The Role of Individual Differences in Working Memory in the Encoding and Retrieval of Information

by

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Abstract

Individual differences in working memory capacity have been examined in relation to general fluid intelligence and higher-order cognitive tasks. Little research, however, had focused on the role that individual differences in working memory might play in the encoding of new information. The current experiment examined how individual differences in working memory capacity affect encoding of new information and how cognitive load modulates this effect. Participants encoded new information and then were subsequently tested on this information twice; in a single-task condition and a dual-task condition. The two conditions investigated whether individual differences in working memory capacity mediated differential retrieval of newly learned information under cognitive load. The results from the study indicated that working memory does play a role in the encoding of new information and that the dual-task condition reduced accuracy differentially across working memory ability. Previous research examining individual differences in working memory had focused primarily on retrieval processes instead of encoding. It is possible that the differences documented in previous studies at the retrieval stage may in fact be a byproduct of differences that are present at encoding.

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Introduction

Most everyday tasks that require a person to mentally hold and manipulate information involve working memory processes. For example, recalling directions and rerouting oneself to the same location from a new starting point. The definition put forth by Baddeley (2002), stating that working memory refers to the memory system used to temporarily maintain and manipulate information, is the most concise descriptor of working memory. Working memory is often confused as being isomorphic with short-term memory; thus it is important to point out that short-term memory strictly refers to the ability to store information for a limited time period. Asking a person to only remember a seven digit phone number for a brief period of time will not generally tax their working memory. In order to use their working memory, a person should remember a seven digit phone number while continuing to carry on a phone conversation.

Working memory goes beyond simple tasks and may play a role in the encoding and retrieval of new information. Take the seemingly easy task of following directions while driving to a friend's house. There are a number of potential distracters: listening to the radio, attending to other cars while trying to concentrate and remember the directions, while still driving safely. Working memory is active in this situation as you attempt to remember the directions while simultaneously avoiding an accident. You are attempting to learn this new information while contending with a variety of different distracters competing for your attention. The next time you make a return trip to your friend's house, you must do so by recalling the information that you encoded during your first trip. This is an example of how working memory may play a role in the encoding of new information and the retrieval of newly learned information.

Working memory has been thoroughly investigated in a variety of different fields. However, despite its commanding presence in the literature, there has been relatively little research investigating the role that working memory plays in the encoding of new information. The aim of this paper is to examine how individual differences in working memory contribute to the encoding of new information as well as the retrieval of previously learned information. In the next section, I discuss the concept of working memory and the general approaches to understanding how it works. Next, I outline how working memory might be connected to learning followed by a review of the literature detailing the role of individual differences in working memory across a variety of different tasks. Lastly, I present an experiment that investigated how individual differences in working memory play a role in the learning of new information.

Working Memory: General Issues

Although, there are several models and theories of working memory, the most widely accepted models are those proposed by Baddeley and Hitch (1974) and Postle (2006). Baddeley and Hitch's (1974) original model of working memory consisted of a three-component system. In this model, the central executive was paired with the visuospatial sketchpad, a subsystem used to interpret visual and spatial information, and the phonological loop, a subsystem used to interpret acoustic and verbal information. Baddeley (2000) further extended the three-component system to include connections between the central executive and long-term memory through the episodic buffer. The episodic buffer is a storage system as well as the primary link between the central executive and long-term memory. It acts as a buffer between the primary systems and their respective coding modalities. However, this theory does not account for various other modalities beyond audio and visual processes.

Postle built upon Baddeley's updated model by asserting that for every type or modality of information that exists, a separate working memory must exist in order to effectively hold and manipulate the information. Although Baddeley focused primarily on visual and auditory information, Postle extended his theory to allow for virtually every type of information or modality (e.g., olfaction, tactile, etc.). Postle (2006) asserted that it is irrefutable that many different types of information can be actively retained in working memory and to account for this, an individualized type of working memory is required for any mode of information being processed. Hence, it follows that when attention is focused on a type of information, the working memory for that type of information simply "emerges."

A number of studies support Postle's emergent property view. For instance, a recent study examining olfactory working memory demonstrated that participants correctly identified certain odors presented in a "2-back" task (Dade, Zatorre, Evans, & Jones-Gottman, 2001). Studies have also identified both tactile and auditory working memories (Clement, Demany, & Semal, 1999; Harris, Miniussi, Harris, & Diamond, 2002). If the emergent model of working memory allows for a better explanation, then working memory is simply a property that emerges from the ever evolving nervous system, regardless of the modality in which the information being attended to is presented.

Although Baddeley's model is merited in having a number of subsystems the central executive uses to process information, it appears that Postle's emergent properties model is the better approach to understanding working memory. It remains parsimonious, and also retains the makings of a theory-based model. Baddeley attempts to explain how the visuospatial sketchpad is related to the central executive and the episodic buffer, but Postle explains that due to the way our nervous system works, working memory emerges for any new modality that is required. If participants are asked to recall certain scents, then an olfactory working memory would emerge to facilitate the maintenance and manipulation of the information in that modality. The same would occur in situations requiring participants to deal with visual or tactile information as well as information in a variety of other modalities. These models primarily exist to describe the basis for working memory. A number of other models also attempt to describe the domain-general nature of working memory. If working memory is in fact a domain-general construct, then it becomes unnecessary to argue about whether a task specifically requires working memory. The domain generality of the construct allows it to be utilized in a wide range of different areas.

Working memory can be taxed by placing demands on the system. For example, instituting a cognitive load places additional demands on attentional resources in working memory by requiring the participant to complete a secondary task (e.g. randomly generating a letter from the alphabet every one second) while trying to complete the primary task concurrently (Sweller, 1988). The introduction of a cognitive load allows for one to examine how the modulation of attentional control occurs in working memory. Researchers can investigate the effects of increasing the level of cognitive load on the controlled attention of participants, and determine how the load differentially affects participants with high or low working memory.

Cognitive load has not solely been studied in relation to working memory; it has also been studied in tandem with decision making. Researchers have found that cognitive load leads to increased random responding by participants for online decisions (Franco-Watkins, Pashler, & Rickard, 2006). Online decisions are made without retrieving prior knowledge but are based on processing information as one makes a decision. However, in many situations, people rely on their past knowledge or experiences to make decisions. In this case, the person would retrieve relevant information to assist in the decision making process. Franco-Watkins, Rickard and Pashler (under review) had participants make judgments about relative population between national and international cities under a single-task condition and under a dual-task condition (2x2 design). The results suggest that cognitive load significantly disrupted the retrieval processes for the judgments made about the national cities. In a second experiment the results were replicated in a condition that had participants make judgments between cities with drastically different populations. Although participants were able to perform well in the single-task condition, the dual task significantly reduced accuracy. Even in a condition in which the correct choice was fairly evident, the cognitive load adversely affected accuracy. Although that study examined decision making based on the retrieval of information from memory, there has been relatively little research combining working memory in conjunction with a decision making task.

Working memory and Learning

A number of studies have examined the role of working memory in learning. However, most studies have focused primarily on the role working memory plays in relation to general cognitive ability. Many studies have examined the relationship between working memory and higher-order cognitive functions ranging from reading and listening comprehension (Daneman & Carpenter, 1983), to vocabulary learning (Daneman & Green, 1986), and even computer language learning (Kyllonen & Stephens, 1990; Shute, 1990).

In terms of sentencing learning, children in an experimental group were provided with additional lessons on how to think of pictures to represent the sentences. The researchers found that when comparing the experimental and control groups, the individual differences in memory and verbal competence were more related to the accuracy of sentence retrieval in the experimental condition and predicted better sentence learning than in the control condition (Pressley, Cariglia-Bull, Deane, and Schneider, 1987). The results from the study indicated that working memory allowed for more effective sentence learning and also led to better implementation of the given strategies for learning the sentences at subsequent retrieval.

The role of controlled attention in childhood has been documented through a number of studies (Bull & Scerif, 2001; Bull, Johnson, & Roy, 1999; Lorsbach, Wilson, & Reimer, 1996; Lehto, 1995). These studies indicate that working memory plays a role in the academic achievement of children and adolescents. A recent study supports these findings by studying the relationship between working memory and scholastic achievement as well as a number of other variables. The results demonstrate that there is a strong relationship between working memory and achievement in English, math, and science. Specifically, the researchers also found that even stronger associations existed between verbal working memory in English achievement although stronger associations were found between visuo-spatial working memory and math achievement (St. Clair-Thompson & Gathercole, 2006).

These studies assert that working memory plays a significant role in academic achievement, but a number of other studies extend this line of research and posit that working memory plays a large part in general reasoning abilities. Halford, Cowan, and Andrews (2007) argue that working memory and reasoning share similar capacity limits. As such, the reasoning ability (and the connections between items) as well as the number of items that can be kept active in working memory are directly related.

The relationship between working memory and reasoning might explain how people are able to learn categories. A number of different studies have demonstrated that people use a variety of different methods to learn how to classify new information into categories (Erickson &

Kruschke, 1998, 2002; Smith, Patalano, & Jones, 1998). However, when required to learn a set of categories, the participant must be able to effectively remember the categories and successfully determine which items belong in each category. This process requires the maintenance and manipulation of information which is definitive of working memory. One study has had participants use different category representations to classify a variety of stimuli. In this condition, the researchers documented that there is a strong correlation between working memory and learning performance (Erickson, 2008). The controlled attention of working memory is facilitating the effective learning of the categories. Being able to maintain and manipulate a number of different categories allows participants to perform with a higher degree of accuracy in the task.

Additionally, there have been a number of studies examining how the relationship between working memory and learning can affect problem solving. These studies rely on working memory's limited capacity in order to investigate the interaction of memory and problem solving. A study by Reber and Kotovsky (1997) demonstrated that when a cognitive load is placed upon working memory during the solving of the Balls and Boxes puzzle, the time to solve increased. The ability to solve the puzzle was hindered by the cognitive load. However, working memory was related to decreased puzzle solving times, especially under the cognitive load condition.

There is a plethora of research involving the role of working memory, especially in terms of its role in the learning of new information. This research has demonstrated the role that working memory plays in reasoning, category learning and even problem solving. Although these studies all examine working memory's role in learning, to my knowledge, there seems to be little or no research investigating any individual differences in working memory and how these differences translate into potential differences in the learning and encoding of new information.

Individual Differences in Working Memory

Measurement of individual differences.

Working memory has been identified a domain-general process with a limited capacity of four plus or minus one (Cowan, 2001). However, individual differences exist in working memory capacity and are often attributed to controlled attention (Colefish and Conway, 2007; Engle and Kane, 2004; Kane, Bleckley, Conway, & Engle, 2001). In order to effectively study individual differences, researchers rely on tasks where working memory performance requires the participant to process, maintain, and manipulate information. Most tasks used to assess individual differences in working memory follow a common procedure pioneered by Daneman and Carpenter (1980). In their reading span task, participants are required to read a number of sentences aloud, verifying whether the sentence is grammatically correct. Directly following each sentence is a word which the participant had to maintain in order to recall later. After reading between two and six sentences, the participant is asked to recall the words that appeared at the end of each sentence in the order presented. This task taps into the construct of working memory by requiring the participant to process information (reading the sentences) while maintaining other information (the words following the sentences). As such, the additional attentional demands included in the reading span task provided a basis for the measuring and examination of working memory capacity at the individual level.

A similar task is the operation-span, which pairs math problems with words as opposed to the sentences paired with words that the reading span utilizes. The symmetry span requires participants to determine whether a given shape is symmetrical while remembering the location of a colored square on a grid. The type of task or stimuli used is unimportant; the essential criterion is the measurement of individual differences in working memory.

Working memory and general cognitive abilities.

Individual differences in working memory have been examined as they relate to performance on various cognitive tasks. There is considerable overlap between measures of working memory capacity, general fluid intelligence and performance on cognitive tasks (Colom, Rebello, Palacios, Juan-Espinosa, & Kyllonen, 2004; Engle, Tuholski, Laughlin, & Conway, 1999; Kyllonen & Christal, 1990). Children who displayed deficits in certain areas such as math or reading were studied to determine if their working memory scores were correlated with test scores. After the administration of these tests and working memory span tasks, the researchers found that the children with the greatest difficulty in a given subject area also performed poorly on the span task (Swanson, Ashbaker, & Lee, 1996). The individual differences in performance on the tests translated into similar differences in working memory capacity. Hitch, Towse, and Hutton (2001) demonstrated a correlation of .55 between proficiency in skills such as mathematics with individual scores on complex span tasks. Variance documented in the span task performance was able to accurately predict the length of time spent acquiring the skill in question. This indicates that individual differences in working memory capacity are actually related to the development of certain skills like math or reading.

In fact, a number of studies have found moderate to high positive correlations between working memory capacity and general fluid intelligence. Specifically, some report the correlation to be around 0.50 (Ackerman, Beier, Boyle, 2005; Engle et al., 1999). Oberauer, Schulze, Wilhelm, and Sü (2005) found the correlation to be 0.85 after performing a meta-analysis that indexed measures of working memory and Spearman’s *g*.

Another recent study has also linked working memory with thought suppression (Brewin & Beaton, 2002). Participants in this study completed a thought suppression task as well as measures of working memory and fluid intelligence. In thought suppression tasks, participants are instructed to suppress a specific image but to notify the experimenter if they think of the image. Controlled attention must be used in order to suppress the target image from their thoughts. As such, the results suggest that thought suppression and working memory span are highly correlated (r= .51). The controlled attention used by those with high working memory is believed to assist in the suppression of the thoughts that may be occurring automatically despite the participant having been instructed to suppress them.

Additionally, the correlation between working memory and other factors or measures of cognitive ability has been documented by a number of researchers (Engle, Cantor, & Carullo, 1992; Turner & Engle, 1989). Engle et al. (1992) examined the relationship between measures of working memory and intelligence or reasoning ability to determine whether processing speed was mediated by working memory capacity. After accounting for the variability due to processing speed, the authors were able to determine that a strong relationship remained (*r* =.59).

To summarize, the effects of individual differences in controlled attention and processing speed have been documented when examining working memory span as well as with a variety of cognitive tasks considered to require higher-order processing. The controlled attention that is required to complete the working memory tasks is related to differences in performance on other tasks.

Individual differences on perceptually-based tasks.

Working memory also plays a role in terms of performance at the individual level on perceptual-based tasks such as the Stroop task and dichotic listening task. It is believed that individuals with low working memory are less effective at inhibiting interference and controlling attention, which in turn results in lower levels of task performance (Kane & Engle, 2003; Conway, Cowan, & Bunting, 2001; Kane & Engle, 2000; Rosen & Engle, 1997). In the Stroop task, when the participants were instructed to attend to and state the color of the words instead of the actual word itself, those with high working memory responded faster and with a higher degree of accuracy in trials involving incongruent word color pairs than those with low working memory. It is assumed that the increased attentional control allowed these participants with high working memory to focus on the goals of the task, which lead to higher accuracy and faster responses.

Conway, Cowan, and Bunting (2001) examined how individual differences in working memory led to differential performance associated with the cocktail party phenomenon. Specifically, participants in the dichotic-listening task were instructed to attend to one stream of information while ignoring the other stream of information in the opposite ear. The participants' name was played in the ear which they were instructed to ignore. Individuals with low working memory capacity reported hearing their name 65% of the time whereas the participants with high working memory capacity only reported hearing their names 20% of the time. The high working memory individuals heard their name fewer times, indicating that their selective attention allowed them to inhibit irrelevant stimuli, in this case their name. However, when instructed to repeat the message playing in the attended ear while simultaneously listening for their name in the unattended ear, participants with high working memory reported hearing their names twice as often (66.7%) as those with low working memory (34.5%: Coleflesh & Conway, 2007). The controlled attention displayed by participants with high working memory allowed them to outperform those with low working memory in this task.

Individual differences on memory-based tasks.

Working memory has also been examined at the individual level in a variety of memory-based retrieval tasks such as the verbal fluency task. In this task, participants with high working memory consistently recalled more examples of a given category than those with low working memory (Rosen & Engle, 1997). Controlled attention is assumed to account for differences in performance. Individual differences in working memory have also been examined in relation to hypothesis generation and retrieval (Dougherty & Hunter, 2003). They found that the number of alternatives retrieved was positively correlated with working memory span. These results indicated that the participants with high working memory were able to utilize their greater degree of controlled attention to generate and retrieve hypotheses more effectively than those with low working memory.

Proactive interference has also been examined in relation to working memory capacity. Research indicates that while under a single-task condition, individuals with low working memory span demonstrate larger proactive interference effects than did high working memory span participants (Kane & Engle, 2000). However, when placed in a cognitive load condition, one in which a dual-task was in place, both groups demonstrated similar proactive interference effects. Specifically, the low working memory span group did not increase in their level of proactive interference; rather, the high working memory group had more proactive interference. The results indicate that attention is necessary to prevent the effects of proactive interference under normal conditions and relate to working memory. A similar study investigating the relationship between working memory capacity and the ability to suppress task irrelevant information found that individuals with high working memory capacity were able to better suppress extraneous information (Rosen & Engle, 1998). The mixed results from these studies seem to indicate that there is an interaction between working memory and cognitive load. In some situations, the load component impairs the ability of those with low working memory to control their attention and focus on the task at hand. However, in other tasks, cognitive load affects those with high working memory more than those with low working memory.

Individual differences on higher-level processing tasks.

Tasks involving higher-level processing have been studied in relation to working memory and some studies have also included a cognitive load component to examine the effects of reducing attentional control. For instance, Gilhooly, Logie and Wynn (2002) conducted a study investigating the role that working memory played in syllogistic reasoning. Participants were instructed to complete a dual task of random number generation while completing a syllogism task. The results indicated that the cognitive load decreased accuracy on the primary syllogism task. Similar results were documented in a separate study in which participants were asked to complete a conditional reasoning task while simultaneously repeating a random set of 6 numbers concurrently (Toms, Morris, & Ward, 1993). The cognitive load decreased accuracy in responding by participants and also increased reaction time.

Counterfactual thinking has also been studied with working memory (Goldinger, Kleider, Azuma, & Beike, 2003). When participants are presented with situations that have negative outcomes they will often imagine how the outcome could have been changed; this is known as counterfactual thinking. Participants were placed under a cognitive load condition during the judgment phase. When the cognitive load condition was in effect, participants with low working memory engaged in more counterfactual thinking. This indicates that counterfactual thinking occurs automatically and that participants with high working memory are better able to control their attentions and suppress the thoughts.

Rationale

There has been an influx of studies investigating individual differences in working memory capacity using various cognitive tasks. These tasks, many of which have been studied in tandem with cognitive-load research, range from simple perceptually-based tasks such as the Stroop, to memory-based tasks focusing on retrieval, to higher-level processing involving reasoning. Despite the preponderance of research, most tasks involving individual differences in working memory have focused on the retrieval of information from memory and there has been very little emphasis on the process of encoding.

Previous research assumes that formerly existing knowledge continues to exist in memory; specifically, that people can readily retrieve preexisting knowledge to be used during the decision making process. However, the encoding of information is essential for subsequent retrieval. Due to the fact that there are differing degrees of previous knowledge across participants, the only way to know the basis of the information on which participants will be tested is to train participants to a criterion before examining the effect of controlled attention on retrieval processes.

The current study aimed to combine research investigating individual differences in working memory with decision making under cognitive load. This allowed for the examination of how differences in working memory can affect the encoding of new information and the retrieval of the new learned information under cognitive load during decision making. Encoding is an important process when decisions are made from new information. If some participants are able to better encode certain information that must then be later retrieved for use in a decision task, then they will perform better on subsequent tests of recall. This study will help to determine whether retrieval performance is based on poor encoding or poor attentional control during retrieval.

Pilot Study 1

As mentioned previously, we do not know of any research examining individual differences in working memory capacity during encoding of information. Thus, a pilot study was conducted in order to determine what type of stimuli should be used for training and examine the relationship between individual differences in working memory and encoding. The stimuli must be simple enough to for naïve participants to learn over a number of blocked trials but difficult enough to ensure there are no ceiling effects. Previous studies have relied on participant's previous knowledge of cities and asked that decisions be made using this pre-existing knowledge. In order to remove the bias associated with the city names, which had previously been utilized, the current pilot study trained participants to criterion on pictorial stimuli. Participants underwent a training phase in which they were trained to choose the most highly populated city when presented with pictures depicting various cities. This training phase allowed for the encoding of information, of which the participant is completely naïve. The criterion component in this training block allowed participants to learn the new information over the course of a number of blocks. Due to their better attentional control, it was expected that participants with high working memory would reach the set criterion faster than those with low working memory. Upon the completion of the training phase it was predicted that the participants would perform similarly in the testing phase due to having successfully completed the training phase in which they learned all the stimulus pairs to the set criterion.

Method

Participants

Undergraduate students (n = 18) enrolled at Auburn University participated in the study in exchange for extra credit.

Design

The experiment used a between-subjects design. The independent variable was working memory span and the dependent variables were number of training blocks to reach criterion during the training decision task, accuracy during the final training block, and accuracy during the decision task.

Materials

Automated operation span (auto o-span). The auto o-span consists of a set of simple mathematical problems presented on screen with a letter directly to the right of the given answer (i.e. 2*2+5 = 9 G). There are a total of 75 math/letter pairs. The task consists of three practice trials with three math/letter pairs and there are 18 span trials varying in length between two and six math/word pairs. The task is scored by summing the total number of letters recalled in the correct position. This task has a reliability of .83 (Unsworth, Heitz, Schrock & Engle, 2005).

City stimuli. Ten pictures depicting United States cityscapes were used. The pictures measured 350 pixels by 289 pixels. The city stimuli that were used in this task were taken from the top ten most highly populated national cities excluding New York and Los Angeles due to their highly recognizable cityscapes. The associated populations of the city stimuli are based on the 2007 Census data. In the training phase, two pictures of cities were presented in the center of the screen and remained on screen until a response was made (see Figure 1). During training, feedback regarding each decision made was provided on the following screen for one second.

Each block of training contained 45 trials with the cities paired in an alternating fashion (See Appendix 1 for a listing of stimuli and the pairings for training). The testing phase included 90 trials (every possible combination) with no feedback. There was a delay of one second after each choice was made.

Figure 1. Screenshot of the training decision task.

Distracter task. Consisted of 10 general knowledge questions (ex. “Which mountain has the highest altitude?”). Participants responded to these questions by pressing the corresponding letter to the correct answer (A or B). The task took approximately 3-4 minutes for the participants to complete.

Procedure

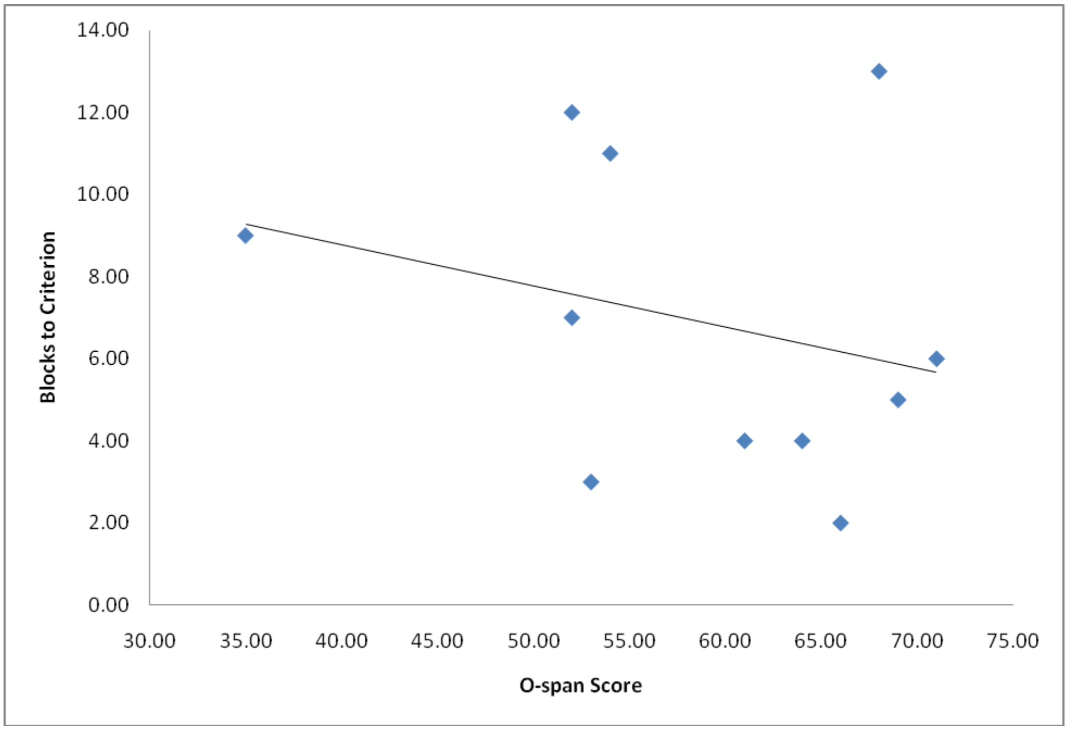
After consenting to participate in the experiment, each participant completed the auto o-span. Participants were instructed to complete a number of math problems while trying to remember each letter of the alphabet that was displayed after each problem. After a set size ranging from two to six, participants were asked to recall the letters in order of presentation. Their auto o-span score was then calculated by determining the total number of letters that were recalled in the correct order across the entire task. This scoring method makes up the o-span total score.

Next, participants began the training phase of the experiment. Participants were presented with two pictures of cities on the computer monitor and were instructed to choose the picture of the city they believed to have the larger population. Participants selected their choices by pressing the “1’ key to indicate the city on the left and the “2” key to indicate the city on the right. After completing the first training block by having undergone 45 city pairings with feedback, the participant’s accuracy on the task was assessed. If the accuracy achieved was less than the set 80% criterion, then the participant began a second block of training, receiving the same 45 pairings with feedback. The participant completed consecutive blocks of training until they had reached criterion. After the distracter task, participants completed the testing phase in which they were tested on every combination of the city stimuli. This testing phase included the stimuli that they were trained on, in addition to novel untrained stimuli. The testing phase consisted of 90 trials with no feedback.

Results and Discussion

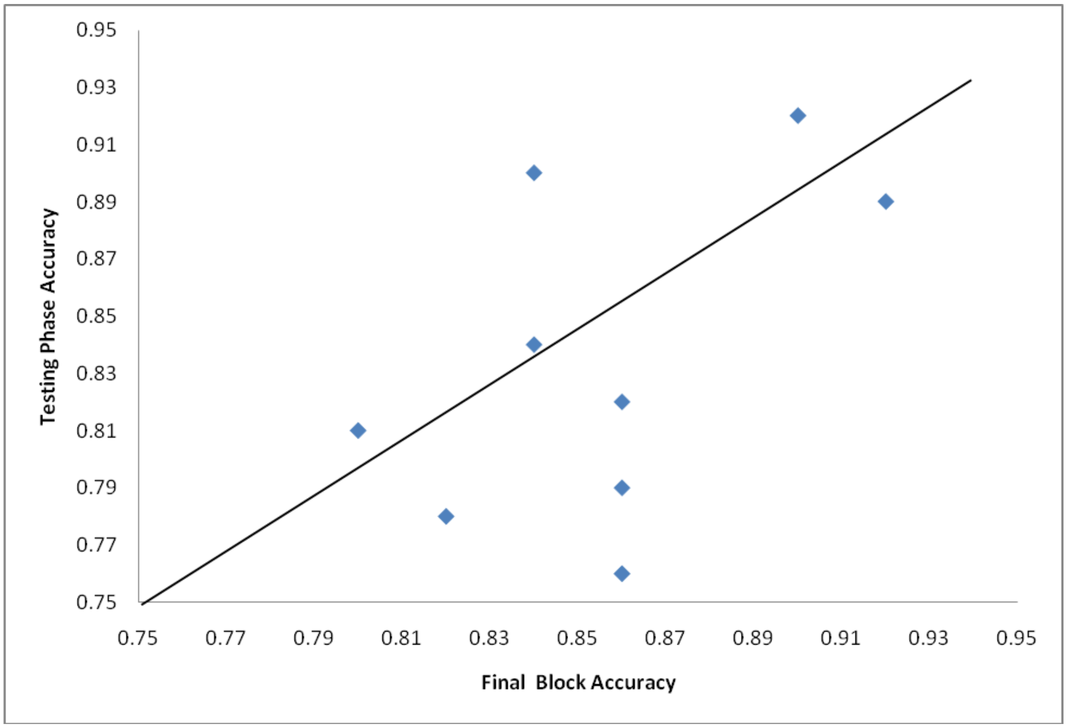
After the initial data collection ($n = 18$), it became clear that alterations would have to be made to the procedure. Participants were taking on average 7.33 blocks in order to reach criterion. This would not have been disconcerting had it not been for the high level of participant dropout ($n = 6$). Participants were electing to leave the study before having reached the criterion, citing that the task was too difficult to complete as the reason for their departure. Examination of the data for participants who completed the experiment ($n = 12$) found a negative correlation between working memory span and the number of blocks to reach criterion, $r = -.27$, $p < .05$. The correlation is illustrated in Figure 2.

Figure 2. Scatter plot illustrating the negative correlation between the number of blocks required to reach criterion and o-span.



This provided some initial evidence that working memory might play a role in the encoding of new information. Additionally, once participants reached the criterion of 80%, they continued to perform as well with the full set of trials in the decision task as illustrated in Figure 3. A t-test supported that the accuracy on the final block of training and the testing phase accuracy were similar, t (17) = .063, p > .05.

Figure 3. Scatter plot illustrating accuracy retained from training through to the decision task.

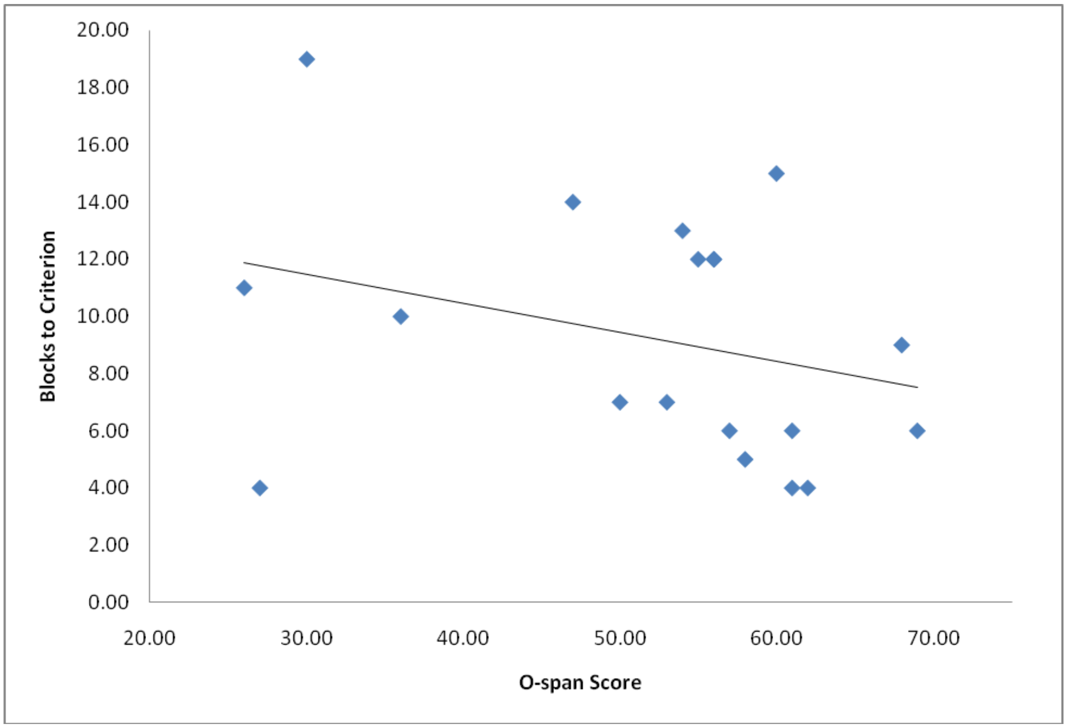


Having one third of the participants elect to leave the study indicated that the training phase was too difficult. Therefore, the experiment was altered by reducing the city set size to 8 instead of 10 cities. This resulted in 28 trials for each training block and 56 trials during the testing phase.

Pilot Study 2

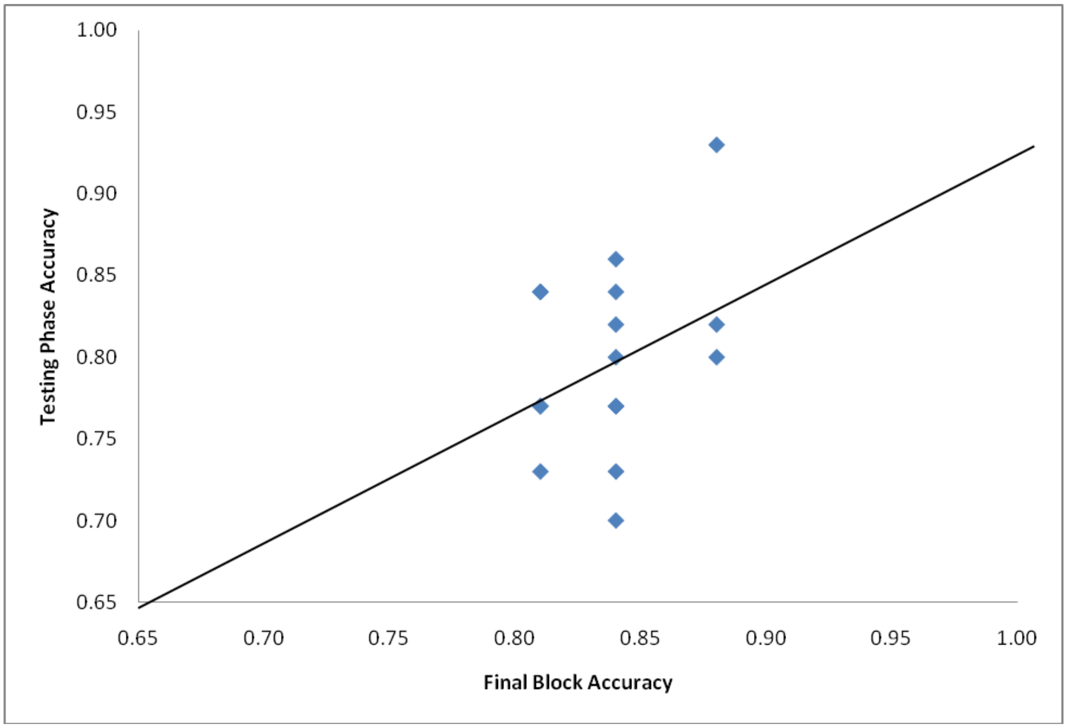
The reduced set size of the city stimuli resulted in no participant dropout (*n* = 19) and still retained similar results to the previous pilot. Participants continued to take, on average, 9.1 blocks to reach criterion, but each block took less time to complete due to there being fewer trials. Figure 4 illustrates the negative correlation that remained between working memory span and number of blocks to criterion, r = -.30, $p < .05$.

Figure 4. Scatter plot illustrating the negative correlation between the number of blocks required to reach criterion and o-span.



Participants were continuing to retain the information they had been trained on, averaging a mean of 78% correct during the testing phase which is illustrated in Figure 5. A t-test was performed comparing the final training block accuracy to the testing phase accuracy which indicated that there was no difference between them, *t* (18) = .01, *p* > .05).

Figure 5. Scatter plot illustrating accuracy retained from training through to the testing phase.



To summarize, the city task with ten stimuli was too taxing for the participants, however, the second version allowed for participants to complete the entire procedure without dropping out. Preliminary results indicated that there may be differential encoding based on working memory.

Current Experiment

After establishing the relationship between working memory and encoding, an experiment was conducted to further examine this relationship while also introducing a cognitive load in the form of a dual-task condition during retrieval. This dual-task condition allowed for the investigation of the effect it had on working memory and the process of retrieving newly learned information.

Hypotheses

Due to the fact that participants with low working memory do not have the attentional control necessary to effectively hold the stimuli in working memory, it was expected that they would require more training blocks to reach criterion during the training phase than those with high working memory.

The results from the pilot study indicated that once participants had reached criterion, they performed at the same level of accuracy during the decision task as they did in the final block of the training task. Therefore it was also expected that participants would perform at similar accuracy levels during both the final block of the training task and the decision task.

Additionally, because it was hypothesized that through training, the participants had encoded the information to the same criteria, there should be similar performance between groups during the testing block under the control condition. Therefore it was believed that there would be no differences in accuracy between participants with high working memory and low working memory during the testing phase in the control condition. However, in the dual-task condition, due to the individuals with high working memory have better attentional control, it was expected that participants with high working memory would outperform those with low working memory.

Method

Participants

Fifty-five undergraduate students enrolled at Auburn University participated in the study and were recruited through SONA systems.

Design

The experiment used a 2 (cognitive load: single-task vs. dual-task) x 2 (working memory ability: high vs. low) mixed factorial design. Participants were split into tertiles based on working memory span. Only participants whose working memory spans fell in the upper and lower tertile (high and low) were used in the analyses. The cognitive load was examined within-subjects and working memory ability was a between-subjects variable. The dependent variables were number of blocks to reach criterion during the training phase, accuracy during the final training block, accuracy during the single-task condition, as well as accuracy during the dual-task condition.

Materials

Training phase / testing phase / city stimuli. The training phase, testing phase, and city stimuli were identical to those used in the previous pilot study. (see Appendix A for a listing of cities as well as their associated population based on the 2007 Census data).

Random number generation task. Participants responded verbally with a random number between zero and nine each time a tone was played every one second. Responses were recorded using a headset with a microphone.

Procedure

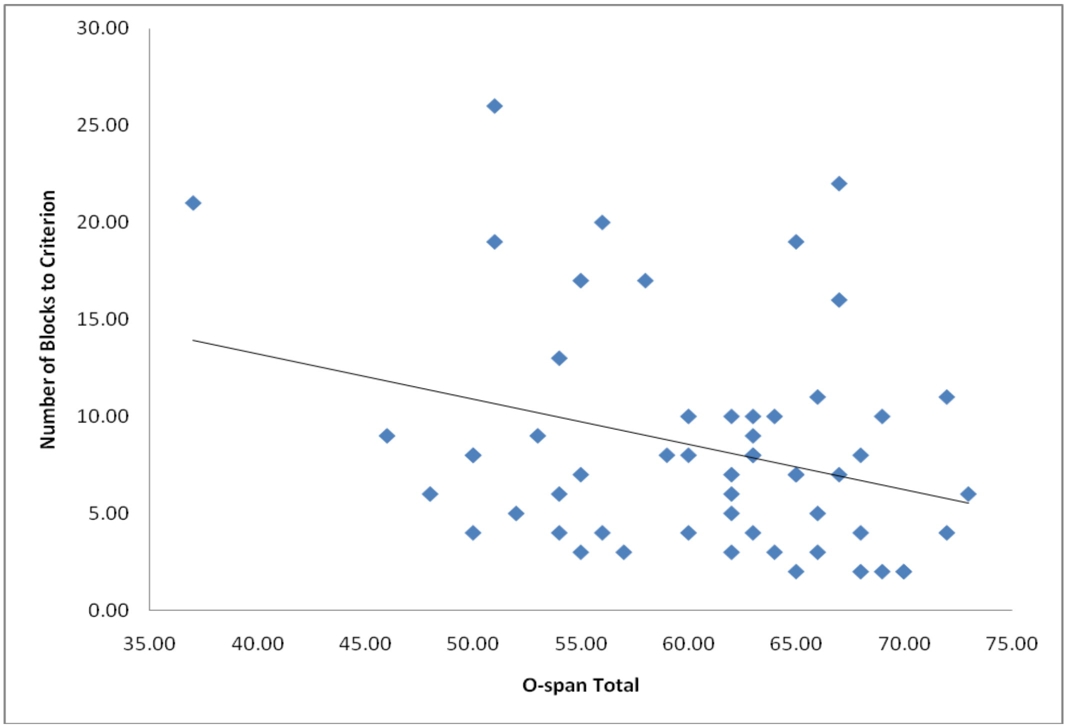
All participants completed the auto o-span before completing the training phase. After criterion was reached in the training phase, participants completed the testing phase with a single-task followed by a dual-task condition. The dual-task condition differed from the single-task condition with the inclusion of the random number generation task. In the dual-task condition, they were instructed to perform the random number generation task, by generating a number aloud between zero and nine each time they heard a tone, concurrently with the decision task. The instructions emphasized that it was important to try to complete both tasks simultaneously to the best of their ability.

Results

Working Memory Correlation

There was a significant correlation between the number of training blocks required to reach criterion and scores on the o-span, *r* = -.31, *p* < .05, indicating that as working memory increased, the number of training blocks required to reach criterion decreased. These results supported the hypothesis that participants with high working memory would reach the criterion during the training blocks after fewer training blocks than those with low working memory. The scatter plot of the correlation is illustrated in Figure 6.

Figure 6. Scatter plot illustrating the negative correlation between the number of blocks required to reach criterion and o-span.



Accuracy and Training Block Results

In order to capture its entire range, working memory was first examined as a continuous variable to determine if it influenced the learning of new information. After analyzing the correlation between working memory and the number of blocks to reach criterion, the participants were categorized into tertiles according to their o-span scores in order to facilitate the comparison between the extreme groups of high and low working memory similarly to previous studies. The o-span scores for the participants in this study ranged from 19 to 68 with a mean of 43.67 (SD = 13) and a median of 43. Participants with scores of 52 and above were classified as having high working memory and participants with scores of below 36 were classified as having low working memory. This resulted in 16 participants in each group.

Training Blocks by Working Memory Results

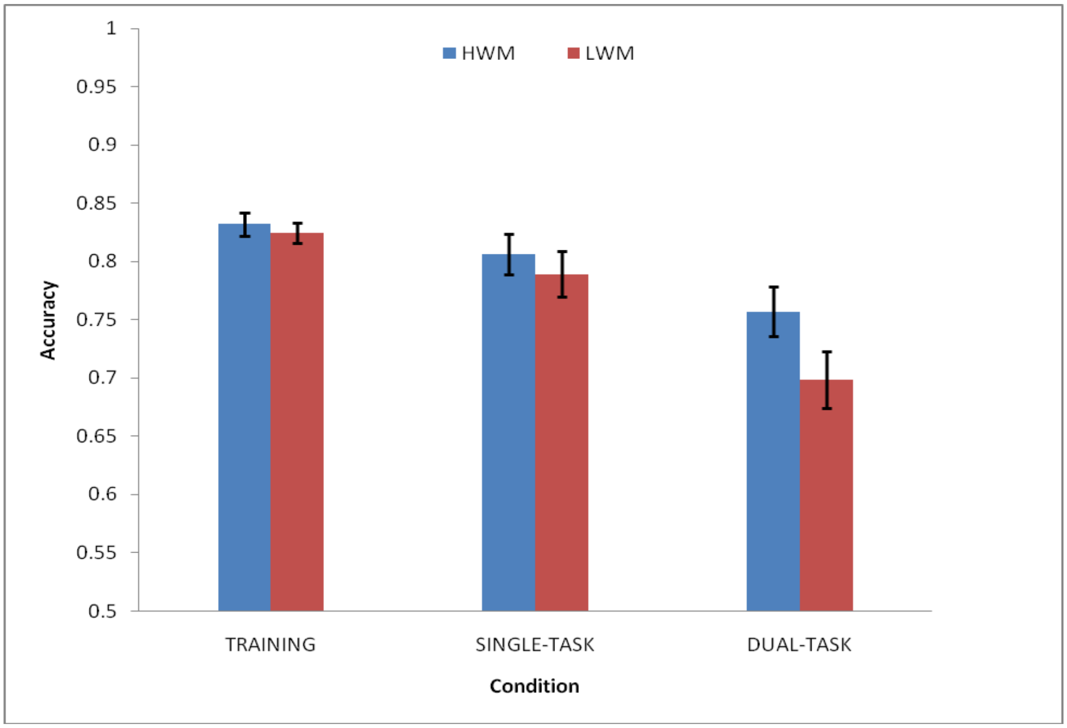
The results indicate that there was a significant difference between the number of blocks required to reach criterion for those with high working memory (M = 6.13, SD = 3.24) and low working memory (M = 10.25, SD = 6.95), t (30) = -2.15, $p < .05$, $d = .76$.

Accuracy Results

A factorial repeated measures ANOVA (working memory and cognitive load) with planned comparisons was used to examine the difference from the final block of training, the single-task condition and the dual-task condition between participants with high and low working memory. There was no significant main effect for the between-subjects effect examining differences between high and low working memory, F (1, 30) = .92, $p > .05$, $\eta^2 = .03$. For the within-subjects effects, there was a significant main effect for the difference scores in accuracy across conditions F (1, 30) = 21.35, $p < .05$, $\eta^2 = .39$. The interaction between working memory and accuracy across conditions was not statistically significant, F (1, 30) = 3.48, $p >$

.05, η^2=.06. Planned comparisons examining the differences in accuracy across the training, single-task, and dual-task conditions were performed. A paired samples t-test was performed between the accuracy on the final block of training and the accuracy in each of the testing conditions by working memory tertile (high or low) to investigate each planned comparison as indicated in the hypotheses.

Figure 7. Chart illustrating the accuracy in the training, single-task and dual-task conditions for high and low working memory groups.



Planned comparison 1: final training accuracy and single-task accuracy.

For participants with high working memory, there was no significant difference between the accuracy on the final block of training (M =.84, SD =.01) and the accuracy in the single-task condition (M =.81, SD =.02), *t* (15) = 1.35, *p* >.05, *d* = .42. Similarly, there was not a significant difference between the accuracy at the end of training (M =.83, SD =.01) and the accuracy in the single-task condition (M =.80, SD =.02) for those with low working memory, *t* (15) = 1.61, *p*

>.05, *d* = .52. The results for both groups can be seen in Figure 7. Although the groups of participants took different number of blocks to reach criterion during training, the information has been encoded effectively across the groups and was retrieved similarly during the single-task condition. This supports the hypothesis that through training, the participants have encoded the information to the same criteria, and therefore both groups should be performing similarly during the single-task condition.

Planned comparison 2: final training accuracy and dual-task accuracy.

When examining the differences between the accuracy on the final block of training (M =.84, SD =.01) and the accuracy in the dual-task condition (M =.77, SD =.02), there was a significant difference for participants with high working memory *t* (15) = 2.59, *p* <.05, *d* = .92. A significant difference between the two conditions (Training: M =.83, SD =.01; Dual-task: M =.71, SD =.03) was also found for participants with low working memory *t* (15) = 4.87, *p* <.05, *d* = 1.49. Both groups exhibited a significant decrease in accuracy from the final block of training to the accuracy attained in the dual-task condition, seen in Figure 7.

Trained versus Novel Stimuli Results

It was important to determine whether there were differences in accuracy between the items that the participants were originally trained on during the training phase and the additional items that they were tested on during the testing phase. A t-test was performed between the items that the participant was trained on and the novel stimuli that were introduced in the single and dual-task conditions. There were no significant differences between accuracy on trained (M = .79, SD = .01) and novel stimuli in the single-task condition (M = .79, SD = .01), *t* (54) = 1.06, *p* >.05, *d* = .28, or the dual-task condition (Trained: M = .71, SD = .03; Novel: M =.72, SD =.02), *t* (54) = -.14, *p* >.05, *d* = -.03. The data was further analyzed to determine whether participants with either high or low working memory experienced differences in accuracy on trained versus novel stimuli. For the participants with high working memory there was no significant difference in accuracy between the trained (M = .79, SD = .02) and novel stimuli (M = .83, SD = .03) in the single-task condition, *t* (15) = 1.08, *p* >.05, *d* = .53, or in the dual-task condition (Trained: M = .78, SD = .03; Novel: M =.76, SD =.03), *t* (15) = -1.09, *p* >.05, *d* = -.50. Similar non-significant results were found for the participants with low working memory. There were no differences between the trained (M = .79, SD = .03) and novel (M = .80, SD = .02) stimuli in the single-task condition, *t* (15) = -.21, *p* >.05, *d* = -.10, or the dual-task condition (Trained: M = .70, SD = .03; Novel: M =.74, SD =.03), *t* (15) = -.57, *p* >.05, *d* = -.28. This indicates that there was no difference in accuracy between the items that participants trained on during the training decision task and the novel stimuli that were added during the single and dual-task conditions for either group (high or low working memory). These results suggest that participants have fully formed the hierarchy of city stimuli for the decision task, despite only being trained on half of the possible combinations of city stimuli.

Response Rate Results

The responses that were made during random number generation portion were also analyzed in terms of rate of generation. Participants completed the dual-task condition from anywhere between 58s and 262s. Because the participants were instructed to generate a random number every one second, their total number of responses was divided by the number of seconds to complete the task in order to determine the rate of generation. The rate of generation ranged from .62% to 102% due to the fact that some of the participants generated more than one number every second. The average rate of generation across participants was 85% (SD = .11) which indicated that the participants were following the instructions and attempting to do the random number generation task concurrently with the dual-task of the decision task. A significant correlation was observed between the rate of number generation and working memory, $r = .29$, $p < .05$. The participants with higher working memory are able to utilize their controlled attention to generate at a higher rate than those with lower working memory. However, the results of an additional correlation indicated that the rate of generation did not impact the accuracy in the dual-task condition, $r = .03$, $p > .05$. Working memory played a role in the rate of generation but the differences in generation rate did not translate into differences in accuracy.

Discussion

The results of the current study shed light on a number of very interesting findings. The primary finding from this study is that working memory does appear to play a role in the encoding of new information. The findings indicated that the participants with high working memory required fewer blocks to reach criterion and thereby encoded the information more effectively than those with low working memory. These results demonstrate that although studies examining the retrieval stage are important, the encoding stage must be taken into account when examining individual differences in working memory. The findings demonstrating the differences between high and low working memory have implications for previous studies as well as those that will be done in the future. Results from previous studies that have found differences between high and low working memory at the retrieval stage should be re-examined to determine whether these differences could be a by-product of differential encoding prior to retrieval. Additionally, future studies should take into account that there are differences at the encoding level if retrieval between groups is being examined.

Additionally, the results indicated that the participants were able to effectively encode the information that they were trained on during the training task because both groups (high and low working memory) showed no difference in accuracy from the final block of training to the single-task condition.

It is also important to remember that participants were only trained on half of all potential combinations of the city stimuli. Despite only being seeing a partial set, participants performed at the same level of accuracy when presented with the full set of city stimuli. This indicates that they encoded the new information successfully during the training phase and retained it in order to be retrieved later during the testing phase. Even though the participants were able to retain a high degree of accuracy in the single-task condition, the cognitive load condition significantly reduced the accuracy in the dual-task condition for both the high and low working memory participants.

Working memory is a construct that has been studied extensively throughout the literature, and in many ways these results fit well with results that have been discussed in previous studies. Individual differences have been examined in many different cognitive tasks and the findings have indicated that there is a marked difference between participants with high and low working memory. These differences have been demonstrated on tasks including the Stroop and the dichotic listening task. Participants with high working memory are able to outperform those with low working memory in these types of situations. Despite the fact that none of these tasks involve any type of encoding or learning component, they are similar to the results found in the current study. Participants with high working memory were better able to focus their controlled attention and eliminate any extraneous information while focusing on the task at hand. The results from the current study demonstrated that the participants with high working memory were able to complete the training task after fewer blocks than those with low working memory. These results, illustrating the differences between high and low working memory, seem to indicate that indicate that working memory plays a role in the encoding or learning of new information.

This is consistent with previous research illustrating that working memory has been shown to play a role in the utilization of training in terms of strategies as well as sentence learning (Pressley, Cariglia-Bull, Deane, and Schneider, 1987). Additionally, studies have demonstrated that working memory plays a role in academic achievement as well as general scholastic achievement (St. Clair-Thompson & Gathercole, 2006). Given that so many studies have covered working memory and task performance as well as learning and scholastic achievement, the results from the current study, demonstrating that people with high working memory are able to better complete the training decision task, seem to fit well with the previous literature. Additionally, the effects of cognitive load have been shown in a number of studies to reduce accuracy in responding, similar to that seen in the current study (Gilhooly, Logie, & Wynn, 2002; Tomms Morris & Ward, 2002). These studies show how cognitive load disrupts the focus on the task at hand for participants so it follows that the reduction in accuracy demonstrated by the current study is predicted by the previous literature. The results demonstrating that both groups were affected by the cognitive load when comparing the final block of training to the dual-task condition, demonstrates how much of a disruptive force a cognitive load can be.

Even though the results from the current study seem to be supported by the previous literature, there are always a number of limitations that exist which the researchers can hope to overcome in the future. One of the main limitations of the current study was the small sample size. Fifty-five participants were collected in total. However, after dividing the participant pool into tertiles by working memory, there were only 16 participants in each group (high and low). This low number may explain the lack of differences between high and low working memory in the cognitive load condition. One step that is currently being undertaken to rectify this issue is the collection of more participants in order to increase the sample size for each group in order to more thoroughly investigate the differences between high and low working memory.

Additionally, the cognitive load component could potentially be altered to better examine the effect that it has on different groups of working memory. There was only one type of cognitive load utilized in the current study (random number generation) but perhaps with the inclusion of different conditions with varying levels of load, differing effects could be documented across conditions. Specifically, if the cognitive load had a stronger working memory component, the differences between the groups may become more evident when the differences in accuracy between the final block of training and the dual-task condition are examined. The n-back task, for instance, requires participants to indicate when the current stimulus, auditory or visual, matches that which was presented '*n*' stimuli earlier in the list (Kirchner, 1958). This task has been previously utilized to investigate working memory processes (Gavins & Cutillo, 1993). Because this task seems to utilize working memory, especially when paired with a secondary task, if utilized as a cognitive load, it could provide a sharper contrast between participants with high and low working memory.

These findings are certainly very interesting but there are also a number of future directions that this research can take in order to expand upon the results demonstrated here. Now that the differences between high and low working memory have been demonstrated at the encoding stage, the next step in this line of research would be to determine if there are certain strategies that are being employed by participants to learn the novel stimuli. There was no particular strategy that would allow for the completion of the training phase in this study (e.g. the pictures with tall buildings are always the correct choice). Additionally, the results from the current study seem to indicate that participants are not simply memorizing the city combinations due there being no differences between those stimuli that were trained on and the novel stimuli seen during the testing phase, indicating that they were forming a mental hierarchy between the stimuli. However, a study in which participants could utilize a specific strategy in order to increase performance could be beneficial to the understanding of the encoding process. A new study is currently in the development stages in which the researchers aim to determine what types of strategies are used when being trained on novel stimuli and if there are differences in strategy use based on working memory.

Because previous research has demonstrated that working memory is differentially affected by performance pressure, another potential way to extend this line of research would be to see if similar results occur after training participants to criterion. Past research has demonstrated that the effects of cognitive load on decision making depend on the type of load being utilized, particularly when differences in working memory are being examined. If the cognitive load is based on a dual task, then generally people with high working memory outperform those with low working memory, but Beilock and Carr (2005) demonstrated that a performance pressure will primarily inhibit the individuals with high working memory from being able to successfully complete the task at hand because the task irrelevant stimulus, in the form of a video camera, captures their attentional resources which leaves them performing similarly to those with low working memory. The current experiment looked at individual differences in working memory ability under single-task and dual-task conditions, but a future experiment could replace the dual-task condition and replace it with a performance pressure condition. If the results were similar to those in the study by Beilock and Carr (2005), the results from the study could demonstrate a situation in which participants with low working memory could outperform those with high working memory.

Additional studies could also examine differences in encoding on decreasing set sizes. The current study stopped decreasing the set size after finding a number of stimuli that could be encoded without dealing with participant dropout. If the set size was decreased further would the results of the training phase be similar to those returned in the current study? Or upon being presented with fewer stimuli, would the differences between high and low working memory at the encoding stage simply disappear as both groups begin performing at ceiling? This could be an interesting study to investigate where the advantages of high working memory cease to provide any greater performance over those with low working memory.

In order to effectively study individual differences, researchers rely on tasks where working memory performance requires the participant to maintain and manipulate information. Once working memory has been effectively measured, researchers can begin examining how these individual differences translate into differences on various cognitive tasks. There are a number of other tasks in which these individual differences in working memory have been documented to show differences in task performance.

It is important to take into account the primary findings indicating the role that working memory plays in the encoding of new information, demonstrated by the correlation between blocks to criterion and o-span. This is an important finding due to the fact that previous research examining individual differences in working memory had focused primarily on the process of retrieval instead of encoding. It is possible that these differences that have been documented at the retrieval stage may in fact be a byproduct of differences that are present at encoding. Any future research that is currently being conducted should take into consideration that there may be differences at encoding that can account for any potential differences that may be demonstrated at the point of retrieval.

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Appendix A

List A
Chicago, Illinois (2,836,658)
Phoenix, Arizona (1,552,259)
San Diego, California (1,266,731)
Detroit, Michigan (916,952)
Jacksonville, Florida (805,605)
San Francisco, California (764,976)
Memphis, Tennessee (674,028)
El Paso, Texas (606,913)
Boston, Massachusetts (599,351)**
Denver, Colorado (588,349)**

	Chicago	Detroit	El Paso	Jacksonville	Memphis	Phoenix	San Diego	SanFrancisco
Chicago	q	Training		Training		Training		Training
Detroit		q	Training		Training		Training	
El Paso	Training		q	Training		Training		Training
Jacksonville		Training		q	Training		Training	
Memphis	Training		Training		q	Training		Training
Phoenix		Training		Training		q	Training	
San Diego	Training		Training		Training		q	Training
SanFrancisco		Training		Training		Training		q

**cities used only in pilot study 1, not in Pilot study 2 or the current experiment

All populations are based on 2007 Census data.