Article ▸ # Working Memory – Theory, Deficits, Diagnosis, and Vision Therapy

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## ABSTRACT

Working memory (WM) is one of the most significant psychological ideas developed in the last forty years. WM is the cognitive function responsible for storing information, manipulating it, and using it in thinking. WM is a multidimensional system comprising three separable yet interactive domains. They are an executive domain and verbal and visual domains. Working memory affects many perceptuo-cognitive activities, and WM deficits can create a variety of problems, many of which fall under the domain of developmental optometry. Research has repeatedly affirmed the hypothesis that WM underlies individual differences in learning ability. The disabilities affected by WM range from ADHD to learning disabilities to traumatic brain injury. Fluid intelligence and working memory have generated much interest and a significant amount of literature. Many studies show that WM training increases fluid intelligence, but others do not agree.

A number of WM tests have been produced over the years. A battery of tests should be utilized by practitioners to ensure all aspects of WM. A variety of therapeutic procedures have been developed mostly by psychologists and some educators for improving WM deficits. Techniques that have achieved the best results involve implicit computerized therapy. To determine whether a WM test or therapy technique is truly WM, it must meet one or more of the following requirements: 1. Is any manipulation or transformation of the information required? 2. Is any concurrent or intervening processing required? 3. Are both storage and processing required? 4. Does the task involve the concurrent retention of both visuospatial and verbal information or the recoding of one modality to another?

While most developmental optometrists use perceptuo-cognitive tests and therapy materials, some of which touch on WM, many optometrists are not conversant enough with the concepts of WM and how it can benefit our optometric vision therapy patients.

**Keywords:** computer-based vision therapy, vision therapy, working memory

## Introduction

Joshua Foer[1] is the author of *Moonwalking With Einstein – The Art and Science of Remembering Everything* and was a finalist in the U.S. Memory Championship. He chose the legend of Simonides as the preface for his popular book.

*There were no other survivors.*

*Family members arriving at the scene of the fifth-century banquet catastrophe pawed at the debris for signs of their loved ones---rings, sandals, anything that would allow them to identify their kin for proper burial.*

*Minutes earlier, the Greek poet Simonides of Ceos had stood to deliver an ode in honor of Scopas, a Thessalian nobleman. As Simonides sat down, a messenger tapped him on the shoulder. Two young men on horseback were waiting outside to tell him something. He stood up again and walked out of the door. At the very moment he crossed the threshold, the roof of the banquet hall collapsed in a thundering plume of shards and dust.*

*He stood now before a landscape of rubble and entombed bodies. The air which had been filled with boisterous laughter moments before was smoky and silent. Teams of rescuers went to work frantically, digging through the collapsed building. The corpses they pulled out of the wreckage were mangled beyond recognition. No one could say for sure who had been inside. One tragedy compounded another.*

*Then something remarkable happened that would change forever how people would think about their memories. Simonides sealed his senses to the chaos around him and reversed time in his mind. The piles of marble returned to pillars and the scattered frieze fragments reassembled in the air above. The stoneware shattered in the debris re-formed into bowls. The splinters of wood poking above the ruins once again became a table. Simonides caught a glimpse of each of the banquet guests at his seat, carrying on oblivious to the impending catastrophe. He saw Scopas laughing at the head of the table, a fellow poet sitting across from him sponging up the remnants of a meal with a piece of bread, a noblemen smirking. He turned to the window and saw a messenger approaching, as if with some important news.*

*Simonides opened his eyes. He took each of the hysterical relatives by the hand, and carefully stepping over the debris, guided them, one by one to the spots in the rubble where their relatives had been sitting.*

*At that moment, according to legend, the art of memory was born.*

Simonides' legendary feat is a classic example of a remarkable working memory. During his ode to Scopas, while facing the entire room and the guests, he used his short term memory. After the catastrophe, he called his working memory into play, and he was able to reconstruct every detail of the room, including where the guests were seated. Working memory enabled him to provide solace to all of the distraught relatives.

**What is Working Memory?**

Working memory is the cognitive function responsible for storing information over a brief time, manipulating it, and using it in thinking. It is typically measured by dual tasks, in which an item must be remembered while simultaneously processing an unrelated task. Working memory is necessary for staying focused on a task, blocking out distractions, and keeping updated and aware about what's going on around us. It is a critical contributor to such essential cognitive functions and properties as language comprehension, learning, planning, reasoning, spatial relations, visualization, and general fluid intelligence.[2] Working memory is the central cognitive factor in human information processing and may, to a large extent, account for individual differences in intellectual functioning. WM is independent of IQ and appears to be relatively unaffected by environmental and familial influences.[3] It serves as an essential workspace for the mind, allowing for the active maintenance of information to support short-term cognitive goals.[4]

Working memory is used constantly in daily life, helping us to perform efficiently and effectively in academic, professional, and social settings. Mental arithmetic is a typical example of working memory. Solving the arithmetic problem 45 x 67= ? presented to you verbally, without being able to use a calculator or pencil and paper, requires WM. Working memory is the search engine of the mind.

The term WM refers to the capacity to store and to manipulate information over brief periods of time. Working memory is more than just the ability to remember a series of numbers long enough to repeat them. It is the capacity to manipulate the information you are holding in your mind. Working memory is a multidimensional system comprising three separable yet interactive mechanisms.[5] One is a domain-general central executive responsible for coordinating and controlling the different activities within WM. The executive has finite attentional resources and mental energy capacity that are controlled in a flexible manner. Attentional control is a key factor in WM, and its regulatory functions include allocating mental energy, attention switching to different levels of a task, sustained attention in the midst of interference, and focusing attention by blocking irrelevant stimuli from WM.

The second and third mechanisms are two domain-specific storage devices. One, verbal WM, is devoted to the manipulation and transformation of verbal material. It stores phonological and specific language information[6] and prevents its decay by continually articulating its contents. The second, visuospatial WM, is involved in the analysis, manipulation, and transformation of visual material. It is used for constructing and manipulating visual images and/or the representation of spatial maps. It can be further broken down into a visual subsystem dealing with a "what" visual component (pattern, shape, color, texture, etc.) and a spatial subsystem dealing with a "where" component (location, movement, orientation).[7] It is vital for mathematical concepts. Working memory components are said to be in place by four years of age.[8] Kandell,[9] a Nobel Prize winner, writes that "working memory is known to be critically dependent on the prefrontal cortex, a part of the frontal lobe that mediates our most complex mental processes. When we are challenged by a task that requires working memory, metabolic function in [the] prefrontal areas increases dramatically."

**Impact of Working Memory Deficits**

**Learning Disability**

The children in Nathan's class were asked to identify the rhyming words in a text read aloud by the teacher. They had to wait until all four lines had been read before telling the teacher the two words that rhymed: tie and fly. This task involves matching the sound structures of a pair of words and storing them. Nathan was unable to do this, although he was able to remember two words under conditions where no concurrent processing was required. Nathan has a verbal WM deficit.

Jay, a ten-year-old, still struggles with basic arithmetic. Learning to tell time is very hard, and he has a lot of trouble with half-past. Arithmetic problems are very difficult, and he tends to transpose numbers. He has right-left confusion and other spatial problems. Jay has a visuospatial WM deficit.

Jane's teacher asked the class to open their science book to page 96, to look at the two photographs of groups of children, and to decide which photo had more boys than girls. Jane could not complete the task because she lost attention while the teacher was speaking and did not know what to do. Jane has an executive WM deficit.

Nathan, Jay, and Jane exhibit specific WM deficits that relate to learning disability. Poor WM affects approximately 8-10% of children. Working memory capacity, both short term and long term, is more highly related to learning than any other cognitive factor.[10] Research has repeatedly affirmed the hypothesis that WM underlies individual differences in learning ability.[11] A recent study[12] screened over 3000 school-aged students in mainstream schools. Ten percent were identified as having WM difficulties, with a majority performing below average in reading and mathematics. Working memory is required for all learning because learning requires manipulation of information, interaction with long term memory, and simultaneous storage and processing of information. Nearly all of what must be learned and remembered must pass through WM. Working memory capacity also predicts performance on a wide range of real life cognitive tasks.[13] Working memory performance was examined[14] in children ages 11-12 years who had borderline, mild, and moderate learning disabilities. Children of average abilities were used as a control group. Children with mild and moderate learning problems on all measures of WM were compared to children of average ability. Those with borderline learning problems showed WM deficits only in the verbal loop. For the group as a whole, WM was strongly related to mental age. Swanson[15] found that ten-year-old children with a reading or math learning disability were not differentiated by their performance on verbal and visuospatial WM measures. Swanson and Siegel[16] believe that intrinsic WM limitations are the primary cause of learning disabilities.

Very low levels of performance on WM tasks are common in children with reading difficulties.[17] Children with specific language impairments exhibit significant WM deficits relative to same-age peers. Dyslexia is a very common learning disability; 7% of children suffer from dyslexia. It is commonly defined as a difficulty in learning to read that cannot be accounted for by limited intelligence, poor instruction, sociocultural opportunity, emotional factors, or other extraneous factors. It has been defined by Berninger et al.[18] as a specific learning disability with underachievement relative to verbal intelligence and one or more of the following skills: accuracy of rate of oral reading of words on lists or connected text in passages or spelling. They put forth a theoretical framework of three WM components that provide a systematic perspective for discussing past and new findings. This framework points to heterogeneity in the genetic and brain basis and behavioral expression of dyslexia and postulates impairment in any one or a combination of the three working memory components in dyslexia. This WM tripartite consists of: 1. Time-sensitive Phonological (verbal WM); 2. Orthographic (visual WM); and 3. Executive WM functions such as rapid automatic switching of attention. Optometrists use a variety of theories, techniques, procedures, and instrumentation in the management of dyslexia.[19] Dyscalculia or mathematics learning disability (MLD) is defined as a specific learning disability affecting the normal acquisition of arithmetic skills.[20] There is no single form of MLD, and it can change throughout a lifetime, according to the National Center for Learning Disabilities. The incidence of MLD is between 6-7% of the population.[21] This is unfortunate, because math skills are of prime importance in everyday life, enabling us to understand number concepts and do calculations. Math ability is essential for many occupations and professions. Many investigations have consistently found WM as a central deficit in children with mathematical disabilities.[22] All three components of the WM system play a major role in math disability.[23] Optometric interest in MLD has been mainly limited to deficiencies in various visual perception skills. Flax[19] discusses the relationship of visual factors in mathematics and points out that those children who are unable to visualize spatially may have difficulty acquiring fundamental understanding of such subjects as trigonometry and geometry. Research and clinical experience has shown the importance of spatial relations and simultaneous processing in math.[24-25] Subitizing is the immediate visual perceptual apprehension and enumeration of a small set of elements. Subitizing deficits are correlated with difficulty in math at all ages. Groffman,[27] following Fischer's[28] concept, has designed a subitizing computer program that is vision therapy for math deficits. Visuospatial working memory should be included in vision therapy for MLD.

**Developmental Disorders**

In a recent book, Temple Grandin, a friend of developmental optometry, describes her difficulty with working memory despite her excellent vsual memory.[29]

*I know that my short term memory is horrible, which isn't unusual among high-functioning autistics. We're not good at multitasking. We have poor memory for faces and names. And sequencing? Forget it. A 1981 study showed that high-functioning children with autism remembered significantly less about recent events than normal age-matched and mentally handicapped age- and ability-matched control subjects. In a 2006 study of 38 high-functioning autistic children and 38 controls, the most reliable and accurate test to distinguish between the 2 groups was the Finger Winows subtest—a measure of visual spatial memory in which the experimenter touches a series of pegs on a board and the subject has to duplicate the pattern sequence. The controls easily outperformed the high-functioning autistics. When I took this test, I trashed it; it placed too much of a load on my working memory.*

Working memory disorders are found in a number of psychological and neurological disorders.[32] Attention Deficit Hyperactivity Disorder (ADHD) has been closely associated with WM deficits.[33-35] A paper by Klinberg et al.[36] describes computerized WM training programs for subjects with ADHD. Their results demonstrate that WM can be significantly improved along with tasks related to prefrontal functioning. It also had a significant effect on motor activity in ADHD. They concluded that WM training could be of clinical use for ameliorating the symptoms in ADHD.

Working memory studies involving subjects with autism have been inconsistent, but recent studies demonstrate reduced spatial working memory abilities and extend previous findings by demonstrating that these findings are significant when tasks impose heavier demands on WM.[37] Steele et al.[38] found that autistic subjects had deficits in spatial WM and attributed it to the involvement of the prefrontal cortex in spatial WM.

Williams syndrome is a rare genetic disorder characterized by physical anomalies, a friendly personality, and an uneven cognitive profile. These patients show strong skills in social interaction, including visual tasks such as face recognition, and severe deficits in other types of visuospatial processing such as block construction and drawing tasks.[39] O'Hearn et al.[40] explored whether the uneven deficit in visuospatial tasks evident in Williams syndrome extends to WM, with memory for location more impaired than object/face identification. They concluded that there is an overall WM impairment in Williams syndrome.

Down syndrome (DS) is caused by abnormalities of chromosome 21; in 95% of cases the specific chromosome has an extra part. It affects about 1 in 1000 live births. The great majority of people with DS have mild to severe levels of intellectual impairment and a wide range of associated physical, medical, and cognitive deficits. A recent analysis of WM in DS children[41] revealed deficits in central executive WM and verbal WM. Visuospatial WM was not affected.

Cognitive impairments in schizophrenia have been recognized as a prominent feature of the illness. There is solid neuropsychological evidence that patients with schizophrenia demonstrate deficits in all subsystems of WM but are consistently more impaired in spatial WM. Cognitive exercises may improve WM in schizophrenia.[42,43]

Memory impairments constitute an increasing problem with advancing age. There is also an age-related decrement in WM that is generally associated with slowing speed of processing,[44] which would reduce the speed in which information is processed in WM. Ozen et al.[45] found similar executive function and WM deficits in healthy older adults and younger adults with traumatic brain injury (TBI). In a Swiss study,[46] 80-year-old adults received WM training twice a week for three months. The results indicate overall increased memory performance that was especially pronounced in visual WM. After one year, the increases in WM were still present.

**Traumatic Brain Injury**

Disturbances in memory functioning are among the most marked and persistent sequelae in TBI. The effects of this impairment on individuals have been found to be long-term, debilitating, and a major obstacle to rehabilitation.[47] Many researchers point to memory loss as being the most common symptom following mild, moderate, and severe brain injury.[48] Memory deficits due to TBI have been reported to occur in 69% to 80% of victims. Traumatic brain injury in the U.S. has been estimated to result in over 70,000 new cases of disability each year, including a disproportionately large number of teenagers and young adults.[49] Impairments in WM are the core component of the cognitive deficits associated with TBI.[50] Working memory is particularly vulnerable to disruption after TBI.[51] Visual WM deficits consistently occur in athletes who suffer multiple concussions. A history of multiple concussions also significantly increases the severity of the deficit.[52] A study[53] exploring the effect of severe traumatic brain injury on WM found that verbal and visuospatial WM showed only marginal group differences compared with a control group. However, the TBI group was much poorer on central executive WM than the control group. These results suggest that severe TBI is associated with an impairment of executive WM. A computerized WM training program was used with a group of adult stroke patients and a control group. The intervention involved therapy on various WM tasks for five weeks. Statistically significant therapy effects were found on non-trained WM tests and attention. There was also a significant decrease in symptoms of cognitive problems. They concluded that more than one year after a stroke, systematic WM therapy can significantly improve WM and attention.[54]

**Attention**

During the last decade, one of the most contentious and heavily studied topics in the attention literature has been the role that WM plays in controlling perceptual selection. The hypothesis has been advanced that in order to have attention select a certain perceptual input from the environment, we only need to represent that item in WM.[55]

**Does Working Memory Training Work?**

This question was asked and answered by Morrison and Chein.[56] They feel that there is theoretical justification for training WM because it has been extensively characterized as a construct vital to higher cognition. The approaches to training WM can be readily classified according to their focus on domain-specific or domain-general components of the WM system. Specifically, one class of training involves explicit training intended to promote the use of supplemental domain-specific strategies that might allow patients to remember increasing amounts of information of a particular type.[57] Explicit or strategy training, such as rehearsal, chunking, and metacognitive strategies, is a conscious strategy. In contrast, implicit or core training[58] involves repetition of demanding WM tasks designed to target domain-general WM mechanisms. A variety of vision therapy modalities may be adapted for WM training:[59] motoric techniques including chalkboard exercises and gross and small motor techniques; manipulatives such as concrete table top items like pegboard pattern reproduction, parquetry blocks, tangram, and memory games; auditory memory procedures such as repeating stimuli backwards, rapid automatized naming, solving arithmetic problems orally; and workbooks with memory material. In my experience, it is difficult to adapt these VT modalities for WM; they can be awkward to use and do not provide intensive therapy. My opinion is that they are very valuable for Visual Information Processing and have some home therapy value for WM therapy. A large majority of the articles cited in this paper and in the literature utilize computerized techniques for WM experiments and therapy.

Implicit training uses computerized tasks with feedback and rewards based on the accuracy of every trial. Some studies have shown that implicit therapy improves not only the specific WM component that was targeted; fMRI measurements of brain activity before, during, and after training indicate increased brain activity related to WM in the middle frontal gyrus and superior and inferior parietal gyrus.[60] These findings show that the improvements in the problem areas presented by the patients result from computerized implicit WM therapy.

Some studies of explicit training suggest that it could provide a means of improving WM in young children. However, there is mixed evidence of transfer of benefits to other tasks. Morrison and Chein[44] answer their question of whether WM training is successful as follows: "In the case of core (implicit) training our answer is a tentative yes. Studies of core training show that improvements in a variety of areas of cognition (e.g. cognitive control, reading comprehension) persist even with the use of tightly matched controls and are consistent with neuroimaging studies demonstrating activation changes in regions associated with domain general cognitive performance. Implicit WM training thus represents a favorable approach to achieve broad cognitive enhancement." Takeuchi et al.,[61] in a comprehensive review of the WM literature, found that WM plays a key role in a wide range of higher-order cognitive functions and its impairment in a wide range of psychiatric or neurological disorders, making it clinically important. Training of WM is associated with a wide range of clinical improvements in clinical and non-clinical subjects. In clinical studies, training of WM was associated with an improvement of clinical symptoms outside of the laboratory. Neuro-imaging studies of WM training revealed the effect of WM training on the neural systems of the frontal-parietal network, which plays a role in WM. A number of important issues remain uninvestigated, but they anticipate that future studies will solve those issues.

**Fluid Intelligence and Working Memory**

In over 30 years of extensive research, psychologist Raymond Cattell and colleagues concluded that general intelligence consisted of two correlated subtypes of mental ability, crystallized intelligence (Ge) and fluid intelligence (Gf).[62] Fluid intelligence is a complex ability that allows us to adapt our thinking to a new cognitive problem or situation. It is the capacity to think logically and to solve problems in novel situations, independent of acquired knowledge. It is the ability to analyze novel problems, to identify patterns and relationships that underpin these problems. It is necessary for all logical problem solving. Gf includes inductive reasoning and deductive reasoning. It generally correlates with measures of abstract reasoning and puzzle solving.[63,64] Crystallized intelligence is the ability to use skills, knowledge, and experience. Ge is one's lifetime or intellectual achievement indicated by an individual's general knowledge, vocabulary, and the ability to reason.[65] Decades of research ranging from empirical to brain behavior studies have shown a strong link between working memory and intelligence.[66] Fry and Hale[67] assessed processing speed, working memory capacity, and fluid intelligence in a large sample aged 7-19 years. Their analyses revealed that almost half of the age-related increase in fluid intelligence was mediated by developmental changes in processing speed and WM. Another study investigated how WM and Gf are related in young children and how these links relate in time. The data showed that working memory, short-term memory, and fluid intelligence were highly related but separate constructs in young children. However, when short term memory and working memory were controlled, the WM manifested significant links with Gf while the short-term memory did not. It has been suggested[68,69] that since WM and Gf are closely related, WM therapy may improve Gf.[70] Jaeggi et al. in their well-known experiment present evidence for transfer from training on a demanding WM task to measures of Gf. This transfer results even though the trained task is entirely different from the fluid intelligence test itself. Another significant finding was that the extent of gain in Gf critically depends on the amount of therapy; the more training, the more the gain in fluid intelligence. The study and its results have met with some criticism primarily because of a lack of an active placebo, even though the critic[71] did not question the obtained results. Moody[72] put forward more strict criticism. His main objection was that different tests were used for the so-called control group and the experimental group, where individuals were tested with an alternative test with a time restriction that may have biased results. In Moody's opinion, this brings into question the results and inferences reported in the study. Jausovec and Jausovec cleverly designed a study to investigate whether training on WM could improve Gf and what effects WM training had on brain activity. Further, the experiment was designed to eliminate some of the criticisms by Moody and Sternberg of Jaeggi's study. They concluded that the results lend further support to the hypothesis that WM training can improve Gf, which is also reflected in changed brain activity.

The New York Times Magazine section of April 18, 2012 published an article by Dan Hurley titled *Can You Make Yourself Smart?* It is an excellent article regarding working memory and fluid intelligence.

The Scientific American magazine issue of April 15, 2013 published an excellent article by Scott Barry Kaufman titled *In Desfense of Working Memory Training.*

It is very worthwhile reading.

**Working Memory Assessment**

Before starting a WM therapy program, it is advisable to use specific diagnostic procedures. It is important that more than one test be used to diagnose WM issues. The tests should cover the three aspects of WM: visual, phonological, and executive. There are seven tests that provide tests for all aspects of WM. They are easy to obtain and to administer. The PTS Test battery (Computerized Perceptual Therapy Assessment), designed by the author and produced by HTS,[A] has three useful tests. Two of them are Short Term Memory (STM) tests rather than WM tests. Short term memory is the capacity for holding a small amount of information in the mind in an inactive and readily available state for a very short period of time. It is important to test STM, because if the patient has a deficit in that area, it will affect ability to improve WM.

Results displayed at the completion of each test include Raw Score, Percentile, Scaled Score, and Descriptors.

One of the two STM tests is Tachistoscope, which is a test of visual processing speed. It requires the patient to identify stimuli that are exposed as a whole at a rapid speed and then enter them on the computer screen. The program begins with one digit and increases in increments of one until a maximum of eight digits is reached. If the patient's responses on two trials at any level are incorrect, the test is terminated, and the computer displays the patient's scores.

The second STM test, Visual Span, probes visual sequential memory. It requires the patient to perceive and remember a sequence of stimuli. The computer displays sequences of digits one at a time at 0.5 second intervals. The patient responds by entering the sequence on the screen. The sequences begin with one digit and increase, one digit at a time, until a maximum of eight digits is reached. If the patient responds incorrectly on two trials at any level, the program is terminated, and the computer displays the patient's scores.

Visual Closure is a WM visual test. Visual Closure is a complex perceptual task that provides the ability to recognize an object from a partial or limited stimulus or to form a "gestalt." The patient with a difficulty in this area is unable to perceive the "whole-part" relationship in partially-visible stimuli. Visual Closure helps us quickly to process information in our environment because our visual system does not have to analyze every detail. The skill to recognize an object when we are seeing only small pieces is a WM task. The Visual Closure test consists of eight levels. The stimuli are presented using small blocks, with the patient's age determining the allowed stimulus completion. There are three trials for each level. If the patient scores correctly at least once on a given level, the next level is presented until all eight are completed. If the patient is incorrect on all three trials of a level, the test automatically stops, and the computer displays the patient's score. Two stimuli modes are possible. Levels 1-5 show four possible answer targets; this is a lesser WM difficulty level. Levels 6-8 do not show any possible answer targets. This is a higher WM difficulty level because the patient mostly relies on visualizing the small blocks into the stimulus.

The fourth computerized test, which is only part of the CPT program, is Auditory Visual Integration. It is an intermodal task that requires patients to match sound patterns to corresponding dot patterns. In other words, the patient has to integrate a temporally-distributed auditory pattern to a spatially-distributed visual pattern. It is a dual WM task that requires both visual and auditory WM skills. There are twenty levels of increasingly difficult items. Patients under age 10 are only tested on items 1-10, while all other ages complete all 20 test items.

The next three tests are widely used by other professions and behavioral optometrists for a number of reasons as well as WM.

The Corsi block-tapping task has enjoyed extensive use in clinical and experimental studies since the 1970s and is arguably the single most important nonverbal task in neuropsychological research.[73] The Corsi test was developed as a visuospatial counterpart to the verbal-memory span task. Over the years, it has been used to assess visuospatial short term memory performances in children and adults. The original Corsi apparatus consisted of a set of nine identical blocks irregularly positioned on a wooden board. The tester points to a series of blocks at a rate of one block per second. The patient is required to point to the same blocks in the same order of presentation. The length of the block sequences increases until the response is no longer correct. A number of variations have been used, including computerized versions. Not only is visuo-spatial WM tested with the Corsi test, but it also tests central executive and verbal WM.[74] A demonstration of the Corsi test can be seen by going to this YouTube video: http://bit.ly/1vHvGGu. A computerized version can be obtained through the Lafayette Instrument Company.[B]

Another test of spatial scan designed to measure attention and working memory is the Cambridge Neuropsychological Test Automated Battery (CANTAB).[C] A recent study[75] of CANTAB points to the suitability of the task for the assessment of attention and WM.

The Rapid Automatized Naming and Rapid Alternating Stimulus Tests (RAN/RAS) measure a patient's ability to perceive a visual symbol such as a letter, color, or number and retrieve the name for it accurately and rapidly. Naming speed tests provide one of the best means of differentiating good from poor readers.[76] They also determine whether the patient's reading problem is solely caused by a phonic deficit, or naming speed problem.

This is of great interest to optometry because vision therapy for naming speed, speed of processing, perceptual speed, and WM can improve these factors and subsequently improve reading. The RAN/RAS test consists of four RAN tests: Objects, Colors, Numbers, and Letters and two RAS tests: 2-set Letters and Numbers and 3-set Letters, Numbers, and Colors. On all tests, the patient is asked to name each stimulus item as fast as possible without making any mistakes.

An important study of both children and adults with dyslexia using the RAN/RAS concluded that taken together, RAN, which may assess phonological WM, and RAS, which may assess executive WM, may explain the timing deficit in dyslexia in sustaining coordinated orthographic-phonological processing over time.[77] A recent experiment[78] of RAN testing of reading and math found that speed of processing and WM shared predictive variance with the pause time factor in RAN. Another study determined that significant predictors suggested that WM underlies part of the relationship between RAN and reading ability.

The psychological phenomenon we now call the Stroop effect was first described in 1935 by psychologist John Riley Stroop.[80] His experiments with color naming led him to conclude that there is less interference with word reading than color naming. The Stroop Test[E,F] is based on this phenomenon. Patients are presented with a color name printed in a different color. They are required to name the color, not the "word." The test is based on the fact that we can read words much faster than we can identify and name colors. This video link (http://bit.ly/1yDtze0) shows an example of the test. The Stroop Test is a widely used tool in many areas, and in recent years executive WM has been related to it. Individual differences in WM capacity predicted performance on the Stroop test in five experiments, indicating the importance of executive control and goal maintenance to selective attention. When the Stroop task included large numbers of congruent trials (RED presented in red), individuals with poor WM committed more errors than did individuals with high WM on the incongruent trials (BLUE in red). The data show that Stroop interference is partly determined by WM capacity.[81]

**Why Computers are Valuable for Vision Therapy?**

Optometrists who use computers for treating binocular vision problems, amblyopia, and visual perception deficits are not surprised by the effectiveness of implicit (computerized) programs for WM.[82] Computers are as popular with patients as with optometrists because they have many desirable features:[83]

1. Patient acceptance: It is stimulated by the ubiquitousness of computers in all aspects of society and the feeling that computers do everything more rapidly and efficiently. Patients expect to use and benefit from complex electronic devices. Therapy is more effective when patients believe in the mystic of the modality.
2. Flexibility: Computers are not limited to one function or level of difficulty. With appropriate software, it is possible to use computers for a large number of VT procedures. Almost all visual information processing abilities can be trained using a computer. They are particularly useful for speed of information processing, spatial relations/perceptual organization, visual spatial memory/visual sequential memory, auditory-visual integration, visual sequencing, etc. Many of these are available for working memory therapy.
3. Proven learning principles: Vision therapy is subject to the principles of educational therapy and the laws of learning.[84] The general procedure in rehabilitation is to raise individual processes, motivation,[85] abilities, and components to higher levels of performance. This requires a thorough and well-structured protocol consisting of programmed steps. Computers are well suited for this.
4. Adaptable programming: Computers are uniquely adaptable for explicit WM therapy because:
   - Programs are user-friendly and self-instructional.
   - The primary interaction can be between the patient and the program rather than between the patient and the therapist when indicated.
   - The stimuli are divided into small, discrete units.
   - Computer programs can provide a large, and in some cases, an infinite number of stimuli for many activities.
   - Many programs can be easily adapted for either age and/or ability. The stimuli can be programmed in sequences ranging from simple to complex.
   - Each stimulus demands an overt response from the patient, each response is recorded by the computer, and immediate feedback can be provided.
   - Information stored by the computer is available during each session, and visual, auditory, or printed summaries of the patient's activities can be furnished.
   - Computer programs can feature bottom-up information processing, top-down information processing, or interactive information processing.

**Computer-Based Vision Therapy for Working Memory**

As discussed previously, implicit therapy is advisable for treating WM. Computerized programs have been shown to be superior WM therapy. Computerized Therapy Program (designed by the author and published by HTS) is composed of 18 vision therapy modules, of which seven can be used for WM therapy. To be effective for WM, a program's only requirement is that it must not be just a passive serial recall of the information.

To determine whether a program is primarily developing short term memory or WM, consider whether the program meets one or more of the following WM requirements:

1. Is any manipulation or transformation of the information required?
2. Is any concurrent or intervening processing required?
3. Are both storage and processing required?
4. Does the task involve the concurrent retention of both visuospatial and verbal information or the recoding of one modality into another?[86]

**The CPT Modules are:**

Tachistoscope – The Tachistoscope program requires patients to identify stimuli displayed simultaneously for varying brief exposure times. It trains visual and perceptual processing speed. Basic tachistoscopic therapy does not stimulate WM because passive, serial recall of the information is the only requirement. Three options included in the program stimulate WM: 1. Delayed response option that requires the patient to withhold their response for a specified time period, 2. Interactive response option (distraction) that requires the patient to perform a hand-eye coordination task for a specified time period, and 3. Reversed response option that requires the patient to enter the stimuli in reverse order. The options may be used singly or in any combination of the three.

Visual Span – The Visual Span program requires patients to identify stimuli displayed sequentially for varying exposure times. It trains visual sequential memory. Visual sequential memory is the ability to perceive and to remember a sequence of stimuli in the same order as originally displayed. A visual sequential memory task asks the question, "What is it?" Two

***Figure 1:*** *Visual Span*

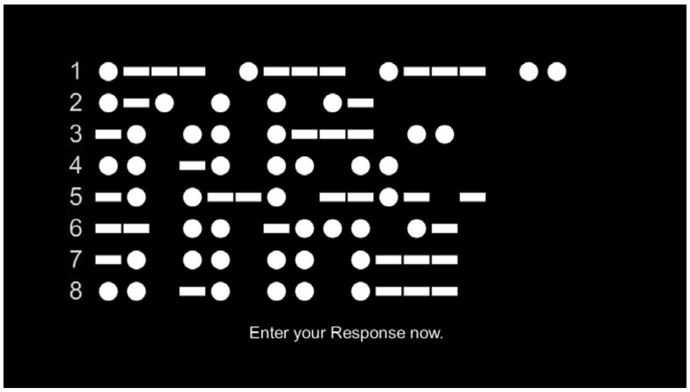


***Figure 2:*** *Auditory-Visual Integration*

options included in the program stimulate WM: 1. Delayed response option that requires the patient to withhold their response for a specified time period, and 2. Interactive response option (distraction and interference) that requires the patient to perform a hand-eye coordination task for a specified time period. The program stimulates WM because it requires storage and processing. Most patients rely on both verbal and visual recall to perform well on the Visual Span program. This is valuable because verbal WM is enhanced (Figure 1).

Auditory-Visual Integration – The ability to integrate information arriving as an input, with other stimuli, from the same or different modalities may be deficient in many patients. The forms of integration that are significant are intramodal and intermodal. Intramodal integration is the input, organization, and output of various stimuli received in one perceptual modality. Examples are visual-visual or auditory-auditory. Intermodal or cross-modal integration is the input, organization, and output of stimuli received in different modalities. Examples of cross-modal integration are auditory-visual or visual-auditory. The program presents the patient with either an auditory or visual stimulus consisting of dots, dashes, or dot-dashes. The computer will then present three to eight possible response choices that are either visual or auditory. The intramodal presentations are much simpler than the intermodal presentations. The intermodal stimuli require WM because of the recoding of one modality into another. Other stimuli for WM are a wait delay before responding,

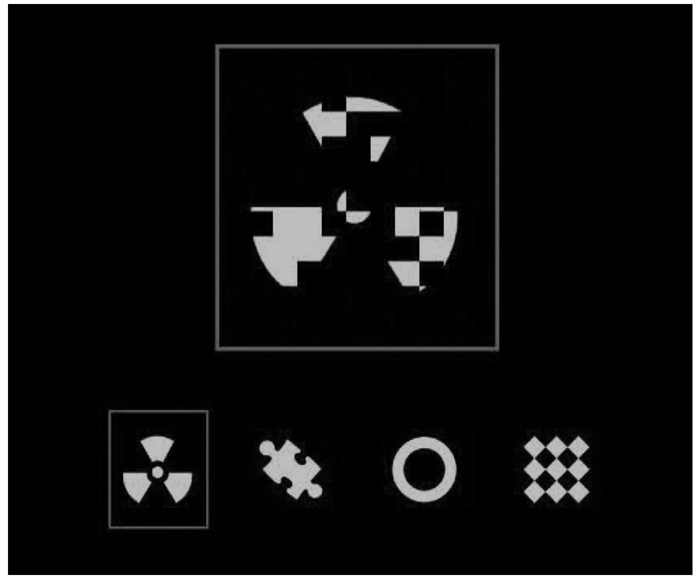

***Figure 3:*** *Visual Closure*

a distraction procedure before responding, and requiring stimulus reversal before responding (Figure 2).

Visual Closure – Visual closure is the ability to visualize and to unify an apparently disparate and incomplete visual perceptual field into a single percept. Closure is considered one of the basic organizing tendencies in perception. The Visual Closure Program requires patients to identify incomplete stimuli (letters, numbers, and pictures of familiar objects) as rapidly and as accurately as possible. The percentage of completeness starts at 1% and finishes at 100%. There are three target display (foil) choices (Figure 3).

A. Show All Targets – Four targets will be displayed concurrently with the stimulus. When the patient decides on a response, the target box is moved with the keyboard arrow keys to the choice and is entered by pressing the space bar or the mouse button. This is the least difficult WM therapy.
B. Sequential Targets – No foils will be displayed concurrently with the stimulus. The patient waits until they recognize the target in the center box and then presses the space bar. When the recognized target appears in the box below the center box, they press the space bar again. This is more difficult WM therapy.
C. No Targets – This option is not available for picture stimuli. No targets will be presented to the patient at any time. A response is made by pressing the letter or number key corresponding to the stimulus. This is the most difficult WM therapy.

Visual Sequential Processing – The Visual Sequential Processing Program (multi-stimulus) requires patients to identify and to respond to targets that are repeated in a sequence of targets presented one at a time in a designated speed, pattern, and number of stimuli. The large numbers of concurrent non-repeated targets in the sequence are a significant interference with storage and processing, so the task clearly involves working memory.

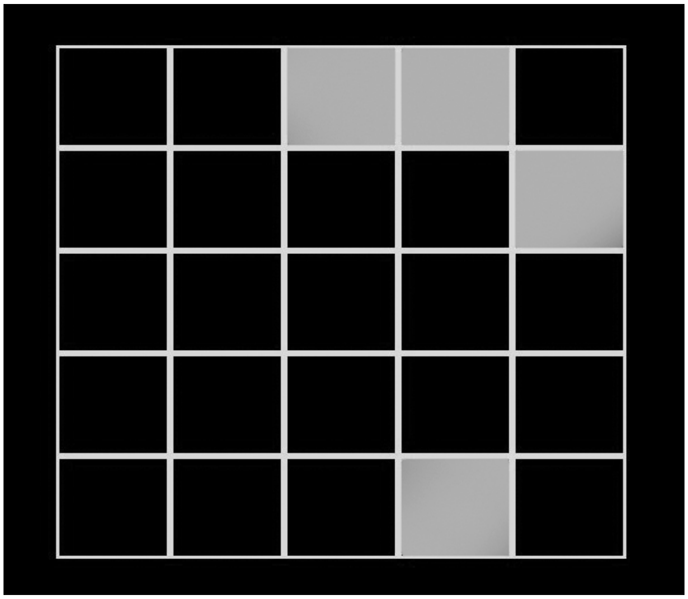

***Figure 4:*** *Visual Spatial Memory*

It is important that the patient not be overwhelmed by the multi-stimulus task. Start by using a slow presentation of individual targets and increased time when the individual presentation is off. There are nine target types of varying complexity. Start with simple ones such as letters or numbers. The more difficult targets are colors and symbols. Increase the speed, length, and target complexity gradually as the patient develops skill in this task. The patient counts the number of times a repeating target is seen by clicking the left mouse button. For some patients, this answer mode may be difficult because it is a double task situation that requires the patient visually to recognize the targets and rapidly respond motorically. The Visual Sequential Processing Program requires visual vigilance that may be difficult for patients with attentional disorders, particularly at the slow speeds. Training in this type of task is useful.

Visual Memory – This module contains two WM programs: Visual Sequential Memory and Visual Spatial Memory.

Visual Sequential Memory requires the patient to identify, to recall, and motorically to indicate the correct order of sequences of colored stimuli that are briefly displayed in the cells of a matrix grid. Visual sequential memory is often aided by the use of verbal mediation, the assigning of verbal labels to the visual stimuli as a help in recall. This program has been designed to minimize verbal mediation, so the patient must rely primarily on visual recall without verbal mediation. This technique emphasizes visual WM.

Visual Spatial Memory is the recognition and recall of the location of a stimulus rather than the sequence or description of a stimulus. It answers the question "where?" not "what?" regarding a visual stimulus. It requires the patient to identify, to recall, and motorically to indicate the spatial location of an array of single colored stimuli that are briefly displayed in the cells of a matrix grid. Working memory is enhanced by the use of the following options for both programs (Figure 4):

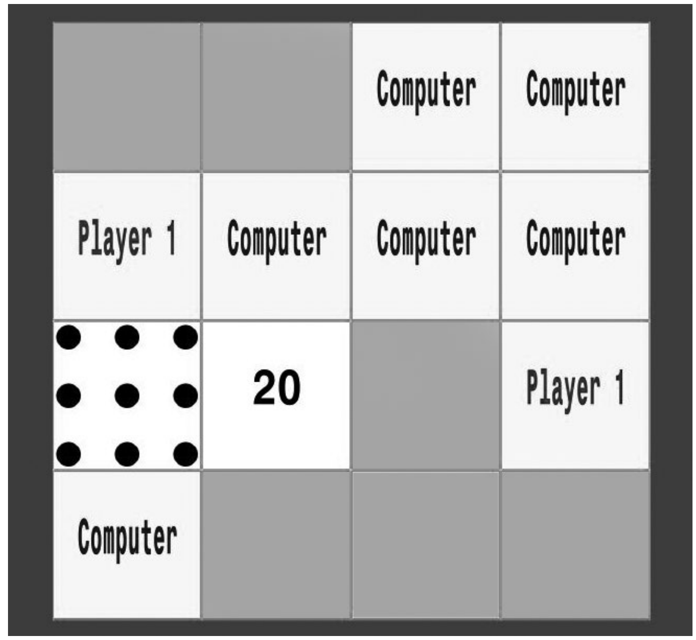


***Figure 5:*** *Visual Concentration*

1. Wait Delay – The patient is required to withhold responding for a specified time period. This option is designed to enhance the ability to retain a visual stimulus for longer periods of time.
2. Distraction – The patient is required to perform an eye-hand coordination task during a specified time period. This task addresses the problem of difficulty integrating various perceptual modalities. The ability accurately to retain a visual stimulus while performing a motoric activity is basic for improving WM.
3. Stimuli Grid Off – The patient must visualize the sequence or spatial location of the stimuli that will appear on the screen without the grid. This is a complex task and should not be used until the patient has demonstrated improved competence. Introduce it at a low level of performance.
4. Transform Response – This complex option requires the patient to alter the spatial direction of the stimulus in order to complete the task. The order of difficulty is: upside down, side to side, rotate left, rotate right.

Visual Concentration – The Visual Concentration program requires patients to memorize the spatial location of hidden pairs of stimuli that are located on various sized grids. It is a WM task which asks the question, "Where is it?" The program requires the patient's WM to store and to process a large number of stimuli.

Visual Concentration is an excellent program for developing good strategies for developing WM. Patients with WM deficits may demonstrate an inflexible strategy by continuing to choose the same box repeatedly. They demonstrate poor attention by not concentrating on the placement of the stimuli. They demonstrate poor planning by not developing a logical, coherent strategy for locating the stimuli (Figure 5).

Patients should be urged to use visualization and imagery as an aid in locating the hidden stimuli. Allow participants to use the preview feature, but they must be reminded to attend visually for the full time allowed and to develop a visual image in their mind of the stimulus location. It is sometimes valuable to have the patient verbalize and/or point to the locations of the stimuli following the preview.

When the game begins, they should be directed to develop a routine for remembering the locations. They might choose the corners of the grid as their initial choice if the preview option was not chosen. Or they could choose all the boxes in a row or column. Whatever routine is used, the concept of visualizing the stimulus locations as they are exposed by the patient or the computer must be emphasized. Of course, patients with head trauma, attention deficit disorder, or other disabilities must receive special attention. These techniques, or similar ones, can be adapted for many of the WM programs.

## Conclusion

Working memory deficits are a significant factor in many patients who are treated by developmental optometrists. WM responds to therapy that falls in the optometric domain and should become an integral part of optometric vision therapy. WM testing is available for optometrists, and optometric vision therapy can easily incorporate WM therapy. Computerized WM training has been shown to be the most effective. The improvement of fluid intelligence following WM therapy is significant because Gf is related to many deficit areas that are found in optometric patients. It would be valuable for our schools to include WM theory, diagnosis, and therapy for both undergraduates and residents. Optometric conventions, conferences, and educational seminars should feature WM concepts. Optometric research and articles should be encouraged.

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