WORKING MEMORY CAPACITY AND EXTRANEOUS COGNITIVE LOAD DURING STRATEGY INSTRUCTION

By

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To Justin, who never considered the possibility that I couldn’t do it.

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LIST OF ABBREVIATIONS

HWM	High working memory capacity
LWM	Low working memory capacity
WM	Working memory. Our limited capacity to simultaneously store and process information for a brief period of time. Also referred to as attentional capacity.

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Strategy use may play an important role in individual differences related to working memory (WM) capacity (Dunlosky & Kane, 2007; McNamara & Scott, 2001; Rosen & Engle, 1997).   When individuals are engaged in a demanding task, subjecting them to additional cognitive load has different effects as a function of their working memory (WM) capacity. I examined the relationships between WM, cognitive load, and individuals' performance in a strategy learning condition. I hypothesized that individuals with low WM span would have more difficulty learning strategies, and that strategy use would be positively related to scores on the probability problem-solving posttest. I also predicted that the level of cognitive load in the learning condition would interact with WM capacity to influence both strategy learning and problem-solving performance.

One hundred and eighty college students completed a mathematical problem-solving task under one of four conditions, each with a different level of cognitive load. WM influenced students' ability to learn a new strategy, supporting the strategy-as-effect hypothesis of WM (Dunlosky & Thiede, 2004a). Higher WM was associated with greater strategy learning success when the learning condition was novel and when overall performance in the condition was lower. Perceived cognitive load was affected

by students' preexisting knowledge about the topic, but not by their WM capacity. Participants performed better in a more traditional learning format, and the relationship between WM and strategy learning disappeared in this format. Together these results indicate that reducing cognitive load during strategy learning is an effective way to teach strategies, particularly to individuals with low WM capacity.

CHAPTER 1
STATEMENT OF THE PROBLEM

Introduction

Research on connections between selective attention and working memory (WM) has resulted in a greater understanding of the role individual differences play during demanding tasks (Conway, Cowan, & Bunting, 2001; Cowan et al., 2005; Engle & Kane, 2004; Gathercole et al., 2008). Strategy use may play an important role in individual differences related to WM capacity (Dunlosky & Kane, 2007; McNamara & Scott, 2001; Rosen & Engle, 1997). Some researchers have proposed that strategies are the cause of individual differences in WM (Cokely, Kelley, & Gilchrist, 2006; Dunlosky & Kane, 2007; McNamara & Scott, 2001), and others argue that WM capacity constrains individuals' abilities to use certain strategies effectively (Dunlosky & Thiede, 2004a; Turley-Ames & Whitfield, 2003; Schelble, Therriault, & Miller, 2012). Both strategy use and WM capacity influence performance on reading (Linderholm & van den Broek, 2002; Linderholm, Cong, & Zhao, 2008), mathematical (Keeler & Swanson, 2001; Geary, Frensch, & Wiley, 1993), and retrieval tasks (Rosen & Engle, 1997; Schelble, Therriault, & Miller, 2012). The purpose of this dissertation study was examine, via a laboratory experiment, how strategy use relates to WM, whether strategies can be successfully taught to individuals, and whether cognitive load affects strategy instruction effectiveness.

Working Memory: Cause or Effect of Strategies?

Theories on the direction and magnitude of the relationship between WM and strategy use differ substantially. Providing evidence that informs our understanding of the relationship between WM and strategies is important for theoretical and practical purposes. Figure 1-1 summarizes the differences between the strategy-as-effect (Dunlosky & Thiede, 2004a) and strategy-as-cause (Dunlosky & Kane, 2008) views of the WM/strategy relationship, as well as related theories that fall under each of these general views.

According to the strategy-as-effect hypothesis, (Dunlosky & Thiede, 2004a), WM influences individuals' abilities to use strategies. During a task involving the selection of items for recall, individuals with high WM (HWMs) were more likely to use a strategy that made the task less difficult, even though all participants were instructed to use the strategy. Dunlosky and Thiede interpreted this finding as evidence that HWMs were more capable of employing the strategy than individuals with low WM (LWMs). Evidence of lack of strategy use in young children (Guttmann, Levin, & Pressley, 1977) and span differences in performance following strategy instruction (Turley-Ames & Whitfield, 2003) provide additional support for the strategy-as-effect hypothesis (Dunlosky & Thiede, 2004a) because they suggest that capacity is a determining factor in whether a strategy can be successfully employed.

McNamara and Scott (2001) found that participants who demonstrated independent use of more effective memory strategies also demonstrated better verbal task performance, providing support for the strategy mediation hypothesis. McNamara and Scott described two ways in which strategy use and WM are related: natural strategy use is related to individual differences in WM task performance, and induced strategy use can improve task performance. The strategy affordance hypothesis takes the strategy mediation hypothesis a step further: It states that strategy use will mediate the relationship between WM capacity and performance on cognitive tasks only if the same strategies can be utilized on both types of tasks (Bailey, Dunlosky, & Kane, 2008). In a comparison of performance on WM, memory, reading, and general cognition tasks, WM correlated with use of strategies previously classified as effective (Bailey et al., 2008). However, WM task strategy use was unrelated to reading comprehension performance. Even when both tasks afforded use of the same strategies, the relationship between WM and other measures was only partially mediated by strategy use. When both tasks did not afford use of the same strategies, strategy use failed to mediate the relationship between performance on those tasks. This finding is important when considering strategy instruction: Students must be both proficient in use of the strategy, and be engaged in a task to which the strategy is applicable (and to which they are aware that the strategy is applicable, see Atkinson, Renkl, & Merrill, 2003). For example, a student who is taught a multiplication strategy during regular, digit-only mathematical problems might not independently apply the strategy during word-problem solving, if the strategy was not explicitly taught with word problems.

The Effect of Strategies on Working Memory Performance

The relationship between WM capacity and attentional control may be partially explained by strategy use (Cokely, Kelley & Gilchrist, 2006). Many researchers conceive of WM capacity as attentional control (Engle & Kane, 2004). Cokely et al. initially found a curvilinear relationship between WM span and interference. During free recall, HWMs outperformed LWMs. However, HWM participants exhibited greater interference effects during a recall task that required participants to learn multiple lists when prompted with cues from the correct list. The highest HWM participants reported using interference-prevention strategies when presented with cues (such as not looking at the cue words). When all participants were required to view cues, a positive linear relationship between span and interference was obtained. LWMs' performance did not change as a result of cue presentation. Cokely et al. suggested that this finding was due to HWMs' elaborative strategies being disrupted when they were required to process cues. When all participants were trained to use a recall strategy (linking the to-be-remembered words together in story format), no span differences in interference effects were found. Learned, as opposed to innate strategies, may account for differences in span performance (Cokely et al., 2006; Ericsson & Kintsch, 1995; McNamara & Scott, 2001). Training LWMs to use effective strategies reduced span differences in recall performance. This suggests that performance differences may not result purely from capacity differences, because, following training, LWMs were able to effectively employ strategies they had not previously employed on their own.

Other Factors Influencing Strategy Use

Task characteristics may also affect strategy use. Fluency may partially explain strategy selection beyond the role of WM. The term fluency refers to how difficult an individual perceives a task to be (Oppenheimer, 2008). From a dual process perspective, more fluent activities require less WM (Evans, 2007). In addition to factors such as cognitive resources and motivation, an individual may choose to adopt a more demanding strategy based on their expectation that a simpler strategy will be unsuccessful (Oppenheimer, 2008). One important consideration is whether WM capacity influences individuals' perceptions of the success of strategies (i.e., do participants with high WM capacity have different expectations for the success of more/less complex strategies than participants with low WM capacity?). The cognitive load of instructional conditions is likely to affect participants' perception of fluency.

HWMs and LWMs, because of their differing attentional capacities, may experience the same instructional condition differently (in terms of fluency).

During recall tasks, participants often rely on previously-learned strategies, even if they are unsuccessful (Atkins & Baddeley, 1998). Individuals' success in the use of strategies differs, and WM's ability to predict performance is not altered by the use of semantic strategies (Atkins & Baddeley, 1998). During strategy instruction, a high level of cognitive load may prevent individuals from effectively learning strategies, and consequently prevent them from employing strategies on future tasks. If the level of cognitive load during instruction does not prevent individuals from acquiring the strategy, both HWMs' and LWMs' later performance may be improved by strategy use.

Working Memory and Strategy Use during Academic Tasks

Previous research on the relationship between WM and mathematical strategy use points to a central question in the relationship between WM and strategy use: Are individuals with high WM capacity capable of different strategies than individuals with low WM capacity, or are they simply better at executing the same strategies? The variation in strategy use in accordance with age (Geary et al., 1993; Imbo & Vandierendonck, 2007), from task to task (Barrouillet et al., 2008), and as a function of cognitive load (Schelble, Therriault, & Miller, 2012) makes a definitive answer to this question difficult. The definition of what constitutes a strategy has also deterred the synthesis of research on strategy use: Some strategy research focuses on problem-solving (Barrouillet et al., 2008; Imbo & Vandierendonck, 2007) and comprehension processes (Linderholm et al., 2008; Swets et al., 2007), while other researchers use the term "strategy" to explain differences in WM span task performance (Miyake & Shah, 1999).

A fundamental difference exists between WM span performance itself and individual differences that arise in other situations as the (partial) result of WM span. In reading, strategies are examined by look-back patterns, which can represent readers' use of text during comprehension tasks (Linderholm & van den Broek, 2002; Linderholm et al., 2008). Mathematical strategies can be broken down into retrieval and non-retrieval categories (Andersson, 2008; Barrouillet et al., 2008; Wu et al., 2008). Retrieval itself can consist of multiple strategies (Barrouillet et al., 2008; Schelble, Therriault, & Miller, 2012) and is alternately conceptualized as pattern activation in long-term memory (Ericsson & Kintsch, 1995).

Evidence of differences in retrieval (Andersson, 2008; Schelble, Therriault, & Miller, 2012), mathematical (Barrouillet et al., 2008), and reading strategy use (Linderholm & Zhao, 2008) across HWM and LWM individuals, combined with evidence of differences in their performance under load (Rosen & Engle, 1997; Schelble, Therriault, & Miller, 2012), suggest that HWMs and LWMs approach use of the same strategies differently. However, additional research is needed in order to determine whether the level of cognitive load during strategy instruction affects individuals differently in accordance with their WM capacity. This goal is particularly relevant for educational research, which is frequently conducted with eventual classroom application in mind. For example, retrieval strategy research frequently involves category fluency tasks (Rosen & Engle, 1997; Schelble, Therriault, & Miller, 2012) which may not be representative of the types of retrieval typically required in academic settings. Consider the types of retrieval students typically encounter in a testing situation: A specific item from a category (e.g., the 26th President of the United States) must be recognized or recalled. Frequently, time limits are in effect, which prevent students from using strategies such as retrieving every category exemplar until the right one is located. In this case, the student may have stored presidential information in a chronological list of presidents, or in relation to other historic events at the time of the president's term. Accessing either type of information could assist the student with retrieving the correct president. Other assessments require students to determine which category exemplar should be retrieved in order to effectively solve a problem (e.g., a statistical word problem that requires the student to determine which statistical test is appropriate). In such cases, the student must retrieve information from a variety of categories: the category that contains information about the purpose of each type of test, the category that contains information about how to carry out the formula for each test, and the significance rules for each test. Depending on the student's level of understanding and the types of connections they made during learning and studying, each type of statistical test information could be stored in completely separate, isolated categories, or it could all be connected in a meaningful way that allows the student to relate, for example, relevant formulaic information to the significance rules for each statistical test.

Differences in students' approaches to obtaining the correct answer in a testing situation may have significant effects on their success. If HWM students approach academic tasks (such as recall, reading comprehension, and mathematical problem-solving) in a systematically different way than LWM students, differences in strategy use could explain some of the performance differences between WM groups. However, simply determining whether there are strategy use differences between HWM and LWM groups does not provide useful information for determining whether certain strategies are more easily employed by HWMs (the strategy as effect and strategy affordance hypotheses) or if WM span itself is explained by strategy use (the strategy as cause hypothesis).

Can Individuals with Low Working Memory Learn to Use Strategies Effectively?

In addition to the numerous situational variables that affect instances of storage and retrieval, individual differences in WM capacity may systematically influence a person's ability to employ the most effective strategy for a given task. Although HWMs appear to "naturally" employ superior strategies (Schelble, Therriault, & Miller, 2012), it may be the case that they were able to pick up these strategies without instruction, but that LWMs would be able to employ them effectively if they were able to learn them under less demanding conditions. WM capacity does not account for all variance in strategy use (Dunlosky & Kane, 2007; Schelble et al., 2012), and although HWMs may have more experience successfully employing effective strategies, the possibility that LWMs can learn to use these strategies has not been ruled out (Burton & Daneman, 2007; Linderholm & van den Broek, 2002). LWMs seem to be capable of adapting to their limited WM capacity, provided they have other advantages (e.g., mature epistemic beliefs, Burton & Daneman, 2007). The present study examines whether effective strategy instruction can afford LWMs similar advantages.

Effects of Working Memory on Strategy Instruction Effectiveness

In their discussion of WM as "enhancing the ability to use prior knowledge in order to improve performance," Carretti, Borella, and De Beni (2007) proposed that HWMs benefit less from strategy instruction because they are more likely to already employ effective strategies during WM tasks (p. 311). Participants (older adults) did not need additional cognitive resources to employ the specific strategy they were trained to use (i.e., imagery) because this strategy drew on participants' existing knowledge. Even when high and low WM participants are given the same strategy instructions, HWMs retain their superior performance due to their unprompted, pre-training strategy use (McNamara & Scott, 2001). Despite HWMs' superior performance, strategy instruction for LWMs may be of benefit, particularly in the case of academic strategies for which factors other than WM are known to impact strategy success.

The effectiveness of self-explanation strategies is dependent upon individual expertise levels (Renkl, 1997). Self-explanation strategies involve explaining the steps of a problem to oneself during problem solving or while studying examples (Renkl, 1997). Self-explanation strategies consist of prompts that allow a learner to "tailor his or her self-explanation according to his or her own mental model of the situation at hand" (Atkinson, Renkl, & Merrill, p. 776). Principle-based self-explanations are most effective for individuals with low prior knowledge (Renkl, 1997). Principle-based self-explanations consist of specifying the goal structure and explaining the principle illustrated by the problem or example. An example of a principle-based self-explanation for a subtraction problem is, "This is the borrowing rule, so that's why the zero becomes a nine when you subtract one from it." Practicing the self-explanation strategy while completing practice problems has been found to be more effective than practicing self-explanation while studying examples (Aleven & Koedinger, 2002). Self-explanation has the potential for wide application; prompting students to explain the steps of a process to themselves while completing the process may be useful for many academic tasks. However, the interaction of WM (a characteristic that affects many aspects of learning) with students' ability to learn the self-explanation strategy has not been previously examined.

Working Memory and Cognitive Load During Instruction

Cognitive load theory stresses the importance of directing students' attention to activities that help them acquire and automate schemas (Sweller, 1994). Schemas are cognitive collections of information organized in accordance with how the information will be used. During initial learning, schema acquisition is important. Activities such as studying worked examples assist with schema acquisition, while minimizing the amount of cognitive load associated with instruction (i.e., extraneous cognitive load; Sweller, 1994). Two other types of cognitive load also affect the learning process: intrinsic load, which is associated with the material itself, and germane load, which improves learning by focusing resources on the acquisition and automation of schemas (Paas, Tuovinen, Tabbers, Van Gerven, & Pascal, 2003). Intrinsic cognitive load is high during initial learning, and cannot be adjusted by the instructor. Germane load and extraneous load can, and should, be varied depending on the expertise level of the learner (Paas et al., 2003).

Because WM impacts various areas of functioning, it is highly desirable for instruction related to improving the use of this capacity to transfer to contexts beyond the laboratory. Kuhn (2007) insisted that practicing problem-solving skills is essential if students are to become effective problem-solvers. WM has been frequently described as a component of problem-solving, a skill that is necessary in many contexts, within and beyond educational settings. If Kuhn's conception of problem-solving skills transfers to strategy use during WM tasks, practice applying strategies should be effective at increasing effective strategy use.

Kirschner, Sweller, and Clark (2006) advocated for the use of direct instruction until learners have a substantial amount of prior knowledge about a topic. According to

Kirschner et al., inquiry-based instruction imposes more extraneous cognitive load than direct instruction. The demands of inquiry-based instruction can be compared to those of the final problem-solving stage described by Paas et al. (2003), although researchers who advocate a direct-instruction approach to instruction suggest that inquiry-based instruction is more demanding (Kirschner, Sweller, & Clark, 2006). Chandler and Sweller (1991) described strategy use as typically related to extraneous cognitive load, because strategies and the load associated with their use can be modified by the instructor. However, if strategies are learned simultaneously with material during initial learning, it is possible that strategy use could be associated with intrinsic load. Additionally, instructors' ability to alter learners' strategy use may be affected by WM's impact on strategy use (Rosen & Engle, 1997; Schelble, Therriault, & Miller, 2012) and strategy instruction effectiveness (Linderholm & Zhao, 2008). Thus, by varying the amount of cognitive load associated with strategy instruction, I sought to examine the effect of WM and its interaction with cognitive load during learning on strategy learning.

Theoretical Implications of Examining the Effect of Strategy Instruction on Performance

The present study is central to the strategy-as-cause versus strategy-as-effect debate. It may also be relevant to the strategy affordance hypothesis and the concept of long term WM. In their description of retrieval structures, Ericcson and Kintsch (1995) emphasized the importance of retrieval cues in accessing information stored in long-term memory. Retrieval structures are said to be domain-specific, and individual differences result from differences in encoding strategies (Ericsson & Kintsch, 1995). More expertise in an area results in more elaborate retrieval structures, which are used to access relevant information in long-term memory. The concept of long-term WM, then, is similar to the idea of retrieval strategies. Experts have more elaborate retrieval structures (Ericsson & Kintsch, 1995) and individuals with higher WM capacity have demonstrated more frequent use of advantageous strategies (Dunlosky & Thiede, 2004b). If strategy instruction and sufficient practice opportunities improve the performance of LWMs, such a finding could be interpreted as support for the long-term WM hypothesis because Ericcson and Kintsch acknowledged the possibility of improving memory capacity by learning to resist interference. If the acquisition of new strategies improves encoding (and/or retrieval), long-term WM theorists might interpret this as expansion of long-term WM.

Some researchers who have found that WM performance improves after strategy training claim that strategy use is the reason for individual differences in WM performance (McNamara & Scott, 2001). Our previous research partially supports this idea, as we found considerable overlap in the types of strategies employed by HWMs and LWMs during a category fluency task, in addition to WM-related differences in the use of the most successful retrieval strategy (Schelble, Therriault, & Miller, 2012). However, this discrepancy is as much the result of task differences as it is the result of different conceptions of the term “strategy.” Our work (Schelble et al., 2012) focused on retrieval strategies used during a category fluency task; McNamara and Scott examined performance during a WM task after mnemonic device training. Is the fact that we can improve performance on a task intended to be completed somewhat automatically relevant to the question of how WM capacity affects other types of strategy use? Other researchers who have obtained similar findings caution against conditions that allow for variation in strategy use because the interpretability of the relationship between WM and other abilities is questionable when something other than “true” WM capacity influences WM span scores (Turley-Ames & Whitfield, 2003).

Even after strategy instruction, HWMs have been found to outperform LWMs (Dunlosky & Kane, 2007; Turley-Ames & Whitfield, 2003). Strategy use, then, may be a contributor to individual differences in WM capacity, but it does not completely explain capacity differences. The design of the present study contributes to our knowledge of whether this is still the case when LWMs are taught using methods that may make different demands on their WM capacity. If, as Rosen and Engle (1997) suggested, increased cognitive load makes it more difficult for HWMs to perform at their usually superior level, an instructional condition that is more demanding may decrease their ability to learn new strategies. Kirschner, Sweller, and Clark (2006) advocated for minimally demanding learning conditions when prior knowledge about a subject is limited. Specifically, they proposed the use of direct instruction. Strategy use can be considered a form of knowledge, however, it remains to be seen whether knowledge of one effective strategy influences an individual’s ability to learn a new strategy for the same task. Both WM capacity and knowledge about a topic affect performance on tasks requiring participants to learn new information about the topic (Hambrick & Engle, 2002). If strategies can be considered domain-specific, previous knowledge about a strategy for the same domain could make learning a new strategy easier, but WM capacity may also affect individuals’ ability to acquire a new strategy. Proponents of the strategy-as-cause view might suggest that learning a new (effective) strategy would increase a person’s WM capacity, while strategy-as-effect theorists would evaluate the likelihood of an individual effectively learning and employing a new strategy in terms of their (pre-existing) WM capacity. Strategy affordance theorists would take the task into account, and I suggest that this is the missing link among the various findings related to the relationship of strategy use and WM capacity.

The strategy affordance hypothesis states that strategy use is only related to WM capacity if the same strategies that can be employed during a WM task can also be employed during the task WM capacity is being compared to (Bailey et al., 2008). However, we know that allowing time for strategy use on a WM span task can alter performance (Turley-Ames & Whitfield, 2003), and that the types of things classified as strategies vary from study to study. A fundamental similarity exists among the strategies used during mathematics, reading, and retrieval tasks found to correlate with WM performance. This similarity is also related to the ways individuals approach WM tasks. Just as expert readers retrieve words from long-term memory, as opposed to sounding them out each time they encounter them, expert mathematics problem-solvers retrieve common math facts from long-term memory (Geary et al., 1993; Tronsky, 2005). Expert strategists are experts because the strategies they employ are no longer effortful, and this is due to an advantage they acquire over time: practice (Naumann et al., 2008).

Practice as a Determining Factor in Successful Strategy Use

LWM individuals may have fewer opportunities for practice if, initially, they find the use of strategies more demanding. Imagine that you are a seven-year-old learning mathematics. You have a worksheet full of problems in front of you. On the chalkboard, your teacher is demonstrating a strategy for two-digit subtraction: To subtract 9 from a 2-digit number, take away 10, then add one. If you already feel competent with single-digit addition and subtraction, you may find this strategy useful. You may find it effortless to retrieve the subtraction facts you have memorized, and then perform some very simple addition in order to obtain the correct answer. In other words, if you have successfully performed subtraction in the past, and were able to store the subsequent answers in long-term memory, the strategy you are currently being taught may not be difficult to apply. Without relevant subtraction facts stored in long-term memory, this strategy requires double the mathematical problem solving: instead of just retrieving the -10 subtraction fact, you must go through the necessary steps to figure out what X-10 is, and then add one to that number. Because you do not have access to a previously memorized correct answer, you may perform further steps to ensure that your answer is correct. At first glance, it may appear that you are less able to perform the strategy of subtracting 10, then adding one. In this case, we do not know whether you are capable of performing the strategy or not, because you do not have the facts stored in long-term memory that are necessary to carry out the strategy. Consequently, you are unable to practice the strategy, because your WM is busy carrying out the mathematical function of subtracting 10, then adding one. LWMs are at greater risk for mathematical difficulty (Keeler & Swanson, 2001); determining the most effective method of strategy instruction may be an effective way to allow them the opportunity for successful practice, resulting in improved the mathematical performance.

Much previous research on strategy instruction does not include any variation in teaching methods (Linderholm & Zhao, 2008; Naumann et al., 2008; Turley-Ames & Whitfield, 2003), however, Atkinson, Renkl, & Merrill (2003) varied instructional methods and found that backwards fading (i.e.., having students first solve part of a problem, then gradually moving towards solving an entire problem) was more effective than having students view an example, then solve a problem. It may be the case that backwards fading and example-problem pairs affect HWMs and LWMs differently. Specifically, if LWMs are given the opportunity to learn to use strategies in low cognitive load (backwards fading) conditions, later attempts to employ those strategies may be more successful because of their previous successful practice opportunities during the learning process. Although this type of instruction may not be possible in every learning situation, it may be possible to teach LWMs a strategy for learning strategies, i.e., to determine how HWMs are approaching tasks differently and give LWMs the opportunity to practice those strategies (Naumann et al., 2008).

The Present Study

I examined whether cognitive load during strategy instruction affected individuals differently as a function of their WM capacity. The effect of the independent variables WM and learning condition on the dependent variables strategy learning, performance during learning, self-reported cognitive load during learning, and post-training test performance was measured. The effect of strategy learning as an independent variable on performance during learning and post-training test performance was also measured, as were the effects of self-reported cognitive load on strategy learning, performance during learning, and post-training test performance.

General Predictions

I expected LWMs' performance to remain lower than that of HWMs, even if they learned to apply effective strategies, due to previous findings regarding the relationships between strategy use, WM, capacity, and performance on cognitive tasks (Bailey et al., 2008; Lehmann & Hasselhorn, 2007; Linderholm & Zhao, 2008; McNamara & Scott, 2001; Touzani et al., 2007). LWMs may be helped by strategy instruction and low-demand practice time; their performance may improve, and they may become more comfortable with employing strategies. However, I expected the general capacity theory of WM (Engle, Cantor, & Carullo, 1992) to hold: LWMs have less WM capacity than HWMs, so their ability to perform WM-demanding tasks and use strategies is constrained. Although low-demand practice opportunities will decrease the WM load of learning to use strategies, strategy deployment is still likely to be somewhat demanding during task performance. Participants assigned to Condition A were expected to perform better on problem-solving tasks than participants assigned to Conditions B, C, and D. Participants were expected to perform better in the two strategy instruction conditions (Conditions A and B) than in either of the control conditions (Conditions C and D) because strategy instruction was expected to improve performance (Atkinson, Renkl, and Merrill, 2003).

Predicted Strategy Learning as a Function of Working Memory and Condition

Both HWMs and LWMs were expected to learn strategies more successfully in Condition A than in Condition B (Atkinson, Renkl, & Merrill, 2003). The difference between high and low WM participants was expected to be smaller in Condition A due to previous research on the effect of load on HWMs (Rosen & Engle, 1997; Schelble, Therriault, & Miller, 2012). Condition A was designed to allow LWM individuals to practice using new strategies under conditions that do not sap all of their WM resources.

Predicted Problem-Solving Differences as a Function of Working Memory and Strategy Learning

HWM participants were expected to learn strategies more effectively due to their higher cognitive capacity, resulting in better problem-solving performance during learning. Individuals who learned strategies better during learning were expected to perform better on problems solved during learning and on the post-training test regardless of WM capacity, however, because higher WM capacity was expected to positively influence strategy learning, HWMs were expected to bring two advantages to the post-training test: Higher WM capacity for problem solving, and more successful previous use of the self-explanation strategy (which should help performance on the post-training test). Among participants who received strategy instruction (i.e., assignment to Condition A or Condition B), HWMs' post-training test performance was expected to be higher than LWMs' because cognitive load in the post-training test was equal for both conditions.

Predicted Differences in Perceived Cognitive Load as a Function of Working Memory

I expected LWMs to report higher perceived cognitive load than HWMs due to LWMs' lower WM capacity and higher likelihood of previous mathematical difficulties (Keeler & Swanson, 2001; Geary, Frensch, & Wiley, 1993). I also predicted that the interaction of WM and self-reported cognitive load would affect problem-solving performance during learning (i.e., LWMs with higher perceived cognitive load were expected to perform worse on problems solved during learning than HWMs who reported high perceived cognitive load).

Strategy-as-effect view (Dunlosky & Thiede, 2004a)	WM causes differences in strategy use and effectiveness.
Strategy affordance hypothesis (Bailey, Dunlosky & Kane, 2008)	Mediation occurs only if same strategies can be used for WM and other tasks.
Strategy-as-cause view (Dunlosky & Kane, 2007)	Strategies are the cause of differences in WM capacity.
Strategy mediation hypothesis (McNamara & Scott, 2001)	WM explains some of the variance in strategy use.

Figure 1-1. Theories of the relationship between WM and strategy use.

CHAPTER 2
METHOD

Participants

The study participants consisted of 231 undergraduate students enrolled in introductory educational psychology courses at a large southeastern university participated in the study. Participants were given course credit in exchange for participation in the study. The experiment took approximately 90 minutes for each participant. Five participants were excluded because they did not follow instructions during one or more of the tasks. Two participants were excluded due to a high number of accuracy errors on the SymSpan task. Twenty eight participants were excluded due to missing data on one or more measures. Outlier removal procedures were used on the remaining 196 participants, resulting in a final sample of 180 participants for all analyses.

Materials

WM capacity was measured using the Symmetry Span task (SymSpan) and a backwards digit-span task. During the SymSpan, participants assess the symmetry of shapes on the screen while simultaneously trying to remember the position of boxes. Participants view a shape followed by a prompt to indicate whether the shape is symmetric or not. After choosing “yes” or “no,” a screen with red and black boxes appears (the participant’s task is to recall the position of the red box). After several shape/box combinations, participants view a screen of boxes, and must recall the correct red box positions (in order). During the backwards digit-span task, participants are presented with sets of series of numbers, then asked to recall each set in reverse order.

Participants received instruction and testing on probability calculation. Modified versions of materials developed by Renkl (1997) and Atkinson, Renkl, and Merrill (2003) were used for the probability knowledge test, post-training test, practice problems, and instructional text. Perceived cognitive load was measured using Paas and van Merrienboer's (1994) cognitive load rating scale.

Procedure

Participants were randomly assigned to one of four conditions: the low-load strategy instruction condition (backwards fading-Condition A), the high-load strategy instruction condition (example-problem pairs-Condition B), a control condition with explanation (Condition C), and a control condition without explanation (Condition D). All participants completed a probability knowledge test in order to account for previous probability knowledge (Atkinson, Renkl, & Merrill, 2003).

Low-Load (Backwards-Fading) Instruction Condition (Condition A)

Participants in Condition A received written probability calculation instructions (Atkinson, Renkl, & Merrill, 2003). Next, participants received additional instruction in the form of faded examples: participants viewed a worked example presented in steps, followed by a problem in which the third (final) step was left blank for the participant to solve, then a problem with the second and third steps left blank, and finally, a problem that the participant solved completely independently, with no worked steps provided. A sheet containing a list of the probability rules/principles that were explained in the written strategy instructions was provided (probability of an event, principle of complementarity, multiplication principle, and addition principle). Participants were prompted to indicate which rule/principle was used in each step of the problem, as they solved each problem (this is the self-explanation prompt). After each problem, participants rated their level of perceived cognitive load (Paas & van Merrienboer, 1994). Finally, participants completed a probability calculation post-training test (Atkinson, Renkl, & Merrill, 2003) and two WM measures (the SymSpan and the backwards-digit span).

High-Load (Example-Problem Pairs) Instruction Condition (Condition B)

Participants in Condition B received written probability calculation instructions identical to those in Condition A. Next, they received additional instruction in the form of worked examples paired with practice problems to complete (Atkinson, Renkl, & Merrill, 2003). The sheet of probability rules/principles described above was provided. As in Condition A, participants were prompted to indicate which rule/principle was used in each step of the problem they were solving. After each problem, participants rated their level of perceived cognitive load. Finally, participants completed the post-training test and WM measures described above.

Control Condition with Explanation (Condition C)

The purpose of Condition C was to demonstrate that open-ended self-explanation is not sufficient to benefit probability problem-solving performance; instead, self-explanation must direct the problem-solver’s attention to specific information that will assist with the current problem solving task. Participants in Condition C received written probability calculation instructions identical to those in Conditions A and B. Next, participants solved the same probability practice problems that were provided in Condition B, except that the participants were not required to solve each step of the problem in a separate box. After each problem, participants described how they solved the problem and rated their level of perceived cognitive load. Finally, participants completed the post-training test and WM measures.

Control Condition without Explanation (Condition D)

The purpose of Condition D was to demonstrate that practice alone would not benefit probability-problem solving performance as much or more than self-explanation strategy instruction. Participants in Condition D received the written probability calculation instructions, followed by the same probability practice problems provided in Condition C. After each problem, participants rated their level of perceived cognitive load. Next, participants completed the post-training test, followed by the same WM measures used in Conditions A, B, and C.

CHAPTER 3
RESULTS

Descriptive Statistics

Participants' SymSpan scores ranged from 6 to 42, with a mean score of 28.64 (SD = 7.51). Backwards digit-span scores ranged from 1 to 10, with a mean score of 6.13 (SD = 1.44). Freshmen, sophomores, juniors, and seniors were included in the sample (mean year in college = 2.41, SD = 1.11), as were a wide range of mathematical ability levels, ranging from no college mathematics courses to high grades in several advanced courses (mean mathematics course score = 2.42, SD = 1.53). 58% of the sample had taken a college-level statistics course. The mean GPA of participants in the sample was 3.15 (SD = 0.97). There were 41 participants in Condition A, 40 participants in Condition B, 51 participants in Condition C, and 47 participants in Condition D. Table 3-1 contains descriptive statistics for the probability problem-solving variables.

Table 3-1. Descriptive statistics for probability problem-solving variables (N = 180).

Variable	Range	Mean	SD
Probability knowledge test score	0-7	5.66	1.50
Percent of problems solved correctly during learning	0-100	41.62	40.24
Strategy use score (Conditions A & B only, N = 81)	1-12	8.99	3.23
Self-reported cognitive load during learning	1-4.7	1.97	0.75
Post-training probability problem-solving test score	0-10	4.84	3.49

Differences in Problem-Solving Performance and Cognitive Load as a Function of Learning Condition

One-way between-subjects analysis of variance (ANOVA) was used to examine differences in participants' performance as a function of learning condition. Performance during learning varied significantly as a function of learning condition, $F(3, 175) = 28.57$, $p < .001$. Thus, the hypothesis that the condition participants were assigned to would affect their problem-solving performance was supported.

A priori hypotheses regarding differences between learning conditions were tested using Bonferroni adjusted alpha levels of .0125 per test (.05/4). The Bonferroni test was used in order to examine differences between specific groups (i.e., to compare the performance of participants in each learning condition to the performance of participants in every other learning condition). Participants in Condition A performed significantly better during learning, $M = 57.32$, $SD = 35.75$, than participants in Condition C, $M = 22.55$, $SD = 34.01$, $p < .001$, and Condition D, $M = 20.21$, $SD = 31.55$, $p < .001$. Participants in Condition B, $M = 75.0$, $SD = 31.52$, also significantly outperformed participants in the control conditions. These results supported the hypothesis that participants in the strategy instruction conditions (Conditions A and B) would perform better than participants in the control conditions (Conditions C and D).

The pairwise comparison of problem-solving performance during learning in Condition A to performance in Condition B was not significant, $p = .107$. On the surface, this result indicates that the hypothesis regarding the relationship between learning condition cognitive load and problem-solving performance during learning was not supported, however, participants' self-reports of cognitive load indicate that there were no significant differences in cognitive load as a function of condition, $F(3, 176) = .825$, $p = .482$, despite Condition A being designed to reduce participants' cognitive load (Atkinson, Renkl, & Merrill, 2003). Table 3-2 contains mean values for strategy use scores, post-training test scores, problem-solving performance during learning, and self-reported cognitive load during learning. Surprisingly, participants performed better (in terms of problem-solving) in Condition B than in Condition A.

Differences in Post-Training Test Performance as a Function of Condition

Differences in post-training test performance as a function of learning condition, measured using a one-way between-subjects ANOVA, revealed significant differences, $F(3, 176) = 6.42$, $p < .001$. Bonferroni tests of a priori hypotheses indicated that post-training test performance was significantly higher in Condition B, $M = 6.76$, $SD = 3.08$, than in Condition C, $M = 3.96$, $SD = 3.32$, $p < .001$ and Condition D, $M = 4.11$, $SD = 3.21$, $p = .002$. The posttest performance of participants in Condition A, $M = 4.88$, $SD = 3.75$, was not significantly different from the posttest performance of any other group, suggesting that Condition A did not provide participants with the most effective learning format. This result contradicted the hypothesis that backwards-fading would lead to more successful problem-solving.

Table 3-2. Mean post-training test scores, problem-solving scores during learning, and self-reported cognitive load by condition (N = 180).

Condition	Strategy use score	Problem-solving score (percent)	Post-training test performance score	Self-reported cognitive load
A (Backwards-faded instruction)	7.98	57.32	4.88	1.14
B (Example-problem pairs instruction)	10.00	75.00	6.76	1.12
C (Practice with self-explanation)	--	22.55	3.96	1.13
D (Practice problems only)	--	20.21	4.11	1.14

Differences in Strategy Use Success as a Function of Condition

Participants in Condition B correctly used the self-explanation strategy correctly significantly more often than participants in Condition A, $F(1, 80) = 8.83$, $p = .004$. The mean number of correct strategy usages in Condition B was 10.0, $SD = 3.21$. The mean number of correct strategy usages in Condition A was 7.98, $SD = 2.95$. These results are surprising because Condition A was expected to be the most successful strategy instruction condition based on previous research (Atkinson, Renkl & Merrill, 2003).

Effects of Working Memory and Cognitive Load on Strategy Learning

The SPSS 19 General Linear Model (GLM) was used to examine all relationships discussed in the remainder of this section. The GLM provides both one-way between-subjects ANOVA results and linear regression results for each model, so the reminder of this section includes descriptions of both types of analyses as appropriate. Table 3 contains all variables included in the GLM analysis for strategy use during learning. Because the dependent variable was strategy use, only data from Condition A ($n = 41$) and Condition B ($n = 40$) was used in this analysis.

Table 3-3. Analysis of variance for strategy use during learning (N = 81)

Variable	*df*	*F*	*p*
Condition	1	5.70	.020
College statistics class (0 = no, 1 = yes)	1	.175	.677
SymSpan score	1	1.28	.262
Backwards digit span score	1	3.78	.056
College math course average	1	.164	.687
GPA	1	2.69	.106
Probability knowledge test score	1	.686	.410
Time spent studying information sheet	1	.051	.823
Problem-solving during learning score	1	1.67	.200
Self-reported cognitive load	1	.510	.478
SymSpan x Condition interaction	1	4.30	.042
SymSpan x Condition score interaction	1	1.66	.202
Error	68	(2.98)	

Values enclosed in parentheses represent mean square errors.

Condition was significantly related to strategy use, as was the interaction of condition and SymSpan score. Participants' self-reported cognitive load was not significantly related to strategy use.

Table 3-4 contains the correlation matrix of all variables included in the linear regression analyses of variables predicting strategy use and post-training test performance. The purpose of reporting regression results for the dependent variable strategy use was to further explain the significant interaction of WM and condition in the ANOVA (please see Table 3-3) with an examination of the specific interactions of each condition with WM. Linear regression analysis revealed that the interaction of being assigned to Condition A and WM significantly predicted strategy use, $b = .500$, $t(68) = 2.07$, $p < .05$, suggesting that higher WM was associated with better strategy use in Condition A, but not in Condition B. Although this result is the opposite of the hypothesized relationship, the hypothesized relationship was dependent upon the assumption that Condition A resulted in lower cognitive load than Condition B. Participants' self-reported cognitive load scores indicate that this was not the case, as there were no significant differences in self-reported cognitive load as a function of condition.

Effects of Working Memory, Strategy Instruction, Strategy Use, and Cognitive Load on Problem-Solving During Learning

Linear regression analysis of performance during learning revealed that the interaction of being assigned to Condition C and SymSpan score was significantly related to performance during learning, $b = .522$, $t(162) = 2.18$, $p < .001$. Thus, higher WM was an advantage in Condition C. Pre-training probability knowledge test performance was positively related to problem solving during learning, $b = .314$, $t(162) = 5.10$, $p < .001$. Self-reported cognitive load had a negative effect during learning, $b = -.218$, $t(162) = -3.73$, $p < .001$. The worse performance of participants assigned to Condition C (compared to participants in Conditions A and B) demonstrates that self-explanation alone does not help with problem solving; it must occur on-line (i.e., during the problem-solving process) in order to benefit the problem-solving process.

A between-subjects one-way ANOVA was used to examine the effect of strategy use on problem-solving performance during learning. Because strategy use was included in the analysis, only data from Conditions A and B ($n = 81$) was used. Results indicated that correct use of the self-explanation strategy significantly predicted problem-solving performance during learning, $F(1,71) = 49.14$, $p < .001$. Having taken a college statistics course, $F(1, 71) = 3.98$, $p = .05$, and a lower level of self-reported cognitive load, $F(1, 71) = 8.10$, $p = .006$, also had significant positive effects on performance. The cognitive load finding is consistent with the regression analysis results for Conditions A, B, C, and D reported above, however, it is interesting to note that having taken a college statistics course was only significantly related to problem-solving during learning in the analysis of Conditions A and B (without Conditions C and D).

Effects of Working Memory, Strategy Instruction, Strategy Use, and Cognitive Load on Post-Training Problem-Solving

Table 3-5 contains the results of the linear regression analysis of independent variables regressed on post-training test performance. Strategy use was not included in this analysis because Conditions C and D did not use the self-explanation strategy, and the purpose of this analysis was to compare the post-test performance of participants in Conditions A, B, C, and D. Linear regression revealed a significant relationship between post-training test performance and the SymSpan/Condition C interaction. The interactions of SymSpan with Conditions A and B were not significant predictors of post-training test performance. Higher WM capacity was an advantage during the post-training test in Condition C, but not in Conditions A and B (the strategy instruction conditions).

Assignment to Condition B helped performance on the post-training test, but assignment to Condition C hurt performance. Performance in Conditions C and D was substantially worse than in Conditions A and B (i.e., participants answered less than

25% of post-training test problems correctly in Conditions C and D, and over half of problems correctly in Conditions A and B, please see Table 3-2). The interaction of SymSpan score and cognitive load had the largest effect on the post-training test; low WM combined with high self-reported load resulted in poor post-training test performance (please see Table 3-5). Interestingly, self-reported load did not independently predict post-training test performance. This result, combined with the direction of the relationship between the SymSpan/load interaction and post-training test performance, suggests that HWM individuals were not affected by experiencing high cognitive load as negatively as LWM individuals were.

Results of a between-subjects one-way ANOVA (including only Conditions A and B, $n = 81$) indicated that correct use of the self-explanation strategy during learning was not significantly related to post-training test performance, $F(1, 69) = 2.00$, $p = .162$. Thus, the hypothesis that more successful use of the self-explanation strategy during learning would result in better post-training test performance was not supported. However, because assignment to Condition B was associated with better post-training test performance, and assignment to the Condition C was associated with worse post-training test performance, it appears that strategy instruction in a specific format (example-problem pairs) did help post-training test performance, even though the overall success using strategies during instruction did not predict post-training test performance.

Table 3-4. Correlation matrix of variables included in linear regression analyses (N = 180)

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Condition	1													
2. Statistics course	.079	1												
3. SymSpan	-.077	.115	1											
4. Back. Dig. Span	.028	-.049	.322**	1										
5. Math average	.003	.281**	.070	.103	1									
6. GPA	-.001	.106	-.073	.040	.402**	1								
7. Knowledge score	.130	.170*	.251**	.236**	.163*	.113	1							
8. Info. sheet time	.031	-.072	-.004	-.090	.196**	-.157*	-.142	1						
9. Learning score	-.456**	.079	.280**	.132	.077	-.007	.399**	-.151*	1					
10. Self-report load	-.006	-.102	-.197**	-.137	.063	.028	-.415**	.077	-.376**	1				
11. Strategy score[1]	.315**	.340**	.321**	.243*	.146	-.073	.536**	-.080	.833**	-.613**	1			
12. Post-train. score	-.167*	.143	.315**	.236**	.120	-.078	.654**	-.188*	.724**	-.452**	.707**	1		
13. SSpan x load	-.072	.092	.961**	.285**	.099	-.065	.146	.019	.173*	.073	.135	.189*	1	
14. SSpan x cond.	.795**	.108	.504**	.191*	.050	-.035	.206**	.026	-.251**	-.080	.391**	.002	.495**	1

* *p* < .05, ** *p* < .001

[1] N = 81 for correlations between strategy score and all other variables.

Table 3-5. Linear regression of variables related to post-training test performance (N = 180)

Variable	*B*	*SE B*	ß
Condition A	.195	1.79	.024
Condition B	-3.23	1.63	-.389*
Condition C	4.01	1.49	.518*
College statistics	.015	.313	.002
SymSpan score	.686	.287	.086*
BD Span score	.148	.110	.061
College math course average	-.002	.028	-.001
GPA	.001	.001	.082
Probability knowledge test score	.820	.122	.353**
Time spent studying information sheet	-.073	.088	-.035
Problem-solving score during learning	.049	.005	.564**
Self-reported cognitive load	13.06	7.25	.107
SymSpan x Cognitive load interaction	-.558	.249	-1.35*
Condition A x SymSpan interaction	-.026	.059	-.094
Condition B x SymSpan interaction	.093	.054	-.343
Condition C x SymSpan interaction	-.149	.051	-.566*

Effects of Working Memory and Condition on Self-Reported Cognitive Load

Data from Conditions A, B, C, and D (n = 180) was used to examine the relationships between WM, self-reported cognitive load, and condition. Neither WM, $F(1,170) = 2.26$, $p = .135$, instructional condition, $F(1,170) = 1.34$, $p = .262$, nor the interaction of WM and instructional condition, $F(1,170) = 1.40$, $p = .246$, significantly predicted self-reported cognitive load during learning. Only average math course grade, $F(1,170) = 3.93$, $p = .049$, and pre-training test score $F(1,170) = 21.9$, $p < .001$, predicted participants' self-reported cognitive load. Thus, the hypothesis that HWMs would experience less cognitive load than LWMs in the high-load conditions was not supported.

CHAPTER 4
DISCUSSION

Learning Condition and Problem-Solving Performance

Participants in Conditions A and B (the strategy instruction conditions) outperformed participants in Conditions C and D (the control conditions) during learning (i.e., while learning to use the self-explanation strategy/completing practice problems). These results supported the hypothesis that strategy instruction would benefit problem-solving. Surprisingly, participants in Condition A, which was designed to reduce cognitive load, did not perform significantly better than participants in Condition B on either measure. On the post-training test, participants assigned to Condition B performed better than participants in Conditions C and D. The scores of participants assigned to Condition A were not significantly different from those of Conditions C, or D on the post-training test. During learning, assignment to either strategy instruction condition (Conditions A or Condition B) appeared beneficial. Following training, however, only assignment to Condition B was helpful.

The unexpected "reversal" of the predicted results in Conditions A and B may be the result of more complex instruction in Condition A due to the novelty and inconsistency of the problem-solving format. Factors such as expertise and procedural errors during problems-solving are known to affect participants' perceived cognitive load (Ayres, 2006). Although Condition A was designed to reduce participants' cognitive load by "fading" them into full problem solving after first solving one, then two, steps of a probability problem, participants may have found the fading format confusing. During the study, several participants who were assigned to Condition A started to solve the faded problems from the beginning, before realizing that they were only required to solve the last step of the problem. Realizing that they had erroneously written solutions to an earlier step of the problem on the part of the answer sheet meant for a later step may have resulted in confusion. This experience, along with possible errors during their initial problem solving (made clear by reviewing the steps that had already been completed for them) could have resulted in increased cognitive load. For each problem, participants had to gauge how much of the problem they were required to solve (i.e., the same number of steps had not been completed for them on each problem). Participants may have faced additional load if the fading format was not something they had seen before, because their cognitive resources were taxed by figuring out the problem design in addition to performing the problem-solving and self-explanation tasks.

Assignment to Condition A benefitted participants during learning (compared to Conditions C and D). Conditions A and B were designed to teach participants to use the self-explanation strategy, which should have been helpful during problem-solving. Although Conditions A and B required additional work of participants (i.e, reporting which probability rule they used to complete each step of each problem), this “work” encouraged them to attend more carefully to their problem-solving process, resulting in better performance due to use of a beneficial strategy (self-explanation) (Chi, Bassok, Lewis, Reimann, & Glaser, 1989).

Strategy Use and Problem-Solving Performance

Taking together the superior performance of participants in Conditions A and B during learning (compared to Conditions C and D), the positive effect of being assigned to Condition B on post-training test performance regardless of WM capacity, and the effect of the interaction of WM and condition for Condition C on post-training test performance, it appears that teaching individuals to use a self-explanation strategy benefits problem-solving more than solving practice problems alone. When strategy instruction was not provided, participants were more heavily reliant on their WM capacity to solve problems, so those with higher WM capacity performed better. However, when strategy instruction was provided, WM capacity did not appear to have a significant effect on performance. Research on other types of strategies has demonstrated that use of a successful strategy can compensate for low WM capacity (Schelble, Therriault, & Miller, 2012). This pattern appears to hold for use of the self-explanation strategy during probability problem-solving. However, it is important to note that successful strategy use (as measured by participants' strategy use score during learning) did not benefit problem-solving when participants were not explicitly told to use the self-explanation strategy (i.e., during the post-training test). Through the strategy affordance hypothesis lens (Bailey, Dunlosky, & Kane, 2008), this suggests that participants were not aware that using self-explanation during the post-training test would benefit their performance.

Additionally, only participants in Condition B demonstrated superior performance on the post-training test, even though participants Conditions A and B were taught to use the self-explanation strategy. Problem-solving scores during learning were higher in the Condition B than in any other condition. Although the problems participants solved in Condition B were identical (content-wise) to the problems in Conditions A, C, and D, the traditional example, then problem, format of Condition B may have facilitated learning more than the format of Conditions A, C, and D. If example-problem pairs are more familiar to students, learning to use the self-explanation strategy in this format may free up cognitive resources for other tasks (e.g., learning to apply probability principles, which is also useful on the post-training test).

Participants who correctly used the self-explanation strategy solved more probability problems correctly during learning. However, this effect did not persist into the post-training test; strategy scores during learning were unrelated to post-training test performance. Participants were not explicitly instructed to use the self-explanation strategy on the post-training test; the hope was that they would elect to use the strategy because it benefitted them during learning. Expecting students to self-explain spontaneously may be unrealistic, even if such behavior has benefitted them in the recent past. Possible explanations for this phenomenon include too little practice self-explaining in order to engage in it without prompting, not thinking to use the strategy due to the level of cognitive load during the post-training test, or simply viewing use of the strategy as unnecessary (and un-required) extra work.

Effect of Perceived Cognitive Load on Problem-Solving Performance

Across conditions, participants' self-reported cognitive load was related to their performance during learning—the more load participants reported experiencing, the worse they did on the task. On the surface, this indicates that cognitive load hindered participants' performance. Another interpretation is also possible: Participants who did poorly may have been aware of their poor performance, which may have influenced the level of cognitive load they reported. However, previous research indicates that poor performers are more likely than successful performers to over-estimate their performance (Dunning, Johnson, Ehrlinger, Kruger, 2003), so the former explanation may be more likely.

Self-reported cognitive load during learning was not related to performance on the post-training test. Thus, participants whose problem-solving performance during learning was negatively affected by cognitive load during learning were not automatically worse performers on the post-training test. Although we did not measure cognitive load during the post-training test, if some participants were more likely to report a high level of cognitive load simply due to the type of problems they were solving (i.e., probability problems), a relationship between self-reported load during learning and post-training test performance should have emerged. The interaction of WM and cognitive load was a strong predictor of post-training test performance; this relationship will be discussed in the next section.

Working Memory as a Predictor of Problem-Solving Performance

Despite the inclusion of other variables related to post-training test performance in the analysis (e.g., previous probability knowledge and problem-solving score during learning), higher WM capacity was associated with a higher score on the post-training test. Thus, regardless of participants' previous probability knowledge or success during learning, solving problems on the post-training test taxed WM. The interaction of WM and being assigned to Condition C was also significantly related to post-training test performance. Participants who were assigned to Condition C did better on the post-training test if they had higher WM capacity. For the strategy instruction conditions (i.e., Conditions A and B), WM capacity did not interact with condition to predict post-training test performance; in Conditions A and B, WM capacity did not influence participants' ability to benefit from strategy instruction for the purposes of performing on the post-training test.

The interaction of WM and cognitive load was the strongest predictor of post-training test performance, demonstrating that LWMs who reported high load during learning were at a distinct disadvantage. Because WM did not predict self-reported load, the possibility that all LWMs experienced high load during learning cannot explain this relationship. Instead, it appears that a combination of factors related to previous mathematical success predicted cognitive load, and LWMs were particularly susceptible to the negative effects of these variables during the post-training test.

WM did not independently predict performance during the learning portion of the experiment. However, the interaction of WM with Condition C was significantly related to performance during learning. Condition C required self-explanation, but because it did not occur on-line (i.e., as part of the problem-solving process), it may not have had the same effect on participants' problem solving approach. Consequently, the way participants approached self-explanation in Condition C may have been different—because it was a separate task, in addition to the primary task of probability problems-solving, participants may have used additional resources shifting their attention to self-explaining (as opposed to viewing self-explanation as part of the problem solving process, which was more likely in Conditions A and B, where self-explanation occurred in the midst of problem-solving). WM capacity affects individuals' ability to shift their attention between tasks (Kane, Bleckley, Conway, & Engle, 2001), which may explain why WM affected performance in the Condition C.

Factors Influencing Successful Strategy Use

Although strategy use was not related to performance on the post-training test, it was related to performance during learning. Both WM and assigned learning condition had significant effects on success of strategy use, however, the relationships between these variables were unexpected: Significant relationships between WM and strategy use were expected in Conditions A and B (i.e., individuals with higher WM capacity were expected to use the self-explanation strategy more successfully than participants with low WM capacity). WM was expected to have a stronger effect on strategy use in Condition B because Condition B was expected to produce higher cognitive load than Condition A. However, the relationship between WM and strategy success was significant in Condition A, but not in Condition B—in Condition A (which was supposed to produce less cognitive load), higher WM was associated with better performance on the strategy use portion of the task, but in Condition B, the relationship between strategy success and WM was not significant.

In Condition A, WM was related to participants' ability to use the self-explanation strategy, but in Condition B (the condition in which participants performed better), WM did not have a significant effect on participants' strategy success. This indicates that success of strategy use is not inevitably tied to WM capacity. Under certain circumstances (e.g., under learning conditions that result in better performance), individuals with low WM are just as capable of using a successful strategy as individuals with high WM. Research on retrieval strategies has provided evidence that LWMs are sometimes capable of using effective unprompted strategies (Schelble, Therriault, & Miller, 2012).

Factors Influencing Participants' Perceived Cognitive Load

Despite the findings that WM was related to performance in the Condition C, and to strategy use in Condition A, WM did not influence participants' perceived cognitive load in any condition. In fact, the only factors that predicted self-reported cognitive load were measures of participants' previous knowledge (average score in college math courses and score on the pre-training probability knowledge test). There are several possible explanations for these unexpected findings: in Conditions A and B, WM was not related to performance, so it is not surprising that WM did not predict how difficult participants found the task, if the task was not particularly taxing of their cognitive resources. Overall, participants did not rate the task as particularly difficult (the mean difficulty rating was 1.97 on a 5-point scale). Thus, another possible explanation for the lack of a significant relationship between WM and self-reported load is that HWMs and LWMs rated the task similarly difficult for different reasons (e.g., perhaps LWMs rated the task less difficult because they were less aware of their own poor performance, while HWMs found the task less difficult due to their previous success on mathematical tasks). These speculative explanations illustrate the possibility that perceived cognitive load could originate differently as a function of WM.

Whether participants found the task difficult seems to be most closely related to their domain-specific experience with mathematical and probability problem-solving, rather than WM. Reducing participants' perceived cognitive load, then, is a promising strategy for improving probability problem-solving performance. Finding ways to reduce cognitive load in instructional settings with similar tasks presents challenges because the factors that predicted cognitive load were previous mathematical success and probability knowledge (as opposed to easily manipulated factors such as learning condition load).

Theoretical Implications

The present research has several implications for theories of WM and its relationship to strategy use. The interaction of WM and learning condition in predicting strategy success indicates that, under some circumstances, WM affects participants' abilities to learn and use the self-explanation strategy. These results provide support for the strategy-as-effect hypothesis, i.e., that strategy use is a result, rather than a cause, of WM capacity (Dunlosky & Thiede, 2004a). The finding that strategy acquisition differences between HWMs and LWMs disappear under some circumstances (i.e., during strategy instruction provided in an example-problem pairs format) indicates that individuals' reliance on WM can be reduced by altering the conditions under which they use to learn strategies. It may be the case that teaching participants to use a strategy during problem-solving without taking steps to reduce cognitive load represents a distinct type of load (perhaps similar to a dual-task situation) that taxes WM differently than simply being given a task in a more difficult format (which still consists of a single task).

Because LWMs' performance was no different than HWMs' performance in the condition that participants performed the best in (Condition B), my results provide support for the theory of long-term WM (Ericcson & Kintsch, 1995). According to Ericcson and Kintsch, learning to resist interference may improve memory capacity. Although I would not suggest that strategy use improves WM capacity itself, learning to use an effective strategy may improve individuals' ability to complete tasks that require use of WM, perhaps by increasing resistance to interference during a particular task through use of an effective strategy. Thus, low-load learning conditions provide a vessel through which LWM individuals can gain access to some of the benefits that HWM individuals experience, resulting in improved performance on tasks that are traditionally more difficult for LWMs.

Practical Implications

The ability of WM to predict strategy use in Condition A, but not in Condition B, supports the findings of Kirschner, Sweller, and Clark (2006) regarding differences between advanced and novice learners' abilities to learn in novel formats. HWMs appear to behave as advanced learners, demonstrating a superior ability (when compared to LWMs) to learn from the novel backwards-faded format of Condition A. This finding may benefit those teaching introductory probability and statistics courses, who are likely to encounter students with a range of WM capacities. Presenting new information about probability may be initially more effective in a traditional format, particularly for individuals with low WM capacity. The strong effect of the WM/self-reported cognitive load interaction on post-training test performance indicates that LWMs who experienced high cognitive load during learning were at a distinct disadvantage during the post-training test, further illustrating the importance of providing low-load instruction for LWMs.

Explicit instruction to use a self-explanation strategy also appears to benefit learners, as demonstrated by the finding that the average scores in Conditions A and B were higher than the average scores in Conditions C and D. Encouraging students to use a self-explanation strategy when teaching them to apply probability principles may enhance their understanding of probability theory. If presented in a traditional format, such instruction does not appear to increase students' cognitive load, and may even improve their application of probability theory when they are not explicitly told to use the self-explanation strategy (as demonstrated by the higher post-test performance of participants in Condition B).

Limitations

Because participants completed all of the study tasks in the same day, I was unable to determine whether the benefits of strategy instruction persisted. Future researchers may consider providing a break of several days or weeks between learning and post-training testing. Similarly, providing additional practice beyond the single learning task is likely to benefit problem-solving and strategy use; future research should examine whether practice-related benefits differ as a function of WM.

The instructional format was primarily self-paced (i.e., participants received some verbal instructions and were time-limited to 90 minutes for all tasks) and involved reading instructions and completing problems independently. Therefore, it was not possible to compare participants' performance in this format to performance in other instructional formats (e.g., individual or group format led by an instructor). Discovering whether findings regarding the interaction of WM, condition, and strategy learning persist following different instructional formats would be beneficial to our understanding of the impact of WM on learning and strategy use. An unanticipated finding of the study was that participants did not perform best in the condition that was designed to produce the least cognitive load (Condition A). I attribute this to the novelty of the backwards-faded format of Condition A, however, future researchers may wish to consider alternate explanations for this finding.

Future Directions

The present study demonstrated that use of a self-explanation strategy during probability problem-solving, when paired with specific instructions, can be useful to participants even following the task where they are explicitly instructed to use the strategy. A related question is whether students believe that self-explanation is helpful, and consequently use self-explanation unprompted in future learning situations. One way to answer this question would be to show students that the strategy helped them (i.e., make it clear that their strategy use scores were related to their performance during learning), and then determine whether providing this information increased their later independent use of the strategy. Finding ways to motivate students to use effective learning techniques can provide valuable information for educators.

A surprising finding of the study was that students did not report significantly different levels of cognitive load as a function of learning condition, even though the conditions were designed to produce different levels of load, and there were distinct differences in student performance as a function of assigned condition. Examining whether the task of reporting the amount of load experienced draws students' attention to their own cognitive load (thus increasing load) may be valuable. We also found that cognitive load was related to participants' previous mathematical success and knowledge of probability, but was unrelated to WM. Future researchers may wish to explore ways to reduce cognitive load specifically associated with mathematical skill level.

Finally, the relationship between WM and cognitive load, and its effect on performance, should be explored in more detail. In some cases, individuals with high WM "choke" under increased cognitive load (Rosen & Engle, 1997; Schelble, Therriault, & Miller, 2012), but in the present study, high WM was an asset under high-load conditions. This may be due to the nature of the cognitive load: does artificial load affect participants differently than task-related load? Alternately, how much load can a learning situation encompass before additional WM capacity (or a successful strategy) is necessary for superior performance? Is there a specific level of load at which WM is no longer an asset? Discovering the answers to such questions may have practical and theoretical benefits.

Conclusion

WM and its influence on strategy use are related to individuals' performance on a variety of tasks (Geary, Frensch, & Wiley, 1993; Keeler & Swanson, 2001; Linderholm, Cong, & Zhao, 2008; Linderholm & van den Broek, 2002; Rosen & Engle, 1997; Schelble, Therriault, & Miller, 2012). In the present study, I found that WM was also related to participants' ability to learn a new strategy, supporting the strategy-as-effect hypothesis of WM (Dunlosky & Thiede, 2004a). Specifically, individuals with higher WM were more successful at learning a new strategy when the learning condition was novel and when overall performance in the condition was lower. This suggests that HWM individuals behave more like advanced learners than novices (Kirschner, Sweller, & Clark, 2006) when learning to use strategies. Participants' perceived cognitive load was affected by their preexisting knowledge about the topic, but not by their WM capacity. In a more traditional learning format, participants performed better, and the relationship between WM and strategy learning disappeared, indicating that reducing cognitive load during strategy learning is an effective way to teach strategies to individuals with low WM capacity.

Although previous research indicates that high WM individuals perform poorly when under increased cognitive load (Rosen & Engle, 1997; Schelble, Therriault, & Miller, 2012), the present study found that high WM was an advantage under conditions in which overall performance was lower. This discrepancy may be due to the type of load experienced in this study (i.e., load related to actual performance of the task) being different from the type of load induced in previous studies (i.e., load produced by requiring participants to engage in an unrelated additional task). Future research should examine the effect of WM on strategy learning in a variety of high-load conditions. Such information would be beneficial to scholars of cognitive control mechanisms and to educators, whose students encounter various forms of cognitive load in their learning environments.

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