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Individual Differences in Working Memory Capacity and Retrieval: A Cue-Dependent Search Approach

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The ability to accurately and efficiently retrieve information from memory is a critical component for successful performance on a number of tasks. Take for instance, performance on a reading comprehension task. Here, an individual is required to read a number of passages and then answer questions concerning those passages. Assuming that the individual accurately encodes and stores (e.g., Melton, 1963) the information, all that is needed to answer the questions is accurate retrieval of the desired information. The pertinent question is, how does the individual go about retrieving the desired information? Additionally, what factors are needed in order for the desired information to be accessed? These basic questions regarding human memory retrieval provide the core concepts in understanding remembering; that is, as advocated by Roediger (2000) and Tulving (1983), in order to understand memory, we must understand retrieval processes.

The work presented in this chapter was heavily influenced by the work of Roediger (2000), in terms of the importance of retrieval processes. Additionally, as will become evident later on, the work presented here was influenced by the Baddeley and Hitch (1974) working memory model, Tulving's arguments for cue-dependent forgetting (Tulving, 1983), Watkins's notion of cue-overload (1979), Shiffrin's elaboration of these concepts into a formal model of cue-dependent search (1970; see also Raaijmakers & Shiffrin, 1981), Glenberg's emphasis on temporal-contextual search (1987), and Wixted and Rohrer's work examining cumulative latency distributions in terms of a random search model (1994; Rohrer & Wixted, 1994). Furthermore, the work here has been influenced by Cronbach and others' (1957; Cohen, 1994; Underwood, 1975) call to combine experimental investigations with individual differences analyses in order to gain a better understanding of the underlying process. Thus, in this chapter we will advocate the view that not only is it important to examine retrieval processes from an experimental point of view, but that investigations of individual differences can also aid us in our understanding of retrieval processes. As proposed by Underwood (1975) and others (Cohen, 1994; Cronbach, 1957), we will discuss an integration of experimental and differential approaches to understanding retrieval processes and individual differences therein. Specifically, we will examine how individual differences in working memory capacity are related to individual differences in retrieval and what this tells us about the nature of working memory capacity and its relation to higher-order cognition.

INDIVIDUAL DIFFERENCES IN WORKING MEMORY CAPACITY

Before discussing the relationship between working memory capacity and retrieval, we will briefly describe working memory capacity, how it is measured, and review the importance of working memory capacity in predicting performance on both higher-order and lower-order cognitive tasks. Working memory is considered to be a system responsible for active maintenance and online manipulation of information over short intervals. In our view, working memory consists of a subset of activated traces above threshold (some of which are highly active), strategies for maintaining activation of those traces, and an attention component. Thus, our view of working memory emphasizes the interaction of attention and memory in the service of complex cognition. In order to measure the capacity of working memory, researchers have relied on complex working memory span tasks based on the working memory model of Baddeley and Hitch (1974). Beginning with Daneman and Carpenter (1980), these tasks combine a simple memory span task with a secondary processing component. Initially, the idea was that these tasks would better measure a dynamic working memory system that traded off processing and storage resources. Thus, in these tasks participants are required to engage in some form of processing activity while trying to remember a set of to-be-remembered (TBR) items. As an example of such a task, consider the operation span task, which requires participants to solve math operations while trying to remember unrelated words. Here, participants are required to solve math operations while trying to remember words presented after the operations. At the recall signal participants must try and recall the presented words in the correct serial order. Several variations exist of this basic paradigm, with most variations consisting of different processing tasks. These include reading sentences (Daneman & Carpenter, 1980), solving math operations (Turner & Engle, 1989), counting different colored figures (Case, Kurland, & Goldberg, 1982), and determining if a figure is symmetrical (Kane et al., 2004). Additionally, variation exists in the type of TBR stimuli that is used. These include remembering words, letters, digits, and spatial locations.

Despite all these variations, performance on these complex span tasks has been shown to covary with performance on a number of both higher-order and lower-order cognitive tasks. Indeed, the original work of Daneman and Carpenter (1980) demonstrated that performance on complex span tasks was highly related to reading comprehension performance as measured by the verbal portion of the Scholastic Aptitude Test (SAT). Thus, as with the example provided in the beginning, reading comprehension is highly related to performance on a memory task. These complex span tasks are also related to other higher-order processes including vocabulary learning (Daneman & Green, 1986), complex learning (Kyllonen & Stephens, 1990), and fluid abilities (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Engle, Tuholski, Laughlin, & Conway, 1999; Kane et al., 2004; Kyllonen & Christal, 1990). This impressive list demonstrates the predictive utility of working memory capacity (WMC) in a number of research domains.

Additional work has shown that WMC is also implicated in performance on many lower-order attentional tasks. This work has demonstrated that individuals who perform well on measures of WMC tend to perform better on basic attention tasks in a variety of conditions. This includes performance on tasks such as Stroop (Kane & Engle, 2003; Long & Prat, 2002), antisaccade (Kane, Bleckley, Conway, & Engle, 2001; Unsworth, Schrock, & Engle, 2004), dichotic listening (Conway, Cowan, & Bunting, 2001), flankers (Heitz & Engle, 2005) and tasks that require object-based attentional allocation (Bleckley, Durso, Crutchfield, Engle, & Khanna, 2004). Clearly, then, WMC is an important predictor of behavior in a number of different situations.

WORKING MEMORY CAPACITY AND RETRIEVAL COMPETITION

Over the last few years, it has become clear that variation in WMC is related to variation in the ability to retrieve information in the presence of interference. Here we examine a number of studies that have demonstrated a relationship between WMC and retrieval competition. In most of these studies, extreme groups of high and low WMC participants were selected based on their scores on a complex span task (typically operation span). Only participants falling in the upper (high spans) and lower (low spans) quartiles of the distribution were selected and asked to perform a basic memory task. The goal in each study is to examine when and where WMC differences will occur. That is, the goal is to understand when individual differences in WMC will covary with performance in meaningful conditions on another memory task.

The first such study to examine WMC differences in memory retrieval was that of Cantor and Engle (1993). Cantor and Engle were interested in the extent to which individual differences in WMC would predict performance on a fact retrieval task developed by Anderson (1974). In this task participants learn a set of propositions such as "The teacher is in the park," "The lawyer is in the park," "The lawyer is in the boat," and so on. In such a task the number of sentences that share a common concept (e.g., lawyer or park) is manipulated. Some concepts will be linked to only one sentence making for fairly accurate and rapid retrieval of information, while other concepts will be associated with many sentences and retrieval will be less accurate and delayed. Importantly, in order to ensure that all participants had accurately encoded the information, Cantor and Engle required participants to learn the sentences to a criterion of three perfect recall cycles. Later in a verification phase, participants had to make a speeded response to indicate whether a presented sentence was one that was learned or not. The typical "fan effect" is that the more sentences that are linked with a given concept, the longer it takes to indicate whether the sentence was presented. Cantor and Engle found that, as fan size increased, low spans were slower than high spans to indicate that a sentence was presented. That is, as fan size increased, low spans were much slower to retrieve information than high spans, even though both groups learned the information to the same levels initially. Cantor and Engle also found that the correlation between WMC and reading comprehension mentioned above was eliminated when the slope of the fan effect for each individual participant was partialed out. Thus, the ability to retrieve information in the presence of competing information differentiated high and low WMC participants and accounted for the covariation between WMC and reading comprehension.

Conway and Engle (1994) followed up on these findings by examining WMC differences in a Sternberg item recognition task (Sternberg, 1966). Like the Cantor and Engle (1993) study, Conway and Engle had high and low spans learn information to a criterion and then examined differences in the time taken to retrieve information. Specifically, Conway and Engle had participants learn sets of two, four, six, or eight items associated with a digit that reflected the set size. For instance, the letters Z, G, R, B might be associated with the digit 4. Participants learned these sets to a criterion of three perfect recall cycles. During the verification stage, participants were presented with a digit (e.g., 4) followed shortly by a letter (e.g., G) and were required to make a speeded response indicating whether the letter was part of that set. Important for the current discussion, Conway and Engle manipulated interference among the items by having some items belong to more than one set (i.e., the letter G could belong to both Set 4 and Set 8). In those experiments where interference was present, Conway and Engle found large WMC differences. However, in those experiments where no interference was present (i.e., letters belonged to one and only one set), WMC differences did not emerge. These findings held for both letters and words. Thus, like the Cantor and Engle findings, WMC differences seem to occur when items have to be retrieved in the presence of interference. If strong interference is not present low spans retrieve information as rapidly as high spans.

This basic finding of WMC differences in retrieval under conditions of interference has been replicated a number of times. For instance, Bunting, Conway, and Heitz (2004) replicated and extended the Cantor and Engle (1993) and Conway and Engle (1994) findings by mixing the methods. Specifically, Bunting et al. examined WMC differences in the fan effect both when items were shared across sets and when items were not shared across sets. Bunting et al. found that individual differences in WMC predicted larger fan effects only when items were shared across sets, but not when items were unique to each set. Similar to the Conway and Engle findings, these results suggest that variation in WMC only occurs under conditions of interference at retrieval. When a large number of items are associated with a common cue, as in the fan effect, low spans will be less efficient at retrieving the desired information than high spans.

Together, these results suggest that variation in WMC is associated with individual differences in the ability to deal with cue overload as suggested by Watkins and Watkins (1975; see also Watkins, 1979). Cue overload is the observation that the more items that are associated with a given cue, the lower the probability of retrieving any given item will be. Watkins and Watkins suggested that proactive interference (PI) could be conceptualized as a cue overload problem. Items from a current list are associated with the same retrieval cue as items from previous lists leading to an overall decrement in recall. For instance, in the Brown–Peterson task (Brown, 1958; Peterson & Peterson, 1959) subjects are presented with a list of items followed by distractor activity for varying amounts of time and then are asked to recall the presented items. Typically recall for the first trial is quite good and then decreases substantially thereafter (the typical PI effect). However, if on subsequent trials the nature of the TBR items is changed (e.g., from one semantic category to another) performance tends to rebound, and a release from PI occurs (Wickens, Born, & Allen, 1963). Thus, according to Watkins and Watkins the reason that PI occurs is because items are being associated with the same retrieval cue (e.g., animals) and as the number of items associated with the cue increases, the probability of selecting any one item decreases. However, if items are subsumed under a new retrieval cue (e.g., flowers) cue overload is negated and a release from PI is obtained.

If it is the case that low spans are less efficient at dealing with cue overload than high spans (as suggested) we should see that low spans are more susceptible to the effects of proactive interference. Relevant data come from a study by Kane and Engle (2000), who tested high and low spans on a version of the Brown–Peterson type task in PI build and release conditions. Specifically, participants were presented with a list of 10 items from a given semantic category (e.g., animals), followed by 16 s of distractor activity, and finally recall for 20 s. In order to assess the build-up and release of PI, participants were given three lists from the same semantic category and then on the fourth list were switched to a new semantic category (e.g., countries). In their Experiment 1, Kane and Engle found typical PI build and release effects. Importantly, Kane and Engle found that low spans were more susceptible to the effects of PI, as indicated by a steeper drop in the number of words recalled across the first three lists, than were high spans. However, once participants were switched to a new semantic category on the fourth list, high and low spans showed equivalent release effects. Thus, in accord with a cue-overload interpretation, low spans were less efficient at retrieving items as the number of items subsumed under a given retrieval cue increased than were high spans. Given a new retrieval cue, however, reduced the number of items associated with the cue and allowed both span groups to retrieve more items. Furthermore, Kane and Engle showed that this recall advantage for high spans was eliminated when the task was performed under a secondary load at either encoding or retrieval. Kane and Engle argued that attentional control abilities were needed to combat PI at both encoding and retrieval and high spans were better able to use attention to combat the disruptive effects of PI.

Clearly, these results suggest that one ability that is tapped by complex working memory span measures is the ability to retrieve information in an interference rich environment. Further support for the notion that variation in WMC is related to variation in PI resistance comes from a large scale factor analytic study conducted by Friedman and Miyake (2004). Friedman and Miyake collected data from a large number of participants on a diverse array of interference and inhibition tasks. Pertinent to the current discussion is the fact that Friedman and Miyake assessed performance on three different memory tasks under conditions of PI. These included assessing PI in a version of the Brown–Peterson task, assessing PI in a paired-associates task, and assessing PI in a cued recall task. Using a latent variable analysis, Friedman and Miyake found that resistance to PI was a significant predictor of recall performance on a version of the reading span task. Participants who scored high on the reading span task showed less susceptibility to PI based on performance from three different tasks. Thus, performance on a putative measure of WMC was substantially related to the ability to retrieve information when interference was present.

RETRIEVAL COMPETITION IN COMPLEX SPANS

All of the results reviewed thus far suggest that individual differences in WMC are related to the ability to deal with interference from information that has been presented recently. Individuals higher in WMC are better able than individuals lower in WMC to retrieve information in a variety of paradigms when competition between items is high. This conclusion is based on correlational evidence in which performance on putative measures of WMC covaries with performance on a number of other memory tasks under conditions of interference. This work provides important insights into the nature of WMC and its predictive power. However, in order to better understand WMC it is important to examine performance on the complex span tasks themselves and determine which aspects of performance are important for individual differences. To this end, a number of studies have examined how interference influences individual differences in the span tasks and their correlation with measures of higher-order cognition.

For instance, May, Hasher, and Kane (1999) examined how PI affected scores on complex span tasks. May et al. hypothesized that one important contributor to performance on complex span measures was susceptibility to PI. May et al. argued that PI builds across lists in the complex spans and thus, individuals who are more susceptible to PI will have lower span scores. Furthermore, May et al. argued that because complex span tasks are typically administered in an ascending format, PI will be greatest for the largest list lengths and thus, only participants who can combat PI will be able to correctly retrieve items on those longer list lengths. In order to test this hypothesis, May et al. employed two experimental manipulations. First, May et al. manipulated the presentation format such that some participants received the standard ascending format, whereas other participants received a descending presentation format. If PI selectively influences the longest list lengths in the standard condition, then reversing the presentation format should allow participants (particularly low spans) to achieve higher recall performance on long list lengths in the absence of PI. Second, May et al. manipulated context between trials by having participants perform an unrelated task in between each trial. Thus, if PI occurs because the current and preceding trial share the same contextual cue (e.g., Gorfein, 1987), then changing context should reduce PI and boost span scores. May et al. found that span scores were substantially higher when both PI reducing methods were combined. In a subsequent study, Lustig, May, and Hasher (2001) replicated these findings and showed that the correlations between the complex span tasks and a measure of higher-order cognition (e.g., prose recall) only occurred in the presence of PI. In the PI reduction conditions, the correlation was near zero. This provides supporting evidence that interference susceptibility is an important contributor to performance on putative measures of WMC and their relation to higher-order cognitive abilities.

A study by Bunting (2006) replicates and extends these findings. Bunting was interested in how interference both across and within lists influenced retrieval in complex spans and their relation to higher-order cognition. Like the work of May et al. (1999), Bunting examined how manipulations that would reduce interference would lead to higher span scores. Bunting had participants perform three versions of the operation span task. One version (the control) was a standard version of the operation span task in which the TBR items were words. In a second version (interlist experimental), created to examine between trial interference, Bunting had participants perform the operation span task in which the TBR items switched from digits to words across lists. Like the procedure of Wickens et al. (1963), mentioned previously, this procedure allowed for a build-up and release from PI across lists. For instance, the first three lists might require remembering digits, while the next three lists might require remembering words. A third version (intralist experimental) of the operation span task was created to examine how within trial interference would influence span scores. In order to examine within list interference in complex span tasks, Bunting relied on a procedure first used by Young and Supa (1941). Young and Supa manipulated whether a list consisted of all one type of item (e.g., digits or words) or whether a list consisted of a switch between items (e.g., digits and then words). They found that recall was much better on lists with two types of TBR items compared to lists composed of only one type of item. Bunting used a similar methodology within the operation span task in which the type of TBR item (digits vs. words) switched half-way through the list.

Thus, Bunting (2006) created three versions of a complex span task, each varying in the degree of interference within and between trials. Using these tasks, a number of important findings emerged. First, proportion correct in the two experimental tasks was higher than in the control task. That is, in those tasks in which interference reduction methods were used, recall performance was better than in a control task. This occurred when reducing interference both between and within lists, thus replicating the findings of May et al. (1999; see also Kane & Engle, 2000; Young and Supa, 1941). Second, these effects were qualified by position between and within lists. Specifically, when PI was at maximum across lists, performance in the control and interlist experimental versions of the operation span task was equivalent. However, when a release occurred in the interlist experimental task (e.g., switching from digits to words across lists), performance in the interlist experimental task was better than performance in the control task.

Additionally, a similar pattern occurred when examining within list interference. Performance was better on the intralist experimental task than the control task, and this effect was more pronounced for second half than first half items. In both cases, presenting participants with a new cue resulted in better recall performance. Finally, Bunting examined how each version of the operation span task would correlate with performance on a measure of fluid abilities (Raven Advanced Progressive Matrices; Raven, Raven, & Court, 1998). Bunting found that the correlation between recall performance on the operation span and accuracy on the Raven was highest in conditions in which interference was high, and was lowest in conditions where interference was reduced. Thus, similar to the findings of Cantor and Engle (1993), this suggests that the covariation between measures of WMC and measures of higher-order cognition is due, in part, to the ability to retrieve items in the presence of interference.

These results are consistent with the cue-overload principle advocated by Watkins (1979). In terms of a cue-overload framework, the release from PI across lists occurs because items are subsumed under a new cue which is not overloaded. A cue-overload approach predicts the same effect for within list interference. When item type switches within a list, items are now subsumed under a new cue, thus reducing the number of items subsumed under one cue by half. As with the work reviewed previously, these results suggest that an important aspect of performance on the complex span tasks in the ability to deal with cue-overload. Additional work from our lab supports these notions. For instance, consider the within list interference effect. This is essentially a variation of a list-length effect. Here, all items are subsumed under the same cue ("list") and all items are target items. This contrasts with the build-up of PI across lists, in which case the items are subsumed under the same cue, but only some of the items are targets. Thus, within list interference occurs when several items are subsumed under the same retrieval cue and the items compete for retrieval. Having two separate retrieval cues for a given list, as Bunting (2006) did, reduces cue overload and increases probability of recall. If individual differences in WMC are partially due to differences in the ability to deal with cue overload, then we should see complex span differences in list-length effects. That is, those participants who are better able to use cues to guide the retrieval process (e.g., high spans), should show smaller list-length effects than those participants who are poorer at using retrieval cues (e.g., low spans).

Relevant data comes from a study by Unsworth and Engle (2006a). We examined performance on two verbal complex span measures (reading and operation span) for list lengths of two–five. We found that low spans had steeper list-length functions than high spans, suggesting that low spans suffered from more cue overload than do high spans. Why is this the case if the number of items per list is the same for the two groups? That is, on a list length of five, there are five target items for both high- and low-span participants, thus both groups should have five items subsumed under the retrieval cue. If low spans are suffering from more cue overload than high spans, how are more items subsumed under the retrieval cue for low span than for high spans? We suggest two reasons. First, we suggest that low spans are less efficient at using context cues to discriminate across lists. Thus, both current target items and items from previous trials are subsumed under the retrieval cue for low spans (i.e., more PI). Second, we suggest that low spans are less efficient at using context cues even within a list. Specifically, one way to reduce cue-overload effects within a list is to use context cues that differentiate items. In accord with Glenberg's temporal distinctiveness theory (1987; Glenberg & Swanson, 1986), and Tulving's encoding specificity principle (1983), items whose context at retrieval best matches context at encoding will be associated with a high probability of recall. As with the reduction of within list interference effects found by Bunting (2006), perhaps high spans are better at using context cues to reduce interference both between and within lists than low spans.

Support for this position comes from a study by Unsworth and Engle (2006b). In this study, we examined the different types of error responses in two complex span tasks (reading and operation span). Most relevant to the current discussion is an examination of input omissions and intrusion. Input omissions are errors in which the correct target item was not recalled. Instead of recalling the correct target item, participants either left the space blank on the recall sheet or intruded an item. Thus, intrusions are a subset of input omissions. We showed that low spans made more input omissions and intrusions than high spans. Furthermore, an examination of these errors by serial position for a list-length of five qualified these results. Specifically, both span groups recalled the last item presented with very high accuracy. However, the further back in time an item was presented, generally, the lower the probability of correctly recalling that item. This was especially true for low spans. We suggested that these results could be interpreted in terms of Glenberg's temporal distinctiveness theory (1987). Those items whose encoded context is similar to the retrieval context were associated with a high recall accuracy. Items whose encoded context was dissimilar to the retrieved context were associated with a low accuracy. Furthermore, those individuals who are better at using context cues to guide the retrieval process (i.e., high spans) had better recall at nearly all serial positions than participants who are poorer at using context cues (i.e., low spans). An examination of intrusion errors suggested that intrusions were most likely to occur at the first serial position and were more likely for low than for high spans. Together, these results suggest that low spans are poorer at recalling items in complex span tasks because they are less efficient at using context cues to reduce cue overload both between and within lists than high spans.

A MODEL OF WMC AND RETRIEVAL

Throughout this chapter, we have alluded to individual differences in WMC and retrieval as being due to differences in interference susceptibility in terms of cue overload. Recently, we have begun to explore a model of WMC and retrieval based on a cue-dependent search process (Unsworth & Engle, 2005). Specifically, we have argued that individuals who differ in WMC differ in their ability to use cues to guide a search process of secondary memory to reactivate representations that are no longer being actively maintained (e.g., Shiffrin, 1970). That is, we assume that there is an upper limit to how much information can be actively maintained and thus, in some situations relevant information will have to retrieved back into working memory. In this view, WMC is not only the ability to maintain distinct representations in active state, but also the ability to use cues to search and reactive representations. The key to this search process is the ability to delimit the search set to only target items via the use of different cues (e.g., temporal, contextual, categorical, etc.). Importantly, retrieval from secondary memory is fraught with potential problems such as PI. As PI builds, the search set gets progressively larger leading to inefficient retrieval (i.e., cue overload; Watkins, 1979; Wixted & Rohrer, 1993). Thus, as argued throughout this chapter, low spans suffer from cue overload to a greater extent than high spans because they are less capable at using cues to guide the search process.

An elegant way of testing this model comes from an examination of response latency distributions in free recall paradigms. Over the last 60 years, researchers have occasionally relied on cumulative latency distributions obtained in recall paradigms to gain a better understanding of retrieval processes. For instance, the classic work of Bousfield and colleagues (e.g., Bousfield, Sedgewick, & Cohen, 1954) demonstrated that in verbal fluency tasks, where a participant is asked to recall as many items from a specified category (e.g., animals) as possible, the rate at which responses are emitted starts fast and then gets progressively slower. Additionally, Roediger and colleagues (Roediger, Stellon, & Tulving, 1977), have shown a similar pattern for episodic memory tasks. In nearly all cases, researchers have found that cumulative latency distributions are well described by a cumulative exponential,

$$F(t) = N(1 - e^{-\lambda t}) \qquad 15.1$$

where $F(t)$ represents the cumulative number of items recalled by time t, N represents asymptotic recall, and λ represents the rate of approach to asymptote.

McGill (1963) has demonstrated that a simple random-sampling-with-replacement process predicts exponentially declining rates of recall and cumulative exponential recall curves, if one assumes a constant sampling time per item (see also Rohrer & Wixted, 1994). Thus, cumulative latency distributions in free recall paradigms are well described by a simple random search model. In this model a retrieval cue delimits a search set that includes target items as well as extraneous items. Items are randomly sampled from the search set at a constant rate one item at a time (serial search). Target items that have not been previously sampled are recalled and placed back in the search set (sampling-with-replacement). Target items that have been previously recalled, extralist items, or target items that are not recoverable, are not recalled but still can be sampled from the search set. Based on an extensive review of the literature, Wixted and Rohrer (1994) have suggested that the rate of approach to asymptotic performance (λ), obtained from fitting the cumulative exponential to a cumulative latency distribution, is indicative of the size of the search set that one is searching through. Wixted and Rohrer argued that the larger the set one is searching from, the slower one will be in reaching asymptotic recall levels. That is, the larger the search set, the lower the probability of sampling any given item will be and hence, the longer it will take you to find the desired item. Wixted and Rohrer provided evidence for this view by demonstrating that rate is slower when recall is required from large categories than when searching through smaller categories, when recalling from longer lists than from shorter lists (Rohrer & Wixted, 1994), when recalling from lists where PI is high than when PI is low (Wixted & Rohrer, 1993), as well as a number of other findings (for a comprehensive review see Wixted & Rohrer, 1994). In each case, the more overloaded a cue was, the slower the rate of approach to asymptote was. Thus, if it is the case that low spans suffer from more cue overload, because they are less efficient at using cues to guide the search process in episodic memory tasks than high spans, we should see that low spans approach asymptote slower than high spans.

This is precisely the case. We (Unsworth & Engle, in press) had high and low spans perform an immediate free recall task in which response latency was measured during the recall phase. Participants received 15 lists with 12 words per list. During recall, participants had 30 s to recall as many items as possible, in any order they wished. For each response that was emitted, an experimenter pressed a key indicating when in the recall period the response was given. Shown in Figure 15.1 are the resulting cumulative recall curves. As can be seen, high spans recalled more items (higher asymptotic levels of recall) than low spans and they approached asymptote at a faster rate than low spans (λ highs = .20, λ lows = .17). Consistent with the work of Wixted and Rohrer (1993), this suggests that low spans were searching through a larger search set of items than were high spans. In line with the work reviewed thus far, we suggest that in episodic memory tasks, low

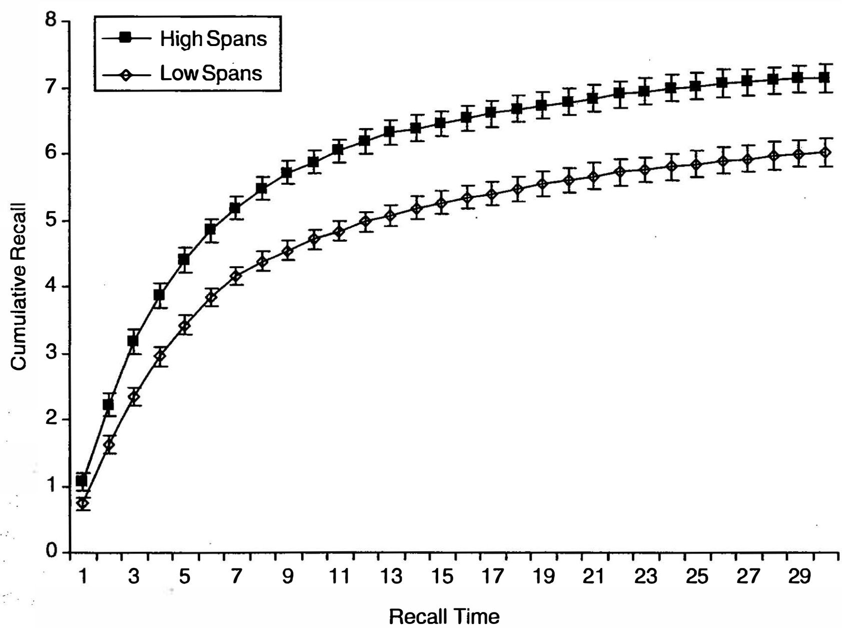

FIGURE 15.1 Cumulative recall functions as a function of complex span for immediate free recall (adapted from Unsworth & Engle, 2005).

spans are less efficient at using context cues to delimit the search set to only the current target items. Thus, low spans have search sets that include target items as well as items from previous trials. This results in a lower number of items recalled (e.g., N) and a slower rate of approach to asymptotic performance (e.g., λ). However, these findings are limited by the fact that some of the items were recalled (theoretically) from a short-term buffer (e.g., Raaijmakers & Shiffrin, 1981) and thus the results do not clearly demonstrate differences in the search process between the two groups. Accordingly, we have since examined the temporal dynamics of recall in a delayed free recall paradigm thought to reduce the contribution of a short-term buffer (e.g., Glanzer & Cunitz, 1966). Preliminary evidence suggests that high spans recall more items than low spans and reach asymptotic levels at a faster rate than low spans (Unsworth, 2005).

Taken together, these results suggest that low spans are inefficient, relative to high spans, in their ability to correctly delimit the search set to only target items. However, the overall view is that low spans are less efficient at using cues to guide the search process. In some situations, it may actually be beneficial to have large search sets in order to aid retrieval. Take for instance the verbal fluency task described previously. Here you are given a category and are told to recall as many items as possible from that cue in a given amount of time. In such a case, in order to recall many items one may actually want to have a larger search set to sample from. That is, one has to ask what is being required in the task (e.g., Humphreys, Bain, & Pike, 1989). In order for accurate performance in an episodic memory task, one has to constrain the search set to the episode. However, in semantic fluency tasks, the search need only be constrained to the specific category cue. Thus, in such a case a larger search set that includes many target representations may be more desirable than a smaller search set. Indeed, contrasting latency distributions in an episodic free recall task and a semantic fluency task, Rohrer (2002) has shown that response latency in the episodic task is constrained by the episode but that response latency in the semantic task is constrained by the size of the category.

Turning back to individual differences in WMC, if high spans are better at using cues to guide the search process, we might expect that high spans will actually have larger search sets than low spans in a semantic fluency task. That is, high spans may be better and more flexible at configuring their search sets based on the task demands than are low spans. Evidence for such a notion comes from a study by Rosen and Engle (1997). Rosen and Engle had participants recall as many animals as possible in 15 min. They found that high spans retrieved more animal names than low spans and plotted their cumulative recall functions. However, they did not attempt to fit the cumulative exponential to their data and examine the resulting parameter estimates. Shown in Figure 15.2 are the results from Rosen and Engle's Experiment 1 (estimated from their Fig. 1). Although the functions have not yet reached asymptotic levels, fitting the estimated functions to the cumulative exponential suggests a reversal of the episodic recall findings in that high spans approach asymptote at a slower rate than low spans (λ highs = .15, λ lows = .19). Indeed, this is the standard finding when examining cumulative latency distributions in semantic memory tasks (e.g., Wixted & Rohrer, 1994).

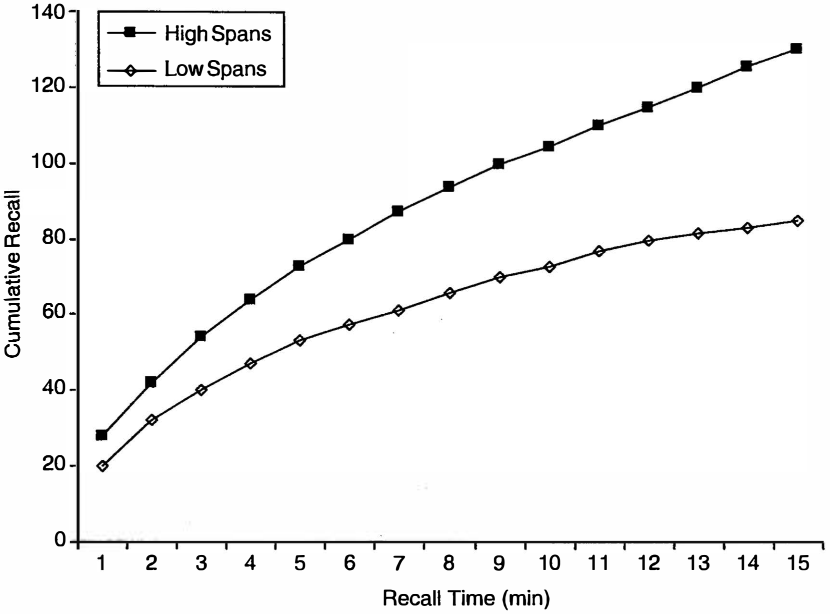

FIGURE 15.2 Cumulative recall functions as a function of complex span for a verbal fluency task (adapted from Rosen & Engle, 1997).

Those individuals who retrieve more items, tend to emit the items at a slower rate (e.g., Johnson, Johnson, & Mark, 1951). Thus, it is not simply the case that high spans always have smaller search sets than low spans, but rather high spans are better at using cues to guide the search process based on the demands of the task. In semantic memory tasks, such as verbal fluency, a hierarchal search process may be the best approach to take (e.g., Wixted & Rohrer, 1994). In such a case, clusters of items are subsumed under a retrieval cue. The retrieval process proceeds by first sampling clusters and then items within the cluster. Those participants who are unable to use cues to sample clusters and items within a cluster will perform more poorly than participants who are good at using cues to guide the search process. In episodic memory tasks, however, where only retrieval of current target items is desired, the search set will need to be delimited and exclude items from previous trials. Those participants who are unable to effectively delimit the search set will show poorer performance due to interference from previous trials. We suggest that high spans are better at retrieval in both situations due to a greater ability to use cues to direct the search process.

CONCLUSIONS AND FUTURE DIRECTIONS

In the present chapter we have shown that individual differences in WMC are related to individual differences in retrieval under conditions of interference. We have argued that low WMC individuals are more prone to cue overload in episodic memory tasks than are high WMC individuals. However, we have said little about the underlying mechanism that may give rise to these differences. In previous work (e.g., Engle & Kane, 2004) we have argued that the ability to control attention is of crucial importance in a number of tasks and that individual differences in attentional control correspond to differences in WMC. In terms of retrieval differences, our previous work has suggested that inhibitory processes likely play a role (see Redick, Heitz, & Engle, in press, for a review; see also Hasher, Zacks, & May, 1999). This view suggests that the reason low spans search through a larger search set of items than high spans is because low spans are inefficient at using controlled attention to exclude irrelevant items. In terms of the current cue-dependent search approach, perhaps high spans are better at using cues to specify which items are relevant, and then they suppress all other items. That is, high spans may be better at using a conceptually guided selective attention process (Anderson & Spellman, 1995) in which attention is focused on target items and irrelevant items are actively suppressed.

Furthermore, the importance of attention at retrieval has also been implicated cue-dependent search approaches of memory. For instance, in the search of associate memory model (Raaijmakers & Shiffrin, 1981) there are several components of the search process that require attention including deciding how to search, what cues should be used for the search, how the cues should be combined for search, and when to stop the search. Each decision is attention demanding and thus, likely related to individual differences in WMC. Consistent with this notion is work by Naveh-Benjamin and Guez (2000), which suggests that dividing attention at retrieval selectively disrupts the cue-elaboration aspect of the search process. Work from our lab supports both approaches. Specifically, both Rosen and Engle (1997) and Kane and Engle (2000) have shown that dividing attention during retrieval disrupts performance for high spans but not low spans. Future work will be directed at examining the combination of these two approaches.

A final limitation of the work we have presented here is the exclusive focus on retrieval factors. As the work on the levels of processing approach has shown (e.g., Craik & Lockhart, 1972), issues of encoding are also important factors in memory theory. In fact, a few studies have explicitly examined encoding strategies in complex span tasks (e.g., Turley-Ames & Whitfield, 2003). However, as shown by Turley-Ames and Whitfield (2003), differences in encoding strategies actually tend to obscure the correlation between complex span performance and performance on measures of higher-order cognition. Furthermore, it is appealing to think that high spans may be better at reinstating the encoding context at retrieval than low spans, and thus are more efficient at implementing encoding specificity (Tulving, 1983). More work is needed to understand the possible role of encoding and encoding-retrieval interactions in terms of individual differences in WMC. As pointed out by Roediger (2000), understanding retrieval processes is of the utmost importance in terms of understanding how memory works. To this we would add that an even fuller understanding can be gained by examining individual differences in retrieval.

REFERENCES

Anderson, J. R. (1974). Retrieval of propositional information from long-term memory. *Cognitive Psychology*, *6*, 451–474.

Anderson, M. C., & Spellman, B. A. (1995). On the status of inhibitory mechanisms in Cognition: Memory retrieval as a model case. *Psychological Review*, *107*, 68–100.

Baddeley, A. D., & Hitch, G. (1974). Working memory. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 8, pp. 47–89). New York: Academic Press.

Bleckley, M. K., Durso, F. T., Crutchfield, J. M., Engle, R. W., & Khanna, M. M. (2004). Individual differences in working memory capacity predict visual attention allocation. *Psychonomic Bulletin and Review*, *10*, 884–889.

Bousfield, W. A., Sedgewick, C. H. W., & Cohen, B. H. (1954). Certain temporal characteristics of the recall of verbal associates. *American Journal of Psychology*, *67*, 111–118.

Brown, J. (1958). Some tests of the decay theory of immediate memory. *Quarterly Journal of Experimental Psychology*, *10*, 12–21.

Bunting, M. F. (2006). Proactive interference and item similarity in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32*, 183–196.

Bunting, M. F., Conway, A. R. A., & Heitz, R. P. (2004). Individual differences in the fan effect and working memory capacity. *Journal of Memory and Language*, *51*, 604–622.

Cantor, J., & Engle, R. W. (1993). Working memory capacity as long-term memory activation: An individual differences approach. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *19*, 1101–1114.

Case, R., Kurland, M. D., & Goldberg, J. (1982). Operational efficiency and the growth of short-term memory span. *Journal of Experimental Child Psychology*, *33*, 386–404.

Cohen, R. L. (1994). Some thoughts on individual differences and theory construction. *Intelligence*, *18*, 3–13.

Conway, A. R. A., Cowan, N., & Bunting, M. F. (2001). The cocktail party phenomenon revisited: The importance of working memory capacity. *Psychonomic Bulletin and Review*, *8*, 331–335.

Conway, A. R. A., Cowan, N., Bunting, M. F., Therriault, D. J., & Minkoff, S. R. B. (2002). A latent variable analysis of working memory capacity, short-term memory capacity, processing speed, and general fluid intelligence. *Intelligence*, *30*, 163–183.

Conway, A. R. A., & Engle, R. W. (1994). Working memory and retrieval: A resource-dependent inhibition model. *Journal of Experimental Psychology: General*, *123*, 354–373.

Craik, F. I. M., & Lockhart, R. S. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior*, *11*, 671–684.

Cronbach, L. J. (1957). The two disciplines of scientific psychology. *The American Psychologist*, *12*, 671–684.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior*, *19*, 450–466.

Daneman, M., & Green, I. (1986). Individual differences in comprehending and producing words in context. *Journal of Memory and Language*, *25*, 1–18.

Engle, R. W., & Kane, M. J. (2004). Executive attention, working memory capacity, and a two-factor theory of cognitive control. In B. Ross (Ed.), *The psychology of learning and motivation* (Vol. 44, pp. 145–199). New York: Elsevier.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. A. (1999). Working memory, short-term memory and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology: General, 128*, 309–331.

Friedman, N. P., & Miyake, A. (2004). The relations among inhibition and interference control functions: A latent-variable analysis. *Journal of Experimental Psychology: General, 133*, 101–135.

Glanzer, M., & Cunitz, A. R. (1966). Two storage mechanisms in free recall. *Journal of Verbal Learning and Verbal Behavior, 5*, 351–360.

Glenberg, A. M. (1987). Temporal context and recency. In D. S. Gorfein & R. R. Hoffman (Eds.), *Memory and learning: The Ebbinghaus centennial conference*. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Glenberg, A. M., & Swanson, N. G. (1986). A temporal distinctiveness theory of recency and modality effects. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 12*, 3–15.

Gorfein, D. S. (1987). Explaining context effects on short-term memory. In D. S. Gorfein & R. R. Hoffman (Eds.), *Memory and learning: The Ebbinghaus centennial conference* (pp. 153–172). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Hasher, L., Zacks, R. T., & May, C. P. (1999). Inhibitory control, circadian arousal, and age. In D. Gopher & A. Koriat (Eds.), *Attention and performance XVII: Cognitive regulation of performance: Interaction of theory and application* (pp. 653–675). Cambridge, MA: MIT Press.

Heitz, R. P., & Engle, R. W. (2005). Focusing the spotlight: Individual differences in visual attention control. *Manuscript submitted for publication*.

Humphreys, M. S., Bain, J. D., & Pike, R. (1989). Different ways to cue a coherent memory system: A theory for episodic, semantic, and procedural tasks. *Psychological Review, 96*, 208–233.

Johnson, D. M., Johnson, R. C., & Mark, A. L. (1951). A mathematical analysis of verbal fluency. *Journal of General Psychology, 44*, 121–128.

Kane, M. J., Bleckley, M. K., Conway, A. R. A., & Engle, R. W. (2001). A controlled-attention view of working-memory capacity. *Journal of Experimental Psychology: General, 130*, 169–183.

Kane, M. J., & Engle R. W. (2000). Working memory capacity, proactive interference, and divided attention: Limits on long-term retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26*, 333–358.

Kane, M. J., & Engle, R. W. (2003). Working-memory capacity and the control of attention: The contributions of goal neglect, response competition, and task set to Stroop interference. *Journal of Experimental Psychology: General, 132*(1), 47–70.

Kane, M. J., Hambrick, D. Z., Tuholski, S. W., Wilhelm, O., Payne, T. W., & Engle, R. W. (2004). The generality of working-memory capacity: A latent-variable approach to verbal and visuo-spatial memory span and reasoning. *Journal of Experimental Psychology: General, 133*, 189–217.

Kyllonen, P. C., & Christal, R. E. (1990). Reasoning ability is (little more than) working-memory capacity? *Intelligence, 14*, 389–433.

Kyllonen, P. C., & Stephens, D. L. (1990). Cognitive abilities as determinants of success in acquiring logic skill. *Learning and Individual Differences, 2*, 129–160.

Long, D. L., & Prat, C. S. (2002). Working memory and Stroop interference: An individual differences investigation. *Memory and Cognition, 30*, 294–301.

Lustig, C., May, C. P., & Hasher, L. (2001). Working memory span and the role of proactive interference. *Journal of Experimental Psychology: General, 130*, 199–207.

May, C. P., Hasher, L., & Kane, M. J. (1999). The role of interference in memory span. *Memory and Cognition, 27*, 759–767.

McGill, W. J. (1963). Stochastic latency mechanism. In R. D. Luce, R. R. Bush, & E. Galanter (Eds.), *Handbook of mathematical psychology* (Vol. 1, pp. 309–360). New York: Wiley.

Melton, A. W. (1963). Implications of short-term memory for a general theory of memory. *Journal of Verbal Learning and Verbal Behavior, 2*, 1–21.

Naveh-Benjamin, M., & Guez, J. (2000). Effects of divided attention on encoding and retrieval processing: Assessment of attentional costs and a componential analysis. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26*, 1461–1482.

Peterson, L. R., & Peterson, M. J. (1959). Short-term retention of individual verbal items. *Journal of Experimental Psychology, 58*, 193–198.

Raaijmakers, J. G. W., & Shiffrin, R. M. (1981). Search of associative memory. *Psychological Review, 88*, 93–134.

Raven, J. C., Raven, J. E., & Court, J. H. (1998). *Progressive matrices*. Oxford, UK: Oxford Psychologists Press.

Redick, T. S., Heitz, R. P., & Engle, R. W. (in press). Working memory capacity and inhibition: Cognitive, social, and neuropsychological consequences. In C. M. MacLeod & D. S. Gorfein (Eds.), *The place of inhibition in cognition*.

Roediger, H. L. (2000). Why retrieval is the key process to understanding human memory. In E. Tulving (Ed.), *Memory, consciousness and the brain: The Tallinn conference* (pp. 52–75). Philadelphia: Psychology Press.

Roediger, H. L., III, Stellon, C. C., & Tulving, E. (1977). Inhibition from part-list cues and rate of recall. *Journal of Experimental Psychology: Human Learning and Memory, 3*, 174–188.

Rohrer, D. (2002). The breadth of memory search. *Memory, 10*, 291–301.

Rohrer, D., & Wixted, J. T. (1994). An analysis of latency and interresponse time in free recall. *Memory and Cognition, 22*, 511–524.

Rosen, V. M., & Engle, R. W. (1997). The role of working memory capacity in retrieval. *Journal of Experimental Psychology: General, 126*, 211–227.

Shiffrin, R. M. (1970). Memory search. In D. A. Norman (Ed.), *Models of human memory* (pp. 375–447). New York: Academic Press.

Sternberg, S. (1966). High-speed scanning in human memory. *Science, 153*, 652–654.

Tulving, E. (1983). *Elements of episodic memory*. New York: Oxford University Press.

Turley-Ames, K. J., & Whitfield, M. M. (2003). Strategy training and working memory task performance. *Journal of Memory and Language, 49*, 446–468.

Turner, M. L., & Engle, R. W. (1989). Is working memory capacity task dependent? *Journal of Memory and Language, 28*, 127–154.

Underwood, B. J. (1975). Individual differences as a crucible in theory construction. *The American Psychologist, 30*, 128–134.

Unsworth, N. (2005). Individual differences in working memory capacity and episodic retrieval: Examining the dynamics of delayed and continuous distractor free recall. *Manuscript in preparation.*

Unsworth, N., & Engle, R. W. (in press). The nature of individual differences in working memory capacity: Active maintenance in primary memory and controlled search from secondary memory. *Psychological Review*.

Unsworth, N., & Engle, R. W. (2006a). Simple and complex memory spans and their relation to fluid abilities: Evidence from list-length effects. *Journal of Memory and Language, 54*, 68–80.

Unsworth, N., & Engle, R. W. (2006b). A temporal-contextual retrieval account of complex span: An analysis of errors. *Journal of Memory and Language, 54*, 346–362.

Unsworth, N., Schrock, J. C., & Engle, R. W. (2004). Working memory capacity and the antisaccade task: Individual differences in voluntary saccade control. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 30*, 1302–1321.

Watkins, M. J. (1979). Engrams as cuegrams and forgetting as cue overload: A cueing approach to the structure of memory. In C. R. Puff (Ed.), *Memory organization and structure* (pp. 173–195). New York: Academic Press.

Watkins, O. C., & Watkins, M. J. (1975). Buildup of proactive inhibition as a cue-overload effect. *Journal of Experimental Psychology: Human Learning and Memory, 104*, 442–452.

Wickens, D. D., Born, D. G., & Allen, C. K. (1963). Proactive inhibition and item similarity in short-term memory. *Journal of Verbal Learning and Verbal Behavior, 2*, 440–445.

Wixted, J. T., & Rohrer, D. (1993). Proactive interference and the dynamics of free recall. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 19*, 1024–1039.

Wixted, J. T., & Rohrer, D. (1994). Analyzing the dynamics of free recall: An intergrative review of the empirical literature. *Psychonomic Bulletin and Review, 1*, 89–106.

Young, C. W., & Supa, M. (1941). Mnemic inhibition as a factor in the limitation of memory span. *American Journal of Psychology, 54*, 546–552.