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Chapter 13

A DUAL-COMPONENT ANALYSIS OF WORKING MEMORY TRAINING

Bradley S. Gibson and Dawn M. Gondoli
University of Notre Dame, South Bend, IN, US

ABSTRACT

Working memory (WM) capacity constrains reasoning and learning abilities and students who lack adequate WM capacity do not meet benchmark standards in core academic subjects such as reading and math. This association between WM capacity and academic competence has given rise to the expectation that WM capacity is a malleable factor. Indeed, several adaptive training regimens have attempted to improve student outcomes in reasoning and learning by increasing WM capacity. Unfortunately, there is growing consensus that these particular training regimens neither increase WM capacity adequately nor improve higher-level cognitive or academic abilities. But, before WM capacity can be dismissed as a malleable factor, it must first be shown that these particular training regimens have targeted the proper theoretical mechanisms. For instance, according to the dual-component theory, there are two critical components of WM capacity—an attention component and a memory component—that account for the relation between WM capacity and higher-level cognitive abilities. However, we have recently shown that existing regimens only target one of the two components (the attention component), which may explain why they have proven to be ineffective. There is, therefore, a critical need to create and test new training regimens that are capable of targeting both components of WM capacity. This chapter reviews recent evidence from our lab that has led to the development of a novel training regimen that can target and enhance both the attention and memory components of WM capacity. We argue that this development is significant because it will allow researchers to test the central hypothesis that improvements in student reasoning and learning will be moderated by the number of WM components that are targeted and enhanced by the training regimen.

INTRODUCTION

WM is an executive function that constrains many higher-level cognitive and academic abilities. For instance, individual differences in WM capacity have been found to reliably predict a range of higher-level cognitive and academic abilities in young adults, including reading comprehension abilities (Daneman and Carpenter, 1980; Turner and Engle, 1989), fluid IQ (Engle, Tuholski, Laughlin, and Conway, 1999; Kane and Engle, 2002; Kane et al., 2004; Unsworth and Spillers, 2010), and performance on college entrance exams (Cowan et al., 2005; Turner and Engle, 1989). Likewise, individual differences in WM capacity have also been found to reliably predict a range of higher-level cognitive and academic abilities in children, including fluid IQ (Engel de Abreu, Conway, and Gathercole, 2010), verbal and mathematical aptitude (Cowan et al, 2005; Gathercole and Pickering, 2000; Swanson and Beebe-Frankenberger, 2004), as well as the rate at which children develop syntactic knowledge and reading ability (Engel de Abreu, Gathercole, and Martin, 2011).

Altogether, individual difference studies have suggested that children and adults with higher WM capacities typically demonstrate greater reasoning and learning abilities than children and adults with lower WM capacities (Bull and Scherif, 2001; Cain and Oakhill, 2006; Engle, Carullo, and Collins, 1991; Gathercole, Brown, and Pickering, 2003; Geary, Hoard, Nugent, and Byrd-Craven, 2007; Swanson, Zheng, and Jerman, 2009). In fact, there has been growing interest in the subset of students who are in the lowest 10-15 percentile of WM capacity because these students appear to manifest a common pattern of maladaptive classroom behaviors that put them at risk for academic problems. For instance, students with low WM tend to be inattentive, have poor study skills, are poor note-takers, and are unorganized. Most importantly, students with low WM have poor academic outcomes in core curriculum subjects such as reading and math (Alloway, Elliott, and Place, 2010; Alloway, Gathercole, Kirkwood, and Elliott, 2009; Alloway, Gathercole, and Elliott, 2010; DiPerna and Elliott, 2000; DuPaul et al., 2004).

Many students with low WM capacity also meet criteria for various exceptionalities (e.g., autism spectrum disorder, communication disorder, or learning disability) or other medically defined disorders that may not be formally delineated within the educational exceptionalities (e.g., attention-deficit/hyperactivity disorder, extreme prematurity, traumatic brain injury). However, not all students with these specific disabilities have low WM (Archibald and Joanisse, 2009; Dahlin, 2010; Kyttälä, Aunio, and Hautamäki, 2010; Loo et al., 2007; Montgomery, Magimairaj, and Finney, 2010; Willcutt, Doyle, Nigg, Faraone, and Pennington, 2005), suggesting that the identification of students on the basis of low WM may be important in its own right (see also, Dahlin, 2010; Holmes, Gathercole, and Dunning, 2009; Holmes et al., 2010; Klingberg et al., 2005; Mezzacappa and Buckner, 2010; St Clair-Thompson, Stevens, Hunt, and Bolder, 2010; Thorell, Lindqvist, Nutley, Bohlin, and Klingberg, 2009).

IS WM CAPACITY A MALLEABLE FACTOR?

Because the capacity to reason and learn appears to be constrained by the capacity of WM, there has been great interest in the question of whether WM capacity is malleable and capable of being increased by adaptive training regimens. Indeed, a debate has erupted over the past decade about whether adaptive WM training regimens can enhance WM capacity and associated higher-order cognitive and adaptive functioning. On the one hand, several empirical studies have been interpreted to suggest that training-induced increases in WM capacity can occur and can also be accompanied by improvements in fluid intelligence (Jaeggi, Buschkuehl, Jonides, and Perrig, 2008; Jaeggi, Buschkuehl, Jonides, and Shah, 2011; Klingberg et al., 2005), reading comprehension (Chein and Morrison, 2010; Dahlin, 2010), math competence (Holmes et al., 2009), and ADHD symptoms (Gibson, Gondoli, Johnson, Steeger, and Morrissey, 2011; Klingberg et al., 2005). These positive findings have been emphasized in several recent reviews that have been optimistic about the possibility that training regimens can enhance WM capacity and associated higher-level abilities (Buschkuehl and Jaeggi, 2010; Diamond and Lee, 2011; Klingberg, 2010; Morrison and Chein, 2011).

On the other hand, several other, more comprehensive, reviews have been considerably more pessimistic about the effectiveness of WM training (Melby-Lervag and Hulme, 2012; Shipstead, Hicks, and Engel, 2012; Shipstead, Redick, and Engle, 2010; Shipstead, Redick, and Engle, 2012). For instance, on the basis of their comprehensive meta-analysis of WM training in children and adults, Melby-Lervag and Hulme (2012) concluded that although "[c]urrent training programs yield reliable, short-term improvements on both verbal and nonverbal working memory tasks...there is no evidence that working memory training produces generalized gains to the other skills that have been investigated (verbal ability, word decoding, or arithmetic), even when assessments take place immediately after training" (p. 12). Likewise, on the basis of their comprehensive narrative review of WM training in children and adults, Shipstead et al., (2012) also concluded that there is no evidence that WM training produces generalized gains to higher-level cognitive and academic abilities (see also, Shipstead et al., 2010; Shipstead et al., 2012). Furthermore, Shipstead et al. (2010) also questioned whether WM training can produce short-term improvements of verbal and nonverbal WM, based on a variety of concerns about the measurement of these outcomes, the theoretical conception of WM, and the use of appropriate control groups (see also, Shipstead et al., 2012).

Based on the conclusions of these more comprehensive reviews (Melby-Lervag and Hulme, 2012; Shipstead et al., 2010; Shipstead et al., 2012), there appears to be little evidence that WM capacity is malleable or that WM training can influence student reasoning and learning. However, before these conclusions can be accepted with confidence, it is first necessary to explore an alternative explanation: namely, that existing training regimens have not been optimally designed.

NEW THEORETICALLY- INSPIRED WM TRAINING REGIMES MUST BE CREATED AND EXPLORED

We have recently argued that the full potential of WM training has not yet been adequately tested because existing regimens do not target the proper theoretical mechanisms (Gibson, Gondoli et al., 2012). Likewise, Melby-Lervag and Hulme (2012) state that existing regimens "do not appear to rest on any detailed task analysis or theoretical account of the mechanisms by which such adaptive training regimes would be expected to improve working memory capacity. Rather, these programs seem to be based on what might be seen as a fairly naïve 'physical-energetic' model such that repeatedly 'loading' a limited cognitive resource will lead to it increasing in capacity, perhaps somewhat analogously to strengthening a muscle by repeated use" (p. 3). Similarly, Shipstead et al. (2012) state, "we do not rule out the possibility that WM training could be made effective. The largest issue seems to be that, while there is logic to WM training (increase WM and improve related abilities), this literature is still struggling to find a theory. Specifically, it is important that research move beyond the desire to show that broad change can be realized through a month of training on a limited set of tasks" (p. 22).

According to Gibson, Gondoli et al. (2012), theories of WM capacity have important implications for the design of WM training regimens because it is in virtue of these theories that we come to understand (1) which components of WM distinguish high-capacity individuals from low-capacity individuals, (2) which components are important for supporting higher-level cognitive and academic abilities, and (3) how these components should be measured. In short, if the primary goal of WM training is to increase an individual's WM capacity from low to high so that reasoning and learning abilities can be improved, then theories of WM capacity can indicate which components of WM capacity are the most important to target, and they can also indicate how those components should be trained.

WHICH COMPONENTS OF WM CAPACITY DISTINGUISH HIGH- AND LOW-CAPACITY INDIVIDUALS?

The main purpose of WM training is to increase the capacity of WM. But, what is the nature of this capacity? Answers to this question are provided by theories that attempt to identify the critical mechanisms or components of WM capacity. In this chapter, we distinguish between one-component and two-component theories of WM capacity. The most prominent one-component theories have typically included flexible attention mechanisms such as the "focus of attention" (Cowan, 1995; 2001; Cowan et al., 2005) or "executive attention" (Kane and Engle, 2002) that allow individuals to actively maintain a limited amount of goal-relevant information in "primary memory" (PM), especially in the presence of distraction. Although both attention mechanisms were postulated to explain how information is actively maintained in WM, the focus of attention emphasized the maximum number of items that can be maintained at one time, whereas executive attention emphasized the ability to maintain goal-relevant information in the face of irrelevant distraction.

The most prominent two-component theories have typically included these flexible attention mechanisms, but they have also included memory mechanisms such as "cue-dependent retrieval" that allow individuals to retrieve goal-relevant information from "secondary memory" (SM), after that information has been lost from PM (Mogle, Lovett, Stawski, and Sliwinski, 2008; Unsworth and Engle, 2007a; 2007b; Unsworth and Spillers, 2010). Current theories construe recall from SM as a multi-step process. For instance, Unsworth (2007; 2009) has construed recall from SM in terms of three parameters: the size of the search set, the recovery of potential targets from this set, and error monitoring. In this chapter, we refer to the attention mechanisms as the PM component of WM capacity, and we will refer to the memory mechanisms as the SM component of WM capacity.

Empirical studies that have investigated whether one or two components are necessary to distinguish high- and low-capacity individuals have typically used an extreme-groups approach. In these studies, individuals who fall in the top and bottom quartiles of overall WM capacity are compared on measures that are specifically designed to isolate the PM and SM components of WM capacity (Unsworth and Engle, 2007a). These findings have shown that high-capacity individuals differ from low-capacity individuals in terms of both PM and SM abilities. Based on this evidence, Unsworth and Engle concluded that low-capacity individuals were less likely to maintain goal-relevant information in PM than high-capacity individuals, and they were also less proficient at using cues to retrieve goal-relevant information from SM, after that information was lost from PM (see also, Gibson, Gondoli, Flies, Dobrzenski, and Unsworth, 2010; Unsworth, 2007). Thus, both PM and SM components of WM capacity appear to be necessary to distinguish low-capacity individuals from high-capacity individuals. This notion has come to be called the "dual-component theory" of WM capacity.

WHICH COMPONENTS OF WM CAPACITY ARE IMPORTANT FOR SUPPORTING HIGHER-LEVEL COGNITIVE AND ACADEMIC ABILITIES?

Further evidence for the dual-component theory has come from empirical studies that investigated whether both components are related to higher-level cognitive and academic abilities. These studies have typically used a latent variable approach in which the full range of individual PM and SM abilities is investigated within the context of structural equation modeling (Mogle, Lovett, Stawski, and Sliwinski, 2008; Unsworth and Engle, 2007b; Unsworth and Spillers, 2010). For instance, Unsworth and Engle (2007b) showed that both the PM and SM factors accounted for significant variance in SAT and fluid IQ; however, the SM factor accounted uniquely for more variance than the PM factor. Similarly, Mogle et al. (2008) also showed that SM ability was more important than PM capacity for explaining the relation between WM capacity and fluid IQ. However, Unsworth and his colleagues (Unsworth, Brewer, and Spillers, 2009; Unsworth and Spillers, 2010) have recently provided evidence that both PM and SM ability are equally important for explaining the relation between WM capacity and fluid IQ.

In addition, using tasks that focused solely on the SM component of WM capacity, Unsworth (2009) operationalized the three parameters of the SM component—i.e., the size of the search set, the recovery of potential targets from this set, and error monitoring—in terms of recall latency, recall accuracy, and intrusion errors, respectively, in order to examine how pre-existing individual differences in these three parameters related to pre-existing differences in WM capacity and fluid IQ. The main findings suggested that pre-existing differences in WM capacity and fluid IQ were primarily related to differences in recall latency and recall accuracy, but not intrusion errors. In particular, individuals with higher WM capacity and fluid IQ tended to have faster recall latencies (indicating the use of smaller search sets likely containing less irrelevant information) and higher recall accuracies (indicating better recovery of potential targets from the search set).

In short, these findings suggest that both the PM and SM components are important for explaining individual differences in WM capacity, reasoning, and learning. Hence, these findings have important implications for the design of WM training regimens because they suggest that a regimen that can target both the PM and SM components of WM capacity should have stronger effects on higher-level cognitive and academic abilities than a regimen that can target only one or neither of the two components.

HOW SHOULD THE PM AND SM COMPONENTS OF WM CAPACITY BE MEASURED? IMPLICATIONS FOR TRAINING

Consideration of the measurement of WM capacity is important because the tasks that have been developed to measure WM capacity are also used to train WM capacity. The measurement of WM capacity has generally relied on the span task. Span tasks typically come in two varieties: simple span and complex span. Simple span tasks typically involve the presentation of lists of various lengths that participants attempt to recall in forward serial order immediately following the conclusion of the list (e.g., forward word span or forward digit span). In contrast, complex span tasks typically involve the performance of two tasks on each trial. For instance, in the operation span task (Turner and Engle, 1989), participants must first solve a mathematical operation and then attempt to store a simultaneously (or sequentially) presented list item on each trial. As in simple span tasks, lists of various lengths are presented that participants attempt to recall in forward serial order immediately following the conclusion of the list.

There has been a debate about whether the simple span task or complex span task is a better measure of WM capacity. Initial support for the importance of complex span tasks over simple span tasks came from studies which showed that individual differences in complex span performance correlated more highly with higher-level cognitive abilities such as reading comprehension, SAT, and fluid intelligence than did individual differences in simple span performance (see e.g., Daneman and Carpenter, 1980; Engle et al., 1999; Turner and Engle, 1989). These findings were originally interpreted within a one-component (attention-based) theory of WM capacity. For instance, according to Cowan et al. (2005), the critical feature of complex span tasks is that the processing component suppresses rehearsal strategies that likely operate in simple span tasks. As a result, complex span tasks may provide a purer measure of the focus of attention (the number of items that can be held active at any given point in time). Likewise, according to Kane and his colleagues (Kane and Engle, 2002; Kane et al., 2004), the critical feature of complex span tasks is that the processing component represents a source of interference that is not present in simple span tasks. As a result, complex span tasks may provide a purer measure of domain-general executive attention processes that enable individuals to maintain goal-relevant information in the presence of interference whereas simple span tasks generally do not.

More recently, Unsworth and Engle (2007b) used a two-component theory of WM capacity to explain the stronger correlation that is typically found between complex span tasks and higher-order cognition than between simple span tasks and higher-order cognition. In particular, they argued that simple span and complex span tasks both measure the same processes (rehearsal, maintenance, and updating in PM, and retrieval from SM), albeit to different extents. For instance, using confirmatory factor analysis, Unsworth and Engle showed that simple span tasks such as forward word span loaded more highly on the PM factor than on the SM factor; whereas, complex span tasks such as operation span loaded more highly on the SM factor than on the PM factor.

According to Unsworth and Engle (2007b), complex span tasks that require dual-task performance (e.g., operation span) provide better measures of SM ability than PM capacity because the processing task causes all but the last of the to-be-remembered list items to be displaced from PM into SM. As a result, successful recall in complex span tasks mostly reflects the retrieval of information from SM. In contrast, simple span tasks provide better measures of PM capacity than SM ability because the displacement of items from PM into SM only occurs with relatively long list lengths in these tasks (i.e., with list lengths that exceed the storage capacity of PM). As a result, successful recall in simple span tasks mostly reflects the unloading of information that is actively maintained in PM, at least when list-length is relatively short. However, successful recall in simple span tasks may increasingly measure SM ability (as opposed to PM capacity) as list-length increases beyond the capacity of PM. Indeed, Unsworth and Engle (2006) showed that simple span tasks can predict fluid IQ scores just as well as complex span tasks when list-length exceeds the capacity of PM (greater than 4 items) because the simple span task now measures both the PM and SM components of WM capacity. Thus, according to this analysis, both simple span and complex span tasks appear capable of targeting the PM and SM components of WM capacity under certain conditions. Below we will consider the effects of using simple vs. complex span tasks as exercises in WM training regimens. In addition, we will also consider the effects of using different adaptive training algorithms that adjust the length of the memory lists used during WM training on an individual-by-individual basis.

Furthermore, it is also important to point out that Unsworth and Engle (2007a) have used immediate free recall (IFR) tasks to assess the individual PM and SM components of WM capacity. These tasks are similar to simple span tasks, except that relatively long lists are presented on every trial (e.g., 12 items) and the items can be recalled in any order (see the Research Plan for further details). According to Unsworth and Engle, IFR tasks are valid measures of WM capacity. In their re-analysis of Engle et al.'s (1999) structural equation model of the relation between WM capacity, fluid intelligence, and scholastic aptitude, Unsworth and Engle showed that performance on a verbal IFR task loaded just as highly (0.77) on the latent construct of WM capacity as performance on three more traditional complex span tasks did: operation span (0.77), reading span (0.58), and counting span (0.62).

More importantly, IFR tasks may be better suited for assessing recall from PM and SM than complex or simple span tasks because IFR tasks can provide separate measures of each component, whereas complex and simple span tasks typically provide a single measure that may reflect contributions from both components. In particular, performance on IFR tasks can be divided into recency and pre-recency portions: Typically, individuals are better at recalling the last few presented (recency) items than they are at recalling the earlier presented (pre-recency) items because the recency items can be actively maintained and then simply unloaded from PM whereas the pre-recency items need to be encoded and then retrieved by means of a probabilistic search through SM.

APPLICATION OF THE DUAL-COMPONENT THEORY OF WM CAPACITY TO EXISTING WM TRAINING REGIMENS

Recently, we have used the dual-component theory of WM capacity to provide a detailed task analysis and theoretical account of the mechanisms by which one existing adaptive training intervention influences WM capacity (Gibson et al., 2011; Gibson, Gondoli et al., 2012; Gibson, Kronenberger et al., 2012). In our initial study, we investigated whether the PM component, the SM component, or both components of WM capacity could be enhanced by a span-based intervention known as "Cogmed-RM" (Gibson et al., 2011). We focused on this intervention because it is generally considered to be the best-known WM training intervention in existence today, having been widely-used in both schools and clinics around the world, as well as being either a major focus (Melby-Lervag and Hulme, 2012; Shipstead et al., 2012), or the sole focus (Shipstead et al., 2012) of previous reviews. In addition, Cogmed-RM utilizes both verbal and spatial span tasks as training exercises. Because the dual-component theory is largely rooted in the analysis of span task performance, this theory can be more directly applied to this intervention than it could to other training regimens that utilize other training exercises such as the *n*-back task that are not clearly related to span task performance (Jaeggi et al., 2008)

According to Holmes et al. (2009), of the 10 training exercises contained within Cogmed-RM, three involved the simple storage of verbal information, two involved the simple storage of spatial information, two involved the active updating and manipulation of verbal information, and three involved the active updating and manipulation of spatial information. According to the analysis provided by Unsworth and Engle (2007b), these training tasks may engage the PM component more than the SM component of WM capacity, though these tasks may have the potential to engage the SM component if training routinely involves list lengths that exceed the capacity of PM. In addition, other research has suggested that spatial simple span tasks may function more like complex span tasks than verbal simple span tasks (Kane et al., 2004; Miyake, Friedman, Rettinger, Shah, and Hegarty, 2001; Oberauer, 2005; Shah and Miyake, 1996). Thus, it is possible that adaptive training with spatial simple span exercises may enhance the SM component more than adaptive training with verbal simple span exercises. Accordingly, the Cogmed exercises were divided into two separate training conditions in Gibson et al.'s (2011) study—a verbal training condition ($N = 20$) and a spatial training condition ($N = 17$)—to examine whether spatial training might engage the SM component more than verbal training using a randomized, controlled design. The sample consisted of adolescents (11-14 years of age) with ADHD.

Following Unsworth and Engle (2007a), serial position effects and estimates of PM and SM capacity were derived from performance on verbal and spatial IFR tasks that were administered before and immediately following at least 20 days of training. The main findings showed that training selectively improved the PM component of WM capacity ($d = 0.52$), but not the SM component of WM capacity ($d = 0.15$), regardless of training condition. The finding that span-based training only targets a single component of WM capacity is important because it suggests that this training is not as potent as it could be (Unsworth and Spillers, 2010), and may explain why previous training studies that have used span-based training tasks have resulted in only weak or ineffective training of WM capacity and associated higher-level abilities (Shipstead, Hicks et al., 2012). Hence, according to the dual-component theory of WM capacity, the full potential of span-based training regimens has not yet been adequately tested.

Accordingly, the main purpose of our recent WM training research has been to translate the dual-component theory of WM into a novel WM training regimen that can target both the PM and SM components of WM capacity. In agreement with this goal, Shipstead et al. (2012) concluded, "[o]n the basis of the empirical work of Unsworth and Engle ...which emphasizes the importance of retrieval from secondary memory, Gibson et al. ... have begun modifying Cogmed [i.e., span-based training regimens] in an attempt to produce specific desired training effects (by creating greater need for retrieval). Under mounting evidence that Cogmed and other training programs have not lived up to the promise of early studies ... these endeavors represent a sensible course of action" (p. 22). Translating the dual-component theory of WM capacity into a more potent training regimen will require specific hypotheses about how the SM component of WM capacity is related to aspects of adaptive training that are under the control of the experimenter and/or educational system. Two such hypotheses are examined in the next two sections.

TARGETING THE SM COMPONENT OF WM CAPACITY: EXAMINATION OF EXERCISE TYPE

Gibson et al. (2011) found that span-based training regimens enhanced the maintenance of information in PM, but not the retrieval of information from SM, and they hypothesized that this pattern of results may have occurred because the exercises they used were primarily simple span exercises as opposed to complex span exercises. Accordingly, Gibson, Kronenberger et al. (2012) investigated whether training with complex span exercises would target the SM component more than training with simple span exercises. Chein and Morrison (2010) also developed training exercises based on complex span tasks, but they did not measure the PM and SM components of WM capacity.

The complex span exercises were created by inserting additional processing tasks between to-be-remembered list items in a critical subset of both verbal and spatial exercises, similar to the operation span (Turner and Engle, 1989) and symmetry span tasks (Kane et al., 2004), respectively, and two separate training conditions were compared: a simple span training condition ($N = 31$) and a complex span training condition ($N = 30$) using a randomized, controlled design. The sample consisted of adolescents (9 to 16 years of age) without regard for diagnostic status.

If inserting an additional processing task increases the probability that list items are lost from PM (Unsworth and Engle, 2007b), then training with adaptive complex span exercises should target the SM component of WM capacity more than training with adaptive simple span exercises. Thus, the SM component of WM capacity should be enhanced to a greater extent following training in the complex span training condition than in the simple span training condition. For this reason, the complex span training condition was construed as the treatment condition in this study whereas the simple span training condition was construed as the control condition. Construing the simple span training condition as a control condition may seem unusual given that it is an active training condition. However, the simple span training condition is arguably the most optimal control condition for present purposes because the active component of this condition should induce the same motivation and expectations as the complex span training condition while also having no effect on the SM component.

Although the simple span training condition could be construed as a control condition with respect to SM capacity, it could not be construed as a control condition with respect to PM capacity because the PM component of WM capacity was expected to be enhanced more or less equally across the two training conditions. Nevertheless, no further attempt was made to clarify the nature of the changes observed in the PM component of WM capacity because the main purpose of this study was to determine if training with complex span exercises could target the SM component of WM capacity.

Following Gibson et al. (2011), serial position effects and estimates of PM and SM capacity were derived from performance on verbal and spatial IFR tasks. As expected, the findings reported by Gibson, Kronenberger et al. (2012) showed that the simple span training condition selectively improved the PM component of WM capacity ($d = 0.36$), but not the SM component of WM capacity ($d = 0.04$). These findings replicated the findings reported by Gibson et al. (2011). However, despite evidence that the complex span exercises were more distracting than the simple span exercises during training, the same pattern of results was also observed in the complex span training condition: Namely, the PM component of WM capacity was improved ($d = 0.47$), but the SM component of WM capacity was not ($d = 0.03$). Based on these findings, Gibson, Kronenberger et al. (2012) concluded that training with complex span exercises is not sufficient to target the SM component of WM capacity.

TARGETING THE SM COMPONENT OF WM CAPACITY: EXAMINATION OF RECALL ACCURACY THRESHOLD

Although the use of complex span tasks may increase the probability that any given item is lost from PM during training, satisfaction of this criterion alone does not guarantee that trainees are given adequate opportunities to practice retrieving this information from SM. Rather, providing adequate opportunities to practice retrieving information from SM may require further consideration of how the span length of the adaptive exercises is adjusted on a trial-by-trial basis to match the capacity of the trainee.

According to the dual-component theory, overall WM capacity arises from two sources: the capacity of PM and the efficiency with which information is encoded and retrieved from SM. And, there are at least two reasons to suspect that the adaptive algorithm used in previous training regimens is biased to target PM capacity, but not SM ability. First, the recall accuracy threshold used to adjust list length in previous span-based training regimens (Chein and Morrison, 2010; Gibson et al., 2011; Holmes et al., 2009; Klingberg et al., 2005) has been universally set at 100%. As a result, the length of the upcoming list will not increase until the trainee can consistently recall all the items on the current list with perfect accuracy. Second, recall from SM tends to be less accurate than recall from PM (Unsworth and Engle, 2007a). This is because recall from PM has been construed as simply "unloading" the contents of PM whereas recall from SM involves a probabilistic search through a set of both relevant and irrelevant items (Unsworth, 2007; Unsworth et al., 2009; Unsworth and Engle, 2007a).

If recall from SM is less accurate than recall from PM, then the recall accuracy threshold may constrain the engagement of the SM component. For instance, consider an individual who is training with a 100% recall accuracy threshold, and consider that this individual has just encountered a list that exceeded the capacity of PM by one item. Let us suppose further that this individual was able to recall all the items that were being maintained in PM with perfect accuracy, but failed to recall the one item that was lost from PM and had to be retrieved from SM. Because list length is contingent on perfect recall in this context, the length of the next list will be decreased by one item. In this way, a 100% recall accuracy threshold may enable this individual to train at the maximal (or near maximal) capacity of PM, without providing much opportunity to train the SM component. In contrast, now suppose that this individual had been training with a lower recall accuracy threshold. Although, they failed to correctly recall the one item that was lost from PM, the length of the next list will not decrease, but rather will continue to increase until this individual is unable to satisfy the lower recall accuracy threshold. Consequently, this individual will now be given more opportunity to practice retrieving list items from SM, and as a result, his/her ability to retrieve may improve and SM ability may increase. Thus, increased engagement of the SM component during training may require decreasing the recall accuracy threshold from 100% to a lower value. A decrease in the recall accuracy threshold will likely elicit more retrieval from SM before recall is terminated on any given training trial, and it will also ensure that list length is determined more by the limitations of SM ability than by the limitations of PM capacity.

Gibson, Gondoli, Kronenberger, Johnson, Steeger, and Morrissey (2013) have recently investigated this hypothesis. In this study, the recall accuracy threshold decreased as list length increased, averaging approximately 80%. If lowering the recall accuracy threshold is sufficient to target the SM component, then significant enhancement of SM ability should be observed across time. In addition, this lower recall accuracy threshold was implemented within both the simple span ($N = 10$) and complex span ($N = 9$) training conditions used by Gibson, Kronenberger et al. (2012) in order to examine whether it might interact with exercise type. If lowering the recall accuracy threshold interacts with exercise type, then greater enhancement of SM abilities should be observed across time in the complex span training condition than in the simple span training condition. Furthermore, significant enhancement of PM capacity should also be observed across time in the present study regardless of whether significant enhancement of SM ability is observed. The sample consisted of young adults (21 to 24 years of age) without regard for diagnostic status.

Consistent with previous studies (Gibson et al., 2011; Gibson, Kronenberger et al., 2012), serial position effects and estimates of PM and SM abilities were derived from performance on verbal and spatial IFR tasks. Of greatest importance, both the simple span and complex span training conditions produced significant (and equal) improvements in the SM component of WM capacity ($d = 0.868$ and $d = 0.691$, respectively). Likewise, as expected, both the simple span and complex span training conditions produced significant (and equal) improvements in the PM component of WM capacity ($d = .813$ and $d = .880$, respectively). Thus, the lower recall accuracy threshold had the intended effect on the SM component of WM capacity, and did not interact with exercise type. The present findings are thus consistent with the notion that span tasks may target the SM component when list length exceeds the capacity of PM (Unsworth and Engle, 2007b).

Stronger evidence for this conclusion was also sought by comparing the two training conditions used in this study with the two corresponding training conditions used in Gibson, Kronenberger et al.'s (2012) study. These latter two training conditions can be considered appropriate controls for the SM component of WM capacity because the active component of these two training conditions failed to have any effect on the SM component. A two-way ANCOVA was conducted with post-training estimates of SM ability serving as the dependent variable, and with training condition (simple span vs. complex span) and experiment (100% recall accuracy threshold vs. lower recall accuracy threshold) serving as the two between-subjects factors. Pre-training estimates of SM ability served as the covariate. As expected, there was a significant main effect of experiment, $F(1,75) = 13.19$, $p < .002$, $\eta_p^2 = .15$, indicating that individuals recalled significantly more items from SM after training with a lower recall accuracy threshold (adjusted $M = 2.83$ items) than after training with a 100% recall accuracy threshold (adjusted $M = 2.24$ items)—a 26% increase in performance—even after controlling for pre-existing differences in SM ability between the two experiments. In contrast, neither the main effect of training condition, nor the training condition X experiment interaction approached significance, $F < 1$.These findings are important because they suggest that the improvement in SM ability observed following training can be attributed to the use of a lower recall accuracy threshold. Although decreasing the recall accuracy threshold is subtle in absolute physical terms, this decrease can have important functional consequences because it elicits more retrieval from SM before recall is terminated on any given training trial, and it also allows the length of the training lists to be determined more by the limitations of the SM component than by the limitations of the PM component.

One of the potential virtues of using Gibson, Kronenberger et al.'s (2012) two training conditions as the control conditions in the present study is that these are active treatment conditions. As such, the active component of these training conditions may induce the same expectations for improvement as the lower recall accuracy threshold conditions while also having no effect on the SM component. However, lowering the recall accuracy threshold may increase motivation because individuals will tend to experience more success when they train using a lower recall accuracy threshold than when they train using a 100% recall accuracy threshold. Therefore, it is worth considering whether the significant enhancement of SM ability observed in the present study relative to Gibson, Kronenberger et al.'s (2012) study might be due to differences in motivation rather than differences in recall accuracy threshold.

If an alternative explanation based on motivation is viable, then it is reasonable to expect that the positive effects of motivation should extend to both the PM and SM components of WM capacity. Accordingly, a two-way ANCOVA was also conducted with post-training estimates of PM capacity serving as the dependent variable, and with training condition (simple span and complex span) and experiment (100% recall accuracy threshold vs. lower recall accuracy threshold) serving as the two between-subjects factors. Pre-training estimates of PM capacity served as the covariate. However, none of the effects approached significance (all p's $> .10$). This finding suggests that individuals recalled the same number of items from PM regardless of whether they were exposed to a lower recall accuracy threshold (adjusted $M = 3.08$ items) or to a 100% recall accuracy threshold (adjusted $M = 2.91$ items) during training. Altogether, the findings suggest that only the SM component of WM capacity benefitted from the lower recall accuracy threshold which is inconsistent with the alternative motivational account.

CONCLUSION

A large body of research has established that individual differences in WM capacity can constrain reasoning and learning abilities in both children and adults. Unfortunately, recent attempts to improve these outcomes by intensive training of WM capacity have proven to be unsuccessful, perhaps because these training regimens have not targeted the proper theoretical mechanisms. According to the dual-component theory of WM capacity, there are two critical components of WM capacity—the PM component and the SM component—that account for the relation between WM capacity and higher-level cognitive abilities. Within this context, we have hypothesized that improvements in student outcomes may be moderated by the number of WM components that are targeted and enhanced by a training regimen. In other words, the most potent training regimen would be one that could target and enhance both components of WM capacity. Consistent with this hypothesis, we have shown that existing span-based WM training regiments only appear to target the PM component of WM capacity (Gibson et al., 2011), which may explain why these regimens have proven to be relatively ineffective. In order to create a potentially more potent training regimen, we have provided preliminary evidence that the SM component of WM capacity can also be targeted and enhanced by decreasing the recall accuracy threshold; in contrast, manipulations of exercise type have not had the intended effect on the SM component (Gibson, Kronenberger et al., 2012). With this newly-created training regimen in hand, we are now in a position to provide a stronger test of the moderation hypothesis. Exploration of this hypothesis will not only serve to identify and develop a potentially beneficial educational intervention, it will also contribute to theory building regardless of whether the outcome is positive or negative.

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