompson, Neary, Richardson, & Snowden, 2012), that experience poor WM skills. The importance of WM has been highlighted in previous research, as it helps individuals follow specific steps in a process and transfer new information that they acquire to long-term memory (LTM). WM is also related to reading comprehension and mathematical skills, and has been said to be a better predictor of student success than IQ (Alloway & Copello, 2013; Dahlin, 2013; Egeland et al., 2013; Gropper et al., 2014; Turley-Ames and Whitfield, 2003).

It was once thought that WM capacity could not be changed (Ericsson, Chase, & Faloon, 1980; Butterfield, Wambold, & Belmont, 1973). However, more recent research has since shown that this is untrue and that WM can be improved (Bäckman & Nyberg, 2013; Ellis & Nathan, 2001; Luciana & Collins, 1997; Luciana, Collins, & Depue, 1998; Luciana, Depue, Arbisi & Leon, 1992; Melby-Lervåg & Hulme, 2013; Olesen et al., 2004; Stepankova, 2014; Turley-Ames & Whitfield, 2003; Westerberg & Klingberg, 2007; Yuan et al., 2006; Wong & Stevens, 2012). Since WM affects many important daily functions, such as following multiple steps in directions, reading, and solving math problems (Alloway & Copello, 2013), researching the malleability of WM is of great importance. Examining how interventions affect WM skills and capacity may help identify programs that can reduce academic problems that result from deficient WM.

There are many different types of WM training programs that claim to increase WM skills of individuals without a diagnosed disorder as well as individuals of targeted populations (i.e., children with ADHD, older adults with dementia, etc.). The purpose of this study is use a meta-analysis to examine the effects of a computer-based cognitive training program on WM and related skills. This research will contribute to the growing literature on computer-based cognitive training.

LITERATURE REVIEW

Definition of Working Memory

Working memory (WM) is often used interchangeably with short-term memory (STM). However, STM is only temporary storage of information, while WM is a combination of storage and manipulation of information (Baddeley, 2012). For example, STM would be in use when simply rehearsing and recalling a series of numbers, such as a phone number. In contrast, WM would be used when having to recall the numbers in reverse order. Baddeley and Hitch (1974) proposed the first multi-dimensional model of WM.

Their original model consisted of three components: the central executive, and two "slave" systems (the phonological loop and the visuospatial sketchpad) (Baddeley, 2000). In this model, the *central executive* is responsible for sorting through relevant and irrelevant information, and attending to only the relevant information. The *phonological loop*, one of the two "slave" systems that aid the central executive, is responsible for temporarily holding verbal and acoustic information, and keeping it in WM through rehearsal of the information. The second "slave" system, the *visuospatial sketchpad*, holds and manipulates visual information. A fourth component, the *episodic buffer*, was later added to the model. The *episodic buffer*, which is controlled by the central executive, integrates various forms of information, including visual, auditory, and others, into one unitary "episode" and stores it temporarily.

While other, more simplistic models have been proposed (Unsworth & Engle, 2007), the model originally proposed by Baddeley and Hitch in 1974 has been the most widely accepted model over time, and has been well used in research (Collette, & Van der Linden, 2002; Dahlin, 2013; Gathercole, Pickering, Ambridge, & Wearing, 2004; Osaka et al., 2003a; 2003b; Yuan, Steedle, Shavelson, Alonzo, & Oppezzo, 2006). This model will also be used for the theoretical conceptualization of WM in this paper.

Development of Working Memory

The developmental trend of WM is that it increases during childhood (DeLuca et al., 2003; Huizinga, Dolan, & van der Molen, 2006; Luciana & Nelson, 1998), peaks in young adulthood (DeLuca et al., 2003; Huizinga et al., 2006), and declines through later adulthood (DeLuca et al., 2003). Participants from the ages of 8 through 64 years completed a WM task from the Cambridge Neuropsychological Test Automated Battery (CANTAB), requiring them to search through a number of boxes to find hidden tokens; looking in the same box more than once resulted in an error. An analysis of the participants' performance showed that the age groups with the lowest WM skills displayed during this task were 8 to 10 year olds and 50 to 64 year olds (the youngest and oldest age groups). The groups that performed with the highest proficiency on the task were the 15 to 19 year olds and the 20 to 29 year olds; the two other age groups, 11 to 14 year olds and 30 to 39 year olds, performed in the middle of the other four groups.

The developmental trajectories of three executive functions, including WM, were studied using a sample consisting of four different age groups: 7 year olds, 11 year olds, 15 year olds, and 21 year olds (Huizinga et al., 2006). They tested WM with three different tasks: *Tic Tac Toe, Mental Counters,* and *Running Memory.* *Tic Tac Toe* required the participants to remember the placement of Xs and Os on a grid and recognize the original pattern when shown multiple grids with Xs and Os. *Mental*

Counters required participants to keep track of "counters" and either add or subtract 1 from the number depending on the image displayed and the pre-established rule. The third task, *Running Memory,* was difficult to interpret and not included in the final discussion. The results of the study showed that on two of the three tasks: *Tic Tac Toe* and *Mental Counters,* adult-level performance was not seen until the age of 15. These results show that WM is not fully developed until adolescence and is similar to the findings of DeLuca et al. (2003). There are several components that have been linked to the observed developmental trajectory of WM. Some of the reasons we see this pattern are the increase of knowledge, the learning new processing skills, and the increase in attention skills, which will all be discussed in greater detail in the subsequent paragraphs (Cowan, 1997).

We see an increase in children's knowledge as they get older, with advances in vocabulary, concept formation, and the ability to classify abstract information. An individual with considerable background knowledge can use this database to make meaningful patterns of information when WM is employed. He or she does not have to hold the new meaning in his or her memory during problem solving. A student that understands the components of an equation, like the quadratic formula, has an easier time solving linear equations than someone who has to keep going back to the original explanation of the equation to make sense of the problem. In contrast, deficits in background knowledge may result in an overtaxed WM as the individual tries to make new connections and manipulate novel information.

As children age and learn new things, they learn which strategies for processing information work better than others (Cowan, 1997). For example, when learning to solve simple math problems, such as 3 + 3, a child may learn that instead of adding 3 to 3 every time, it is much quicker to just pull the answer from long-term memory. Additionally, strategies that allow individuals to handle complex math problems often do so by decreasing the load on WM. One strategy that mental math experts teach is that when we square two digit numbers that end in 5, we know the ending will be 25, so we do not even need to calculate that component. It simplifies the problem to multiplying the first digit with the number that is one higher than the second digit (75 x 75 = 7 x 8 = 56 place in front of the 25 = 5625; 35 x 35 = 1225; 45 x 45 = 2025). Other developmental changes in strategies for processing include becoming more active rehearsers (Dempster, 1981) and using spontaneous rehearsal (Cowan, 1997). Younger children rehearse when explicitly instructed to do so; older children learn to spontaneously rehearse information on their own; therefore, increasing WM skills.

Similar to WM, processing speed gradually increases throughout childhood and reaches adult-level in mid-adolescence (Cerella & Hale, 1994). Information is only held in WM temporarily (Baddeley, 2012), meaning individuals with slow processing speeds, such as younger children, may lose the needed information from WM before the task is completed. Therefore, a faster, more mature processing speed means a better chance of WM helping to store information, manipulate it, and use it in daily functions. Researchers found that 71% of the WM age-related effects were mediated by the age differences in processing speed, and when age was statistically controlled for, individual differences in processing speed still had an effect on WM (Fry & Hale, 1996).

The last reason that will be discussed pertaining to why WM increases in childhood is the change in attention seen during childhood (Cowan, 1997). During WM tasks, one must attend to the relevant information and suppress the unnecessary information (Palladino & Ferrari, 2013). Researchers found that children with more attention problems were less able to ignore the irrelevant information, and performed poorer on WM tasks, in comparison to children that were able to ignore the irrelevant information (Palladino & Ferrari, 2013). Ability to discriminate between irrelevant and relevant information increases with age (Maccoby, & Hagen, 1965), and developmentally all facets of attention improve as children get older (Cowan, 1997).

In conclusion, WM performance seems to be the greatest in young adulthood (DeLuca et al., 2003; Huizinga et al., 2006), with increases throughout adolescence (DeLuca et al., 2003; Huizinga et al., 2006; Luciana & Nelson, 1998), and declines in later adulthood (DeLuca et al., 2003). There are many thoughts about why this developmental trend occurs including: the gaining of knowledge in childhood, the learning of new processing strategies, the improved processing speed, and the changes in children's attention (Cowan, 1997).

Neurological Basis of Working Memory

The WM system utilizes an interaction between multiple brain regions (Bunge, Klingberg, Jacobsen, & Gabrieli, 2000). There are several techniques that researchers use to study the brain as it relates to WM. Functional magnetic resonance imaging (fMRI) is one way that researchers have studied what areas of the brain are activated while individuals are using their WM. Researchers have also studied regions of the brain that are involved in WM with individuals that have experienced some sort of trauma to their brain and now show deficits in WM. Finally, researchers have been able to learn about the brain's involvement with WM through animal studies.

fMRI was used to discover brain differences between individuals categorized as high-span subjects (HSS), or individuals with stronger WM skills, and low-span subjects (LSS), individuals with poorer WM skills (Osaka et al., 2003a; 2003b). HSS are the subjects that scored higher on the reading span test (RST), which involves remembering target words while reading sentences, than did the LSS. Two different experiments were conducted. The first experiment used a listening-span test (LST), involving listening to a sentence, stating if the sentence was true or false, and remembering the target word of the sentence; a listen condition (listening and stating if true or false); and a remember condition (listening and remembering the target word) (Osaka et al, 2003a). The second experiment used the RST and a simple read condition (did not have to remember target words) (Osaka et al., 2003b). An fMRI measured brain activity while subjects participated in the tasks described. The results showed that during the LST the temporal, anterior cingulate cortex (ACC), and the pre-frontal cortex (PFC) were activated, with higher activation of the ACC in the HSS group than the LSS group (Osaka et al., 2003a). During the RST, the researchers found that the ACC and PFC were activated, with higher activation of both with the HSS group compared to the LSS group (Osaka et al., 2003b). Therefore, the studies found activation in both the ACC and the PFC during visual and auditory WM tasks.

Another study using fMRI to research brain activity during WM tasks also saw increased activity in the PFC (Bunge et al., 2000). The experiment required participants to complete tasks similar to the tasks utilized in the aforementioned studies (Osaka et al., 2003a; 2003b). The Read condition asked participants to simply read a statement and decide if it was true or false. The Remember condition asked the participants to remember the last word of each sentence displayed. The Read and Remember condition asked participants to combine answering true or false and remembering the last word. Finally, during the Control condition participants viewed “meaningless consonant strings” (Bunge et al., 2000, p. 3573). As stated before, this study found similar results to that of the previous studies (Osaka et al., 2003a; 2003b). The PFC was activated in all three studies when WM was engaged. However, this study also saw activation in the parietal cortex, the cerebellum, and occasionally the striatum during WM tasks (Bunge et al., 2000). There is seen to be an interaction between these areas of the brain when the WM system is in use. Therefore, the study implicates an interaction between the PFC, ACC, the parietal cortex, the cerebellum, and the striatum (Osaka et al., 2003a; 2003b).

The involvement of the PFC with WM tasks has been investigated even further to examine its involvement with specific processes (maintenance, coding, and retrieval) of WM. Another study used fMRI to compare activation of areas in the brain during many different processes that are involved with WM (D’Esposito, Postle, & Rypma, 2000). The first processes that they examined were maintenance of information (requiring participants to remember a sequence of letters over a delayed time period) and the manipulation of information (arranging a sequence of letters alphabetically during a delayed time period). They found that both the dorsolateral and ventrolateral PFC were activated during the maintenance and manipulation tasks; although, the dorsolateral PFC activity was greater when the task required manipulation of the information in WM. They also found that the dorsolateral was activated when more advanced processes were in use, such as scanning (mentally searching information in WM and selecting the relevant information) and when there was a larger WM load (remembering six letters at a time, versus only remembering two letters at a time). This study, like the previous studies, found that the PFC is greatly involved with WM; however, they further investigated the PFC's role and found activation in both the dorsolateral and ventrolateral PFC with greater activation of the dorsolateral PFC during more complex WM demands.

Lesion studies, or studies of individuals with damage to areas of their brains, are used to study what cognitive functions are effected by these damages. These studies examine performance on neuropsychological batteries and tests as a means of understanding the impact of the damage. Several researchers have demonstrated that individuals with damage to their PFC, and right inferior parietal cortex, perform lower on WM tasks (Barbey, Colom, Paul, & Grafman, 2014; Barbey, Koenigs, & Grafman, 2013; Tsuchida & Fellows, 2008).

Neurotransmitters are chemicals in the brain that are responsible for communication between cells in the brain (Siegler, DeLoache, & Eisenberg, 2011). Dopamine is a neurotransmitter that was found to influence WM in a study with monkeys (Brozoski, Brown, Rosvold, & Goldman, 1979). The researchers found that the depletion of dopamine in monkey's brains decreased their performance on WM tasks. This same phenomenon was later found to be true for humans as well (D'Ardennne et al., 2012). Dopamine has shown to have an inverted U-shape interaction with WM (Birsch et al., 2014). This means that too little dopamine or too much dopamine impairs WM, but the proper, moderate amount is ideal for good WM skills.

Malleability of Working Memory

The long-standing question about WM is if individuals are born with a specific WM capacity that will remain unchanged or if it can be improved? The first part of the question, are individuals born with their WM capacity, can be a question of genetics. Is WM hereditary? Twin studies have examined the heritability of WM (Ando, Ono, & Wright, 2001; Kremen et al., 2007). One study reported that 43-49% of the WM scores were linked to heritability (Ando et al., 2001). Another study found similarly that 27-52% of the variance was accounted for by heritable factors (Kremen et al., 2007). These studies show that while WM may have a genetic component, it is also likely to be influenced by the environment in which an individual lives. While we know that genetics do not completely account for WM, the question of whether or not it can be improved has persisted. For a long period of time, researchers believed that WM capacity and WM skills could not be improved.

There were many studies that were thought to show that WM could not be improved (Ericsson, Chase, & Faloon, 1980; Butterfield, Wambold, & Belmont, 1973). For instance, a single-case design study, consisting of one undergraduate student with average intelligence, required the student to practice increasing his performance on a digit span task (repeating a number sequence spoken one-digit per second) for one hour a day, three to five days a week, for one and a half years (Ericsson et al., 1980). The participant was able to increase his digit span performance from being able to remember and repeat back 7 digits, to being able to remember and repeat 79 digits. However, the researchers concluded that WM capacity could not be improved due to the fact that these skills could not be transferred to other tasks. For example, when switching from remembering and repeating digits to recalling letters, the participant dropped back to the number he was first able to recall with digits. This study and many others at the time were convincing evidence that WM capacity was fixed. More recent research has shown that the previous notion of a fixed WM capacity is incorrect.

Many recent studies have found that WM in children and adults can be increased (Bäckman & Nyberg, 2013; Ellis & Nathan, 2001; Luciana & Collins, 1997; Luciana, Collins, & Depue, 1998; Luciana, Depue, Arbisi & Leon, 1992; Melby-Lervåg & Hulme, 2013; Olesen et al., 2004; Stepankova, 2014; Turley-Ames & Whitfield, 2003; Westerberg & Klingberg, 2007; Yuan et al., 2006; Wong & Stevens, 2012). These studies have demonstrated significant improvement on tasks measuring WM in a research setting. However, not all of these studies have found results that are generalizable. This means that even though there may have been an increase in WM performance for the specific task it may not increase WM skills outside of the task utilized for the training.

There have also been several studies that have shown that with practice people with average memory skills can match those of individuals with "world-class memory performance" (Ericsson, 2003; Ericsson & Chase, 1982; Maguire, Valentine, Wilding, & Kapur, 2003). However, these skills are usually exclusive to the material they are exceptional memorizers in (e.g., a list of digits).

A meta-analysis was conducted on studies that used computer-based training programs (Cogmed, Jungle Memory, and Cognifit) to attempt to improve WM (Melby-Lervåg & Hulme, 2013). The authors analyzed the studies for immediate effects on WM, long-term effects on WM, and transfer effects. While analyzing 23 studies they found that there were immediate effects on verbal WM; there were more gains seen in younger children than adults; however, the gains in verbal WM did not last long-term. This means that although individuals did increase their verbal WM skills, these increases were lost after a short amount of time. Visuospatial WM only showed moderate sized immediate gains; these moderate (some small) gains seemed to be maintained at follow up. Finally, the meta-analysis did not find any transfer effects when it came to verbal ability, non-verbal ability, stroop task (inhibitory processes in attention), word decoding or arithmetic. In conclusion, the study found that WM training, specifically computer-based WM training, did not have strong immediate effects on WM, did not show long-term effects on improving WM, and the training did not generalize to other cognitive abilities across these three interventions.

In contrast to the previously mentioned study (Melby-Lervåg & Hulme, 2013) other studies of WM training have shown promising results that training can improve WM and that these newly learned skills are transferrable. Researchers conducted three different studies to examine the implications strategy training has on WM capacity (Turley-Ames and Whitfield, 2003). The first finding was that individuals in the low-span category (individuals that had lower scores on the WM tasks) benefitted more from being instructed on how to use rehearsal strategies, than did individuals in the high-span category (individuals that scored higher on WM tasks). The second finding with large implications is that WM scores predicted reading ability. Therefore, the results from this study show that WM training can improve WM capacity and can be transferred to other skills, such as reading ability.

Researchers used fMRI to research brain activity in regards to WM training (Olesen et al., 2004). The results showed that activity in prefrontal and parietal regions of the brain were increased in individuals that received the WM training. Later, researchers conducted a similar study using fMRI and WM training and found that the inferior frontal and middle gyrus also showed more activity after WM training, and that this training transferred to tasks that were not practiced (Westerberg & Klingberg, 2007).

The studies mentioned above (Olesen et al., 2004; Turley-Ames & Whitfield, 2003; Westerberg & Klingberg, 2007) are only a few of the studies that have found positive, significant results in improving WM from training and transferring these skills to other cognitive abilities; many more of these studies will be discussed in the following section. In conclusion, researchers originally believed that WM could not be improved (Ando et al., 2001; Ericsson et al., 1980; Kremen et al., 2007); however, recent research has shown that WM can be improved with proper training (Bäckman & Nyberg, 2013; Ellis & Nathan, 2001; Luciana & Collins, 1997; Luciana, Collins, & Depue, 1998; Luciana, Depue, Arbisi & Leon, 1992; Melby-Lervåg & Hulme, 2013; Olesen et al., 2004; Stepankova, 2014; Turley-Ames & Whitfield, 2003; Westerberg & Klingberg, 2007; Yuan et al., 2006; Wong & Stevens, 2012).

Specific Interventions for Deficits in Working Memory

Psychopharmacology. Researchers used fMRI and WM tasks to study the effects that stimulants (methylphenidate and dextroamphetamine/amphetamine) had on the WM skills and the brain activity of 18 children with a pre-diagnosis of attention-deficit/hyperactivity disorder (ADHD) (Wong & Stevens, 2012). Participants were either given their regularly prescribed dose of stimulant medication or a placebo pill. The results of the study showed that the participants that were given their medication had faster response times on the WM tasks, meaning that they had to spend less time searching their WM storage. Another finding from the study was that there is increased activity and functional connectivity in the brain with the participants that were medicated. For instance, when using encoding and maintenance on the WM task the left dorsolateral/ventrolateral prefrontal/parietal network increased in the participants that had been given their stimulant medication. Also, there was increased integration of the left dorsolateral/ventrolateral prefrontal cortex with the left inferior parietal lobe regions. The researchers concluded that when children with ADHD had taken their prescribed stimulant medication they showed more efficient use of their WM system.

Another study researched the effects of two medications, modafinil (a drug typically used to treat narcolepsy, and in some cases ADHD) and escitalopram (an antidepressant), on cognitive functions of cocaine addicts with cognitive deficits (Kalechstein, Mahoney, Yoon, Bennett, & De La Garza, 2013). The results showed that cocaine addicts who were administered modafinil had improved performance on WM and sustained attention tasks, but no improvement was seen in those administered escitalopram. It was also found that modafinil improves WM in individuals dependent on methamphetamine (Kalechstein, De La Garza, & Newton, 2010). In alcohol dependent individuals, those with low WM skills saw an improvement in performance when administered modafinil, but those that had good WM skills at baseline did not improve with modafinil (Joos et al, 2013). In summary, Modafinil has been concluded to enhance WM skills in those with drug addictions.

Research has been conducted on the involvement of dopamine with the WM system. It has been stated that dopamine is “critically” involved in WM functioning (Bäckman and Nyberg, 2013). Dopamine enhances the signals between neurons in relation to interferences or background noise, creating an environment with increased neuron firing (Luciana et al., 1998). Much research has been conducted using bromocriptine, a dopamine receptor agonist, to study the effects of dopamine on WM (Bäckman & Nyberg, 2013; Ellis, & Nathan, 2001; Luciana & Collins, 1997; Luciana et al., 1992 Luciana et al., 1998). The interaction between WM performance and bromocriptine is inferred to be an inverted U-shape (Ellis, & Nathan, 2001). Two studies used a higher dose of bromocriptine and found that it did not increase WM performance (Luciana and Collins, 1997; Luciana et al., 1992), whereas another study used a lower dose of bromocriptine and saw increases in WM performance (Luciana et al., 1998). This shows that WM performance is best when a low amount of bromocriptine, the dopamine receptor agonist, is administered, but WM performance is the same, or lower than no bromocriptine when too much is administered (Ellis & Nathan, 2001).

Computer-based interventions. Computer-based interventions, or training programs, are formatted like a video game. There is a pre-training evaluation of the individual’s current skills, and a post-evaluation of their WM skills. The participants start out with games that are adjusted to their specific skill level based on the pre-evaluation. As the participant’s skills increase, the difficulty of the game increases. At the end of the program, the participant is once again given an evaluation to assess his or her WM skills in comparison to his or her pre-evaluation of these skills. Some of these trainings focus on only WM skills, while others focus on a broad range of cognitive abilities.

Lumosity. Lumosity is a web-based cognitive training program created by Lumos Lab (Lumos Lab Incorporated, 2014). The program is available to the public for a fee. Lumos Lab and a team from the Human Cognition Project, Lumosity's research team, have created over 40 games to improve cognitive functioning. The targeted areas influenced by the brain training programs are memory, attention, problem solving, flexibility, and mental speed. Lumosity claims to be effective for all ages, however, they do not suggest the program to be used for individuals under the age of 13. Lumosity is designed to be a "personal trainer" for your brain, meaning that the games adapt the difficulty according to the person's performance and skill level. The website tracks the progress of the member and compares his or her performance to others that are similar. The suggested usage of Lumosity is 15 minutes a day, 3-5 times a week for optimal results.

Lumosity claims that the training program enhances cognitive functioning, although very little research has been published supporting these assertions. Lumos Lab and members of the Human Cognition Project, along with two outside researchers, used Lumosity data to examine correlations between cognitive functioning and age and cognitive functioning and lifestyle habits (alcohol intake and sleep); however, they did not do analyses on the changes in cognitive functioning due to the training (Sternberg et al., 2013). A computer-based math training program designed by Lumos Lab was used to study math skills and related cognitive functions in girls with Turner syndrome (Kesler, Sheau, Koovakkattu, & Reiss, 2011). The results showed an increase in math skills, but also in cognitive flexibility, processing speed, and visual-spatial processing skills. However, the study did not demonstrate an increase in WM with this training program (noted, not the same training program as offered on www.lumosity.com)

Recently, three different studies have examined the cognitive effects (including WM) from Lumosity training (Hardy, Dresche, Sarkar, Kellett, & Scanlon, 2011; Kesler et al., 2013; Mayas, Parmentier, Andrés, & Ballesteros, 2014). All three studies used different populations for their samples. Researchers studied healthy middle-aged adults WM and visual attention skills before and after 5 weeks of training on Lumosity (Hardy et al., 2011). The results showed that the WM performance and visual attention performance increased from pre-test to post-test for the group that participated in the training compared to the control group. Another group of researchers used a sample of 41 breast cancer survivors that had been treated with chemotherapy (Kesler et al., 2013). Breast cancer patients that have gone through chemotherapy experience a decline in executive functions (including WM) and other cognitive functions. The participants used a training program designed by Lumos Lab for the study, keeping all of the programs (or games) stable for each participant; these games were similar to games used on the public website. The study found increases in cognitive functions, such as cognitive flexibility, processing speed, and verbal fluency. The study failed to find an increase in WM from pre-test to post-test following the computer-based training. Finally, a study using a sample of 60 healthy older adults (between the ages of 57-77 years old) measured increases in attention (Mayas, 2014). Although the study was not designed to measure WM, attentional gains may increase WM skills. The results showed that participants were more alert and were less distracted by irrelevant information.

As noted before, there is a limited amount of research examining the effects Lumosity training has on cognitive functions as claimed by the company. While the findings are limited, recent studies have suggested that it is possible that this type of training may impact cognitive functions including WM. Future research that targeted younger populations, individuals with disabilities that effect their cognitive functioning (i. e., ADHD and dementia), and individuals with brain injuries are needed to help determine the efficacy of this program. This is important since Lumosity is a considerably cheaper alternative to the Cogmed Working Memory Training program developed by Pearson. Also, replicating studies like the aforementioned would greatly contribute to the literature on Lumosity.

Cogmed Working Memory Training. Cogmed Working Memory Training (CWMT) is also a computer-based cognitive training program (Pearson Education, Inc., 2014). CWMT is accessible from the internet and targets only WM. Each training program consists of 25 sessions, with individual sessions lasting between 30 and 45 minutes. The "standard program" is five weeks long, with five sessions each week. Each participant is set up with a "Cogmed Qualified Coach." The program starts with an Initial Interview, where the participant is contacted by his or her coach and is screened to assess if the user is "suitable". The coach plans out the sessions for the user, and contacts the user weekly to provide feedback and motivation. At the end of the program, the coach summarizes the training and provides the user with feedback. Six months after completing the program, the coach follows up with the user and measures training effects after stopping the program. Similar to Lumosity, CWMT tasks vary according to each individual's skill-level, increasing difficulty as the user performs better.

CWMT is designed for both children and adults with a decreased WM capacity. CWMT claims to benefit three main groups: individuals with ADHD that have deficits in attention and WM skills, individuals that have experienced a brain injury or a stroke impacting the brain, and individuals that have seen a decline in cognitive functioning due to age or a large cognitive demand.

There is considerably more research using CMWT compared to Lumosity. Researchers studied CMWT in the classroom with two separate trials (Holmes & Gathercole, 2013). The first trial had a sample of 22 children ages 8 to 9 years old. The results of the first trial showed an increase in WM skills on tasks different than those used in training. The greatest increase in WM skills were seen with participants that had low WM skills prior to the beginning of the training program. The second trial consisted of 50 children between the ages of 9 to 11 years old that had low academic performance. The second trial studied increases in English and Math scores for groups receiving the training and a comparison group that did not. The results showed that children in their sixth year of school that completed the training program had more gains in Math and English performance than the comparison group, and children in their fifth year of school that completed the training program had more gains in Math than the comparison group.

Another study examined the effects of CWMT on a unique sample of 9 children who were deaf and had received cochlear implants (Kronenberger et al., 2011). Each participant completed a five-week training CWMT program. The results of the study showed that there was an increase in verbal WM skills and non-verbal WM skills. The also found an increase in Sentence Repetition, a speech language skill measurement that is sometimes difficult for children with cochlear implants. However, these increased levels of performance were not maintained through follow up measurements at one month and six months.

The majority of CWMT research has been conducted using samples of individuals with ADHD (Chacko, 2013; Dahlin, 2013; Egeland, Aarlien, Saunes, 2013; Green et al., 2012; Gropper, Gotlieb, Kronitz, & Tannock, 2014; Klingberg et al., 2005). Researchers used a sample of 53 children with ADHD to test the effects that CMWT had on WM skills (Klingberg et al., 2005). They found an increase in WM skills for the children who participated in the high-intensity intervention group and these skills remained at follow-up with the children. Along with the increases in WM skills, they also found a decrease in parent reports of ADHD symptoms, reasoning and response inhibition. Many other studies found increases in WM skills for samples of individuals with ADHD after using CWMT (Dahlin, 2013; Egeland et al., 2013; Green et al., 2012; Gropper et al., 2014). Two of the studies also found an increase in mathematical performance following the use of CMWT (Dahlin, 2013; Egeland et al., 2013), along with increases in many other areas, such as processing speed and reading skills (Egeland et al., 2013). The increase in WM skills and reading skills seemed to sustain when researchers followed up with the participants (Egeland et al., 2013; Gropper et al., 2014).

Two meta-analyses were conducted previously and found similar results (Melby-Lervag & Hulme, 2013; Shipstead, Hick, & Engle, 2012). The meta-analyses did not find significant impacts on reasoning ability, symptoms of ADHD, transfer effects on WM capacity, verbal ability, word reading, or arithmetic as a result of CWMT. However, the studies did find immediate gains on verbal working memory and visual-spatial working memory. These gains did not sustain at follow-up.

Similar to statements made previously about future research with Lumosity, much more research with CWMT needs to be conducted. CWMT claims to improve WM skills in populations that have experienced a decline in WM skills due to brain injuries or stroke. More research to investigate effects that CWMT has on these individuals is needed. Also, studies on older adults who have experienced a decline in cognitive functioning should be conducted. More research on populations of healthy adults and children would be beneficial. Lastly, research on transfer effects and if these increased skills are maintained with time would greatly add to the existing literature on CWMT.

STATEMENT OF THE PROBLEM

WM is an executive function that is used for temporary storage and manipulation of information (Baddeley, 2013; Baddeley & Hitch, 1974). WM develops through childhood and peaks in young adulthood, with a decline starting in later adulthood (DeLuca et al., 2003; Huizinga, Dolan, & van der Molen, 2006; Luciana & Nelson, 1998). It involves an interaction between many different regions of the brain, including the prefrontal cortex (Bunge et al., 2000; Bunge, Klingberg, Jacobsen, & Gabrieli, 2000; D'Esposito, Postle, & Rypma, 2000; Osaka et al., 2003a; 2003b). WM was once thought to be immutable, but has recently been shown to be something that can be improved in individuals with deficits (Ando et al., 2001; Ericsson et al., 1980; Bäckman & Nyberg, 2013; Ellis & Nathan, 2001; Kremen et al., 2007; Luciana & Collins, 1997; Luciana, Collins, & Depue, 1998; Luciana, Depue, Arbisi & Leon, 1992; Melby-Lervåg & Hulme, 2013; Olesen et al., 2004; Stepankova, 2014; Turley-Ames & Whitfield, 2003; Westerberg & Klingberg, 2007; Yuan et al., 2006; Wong & Stevens, 2012).

Some research has shown an improvement in WM from stimulant ADHD medication and dopamine receptor agonists (Ellis & Nathan, 2001; Luciana et al., 1998; Wong & Stevens, 2012). A new area of research on training WM has focused on computer-based training of WM. Lumosity and Cogmed Working Memory Training (CWMT) are the two largest, and most well researched computer-based training programs. There has been mixed results on the efficacy and generalization of Lumosity and CWMT. Some studies have evidenced positive outcomes (Dahlin, 2013; Egeland et al., 2013; Green et al., 2012; Gropper et al., 2014; Hardy et al., 2011; Holmes & Gathercole, 2013), while others have found that these skills do not transfer or last

(Kronenberger et al., 2011; Melby-Lervåg & Hulme, 2013). The two previous meta-analyses that have been conducted found immediate effects on verbal working memory and visual spatial working memory, but failed to find effects on many other areas studied (Melby-Lervag & Hulme, 2013; Shipstead, Hick, & Engle, 2012).

The current study utilized a meta-analytical approach to determining the efficacy of CWMT for improving working memory and related skills in children and young adults under the age of 35. Children with WM deficits may be heavily impacted in school, with things such as reading and mathematics. Children with low WM skills could benefit from an easily administered, computer-based training program used in the school, if effective. Therefore, this study examined the existing body of research to determine the effectiveness, or lack thereof. Implications of this study, if it is found that this intervention technique is effective in increasing children's WM, are that schools may consider using this program. The inclusion of such a program, which is effective, could mean a rise in children's performance in the classroom and in other areas of their life.

Several research questions developed after reviewing the current research on the malleability of WM and the interventions. The research questions that the current study will focus on are: (1) Is there a significant impact on auditory and visual-spatial working after using the CWMT program; (2) Is there a significant impact on attention measures after using the CMWT program; (3) Is there a significant impact on teacher and parent ratings of inattention and hyperactivity after using the CWMT program; (4) Is there a significant impact on self-ratings of ADHD symptoms and executive functioning after using the CWMT program; and (5) Is there a significant impact on academic performance after using the CWMT program?

METHODS

A meta-analysis allows a researcher to combine the results of different studies to determine if the overall effect of a program is statistically significant. In this project, the goal was to examine the effectiveness of CWMT as a means for improving executive functions, working memory, and related skills. The steps involved in conducting a meta-analysis include: (1) deciding which studies to include, (2) locating the studies for the analysis, (3) extracting the data from the studies, and (4) analyzing and interpreting the results.

Inclusion Criteria

Studies were considered eligible for inclusion if they met the following criteria: (1) The study sample consisted of individuals under the age of 35 that were involved in CMWT. The studies included children with a previous diagnosis of Attention Deficit/Hyperactivity Disorder or a Learning Disability, (2) The study included a control group for comparison results. The control group met the same criteria for inclusion as the treatment group. The control group was evaluated prior to outcome assessment to ensure that it matched the CMWT group on relevant demographic variables (such as age, ethnicity, IQ, disorder/disability) and baseline measures, (3) The study used standardized assessments and rating scales to evaluate the effectiveness of the intervention, (4) The full text-text article or manuscript was available in English, and (5) The study was reported in a peer-reviewed journal or unpublished dissertation/thesis from 2011 to 2015. This time period was selected as the studies in the previous two meta-analyses were published prior to 2011.

Studies were not considered eligible if: (1) Participants were over the age of 35, (2) Participants had sustained a traumatic brain injury, (3) The study did not include a standardized measure of relevant dependent variables, and (4) The study did not include a control group for comparison, or used another intervention program as a control group, rather than a placebo. For studies that included more than one control group, the most stringent control condition (usually CWMT placebo) was selected as the comparison point. Studies that included children or adolescents with ADHD that were on medication were included if the control group was matched with the comparison group with regard to medication usage. Studies published prior to 2011 were not included in this study as to examine the most current outcomes since the last meta-analyses examining CWMT.

Search Strategy

Two electronic databases (Google Scholar and EBSCO host) were utilized when searching for studies to be included in the meta-analysis. The search identified 502 citations that included the key words computerized, computer based, cognitive, training, working memory, cogmed, brain, memory, attention, intervention, program after removing duplicate records. The titles and abstracts of these records were reviewed independently by two reviewers and 53 articles were identified as potentially eligible. Of these, 13 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

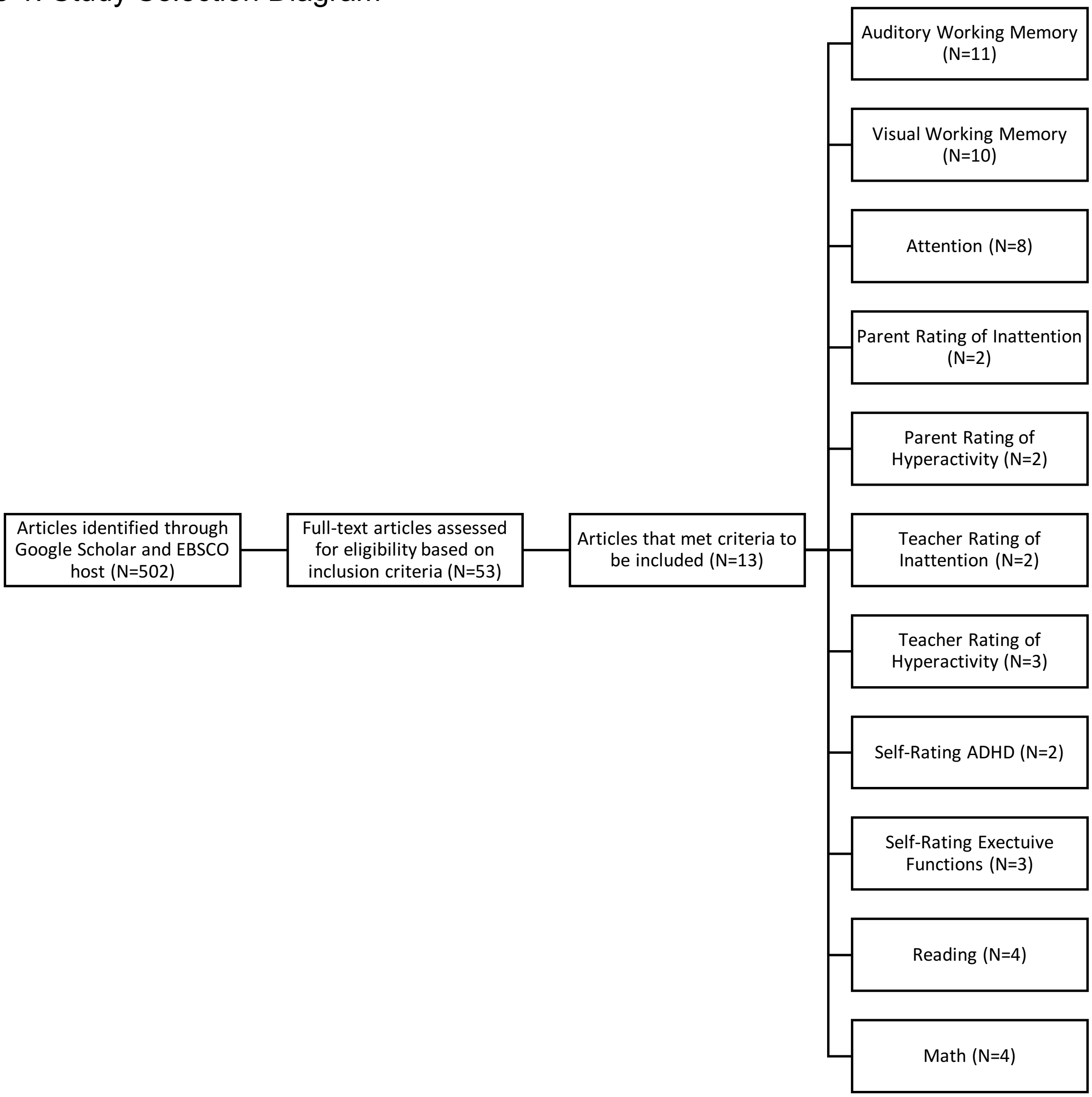


Table 1: Summary of Characteristics of Included Studies

Authors	Treatment N	Control N	Age Range	Diagnoses	Domains Measured
Bergman-Nutley, S., & Klingberg, T.	155	275	7-15 years	None	Odd One Out task performance, Following Instructions, Mathematic performance
Bergman Nutley, S., Söderqvist, S., Bryde, S., Thorell, L. B., Humphreys, K., & Klingberg, T.	24	25	4-4.5 years	None	Working memory/short-term memory, problem solving task performance, fluid intelligence
Brehmer, Y., Westerberg, H., & Bäckman, L.	55	45	20-30 years; 60-70 years*	None	Criterion tasks, near-transfer tasks, far-transfer tasks, maintenance effects
Chacko, A., Bedard, A. C., Marks, D. J., Feirsen, N., Uderman, J. Z., Chimiklis, A., ... & Ramon, M	45	41	7-11 years	ADHD	ADHD symptoms, working memory, attention, activity level, impulse control, and academic achievement
Foy, J. G., & Mann, V. A.	23	27	Kindergarten aged	None	Visuospatial and Verbal Memory, Phoneme Awareness, Letter Knowledge, and Executive Control
Gibson, B. S., Gondoli, D. M., Kronenberger, W. G., Johnson, A. C., Steeger, C. M., & Morrissey, R. A.	36	38	9-16 years	None	Primary and secondary memory of working memory
Green, C. T., Long, D. L., Green, D., Iosif, A., Dixon, J. F., Miller, M. R., Fassbender, C., & Schweitzer, J. B.	12	14	7-14 years	ADHD	Restricted Academic Setting Task Behaviors: off-task, fidgeting, out-of-seat, vocalized, plays with objects, Working Memory, Conner's Parenting Rating Scale-Revised
Hovik, K. T., Saunes, B. K., Aarlien, A. K., & Egeland, J.	33	34	10-12 years	ADHD	Auditory working memory, Visual working memory, and Manipulation working memory
Liu, Z., Glizer, D., Tannock, R., & Woltering, S.	136	41	18-35 years	ADHD	Visual working memory, neural processing during working memory maintenance
Mawjee, K., Woltering, S., Lai, N., Gotlieb, H., Kronitz, R., & Tannock, R.	18	12	18-35 years	ADHD	Executive functioning, academic performance, ADHD symptoms, auditory working memory, visual-spatial working memory.
Mawjee, K., Woltering, S., & Tannock, R.	32	32	18-35 years	ADHD	Working memory, measures of transfer to everyday functioning, academic performance, and ADHD symptomology
Van Dongen-Boomsma, M., Vollebregt, M. A., Buitelaar, J. K., & Slaats-Willemse, D.	50	50	8-12 years	ADHD	Neurocognitive assessment, academic performance, behavior in class, behavior problems, quality of life
Söderqvist, S., & Bergman Nutley, S.	20	22	9-10 years	None	Reading performance, math performance, working memory

*Note: Data utilizing the 60-70 year old population in the study were removed prior to data analysis

Data Extraction

Data was extracted from included studies using the RevMan 5.0 (RevMan, 2014) program. The data was organized by outcome measure and subgroups for analysis.

Outcome Measures

The outcome measures were evaluated by examining the difference between the CMWT intervention group and a Control group on several different domains. Most studies used similar measures for domains, like auditory working memory and visual working memory. In cases where there were multiple measures for a domain, the most proximal assessment information was used as the score for comparison. For example, if a rating scale such as the Conners 3 (Conners, 2016a) was used to measure ADHD related symptoms, the Inattention Scale was pulled specifically as a measure of Inattention rather than a more global scale.

Auditory working memory. Auditory working memory is an individual's ability to manipulate and store auditory information temporarily (Baddeley, 2012). Most of the studies measured auditory working memory using only a few different measures. The most consistently used test involved some type of digits backward or digits sequencing task. For example, several studies used either the Digits Backward subtest from the Wechsler Intelligence Scale for Children (Wechsler, 2003). When there were multiple measures of auditory working memory, the most common metric for measuring this domain was selected for inclusion.

Visual-Spatial working memory. Visual-spatial working memory is an individual's ability to manipulate and store visual information temporarily (Baddeley, 2012). Visual-spatial working memory was also measured using a few different measures. The most commonly used test was from the CANTAB. When there were multiple measures of visual-spatial working memory, the most common metric for measuring visual-spatial working memory was selected for inclusion.

Attention. Attention is an individual's ability to maintain attention during a rote task. Most of the studies measured attention with a few different measures. However, the most commonly used tool to measure attention was the Conners Continuous Performance Test 3rd Edition (Conners CPT 3; Conners, 2016b). When there were multiple measures of attention, the most commonly used tool for measuring this domain was selected for inclusion.

Parent rating of inattention. Parent rating of inattention is a measure of an individual's ability to concentrate, catch careless mistakes, regulate distractibility, or an individual's tendency to give up easily or get bored (Conners, 2016a) based off of a rating scale completed by a parent. The most commonly used tool for measuring parenting ratings of inattention was the Conners 3 (Conners, 2016a). When there were multiple measures used to assess parent ratings of inattention, the most common metric for measuring this domain was selected for inclusion.

Parent rating of hyperactivity. Parent rating of hyperactivity is a measure of an individual's tendency to have high energy levels, be restless or impulsive, and to have have difficulties with being quiet, interrupting others, or being easily excited (Conners, 2016a) based off a rating scale completed by a parent. The most common tool used to measure parent ratings of hyperactivity was the Conners 3 (Conners, 2016a). The most commonly used metric for measuring parent rating of hyperactivity was selected for inclusion when there were multiple measures.

Teacher rating of inattention. Teacher rating of inattention is a measure of an individual's ability to concentrate, catch careless mistakes, regulate distractibility, or an individual's tendency to give up easily or get bored (Conners, 2016a) based off of a rating scale completed by a teacher. The most commonly utilized tool for measuring teacher rating of inattention was the Conners 3 (Conners, 2016a). The most common metric for measuring parent rating of inattention was selected for inclusion when there were multiple measures.

Teacher rating of hyperactivity. Teacher rating of hyperactivity is a measure of an individual's tendency to have high energy levels, be restless or impulsive, and to have difficulties with being quiet, interrupting others, or being easily excited (Conners, 2016a) based off of a rating scale completed by a teacher. The most consistently used assessment tool to measure teacher ratings of hyperactivity was the Conners 3 (Conners, 2016a). When there were multiple measures of parent rating of hyperactivity, the most common metric for measuring this domain was selected for inclusion.

Self-Rating of ADHD symptoms. Self-rating of ADHD symptoms is a measure of an individual's inattentive or hyperactive-impulsive behaviors which interfere with his or her functioning (American Psychiatric Association, 2013) based off of a rating that the individual had completed to evaluate himself or herself. The most commonly used test tool to measure this domain was the Adult ADHD Self-Report Scale–Part A (ASRS-A) (Adler, Kessler, & Spencer, 2013). When there were multiple measures of self-rating of ADHD symptoms the most commonly used measurement was selected for inclusion.

Self-Rating of executive function. Self-rating of executive function is a measure of and individual's inhibition, working memory (WM), and cognitive flexibility skills (Diamond, 2013) based off of a rating that the individual has completed. The common tool used to measure self-ratings of executive function was the Behavior Rating Inventory of Executive Function (BRIEF) (Gioia, Isquith, Guy, & Kenworthy, 2012). When there were multiple measures used for this domain, the most commonly utilized tool was selected for inclusion.

Reading. Reading measures focused mostly on basic reading skills and reading fluency skills. Some of the most common tools used to measure reading skills were Dynamic Indicators of Basic Early Literacy Skills (DIBELS), a reading fluency measure, and a word identification test from the Wide Range Achievement Test 4 (WRAT4; Wilkinson & Robertson, 2006). When multiple measures were utilized to assess this domain, the most common metric was selected for inclusion.

Mathematics. Mathematics measures were mostly focuses on math fluency involving basic operations or math calculation tasks. This included math tasks from measures such as Wide Range Achievement Test 4 (WRAT4; Wilkinson & Robertson, 2006). All of the studies examining CMWT effects on mathematics performance used different measurements.

DATA ANALYSIS

Individual effect size (the standardized mean difference) were based on comparisons between the intervention group (CWMT) and the control group at post-test for a given domain. The inverse-variance method was used to combine the standardized mean differences within each domain. In this approach, the reciprocal of the variance in each study is used to weigh the difference from each condition (intervention versus control) before being combined with the difference from other studies to form an overall estimate. Because of the heterogeneity of the assessments and the demographics of the samples across studies, a random-effects model was chosen a priori, based on recommendations from experts in meta-analytic techniques (Borenstein, Hedges, Higgins, & Rothstein, 2009; Field & Gillet, 2010). I^2 represents the proportion of variation that is a function of heterogeneity. Higher values indicate greater heterogeneity rather than chance. For each domain, results will be interpreted based on Cohen's "Rules of Thumb" for standardized mean difference effect sizes. Effect sizes will be characterized in the following way: .20 reflects a small effect size, .50 reflects a medium effect size, and .80 reflects a large effect size.

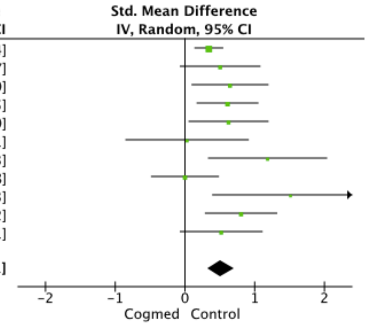
Auditory Working Memory

There were eleven studies (N=909) examining the differences in auditory working memory between the individuals in the CWMT intervention group and individuals in a control group that met inclusion criteria. The overall standard difference effect was moderate and statistically significant (.52. 95% CI .32-.71, z=5.25, p <.001). Heterogeneity across studies was small (I^2 = 34%, X^2 =15, df=10, p =.13). See Figure 2 for the Forest Plot of auditory working memory.

Figure 2: Forest Plot of Auditory Working Memory

Study or Subgroup	Cogmed Mean	Cogmed SD	Cogmed Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Bergman-Nutley, Klingberg 2014	4.1	1.1	153	3.7	1.2	275	22.9%	0.34 [0.14, 0.54]
Bergman-Nutley, Soderqvist, Bryde, ... 2011	17	6	24	14.1	5.3	25	8.3%	0.50 [−0.06, 1.07]
Brehmer, Westerberg, Backman 2012	6.86	1.63	29	5.92	1.18	26	8.9%	0.65 [0.10, 1.19]
Chacko, Bedard, Marks, Feirsen, Uderman, ... 2014	113.15	14.8	44	103.92	15.17	41	11.9%	0.61 [0.17, 1.05]
Foy, Mann 2014	2.05	1.17	23	1.29	1.22	28	8.4%	0.62 [0.06, 1.19]
Gibson, Gondoli, Kronenberger, .. 2013	3.12	19	10	2.54	18	10	4.2%	0.03 [−0.85, 0.91]
Green, Long, Green, Iosif, Dixon, ... 2012	102.3	9.1	12	88	13.5	14	4.4%	1.18 [0.34, 2.03]
Hovik, Saunes, Aarlien, Egeland 2013	8.8	1.7	33	8.8	2.3	34	10.6%	0.00 [−0.48, 0.48]
Mawjee, Woltering, Lai, Gotlieb, ... 2014	12.75	2.49	8	8.78	2.49	9	2.7%	1.51 [0.40, 2.63]
Mawjee, Woltering, Tannock 2015	10.52	2.1	32	8.81	2.1	32	9.7%	0.80 [0.29, 1.32]
Van Dongen, Boomsma, Vollebregt, ... 2014	2.9	0.9	26	2.4	1	21	8.0%	0.52 [−0.07, 1.11]
Total (95% CI)			**394**			**515**	**100.0%**	**0.52 [0.32, 0.71]**

Heterogeneity: $Tau^2 = 0.03$; $Chi^2 = 15.09$, df = 10 (P = 0.13); $I^2 = 34\%$
Test for overall effect: Z = 5.25 (P < 0.00001)



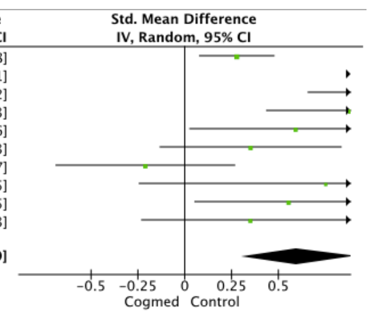
Visual-Spatial Working Memory

Ten studies (N=930) met inclusion criteria that examined the differences of visual-spatial working memory between the individuals in the CWMT intervention group and the individuals in the control group. The overall standard difference effect was moderate and statistically significant (.60 95% CI .30-.89, z=3.96, *p* <.0001). Heterogeneity across studies was substantial (I^2 = 73%, X^2 =33.36, df=9, *p* =.0001). See Figure 3 for the Forest Plot of visual-spatial working memory.

Figure 3: Forest Plot of Visual-Spatial Working Memory

Study or Subgroup	Cogmed Mean	Cogmed SD	Cogmed Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Bergman-Nutley, Klingberg 2014	5.2	1.5	154	4.8	1.4	273	14.0%	0.28 [0.08, 0.48]
Bergman-Nutley, Soderqvist, Bryde, ... 2011	50.6	24.8	24	21.8	7.5	25	8.7%	1.56 [0.91, 2.21]
Brehmer, Westerberg, Backman 2012	7.22	0.97	29	6.17	0.65	26	9.5%	1.24 [0.66, 1.82]
Chacko, Bedard, Marks, Feirsen, Uderman, ... 2014	119.64	20.43	44	102.86	16.89	41	11.2%	0.88 [0.44, 1.33]
Foy, Mann 2014	3.18	1.17	23	2.47	1.19	28	9.7%	0.59 [0.03, 1.16]
Hovik, Saunes, Aarlien, Egeland 2013	11.9	2.7	33	11.1	1.7	34	10.7%	0.35 [−0.13, 0.83]
Liu, Glizer, Tannock, Woltering 2015	0.65	0.23	34	0.7	0.24	34	10.8%	−0.21 [−0.69, 0.27]
Mawjee, Woltering, Lai, Gotlieb, ... 2014	7.75	1.28	8	6.56	1.67	9	5.5%	0.75 [−0.24, 1.75]
Mawjee, Woltering, Tannock 2015	7.16	1.53	32	6.29	1.57	32	10.5%	0.55 [0.05, 1.05]
Van Dongen, Boomsma, Vollebregt, ... 2014	4.9	2.2	26	4.1	2.3	21	9.5%	0.35 [−0.23, 0.93]
Total (95% CI)			**407**			**523**	**100.0%**	**0.60 [0.30, 0.89]**

Heterogeneity: $Tau^2 = 0.15$; $Chi^2 = 33.36$, df = 9 (P = 0.0001); $I^2 = 73\%$
Test for overall effect: Z = 3.96 (P < 0.0001)



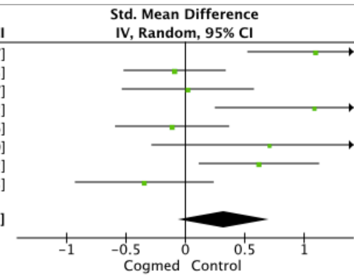
Attention

There were ten studies (N=413), that met inclusion criteria, and that examined the differences in attention between the individuals in the CWMT intervention group and the control group. The overall standard difference effect was small and not statistically significant (.32 95% CI -.06-.70, z=1.64, *p*=.10). Heterogeneity across studies was large (I^2 = 72%, X^2 =24.63, df=7, p =.0009). See Figure 4 for the Forest Plot of attention.

Figure 4: Forest Plot of Attention

Study or Subgroup	Cogmed Mean	Cogmed SD	Cogmed Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Brehmer, Westerberg, Backman 2012	7.14	1.03	29	6.17	0.65	26	13.0%	1.10 [0.53, 1.67]
Chacko, Bedard, Marks, Feirsen, Uderman, ... 2014	4.37	4.55	44	4.83	5.47	41	14.9%	−0.09 [−0.52, 0.33]
Foy, Mann 2014	4.64	50	23	3.93	0.8	28	13.2%	0.02 [−0.53, 0.57]
Green, Long, Green, Iosif, Dixon, ... 2012	22.7	9	12	13.9	6.7	14	9.8%	1.09 [0.25, 1.92]
Liu, Glizer, Tannock, Woltering 2015	0.5	0.26	34	0.53	0.27	34	14.2%	−0.11 [−0.59, 0.36]
Mawjee, Woltering, Lai, Gotlieb, ... 2014	12.5	2.67	8	10.67	2.24	9	8.2%	0.71 [−0.28, 1.70]
Mawjee, Woltering, Tannock 2015	11.32	2.15	32	10.03	1.96	32	13.9%	0.62 [0.12, 1.12]
Van Dongen, Boomsma, Vollebregt, ... 2014	278	97.4	26	311.6	93	21	12.9%	−0.35 [−0.93, 0.23]
Total (95% CI)			**208**			**205**	**100.0%**	**0.32 [−0.06, 0.70]**

Heterogeneity: Tau² = 0.21; Chi² = 24.63, df = 7 (P = 0.0009); I² = 72%
Test for overall effect: Z = 1.64 (P = 0.10)



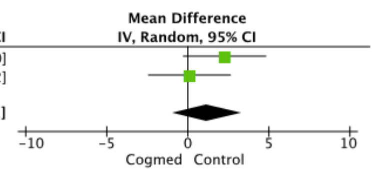
Parent Rating of Inattention

There were two studies (N=132) that examined the differences of parent rating of inattention between the individuals in the CMWT intervention group and the control group. The overall standard difference effect was large and not statistically significant (1.18 95% CI -.95-3.31, z=1.09, p=.28). Heterogeneity across studies was not minimal (I^2 = 29%, X^2 =1.42, df=1, p =.23). See Figure 5 for the Forest Plot of parent rating of inattention.

Figure 5: Forest Plot of Parent Rating of Inattention

Study or Subgroup	Cogmed Mean	Cogmed SD	Cogmed Total	Control Mean	Control SD	Control Total	Weight	Mean Difference IV, Random, 95% CI
Chacko, Bedard, Marks, Feirsen, Uderman, ... 2014	16.51	5.84	44	14.24	6.06	41	49.8%	2.27 [−0.26, 4.80]
Van Dongen, Boomsma, Vollebregt, ... 2014	15	4.7	26	14.9	4.1	21	50.2%	0.10 [−2.42, 2.62]
Total (95% CI)			**70**			**62**	**100.0%**	**1.18 [−0.95, 3.31]**

Heterogeneity: Tau² = 0.69; Chi² = 1.42, df = 1 (P = 0.23); I² = 29%
Test for overall effect: Z = 1.09 (P = 0.28)



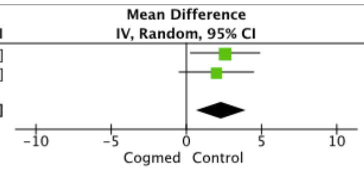
Parent Rating of Hyperactivity

Two studies (N= 132) that met inclusion criteria examined the differences in parent rating of hyperactivity between the individuals in the CMWT intervention group and the control group. The overall standard difference effect was large and statistically significant (2.31 95% CI .63-3.99, z=2.70, p=.007). Heterogeneity across studies was not minimal (I^2 = 0%, X^2 =.11, df=1, *p* =.74). See Figure 6 for the Forest Plot of parent rating of hyperactivity.

Figure 6: Forest Plot of Parent Rating of Hyperactivity

	Cogmed			Control				Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI
Chacko, Bedard, Marks, Feirsen, Uderman, ... 2014	13.9	5.5	44	11.32	5.28	41	53.7%	2.58 [0.29, 4.87]
Van Dongen, Boomsma, Vollebregt, ... 2014	17.4	3.2	26	15.4	5	21	46.3%	2.00 [−0.47, 4.47]
Total (95% CI)			**70**			**62**	**100.0%**	**2.31 [0.63, 3.99]**

Heterogeneity: Tau² = 0.00; Chi² = 0.11, df = 1 (P = 0.74); I² = 0%
Test for overall effect: Z = 2.70 (P = 0.007)



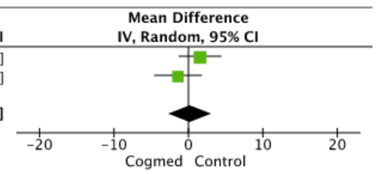
Teacher Rating of Inattention

Two studies (N=132) that examined the differences in teacher rating of inattention between the individuals in the CWMT intervention group and the control group met inclusion criteria. The overall standard difference effect was small and not statistically significant (.17 95% CI -2.73-3.07, z=.12, *p*=.91). Heterogeneity across studies was not minimal (I^2 = 45%, X^2 =1.82, df=1, *p* =.18). See Figure 7 for the Forest Plot of the teacher rating of inattention.

Figure 7: Forest Plot of Teacher Rating of Inattention

	Cogmed			Control				Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI
Chacko, Bedard, Marks, Feirsen, Uderman, ... 2014	15.56	6.66	44	14	6.82	41	53.0%	1.56 [−1.31, 4.43]
Van Dongen, Boomsma, Vollebregt, ... 2014	12.6	6.5	26	14	4.7	21	47.0%	−1.40 [−4.61, 1.81]
Total (95% CI)			**70**			**62**	**100.0%**	**0.17 [−2.73, 3.07]**

Heterogeneity: Tau² = 1.97; Chi² = 1.82, df = 1 (P = 0.18); I² = 45%
Test for overall effect: Z = 0.12 (P = 0.91)



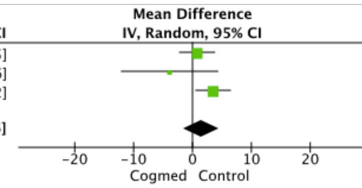
Teacher Rating of Hyperactivity

Three studies (N=158) that met inclusion criteria had examined the differences in teacher rating of hyperactivity between the individuals in the CWMT intervention group and the control group. The overall standard difference effect was large and not statistically significant (1.45 95% CI -1.57-4.46, z=.94, *p*=.35). Heterogeneity across studies was not minimal (I^2 = 45%, X^2 =3.36, df=2, *p* =.16). See Figure 8 for the Forest Plot of teacher rating of hyperactivity.

Figure 8: Forest Plot of Teacher Rating of Hyperactivity

	Cogmed			Control				Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI
Chacko, Bedard, Marks, Feirsen, Uderman, ... 2014	11.36	6.77	44	10.58	7.15	41	43.9%	0.78 [−2.19, 3.75]
Green, Long, Green, Iosif, Dixon, ... 2012	67	12.2	12	70.9	8.3	14	11.6%	−3.90 [−12.06, 4.26]
Van Dongen, Boomsma, Vollebregt, ... 2014	15	5.3	26	11.5	4.9	21	44.5%	3.50 [0.58, 6.42]
Total (95% CI)			**82**			**76**	**100.0%**	**1.45 [−1.57, 4.46]**

Heterogeneity: Tau² = 3.11; Chi² = 3.63, df = 2 (P = 0.16); I² = 45%
Test for overall effect: Z = 0.94 (P = 0.35)



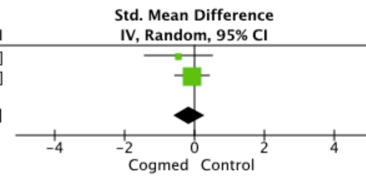
Self-Rating of ADHD Symptoms

There were two studies (N=81) that examined the differences in self-rating of ADHD symptoms between the individuals in CWMT intervention group and the control group met inclusion criteria. The overall standard difference effect was small and not statistically significant (-.15 95% CI -.59-.29, *z*=.67, *p*=.5). Heterogeneity across studies was not minimal (I^2 = 0%, X^2 =.50, df=1, *p* =.48). See Figure 9 for the Forest Plot of self-rating of ADHD symptoms.

Figure 9: Forest Plot of Self-Rating of ADHD Symptoms

	Cogmed			Control				Std. Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI
Mawjee, Woltering, Lai, Gotlieb, ... 2014	46.57	8.44	8	51.44	11.23	9	20.4%	−0.46 [−1.43, 0.51]
Mawjee, Woltering, Tannock 2015	46.48	9.89	32	47.25	11.51	32	79.6%	−0.07 [−0.56, 0.42]
Total (95% CI)			**40**			**41**	**100.0%**	**−0.15 [−0.59, 0.29]**

Heterogeneity: Tau² = 0.00; Chi² = 0.50, df = 1 (P = 0.48); I² = 0%
Test for overall effect: Z = 0.67 (P = 0.50)



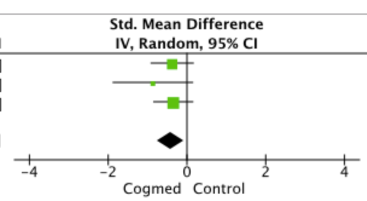
Self-Rating of Executive Function

Three studies (N=136) examined the differences in self-rating of executive function between the individuals in CWMT intervention group and the control group met inclusion criteria. The overall standard difference effect was small and not statistically significant (-.42 95% CI -.76-(-.08), z=2.40, *p*=.02). Heterogeneity across studies was not minimal (I^2 = 0%, X^2 =.86, df=2, *p* =.65). See Figure 10 for the Forest Plot of self-rating of executive function.

Figure 10: Forest Plot of Self-Rating of Executive Function

	Cogmed			Control				Std. Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI
Brehmer, Westerberg, Backman 2012	25.55	12.94	29	30.27	11.78	26	40.8%	−0.38 [−0.91, 0.16]
Mawjee, Woltering, Lai, Gotlieb, ... 2014	41.71	12.15	8	52.88	12.33	9	11.5%	−0.87 [−1.87, 0.14]
Mawjee, Woltering, Tannock 2015	49.9	9.22	32	53.32	10.2	32	47.7%	−0.35 [−0.84, 0.15]
Total (95% CI)			**69**			**67**	**100.0%**	**−0.42 [−0.76, −0.08]**

Heterogeneity: Tau² = 0.00; Chi² = 0.86, df = 2 (P = 0.65); I² = 0%
Test for overall effect: Z = 2.40 (P = 0.02)



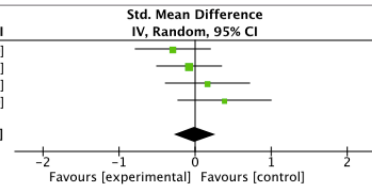
Reading

Four studies (N=242), which met inclusion criteria, examined the differences in reading skills between the individuals in the CWMT intervention group and the control group. The overall standard difference effect was small but not statistically significant (0 95% CI -.27-.27, z=0, *p*=1). Heterogeneity across studies was not minimal (I^2 = 11%, X^2 =3.36, df=3, *p* =.34). See Figure 11 for the Forest Plot of reading skills.

Figure 11: Forest Plot of Reading

Study or Subgroup	Cogmed Mean	Cogmed SD	Cogmed Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Mawjee, Woltering, Tannock 2015	148.78	17.03	32	153.58	15.25	32	26.4%	−0.29 [−0.79, 0.20]
Chacko, Bedard, Marks, Feirsen, Uderman, ... 2014	499	26.66	44	501.06	24.83	41	34.1%	−0.08 [−0.50, 0.35]
Foy, Mann 2014	42.86	13.29	23	40.29	17.14	28	21.5%	0.16 [−0.39, 0.72]
Soderqvist, Bergman-Nutley 2015	0.19	1.24	20	−0.2	0.69	22	17.9%	0.39 [−0.23, 1.00]
Total (95% CI)			**119**			**123**	**100.0%**	**−0.00 [−0.27, 0.27]**

Heterogeneity: $Tau^2 = 0.01$; $Chi^2 = 3.36$, df = 3 (P = 0.34); $I^2 = 11\%$
Test for overall effect: Z = 0.00 (P = 1.00)



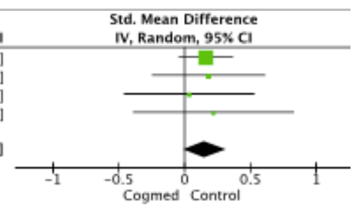
Mathematics

There were four studies (N=593) that examined the differences in mathematics skills between the individuals in the CWMT intervention group and the control group. The overall standard difference effect was small and not statistically significant (.15 95% CI -.01-.32, z=1.83, *p*=.07). Heterogeneity across studies was not minimal (I^2 = 0%, X^2 =.29, df=3, *p* =.96). See Figure 12 for the Forest Plot of mathematic skills.

Figure 12: Forest Plot of Mathematics

Study or Subgroup	Cogmed Mean	Cogmed SD	Cogmed Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Bergman-Nutley, Klingberg 2014	15.8	7	149	14.6	7.7	253	66.3%	0.16 [−0.04, 0.36]
Chacko, Bedard, Marks, Feirsen, Uderman, ... 2014	493.9	24.47	44	489.78	20.12	41	15.0%	0.18 [−0.24, 0.61]
Mawjee, Woltering, Tannock 2015	115.55	22.25	32	114.66	28.7	32	11.3%	0.03 [−0.46, 0.52]
Soderqvist, Bergman-Nutley 2015	0.12	0.95	20	−0.11	1.1	22	7.4%	0.22 [−0.39, 0.83]
Total (95% CI)			**245**			**348**	**100.0%**	**0.15 [−0.01, 0.32]**

Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 0.29$, df = 3 (P = 0.96); $I^2 = 0\%$
Test for overall effect: Z = 1.83 (P = 0.07)



DISCUSSION

Cogmed Working Memory Training (CWMT) is a computer-based cognitive training program that is accessible from the internet and targets WM skills (Pearson Education, Inc., 2014). There is a considerable amount of variability in the existing research on the effectiveness of CWMT. The program is advertised to increase WM capacity in individuals with a deficit in their WM skills. However, the research that has been conducted on the intervention program is not conclusive. CWMT has been a program that has existed for 15 years. It has been evaluated in numerous studies since it was developed, and the results have not given a clear picture of the efficacy of the program.

Previous meta-analyses on CWMT have found that there is no impact on reasoning ability, symptoms of ADHD, transfer effects on WM capacity, verbal ability, word reading, or arithmetic (Melby-Lervag & Hulme, 2013; Shipstead, Hick, & Engle, 2012). They did find immediate gains on verbal working memory and visual-spatial working memory, but it did not maintain at follow up (Melby-Lervag & Hulme, 2013; Shipstead, Hick, & Engle, 2012). These analyses were conducted on research published prior to 2011. The purpose of this study was to update the meta-analytical review on the impact of CWMT on specific subgroups of data regarding targeted areas. The first area was auditory working memory. Consistent with previous research, the current meta-analysis indicated that CWMT has a moderate impact on auditory working memory. It is interesting that though, previous meta-analyses and studies have expressed concern over lack of generalization or long-term effect, only 7 of the 13 studies included in the current meta-analysis examined generalization beyond clinical measures or the long-term effects.

The two previous meta-analyses reported gains on visual-spatial working memory tasks after intervention, however, these gains were not maintained at follow up (Melby-Lervag & Hulme, 2013; Shipstead, Hick, & Engle, 2012). Once again consistent with the previous research, our meta-analysis revealed a moderate effect on visual-spatial working memory, but this difference was seen during post-tests at the end of intervention. This moderate impact on visual-spatial working memory skills will also most likely not generalize to outside uses of WM. There is again very little research that has examined generalization of these visual-spatial working memory skills and long-term effects.

The previous meta-analyses found a small effect on attention, but it did not sustain at follow up (Melby-Lervag & Hulme, 2013; Shipstead, Hick, & Engle, 2012). Our meta-analysis also found that the effect of CWMT on attention skills was not statistically significant. These results could be because attention was not measured precisely enough, or because there is no impact on attention skills. Interestingly, our results also failed to find any significant effect on teacher ratings of inattention or self-ratings of ADHD symptoms. In contrast, our meta-analysis indicated a large effect of CWMT for parent ratings of attention for the intervention group in comparison to the control group. Due to the fact that parents were not blind to the condition that their child was involved in in both of the studies, this finding brings into question whether placebo effects are a concern with parent ratings when they know if their child is in the intervention versus the control group. Across the measures of attention (clinical tests, teacher ratings, self-report of ADHD symptoms, and parent ratings), it appears unlikely that CWMT has short-term positive effects on attention. This may not be unexpected as the program is not explicitly designed to improve attention. That said, attention and working memory are moderately correlated (Archibald, Levee & Olino, 2015); so we may expect to see some carry-over effect of an intervention targeting working memory on attention. CWMT also had a small effect on self-rating of executive functioning. However, this may too possibly be a result from a placebo effect after the individual has gone through the intervention program.

Teacher and parent ratings of hyperactivity showed large statistically significant impacts from CWMT. However, there were only two studies included in the meta-analysis that examined parent and teacher ratings of child symptoms. Once again, the teachers and parents were not blind to the child's participation in the intervention group for one of the two studies. Therefore, this could also be due to a bias in parent and teacher perception based on expectations with the student being in the CWMT group.

There were no demonstrated effects from CWMT on reading or mathematic skills. This finding is also related to the finding of previous meta-analyses that failed to find significant impacts on reading or mathematic skills (Melby-Lervag & Hulme, 2013). It has been noted in previous studies that working memory and academic performance are closely correlated (Gathercole, Pickering, Knight, & Stegmann, 2004). Working memory can influence and individual's ability to hold pertinent information in his or her mind to apply rules and skills while reading and completing mathematical problems. Hence, CWMT influence on reading and mathematical skills was an important are to examine.

LIMITATIONS OF STUDY

As with any study, the current meta-analysis was subject to many limitations. The first limitation is that we did not include any unpublished studies, with the exception of one dissertation. This is a major limitation due to the fact that studies that did not find significant results are less likely to get published. Therefore, our results may be inflated. As the internet continues to expand our resources, it might be interesting for someone to develop a repository for peer-reviewed, non-significant findings to be stored. This would help researchers access relevant studies for meta-analyses and limit the likelihood for inflation.

Research that was published in a language other than English was not included in the study. This is also a significant limitation because CWMT was developed in Europe and there is considerable research examining the program in other countries. Another limitation was that there were too few of studies that met inclusion criteria to examine subgroups. It would have been interesting to tease apart efficacy by looking at specific subgroups (e.g., early elementary children with a previous diagnosis of ADHD compared to older children with a previous diagnosis of ADHD). This type of analysis was not possible as the number of studies was limited for specific demographics.

An additional limitation that was experienced was a lack of consistency between control groups. Some studies used wait-list control groups, while other studies used a CWMT placebo-training program. CWMT is one of the programs that include a specific placebo group so that research can easily examine the efficacy of the program. That said; several studies opted to use a wait-list no-intervention period as a control. This is problematic as placebo effects have been demonstrated in previous research, and a wait-list group will not be prone to this tendency since they are not blind to their condition. This inconsistency between studies made comparison between control groups more difficult. Lastly, we did not examine generalization of impacts or if these impacts continue to exist over time. This was an important limitation as it has been a steady criticism of computerized interventions for working memory. We were not able to look at generalization beyond immediate measures of reading and math since only one study considered generalization or long-term effects.

SUGGESTIONS FOR FUTURE RESEARCH

Research regarding the effectiveness of the computer-based cognitive training program CWMT still has a long way to go. There are many different areas regarding CWMT that could be studied to help add to the body of literature that already exists. An increase in research regarding different subgroups would be beneficial so that differences in age groups, clinical ADHD diagnoses, or individuals with traumatic brain injuries could be examined. Or are there interactions between things like age of the child, condition, and length of CWMT? This might be interesting given the developmental trajectory of working memory.

There were also several studies that were conducted using an adaptive version of CWMT that is shorter. This is an area that should be investigated more thoroughly. The CWMT suggests that you can do a modified, shorter version, but do we have the evidence to demonstrate that this can be effective? Much of the research on computer-based interventions for working memory makes comparisons between the program and a computer-based placebo. It would be interesting to see if overt strategy training would be useful in comparison to CWMT, or if overt strategy training could supplement CWMT to make the changes less incidental. Such as, if an individual is taught how to use rehearsal strategies or mnemonic devices that are known to be effective at helping WM skills would that training be more useful? Would individuals be more likely to employ the working memory strategies if they verbally mediated them or if they could understand the mechanism by which the strategy helps them? Could we also look at trying to modify CWMT such that individuals learn how to generalize the findings to tasks outside of the training through the use of overt strategy development in conjunction with the training?

SUMMARY

The results of the current meta-analysis are consistent with previous studies that suggest small to moderate effects on working memory. There was also no effect found on attention or reading and mathematic skills. Even though previous studies have stressed the poor generalization and long-term maintenance of newly developed skills, few studies have addressed this concern with improved research designs.

It is well shown by research that WM impacts many areas of an individual's life. Research also indicates that WM deficits are related to certain disorders, such as ADHD. However, research on CWMT has failed to demonstrate large effects on WM and related skills. Since we know there are many groups that would benefit from an effective WM training program, it would be useful to find a way to improve CWMT and related programs.

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