How Chunks Form in Long-term Memory and Affect Short-term Memory Limits

Nelson Cowan and Zhijian Chen

University of Missouri - Columbia

Draft: 2 September, 2006

Acknowledgments: Preparation of this chapter was supported by NIH Grant R01 HD-21338. Address correspondence to Nelson Cowan, Department of Psychological Sciences, University of Missouri, Columbia, Missouri 65211 USA. E-mail: CowanN@Missouri.edu.

This is a draft of a chapter for A. Thorn & M. Page, eds., *Interactions between short-term and long-term memory in the verbal domain*. Hove, East Sussex, UK: Psychology Press, Ltd.

OVERVIEW

We address the question of whether information in short-term memory can be conceived as the activated portion of long-term memory. The main problem for this conception is that short-term memory must include new associations between items that are not already present in long-term memory (or sometimes between items and serial positions). Relevant evidence is obtained from a task in which new word pairings are taught and then embedded within a short-term serial recall task. We conclude that rapid long-term learning occurs in short-term memory procedures, and that this rapid learning can explain the retention of new associations. We propose that new associations are formed between elements concurrently held in the focus of attention, and that these new associations quickly become part of long-term memory. An understanding of rapid learning appears to be necessary to understand capacity limits in short-term memory.

INTRODUCTION

This chapter is about how long-term memory information is activated and used when one carries out short-term memory tasks, and how new long-term memory information is formed during short-term memory tasks. The topic is related to Miller's (1956) famous article. He not only pointed out capacity limits in short-term memory (seven plus or minus two units in serial recall, and about the same number of categories along a dimension in perceptual tasks); he also indicated how long-term knowledge can greatly increase short-term memory. It can do so through a process Miller termed *chunking*, the combination of multiple items to form a larger, meaningful item. To offer a simple example, it is much easier to recall the letter sequence *i-b-m-c-b-s-r-c-a* if one recognizes within it acronyms for three American corporations in succession: IBM, CBS, and RCA. This reduces the number of chunks in the list from seven to three.

The issues of capacity and chunking that Miller (1956) raised become entangled with one another when it is considered that people might form new chunks during a short-term memory task, as a mnemonic strategy. For example, given the telephone number *662-5892*, one might memorize three chunks: 662, 58, and 92. In this way, what was a rather taxing list of seven single-digit numbers becomes a less taxing list of three multi-digit numbers. Indeed, the reason that telephone numbers are listed with a break in the middle is probably to facilitate this type of memorization. If one allows this "on-line" basis of chunk formation, though, the true limit in capacity is in question. Can people recall about seven chunks of information or, when seven items are recalled in a memory task such as serial recall, do these items actually make up a smaller number of multi-item chunks that the participants have formed? This chapter will examine the basic capacity limit of short-term memory and the role of long-term learning in the use of this limit. First, though, a brief history of research on this topic lends perspective.

BRIEF HISTORY OF RESEARCH ON INTERATIONS BETWEEN SHORT- AND LONG-TERM MEMORY

Some researchers believe that a single set of rules applies across all memory procedures (for example, Crowder, 1993; McGeoch,1932; Melton, 1963; Nairne, 2002; Surprenant &

Neath, this volume). Other researchers believe that a distinction must be made between at least two types of memory, which James (1890) called primary and secondary memory. Primary memory is the limited amount of information that one is actively thinking about, whereas secondary memory is the vast amount of information about the past that one can call up at various times. These types of memory have been known by various names with different theoretical origins (for a review see Cowan, 2005a) but they are commonly called short-term memory and long-term memory (e.g., Atkinson & Shiffrin, 1968).

The basis for the distinction between these two types of memory includes patients with dense amnesia, who respond normally on immediate-recall tasks and yet perform poorly on delayed-recall tasks, in which a distracting task comes between the presentation of a list of items and the recall period (e.g., Baddeley & Warrington, 1970; Squire, 1987; Warrington & Weiskrantz, 1970). In rare cases, the converse occurs; certain patients perform poorly on immediate-recall tasks but perform normally on delayed-recall tasks (Shallice & Warrington, 1970).

In normal participants, the evidence for separate functions of short- and long-term memory has been controversial. Nevertheless, one can find important dissociations between patterns of performance on immediate versus delayed recall tasks (for reviews, see Cowan, 1995; Davelaar, Goshen-Gottstein, Ashkenazi, Haarman, & Usher, 2005). For example, some relevant results involve immediate free recall tasks, in which items can be recalled in any order. Those items near the end of the list (recency items) typically are recalled first, and are recalled at a level that is very high, at least relative to items in the middle of the list. Similarly, items at the beginning of the list (primacy items) are recalled well. However, the results are different when recall is delayed by several seconds filled with distraction. Then, recency items lose their advantage over items in the middle of the list, even though primacy items are still recalled well (Glanzer & Cunitz, 1966; Postman & Phillips, 1965).

The original interpretation of this pattern of results regarding primacy and recency advantages was that the early list items are remembered well because they can be rehearsed with undivided attention at first, allowing a strong long-term memory code to form; whereas later list items are remembered well only if they have not yet been displaced from short-term memory by the time of recall. Later research questioned the interpretation of the recency effect on the basis of experiments in which there were distracting periods between items as well as in the retention interval at the end of the list (e.g., Bjork & Whitten, 1974; Tzeng, 1973). An alternative interpretation was that the important factor was the ratio between the inter-item intervals and the retention interval (the *ratio rule*). However, there are important differences between recency effects in immediate versus delayed recall. For example, differences show up in a final free recall task, in which the participant is to try to recall all of the words from all of the lists that had been used in immediate recall. When ordinary immediate recall was followed by a final free recall test, there was a *negative recency effect* in which items that had been presented in the recency portions of lists in immediate recall were now, in final free recall, remembered less well than items that had been recalled in intermediate list positions (even though the primacy effect remained positive, not negative). Because the recency items had been recalled from short-term memory, they presumably were not deeply encoded in long-term memory, and therefore were not recalled well in final free recall. In contrast, when list items were separated by distracting tasks, a recency effect was obtained but it did not lead to a negative recency effect in final free recall (for a review see Davelaar et al., 2005). So there appear to be multiple sources of recency advantages: One based on retrieval from short-term memory, and another based on distinctiveness of the last few items in a way that aids retrieval from long-term memory.

More generally, the most fundamental reason why investigators have questioned the existence of separate short- and long-term stores is that there are strong similarities between performance patterns in immediate and delayed memory tasks, and there is the possibility of accounting for these similarities in terms of general rules of memory such as cue-driven performance and temporal distinctiveness (e.g., Bjork & Whitten, 1974; Keppel & Underwood, 1962; Nairne, 2002). In order to understand both the similarities and the differences between immediate and delayed memory tasks, though, one must carefully consider the relation between short- and long-term memory.

Theorists who believe in a single set of principles for all memory tasks have pointed to interference between items as an important principle. In responding to this type of theorist, Broadbent (1971) stated the following:

> There remain to be considered two points urged by interference theory: the existence of effects on short-term memory from previous long-term experiences, and the continuity which seems to exist between memory at long and short periods of time. The first of these must be admitted straight away, and is perfectly consistent with a view of short-term memory as due to recirculation into and out of a decaying buffer storage...In general one must beware of concluding that the appearance in short-term memory of an effect known from longer-term studies is evidence for identity of the two situations...Only the success or failure of attempts to show differences between the two situations is of interest in distinguishing the theories.
>
> [Broadbent (1971), pp. 342-343]

He suggested that immediate and delayed memory tasks involve similar mechanisms, but that the contribution of the recirculation of information in and out of a buffer store will be greater in immediate-recall procedures, with a greater influence of retrieval cues and interference in delayed-recall procedures.

ACTIVATION AND ATTENTION: TWO COMPONENTS OF SHORT-TERM MEMORY STORAGE?

The possible relation between short- and long-term memory becomes clearer if one distinguishes between different potential components of short-term storage. In the model of Alan Baddeley and colleagues (Baddeley & Hitch, 1974; Baddeley, 1986; Baddeley & Logie, 1999), short-term storage was said to take place in dedicated, code-specific buffers (the phonological loop and the visuospatial sketchpad). In contrast, in the conception of Cowan (1988), similar to some previous papers (e.g., Massaro, 1975; Shiffrin, 1975, 1976), there were said to be two separate types of storage component that cut across domains. One component is the set of currently-activated items and features from long-term memory, and a second component is the information currently in the focus of attention. The latter information is a subset of the activated portion of long-term memory, and it may be in a more deeply-analyzed form than information that is activated without the involvement of the focus of attention. For example, suppose that a person is listening to someone on a telephone and, concurrently, ignoring a conversation going on in the room. Both sources of speech will activate features from long-term memory. However, the ignored speech may activate primarily physical features related to the voice quality and the identity of some of the speech phonemes, whereas the attended speech is more likely to activate long-term memory features related to the lexical identity and meaning of the speech, in addition to physical features. The information in the focus of attention is presumably categorical information and that is not true of all of the information in the activated portion of long-term memory, although items that were attended a few seconds ago may remain temporarily active in the more categorical form.

One source of evidence in favor of the type of processing that we have suggested comes from experiments on selective listening, in which two different messages are presented to the two ears through headphones and the message presented to one ear is to be attended (monitored or repeated). Cherry (1953) found that people do not notice and cannot recall much of the information presented to the ignored message, although changes in physical features, such as the speaker's voice, are usually noticed. Moray (1959) then found that, in an exception to this pattern, people do sometimes notice their own name presented in the channel to be ignored. However, Conway, Cowan, and Bunting (2001) found that it is most often individuals with low working memory span who notice their names in the ignored channel. Given a great deal of other evidence relating low working memory span to the relatively poor control of attention (e.g., Kane et al., 2001; Kane & Engle, 2003), Conway et al. suggested that noticing one's own name may occur only in individuals who do not have very good control of attention, which may sometimes wander to the channel that is supposed to be ignored.

The overall concept, then, is that the focus of attention is the core of primary memory and that the activated portion of long-term memory is its fringe. One difference between these two components would be that the focus of attention would be limited to just a few chunks of information at a time (normally 3 to 5 chunks in adults; see Cowan, 2001), whereas the activated portion of long-term memory would be limited only by interference from other stimuli with similar features, and possibly by decay over time.

THE PROCESSING OF NEW LINKS BETWEEN ITEMS IN SHORT-TERM MEMORY

One problem with the conception of short-term memory as comprising the activated portion of long-term memory is that, taken literally, it cannot account for everything that must be held in short-term memory. Often, it is the serial order of items or the particular new associations between items that must be remembered, and such new information does not exist within the previously-learned knowledge stored in long-term memory. For example, one might need to store the association between each item in a list and its serial position, between adjacent items in a list, or between each object in a spatial array and its location. One might have to save associations between features that are coded quite differently, such as associations between names and faces in a group of people. This problem was noted by Cowan (1995, 1999) and also by Baddeley (2000).

Cowan (1999, 2001, 2005a, 2005b) suggested that new associations or links between elements are stored as a specific function of the focus of attention, a point that will be explained further a bit later on, in conjunction with Figure 2. Baddeley (2000) saw these new links as one of the main justifications for a new component in his model of working memory, the episodic buffer. It could hold associations between elements that could not be held in the other two buffers (cf. Allen & Baddeley, this volume). One important question is how similar or different these two theoretical views really are.

One might suggest that the episodic buffer is entirely a function of the focus of attention, in which case the two theoretical approaches would not differ. Another possibility is that what is taken as the result of an episodic buffer is actually a composite of information in the focus of attention and the preservation of associations in newly-formed long-term memory traces.

Recent information from amnesic individuals suggests that there may be something more to the episodic buffer, outside of either the focus of attention or long-term memory. In particular, Cowan, Beschin, and Della Sala (2004) found that some densely amnesic individuals could remember considerable information for up to an hour in the absence of any interference (in a quiet, dark room), even on trials in which they slept during this retention interval. This suggests that they must have used some sort of storage mechanism outside of the focus of attention that does not depend on long-term memory, at least not as we normally think of it. This theoretically could be the same as an episodic buffer. Although will not pursue that question further, we provide evidence and ideas suggesting that, in normal individuals, immediate memory performance can be accounted for by a combination of information in the focus of attention and activated elements of long-term memory, if the latter includes the results of rapid long-term learning of new associations.

EVIDENCE ON LONG-TERM MEMORY CONTRIBUTIONS TO CAPACITY LIMITS

Evidence, Part 1: Basic capacity limits

Given that long-term memorization can be used to increase the size of chunks to be recalled in an immediate-memory task, there is no practical limit on how much can be recalled. This point was dramatically demonstrated by Ericsson, Chase, and Faloon (1980). They studied an individual who could remember only about seven digits at a time, like most people; but, in the course of a year of practice, his immediate-memory span for digits increased to about 80. This appeared to happen through a process in which he learned to group several digits together on the basis of past knowledge of athletic times, supplemented by other knowledge (e.g., 89.5 could be remembered as the age of a very old man). That process allowed him to retain lists of up to about 20 digits. Then he mastered a process of grouping the multi-digit groups together into higher-order super-groups, bringing the span up to about 80.

Because of this sort of finding, researchers sometimes have maintained that there is no basic capacity limit. However, that conclusion does not follow from the data. One could recall any number of items based on a higher-order grouping, and there still could be a basic limit in how many groups can be retained at once. Cowan (2001) examined a wide variety of experimental situations in which it seemed reasonable to assume that items could not be grouped, for one reason or another (e.g., because they could not be fully attended and rehearsed at the time of their presentation). This can occur when the items are presented quickly in a list of unpredictable length, when they are presented in a multiple-item simultaneous array, or when they are presented along with a secondary task that suppresses rehearsal or causes distraction. In such circumstances, each item recalled should represent a separate, 1-item chunk in memory. It appeared that, across many different situations of this general type, a common limit of 3 to 5 items applies in young adults. Thus, the hypothesis emerging from this review was that the basic capacity limit is in the range of 3 to 5 chunks.

Evidence, part 2: Chunk limits and length limits in verbal memory

The limitation in the evidence described by Cowan (2001) is that the capacity limit was observed entirely with 1-item chunks. It remained possible that the capacity limit would depend on the size of the chunks. To rule out this possibility and establish a more general capacity limit, Cowan, Chen, and Rouder (2004) and Chen and Cowan (2005) took a different approach. Instead of preventing new chunks from being formed, the process of chunking was carefully monitored.

It had already been shown that associations between items can assist in short-term recall (Stuart & Hulme, 2000) and that the increased availability of prior knowledge about the associations between items tends to increase the size of chunks rather than the number of chunks recalled (Tulving & Patkau, 1962). For a controlled investigation, Cowan et al. (2004) used a training session in which words were presented a variable number of times, singly or in consistent pairs, to assess the effects of pairing. Memory was then tested in serial recall of 8-item lists that included pairs that had been used in a particular amount of associative training, and in cued recall. In that study, which will be presented in greater detail later, the basic findings were (1) that both serial and cued recall improved as a function of the number of prior training exposures to the consistent word pairings, and (2) that the increase in serial recall could be attributed entirely to an increase in the proportion of recalled chunks comprising two words rather than one.

The number of chunks recalled (two-item pairs plus singletons) did not appear to increase with training. This conclusion of Cowan et al. (2004) was dependent upon a model that was used to estimate how often the recall of two items in a pair could be interpreted as recall of a single, two-item chunk as opposed to the separate recall of the two items comprising the pair as two one-item chunks. The model suggested that the recall of two items in a pair that was familiar from the training session almost always could be interpreted as the recall of a single two-item chunk. The number of chunks recalled averaged about 3.5 across training conditions, closely in line with the expectations of Cowan (2001) based on a review of very different procedures.

Chen and Cowan (2005) addressed the issue of boundary conditions for capacity limits in serial and free recall. In serial recall at least, there is a large body of work suggesting that the limit in recall is not so much in the number of chunks to be recalled, but rather in the phonological length of the list to be recalled. Baddeley, Thomson, and Buchanan (1975) found that memory for lists of multisyllabic words was poorer than memory for lists of an equivalent number of monosyllabic words; memory was equivalent to the number of words that could be recalled in about 2 s. The theoretical explanation given in that paper was that a phonological form of memory lasts about 2 s and that an individual can recall as much as he or she can rehearse in a repeating loop before it decays. Although the existence of time-based decay is controversial (e.g., Lewandowsky, Duncan, & Brown, 2004; Lovatt, Avons, & Masterson, 2002; Mueller, Seymour, Kieras, & Meyer, 2003), the finding of the word length effect based on how much phonological material is in each word in the list is highly replicable, being found even by those who question the existence of a time-based effect

(Service, 1998; Tolan & Tehan, 2005). A word length effect has been obtained also in free recall (Turner & Engle, 1989). The question becomes, then, when a chunk capacity limit applies and when a length limit applies instead.

Chen and Cowan (2005) addressed the issue by manipulating the length of lists composed of singletons or well-learned pairs. In the training condition, the entire set of singletons and pairs was re-presented over and over until the participant performed 100% successfully on the set. On each training trial, a word was presented that was either a singleton or the first word in a pair that had already been presented. The correct response was to recall the associated word, if any, and otherwise to indicate that the word was a singleton. Responses were typed into the computer; the words were easy enough that remembering the spelling was not an important issue. Then feedback was received. For pairs, the complete pair was presented as feedback.

The training session was followed by serial or free recall. Each list was composed entirely of singletons or of learned pairs. Given the high criterion of training, it was possible to assume that, when a pair within a list was recalled, it was recalled as a single, two-word chunk. Therefore, it was possible to compare performance on lists of short chunks (singletons) and lists of long chunks (learned pairs) to assess an analogue to the word length effect.

One comparison was for lists of 6 learned pairs. If a chunk limit governs performance, the proportion of words correct on such lists should be equivalent to that for lists of 6 singletons. If, in contrast, a length limit governs performance, the proportion of words correct on lists of 6 learned pairs should be equivalent to that for 12 singletons (a much lower level than for 6 singletons). Similarly, lists of 4 learned pairs were examined and, according to a chunk limit, the proportion of words correct on such lists should be equivalent to that for lists of 4 singletons. If a length limit governs performance, the proportions should be similar for 4 learned pairs and 8 singletons (much lower than for 4 singletons).

For free recall of the longer lists, a chunk capacity limit worked very well. Lists of 6 learned pairs were recalled about at the same proportion of words correct as lists of 6 singletons. The same was true for serial recall when it was scored in a free manner, not deducting points for words recalled in the incorrect serial positions. However, for serial recall of shorter lists strictly scored, a length limit applied instead. With that scoring of serial recall, lists of 4 learned pairs were recalled only at about the same proportion of words correct as lists of 8 singletons. Other conditions produced results that were intermediate, not conforming closely to either prediction. These intermediate results were obtained for free recall (or free scoring of serial recall) of the shorter lists, and for serial recall (strictly scored) of the longer lists.

Figure 1 shows one way in which these results might be explained. A mechanism could exist that holds a limited number of chunks at once; it could be the focus of attention that holds the information (Cowan, 1988, 1995, 2001). A phonologically-based storage and rehearsal mechanism, such as the phonological loop mechanism of Baddeley (1986), may come into play primarily when items have to be recalled in the correct serial order, although it theoretically also might be of some use in retaining a limited amount of item information. Information from both sources would be considered in recall, and the weight given to each mechanism would depend on its suitability to the task. The phonological mechanism is best suited when one needs to repeat a sequence lasting about 2 s in order, and the chunk mechanism is better suited when order is not needed and/or the sequence is too long for the phonological mechanism. Also, the availability of within-list structure (e.g., lists of mixed short and long words: Cowan, Baddeley, Elliott, & Norris, 2003; Hulme, Surprenant, Bireta, Stuart, & Neath, 2004) may encourage the use of the chunk-based mechanism because the structure can be used to form groups, whereas phonological memory may be more useful when the list is homogeneous.

--- FIGURE 1 NEAR HERE ---

In the view of Cowan (1999, 2001, 2005a, 2005b), the focus of attention is used to remember information, and the process by which this occurs involves new long-term memory formation, as illustrated in Figure 2. Each panel of the figure shows one state of the memory system, which always includes two components of short-term memory: the activated portion of long-term memory, and the focus of attention as a subset of that activated portion. As shown in Panel 1, new inputs result in the activation of elements in long-term memory. These elements may represent only some of the features by which the stimuli can be encoded (e.g., physical but not semantic features, as is often the case for unattended stimuli). Associations to the stimuli also may be activated (the basis of priming), or features may be activated through internal thoughts alone. As shown in Panel 2, some of the activated features may enter the focus of attention. Panel 3 shows that concurrently attended features are linked together to form a new structure. Finally, as shown in Panel 4, the new structure is available for memory responses, in either short- or long-term memory tasks. This structure may be sufficient for retaining serial order information for the items within a newly-formed chunk, but it would be deficient in between-chunk serial order information.

--- FIGURE 2 NEAR HERE ---

The phonological storage mechanism may be another instance of the use of the focus of attention to assemble a new structure in long-term memory. It is clear that a phonological storage mechanism is involved in learning new vocabulary (Baddeley, Gathercole, & Papagno, 1998). Perhaps the mechanism contributing to immediate recall is one that uses the temporal aspect of language to avoid the capacity limit. Suppose a list of six words, A-B-C-D-E-F, is presented. It might be that A-B-C can be in the focus of attention at one time, forming a structure that, when followed by D, can be knitted into A-B-C-D; and so on until the entire list rapidly is assembled into a new, united long-term memory representation even though six separate elements would not fit into the focus of attention. The limit on formation of that sort of associative structure might depend on the assembly taking place fast enough so that the earlier segments remain available throughout the process; hence the mechanism is limited to the amount that can be recited in about 2 s. Any such newly-formed long-term memory representation will be very susceptible to subsequent interference, given that it shares many properties with other lists in the experiment. However, it may allow immediate recall because there has not yet been interference with a structure that is now held as a single chunk.

The chunk-storage mechanism would hold items to be recalled, some of which are multi-word chunks. The phonological mechanism would provide additional cues to a time-limited number of items in the list along with strong cues to their order. For items held in the chunk-storage mechanism (such as the focus of attention), order information could be forgotten without the loss of item information, but that event is less likely for information held in the phonological storage mechanism because the structure is explicitly serial.

This model helps to explain why a chunk limit governed recall for long lists in free recall (because the phonological ordering mechanism was not critical), whereas a length limit governed recall for shorter lists in serial recall (because the ordering mechanism was both critical and useful). Lists of more than about 8 syllables would exceed the limits of the phonological mechanism and would especially hurt order information. Intermediate results would occur when both the chunk-limited mechanism and the phonological storage mechanism are used and contribute to recall. Both meaningful chunks and phonological representations may be used for both item and order information, but to different degrees, with more extensive item information based on chunks and more coherent order information based on phonology. We are engaged in further research to determine how the mechanisms interact.

Evidence, part 3: On-line chunk formation and storage in long-term memory

The data of Cowan et al. (2004) can be used to explore further the interaction between short- and long-term memory stores. A re-analysis of the results of Cowan et al. (2004) supports this theoretical account. The procedure of that study needs further explanation before the results are presented. A training phase was followed by a serial recall phase (recall of 8-word lists) and a cued recall phase (recall of the second word in each pair, given the first). In Experiment 1, list recall came before cued recall whereas, in Experiment 2, it was the reverse. In the training phase that began the experiment, the total number of presentations of a word was four. Some words were presented four times as singletons. Others were presented three times as singletons and once in a pair; twice as singletons and twice in consistent pairs; or four times in consistent pairs. These comprised the 0-, 1-, 2-, and 4-pairing conditions, respectively. They differ in the number of presentations of each word pairing, but not in the number of presentations of each word itself. There also were words in a control condition that were not included in the training phase at all.

In cued recall, the task was to recall the second word in a learned pair, given the first. Participants in Experiment 2 had no prior exposure to the pairings in the unstudied-word control or the 0-pairing condition (given that the cued-recall test came before list recall), whereas participants in Experiment 1 had seen the words in these two conditions paired together previously one time, namely within the list presentations.

In serial recall, the 8 items in a list were presented in pairs. The words in each of the four pairs within a list were presented concurrently for 2 s, with the words on both sides of the center of the screen, and with each successive pair replacing the previous one. All of the pairs in a list were drawn from pairs used in one particular training phase although, in the 0-paired and unstudied-control conditions, the particular pairings themselves had not been seen in the training phase. In the unstudied-control condition, the words had not been seen in training, either.

The training manipulation was highly effective. In both experiments, cued recall increased steadily with the number of training exposures to the pairs (0 through 4; the no-study control condition produced results slightly lower than the 0-paired condition). Cowan et al. (2004) plotted the results as a function of the number of paired presentations in training. However, a more accurate impression of how the pairs were learned (as measured in cued recall) could be obtained by taking into account the further presentation of word pairs within list recall, which preceded cued recall in Experiment 1. The cued-recall data of Cowan et al. (2004) are re-plotted in Figure 3 with list presentations taken into account. This adds one presentation to every condition in Experiment 1, but not Experiment 2. (In the 0-paired condition in Experiment 2, there was no basis for cued recall, unlike Experiment 1 in which the pairing had been seen once, in list recall.) One can see from the figure that the effect of pair presentation within a list in serial recall caused about the same amount of learning as in the training phase. The overall learning function is smooth and decelerating. This experimental example approximates the practical example given earlier, of people rapidly learning grouping information for telephone numbers.

--- FIGURE 3 NEAR HERE ---

Figure 4 shows the proportion of words correctly recalled from lists in each training condition used by Cowan et al. (2004), based on free scoring of serial recall (i.e., full credit for words recalled even in the wrong serial position). It is clear from this figure that learned associations between words did contribute to list recall when the lists included learned pairs.

--- FIGURE 4 NEAR HERE ---

One finding that warrants further discussion is that the proportion of words recalled was slightly higher in Experiment 1, in which the list-recall procedure came before cued recall, than in Experiment 2, in which the list-recall procedure came only after cued recall (Figure 4). Apparently, then, a cued recall test did not help list recall. In this experiment, there was no feedback within cued recall (or within list recall, for that matter). Therefore, it appears that retrieving what was already known, in cued recall, did not reinforce knowledge of the pair; at least, not in a way that was of discernable use in list recall. This is in contrast to the finding that *presentation* of a pair in list recall did aid cued recall (see Figure 3).

Further supporting this conclusion are data on the rates of success with individual pairs of words in list and cued recall in both experiments, shown in Table 1. First, successes on both the first and second item in a pair in list recall were scored free, without regard to serial order. When list recall preceded cued recall (Experiment 1), recall of the first and second items in a pair both were associated with success for the same word pair in cued recall. In contrast, when cued recall preceded list recall (Experiment 2), success on the first, but not on the second, item in a pair in list recall was associated with prior success in cued recall. A strict serial order scoring of list recall produced a statistical pattern that differed only in that the associations with the first item in a pair were no longer significant.

The associations in Table 1 need not indicate learning effects, inasmuch as certain words may just be more memorable than others in either list-recall or cued-recall procedures. However, the finding that the associations with the second word in a pair in list recall were significant only when the list procedure was presented first (i.e., in Experiment 1, but not Experiment 2) seems to reinforce the notion that presentation of the item caused learning, not its recall. Thus, in cued recall, only the first item in a pair is presented, and successful cued recall did not cause the second item to be remembered better in list recall.

--- TABLE 1 NEAR HERE ---

This pattern of results seems to go against an often-observed effect in which items are recalled better when generated by the participant than when actually presented (e.g., Hendry & Tehan, 2005). However, it could indicate that, in Experiment 2, the frequent mistakes committed during cued recall and the absence of feedback discouraged participants from using the cued-recall episode as a source of information for the subsequent list-recall task.

Finally, Figure 5 is an examination of the number of chunks recalled. (It uses free scoring of item recall whereas, if strict serial order scoring is used, the estimates are similar but lower, ranging from 2.2 - 3.2.) In the article of Cowan et al. (2004), a multinomial model was used to estimate what proportion of the recalled word pairs actually were two-word chunks, as opposed to being two words separately recalled. Here, instead of that multinomial-model-based approach, cued recall was used to validate the estimate of chunking. In particular, the mean number of chunks recalled in each adjacent pair of odd-even serial positions i and $i+1$ was judged according to Equation 1:

$$(1) \qquad chunks_{[i,(i+1)]} = [pc_{i} + pc_{(i+1)}] / (1 + cued_{[i,(i+1)]})$$

where pc_i and $pc_{(i+1)}$ are the proportions correct in list recall at Serial Position i and $i+1$ according to a free scoring, and $cued_{[i,(i+1)]}$ is the proportion correct in cued recall for this word pair. If list recall at these serial positions is perfect, for example, then the number of chunks recalled in those two positions could be as high as 2 (if $cued_{[i,(i+1)]} = 0$) or as low as 1 (if $cued_{[i,(i+1)]} = 1$). In the latter case, the two words in the pair are consistently considered to contribute to a single 2-word chunk. The formula works essentially by dividing *items recalled* by *items per chunk* to arrive at an estimate of *chunks*. The better cued recall is, presumably the more items per chunk there are, the allowed range being from 1 to 2.

--- FIGURE 5 NEAR HERE ---

Figure 5 shows that the number of chunks recalled stayed roughly constant across training conditions and across experiments, except for the unstudied-control and 0-pairing conditions. There are several factors underlying discrepancies in these conditions. First, the assumption embodied in Equation 1, that cued recall reflects the amount of long-term learning available at the time of list recall, should produce an underestimate in Experiment 2 because its cued-recall test cannot take into account any learning of pairings that occurred during the list-recall presentation itself, as it followed cued recall. The effect of neglecting learning of pairings during the list presentation itself is most important in the unstudied-control and 0-pairing conditions because, in those conditions, the list presentation provided the only possible exposure to the pairing in the experimental session.

In Experiment 1, which presumably yields the best estimates of capacity because of the considerations just mentioned, the capacity estimate was fairly constant across the 0- through 4-pairing conditions. The fact that it was lower in the unstudied-control condition than in the 0-studied condition suggests that there was a benefit from the training exposure to isolated words but that it did not benefit list recall as much as it benefited subsequent cued recall. In Experiment 2, in which there was no basis at all to retrieve the paired word in cued recall in the unstudied-control or 0-pairing conditions, the estimates of chunks recalled from the list were probably inflated by this method of estimation, inasmuch as the estimate of words per chunk was in principle limited to 1.0, probably unrealistically.

To summarize, we have discussed a theoretical framework to examine capacity limits in a serial recall task using long-term learning information from a cued-recall task (Cowan et al., 2004). This framework suggests certain boundary conditions for an accurate estimate. The boundary conditions were best met for 0-, 1-, 2-, and 4-pairing conditions in Experiment 1 because the words were made equally familiar across these conditions and the cued-recall data could take into account on-line memorization of word pairings during the list presentation itself. The capacity limits across these conditions ranged narrowly between about 3.75 and 4 chunks, convergent with results from a previous literature review on memory for sets of 1-item chunks (Cowan, 2001).

SUMMARY AND CONCLUSIONS

This chapter addresses a basic question about the nature of short-term or working memory. Cowan (1988) suggested that it consists of the activated portion of long-term memory along with a capacity-limited subset of that activated memory, the focus of attention. The two components supposedly serve complementary roles, with deeper perceptual analyses taking place in the focus of attention. A problem with this view (noted by Cowan, 1995, 1999) is how to understand the formation of new links between elements in a short-term memory task when those elements have not previously been linked in long-term memory.

Baddeley (2000) suggested that there is a mechanism that can hold new links of diverse types, the episodic buffer. A way to accomplish what the episodic buffer does, but without adding a new component to the model of Cowan (1988), is to add the assumption that new long-term memories can form on line during a short-term or working memory task, contributing to performance (Cowan, 2005a, 2005b). We have demonstrated that this is possible in a reanalysis of results from the serial recall and cued recall tasks of Cowan et al. (2004). Learning of word pairings from a training phase summated with learning from list presentations to produce a smooth learning curve (Figure 3), and this long-term learning proved to be a good basis upon which to estimate the use of multi-word chunks in recall. Using that basis, evidence of a constant capacity limit of about 4 chunks was obtained. Learning changed the frequency of recalling longer (2-word) as opposed to shorter (1-word) chunks, but did not appear to influence the basic capacity of short-term memory expressed in chunks. One of the functions of the focus of attention may be to allow items that are represented concurrently to be bound into new structures (i.e., multi-item chunks)

Other evidence of the use of long-term memory to bind items together in short-term or working memory tasks also exists in the literature (e.g., Stuart & Hulme, 2000, and in this volume). One source of evidence, very different from what we have been discussing, comes from the examination by Cowan et al. (2003) of response timing in working memory tasks. In the tasks examined, each processing episode terminates in a verbal item to be retained for subsequent recall after several processing episodes. This type of task shows a high relation to cognitive aptitudes so it is important to learn what processes operate in such tasks. When the items to be recalled could be remembered on the basis of recall cues from the processing (because they were the final words of sentences to be comprehended), Cowan et al. found that the response times were much longer than when the processing episodes served as poor cues to recall (screens with objects to be counted, all looking much like one another) or when there were no processing episodes (in digit span). These response times suggest that recall cues from long-term memory can be used in working memory tasks. Specifically, sentences may be retrieved to provide cues for retrieval of the sentence-final words in reading and listening span tasks.

One complication for the model of Cowan (1988) is that amnesic individuals presumably form new links between items in short-term memory, but nevertheless do not save the information in a way that allows it to be remembered later. Somehow, this needs to be accounted for in terms of neural mechanisms. A large amount of research has suggested that memory representations are formed in diverse cortical regions, whereas the conscious retrieval of those memories at first depends on temporal lobe regions surrounding and including the hippocampus (e.g., Cowan, 1995, 2005a; Schacter, 1989; Squire, 1987). However, the focus of attention itself involves frontal and parietal areas (as reviewed in these same articles). If the focus of attention is intact in amnesic individuals, then it would be expected that new links between items could be formed as usual without becoming available for later long-term recall.

We thus propose that although the mechanisms of short-term memory are separate from those of long-term memory, they are closely related. Everything in memory has to be returned to short-term memory in order to be recalled. As an analogy, cooked food typically should be warm at the time it is served, either from its initial cooking (analogous to short-term retrieval) or from re-heating (analogous to long-term retrieval). Similarly, the rules of short-term memory should influence even long-term recall (and, for evidence suggesting that they do, see Nairne & Neath, 2001).

One purpose of the focus of attention may be to hold information in a form that is relatively immune to the types of interference that otherwise can occur in both short- and long-term retrieval (Cowan, Johnson, & Saults, 2005; Halford, Maybery, & Bain, 1988). Overall, the most fundamental distinction within the memory system may not be the short- versus long-term memory distinction, but rather the retrieval of information that is versus is not already held in the current focus of attention (Cowan, 1995, 2005a).

REFERENCES

Allen & Baddeley -- THIS VOLUME

Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes. In K. W. Spence & J. T. Spence (Eds.), *The psychology of learning and motivation: Advances in research and theory* (Vol. 2, pp. 89-195). New York: Academic Press.

Baddeley, A.D. (1986). *Working memory*. Oxford Psychology Series #11. Oxford: Clarendon Press.

Baddeley, A. (2000). The episodic buffer: a new component of working memory? *Trends in cognitive sciences*, *4*, 417-423.

Baddeley, A., Gathercole, S., & Papagno, C. (1998). The phonological loop as a language learning device. *Psychological Review, 105*, 158-173.

Baddeley, A., & Hitch, G.J. (1974). Working memory. In G. Bower (ed.), *Recent advances in learning and motivation*, Vol. VIII. New York: Academic Press. (pp. 47-89)

Baddeley, A.D., & Logie, R.H. (1999). Working memory: The multiple-component model. In A. Miyake & P. Shah (eds.), *Models of Working Memory: Mechanisms of active maintenance and executive control*. Cambridge, U.K.: Cambridge University Press. (pp. 28-61)

Baddeley, A.D., Thomson, N., & Buchanan, M. (1975). Word length and the structure of short-term memory. *Journal of Verbal Learning and Verbal Behavior, 14*, 575-589.

Baddeley, A.D., & Warrington, E.K. (1970). Amnesia and the distinction between long- and short-term memory. *Journal of Verbal Learning and Verbal Behavior, 9*, 176 - 189.

Bjork, R.A., & Whitten, W.B. (1974). Recency-sensitive retrieval processes in long-term free recall. *Cognitive Psychology, 6*, 173-189.

Broadbent, D.E. (1971). *Decision and stress*. London: Academic Press.

Chen, Z., & Cowan, N. (2005). Chunk limits and length limits in immediate recall: A reconciliation. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31*, 1235-1249.

Cherry, E.C. (1953). Some experiments on the recognition of speech, with one and with two ears. *The Journal of the Acoustical Society of America, 25*(5), 975-979.

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

Cowan, N. (1988). Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information processing system. *Psychological Bulletin*, *104*, 163-191.

Cowan, N. (1995). *Attention and memory: An integrated framework*. Oxford Psychology Series, No. 26. New York: Oxford University Press.

Cowan, N. (1999). An embedded-processes model of working memory. In A. Miyake & P. Shah (eds.), *Models of Working Memory: Mechanisms of active maintenance and executive control*. Cambridge, U.K.: Cambridge University Press. (pp. 62-101)

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, *24*, 87-185.

Cowan, N. (2005a). *Working memory capacity*. New York: Psychology Press.

Cowan, N. (2005). Working-memory capacity limits in a theoretical context. In C. Izawa & N. Ohta (eds.), *Human learning and memory: Advances In theory and applications*. The 4th Tsukuba international conference on memory. Erlbaum. (pp. 155-175)

Cowan, N., Baddeley, A.D., Elliott, E.M., & Norris, J. (2003). List composition and the word length effect in immediate recall: A comparison of localist and globalist assumptions. *Psychonomic Bulletin & Review*, *10*, 74-79.

Cowan, N., Beschin, N., & Della Sala, S. (2004). Verbal recall in amnesiacs under conditions of diminished retroactive interference. *Brain*, *127*, 825-834.

Cowan, N., Chen, Z., & Rouder, J.N. (2004). Constant capacity in an immediate serial-recall task: A logical sequel to Miller (1956). *Psychological Science, 15*, 634-640.

Cowan, N., Johnson, T.D., & Saults, J.S. (2005). Capacity limits in list item recognition: Evidence from proactive interference. *Memory, 13*, 293-299.

Cowan, N., Towse, J.N., Hamilton, Z., Saults, J.S., Elliott, E.M., Lacey, J.F., Moreno, M.V., & Hitch, G.J. (2003). Children's working-memory processes: A response-timing analysis. *Journal of Experimental Psychology: General, 132*, 113-132.

Crowder, R.G. (1993). Short-term memory: Where do we stand? *Memory & Cognition*, *21*, 142-145.

Davelaar, E.J., Goshen-Gottstein, Y., Ashkenazi, A., Haarman, H.J., & Usher, M. (2005). The demise of short_term memory revisited: Empirical and computational investigations of recency effects. *Psychological Review*, *112,* 3-42.

Ericsson, K.A., Chase, W.G., & Faloon, S. (1980). Acquisition of a memory skill. *Science, 208*, 1181-1182.

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

Halford, G.S., Maybery, M.T., & Bain, J.D. (1988). Set-size effects in primary memory: An age-related capacity limitation? *Memory & Cognition*, *16*, 480-487.

Hendry, L., & Tehan, G. (2005). An item/order trade-off explanation of word length and generation effects. *Memory, 13,* 364-371.

Hulme, C., Surprenant, A., Bireta, T.J., Stuart, G., & Neath, I. (2004). Abolishing the word-length effect. *Journal of Experimental Psychology: Learning, Memory, and*

Cognition, 30, 98-106.

James, W. (1890). *The principles of psychology*. NY: Henry Holt.

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. (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*, 47-70.

Keppel, G., & Underwood, B.J. (1962). Proactive inhibition in short-term retention of single items. *Journal of Verbal Learning and Verbal Behavior, 1*, 153-161.

Lewandowsky, S., Duncan, M., & Brown, G.D.A. (2004). Time does not cause forgetting in short-term serial recall. *Psychonomic Bulletin & Review, 11*, 771-790.

Lovatt, P., Avons, S.E., & Masterson, J. (2002). Output decay in immediate serial recall: Speech time revisited. *Journal of Memory and Language, 46*, 227-243.

Massaro, D.W. (1975a). *Experimental psychology and information processing*. Chicago: Rand McNally.

McGeoch, J.A. (1932). Forgetting and the law of disuse. *Psychological Review*, *39*, 352-370.

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.

Miller, G.A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, *63,* 81-97.

Moray, N. (1959). Attention in dichotic listening: Affective cues and the influence of instructions. *Quarterly Journal of Experimental Psychology*, *11*, 56-60.

Mueller, S.T., Seymour, T.L., Kieras, D.E., & Meyer, D.E. (2003). Theoretical implications of articulatory duration, phonological similarity, and phonological complexity in verbal working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 6*, 1353–1380.

Nairne, J.S. (2002). Remembering over the short-term: The case against the standard model. *Annual Review of Psychology, 53*, 53-81.

Nairne, J.S., & Neath, I. (2001). Long-term memory span. *Behavioral and Brain Sciences, 24*, 134-135.

Postman, L., & Phillips, L.W. (1965). Short-term temporal changes in free recall. *Quarterly Journal of Experimental Psychology*, *17*, 132-138.

Schacter, D.L. (1989). On the relation between memory and consciousness: Dissociable interactions and conscious experience. In H.L. Roediger & F.I.M. Craik (eds.), *Varieties of memory and consciousness: Essays in Honor of Endel Tulving*. Hillsdale, NJ: Erlbaum.

Service, E. (1998). The effect of word length on immediate serial recall depends on phonological complexity, not articulatory duration. *Quarterly Journal of Experimental Psychology, 51A*, 283-304.

Squire, L.R. (1987). *Memory and brain*. New York: Oxford University Press.

Shallice, T., & Warrington, E.K. (1970). Independent functioning of verbal memory stores: A neuropsychological study. *Quarterly Journal of Experimental Psychology*, *22*, 261-273.

Shiffrin, R. M. (1975). The locus and role of attention in memory systems. In. P. M. A. Rabbitt & S. Dornic (Eds.), *Attention and performance V* (pp. 168-193). New York: Academic Press.

Shiffrin, R. M. (1976). Capacity limitations in information processing, attention, and memory. In W. K. Estes (Ed.), *Handbook of learning and cognitive processes* (pp. 177-236). Hillsdale, NJ: Erlbaum.

Stuart, G., & Hulme, C. (2000). The effects of word co-occurrence on short-term memory: Associative links in long-term memory affect short-term memory performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26*, 796-802.

Stuart & Hulme -- THIS VOLUME

Surprenant & Neath -- THIS VOLUME

Tolan, G.A., & Tehan, G. (2005). Is spoken duration a sufficient explanation of the word length effect? *Memory, 13*, 372-379.

Tulving, E., & Patkau, J.E. (1962). Concurrent effects of contextual constraint and word frequency on immediate recall and learning of verbal material. *Canadian Journal of Psychology, 16*, 83-95.

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

Tzeng, O.J.L. (1973). Positive recency effect in a delayed free recall. *Journal of Verbal Learning & Verbal Behavior, 12*, 436-439.

Warrington, E.K., & Weiskrantz, L. (1970). Amnesic syndrome: Consolidation or retrieval? *Nature*, *228*, 629-630.

Table 1

Frequency of cases in which each item within a list pair was recalled along with successful or unsuccessful cued recall for the second item in that pair.

	Cued Recall		Fisher's Exact Test *p*	
List Recall	Successful	Unsuccessful	Lax	(Strict)
	Experiment 1 (List Recall, Then Cued)			
First item				
recalled	305 (261)	170 (150)	.001	(.07 marginal)
not recalled	47 (91)	54 (74)		
Second item				
recalled	324 (291)	177 (145)	.000	(.000)
not recalled	28 (61)	47 (79)		
	Experiment 2 (Cued Recall, Then List)			
First item				
recalled	204 (164)	237 (197)	.01	(n.s.)
not recalled	45 (85)	90 (130)		
Second item				
recalled	200 (176)	272 (235)	n.s.	(n.s.)
not recalled	49 (73)	55 (92)		

Note. Primary data, lax scoring of item recall; in parentheses, strict serial order scoring. The data are collapsed across the 1-, 2-, and 4-pairing conditions. Significance in Fisher's Exact Test here indicates that rates of success in list and cued recall tasks were associated.

Figure Captions

Figure 1. A simple theoretical model of the coordination of chunk and length limits in immediate recall.

Figure 2. A depiction of how new associations between items may be remembered. (1) Elements are activated in long-term memory. (2) Concurrent with this activation or slightly afterward, these particular activated elements happen to be represented in the focus of attention concurrently. (3) New associations are formed between elements in the focus of attention, resulting in a new structure. (4) The new structure quickly becomes a new entry into long-term memory and is available for responses in short- or long-term memory tasks.

Figure 3. The cued-recall results of Cowan et al. (2004), redrawn to show the proportion correct as a function of the total number of prior presentations of each pair, including presentations received either in training itself (in both experiments) or in a serial-recall task when it came before cued recall (in Experiment 1 only). The number of presentations that preceded cued recall was 0, 1, 2, or 4 in Experiment 2 (white bars) because of training presentations of the pair, whereas it was 1, 2, 3, or 5 in Experiment 1 (black bars) because of the additional contribution of a list presentation before cued recall. Notice the smooth learning function. Error bars are standard errors.

Figure 4. The proportion of words correctly recalled within lists in Cowan et al. (2004) in each training condition, with credit given for each recalled word regardless of the serial position in which it was recalled (free scoring). CTL = unstudied-control

condition. The list-recall task was presented either before cued recall (Experiment 1, black bars) or after cued recall (Experiment 2, white bars). Error bars are standard errors.

Figure 5. Number of chunks per list recalled in each training condition by participants in Cowan et al. (2004). CTL = unstudied-control condition. The list-recall task was presented either before cued recall (Experiment 1, black bars) or after cued recall (Experiment 2, white bars). The chunks were estimated here under the assumption that the proportion correct in cued recall in a particular training condition mirrors the proportion of pairs forming 2-item chunks in lists. Error bars are standard errors. There are reasons to believe that the most valid capacity estimate occurs in Experiment 1 for the 0- through 4-pairing conditions (see text).

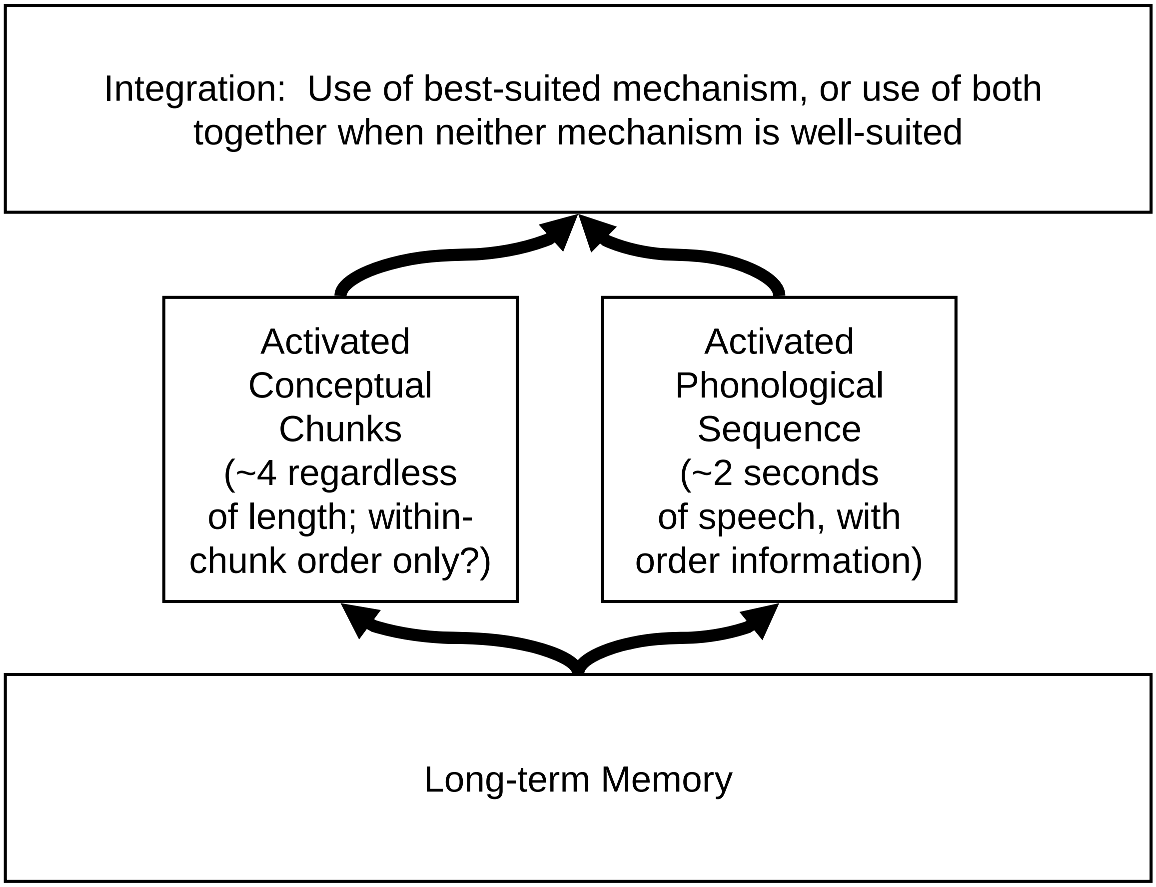

Figure 1. A simple theoretical model of the coordination of chunk and length limits in immediate recall.

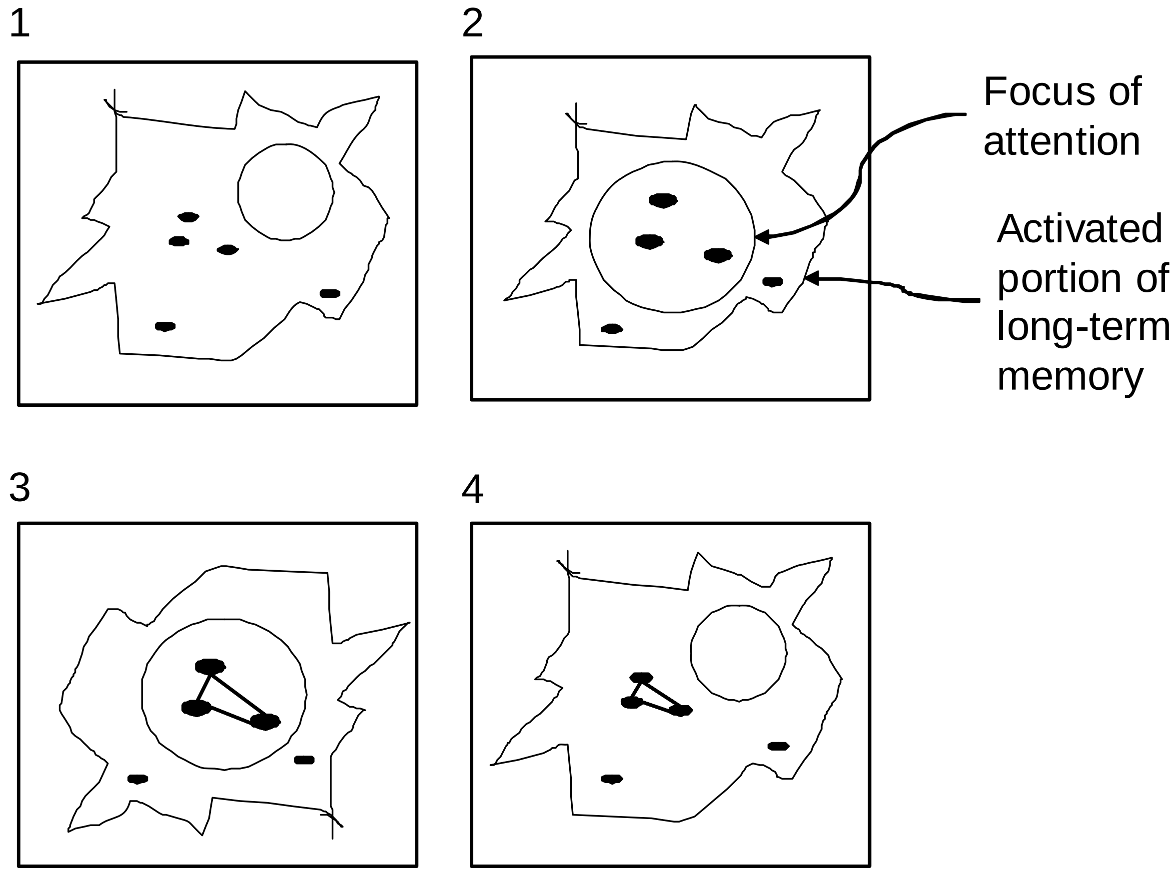

Figure 2. A depiction of how new associations between items may be remembered. (1) Elements are activated in long-term memory. (2) Concurrent with this activation or slightly afterward, these particular activated elements happen to be represented in the focus of attention concurrently. (3) New associations are formed between elements in the focus of attention, resulting in a new structure. (4) The new structure quickly becomes a new entry into long-term memory and is available for responses in short- or long-term memory tasks.

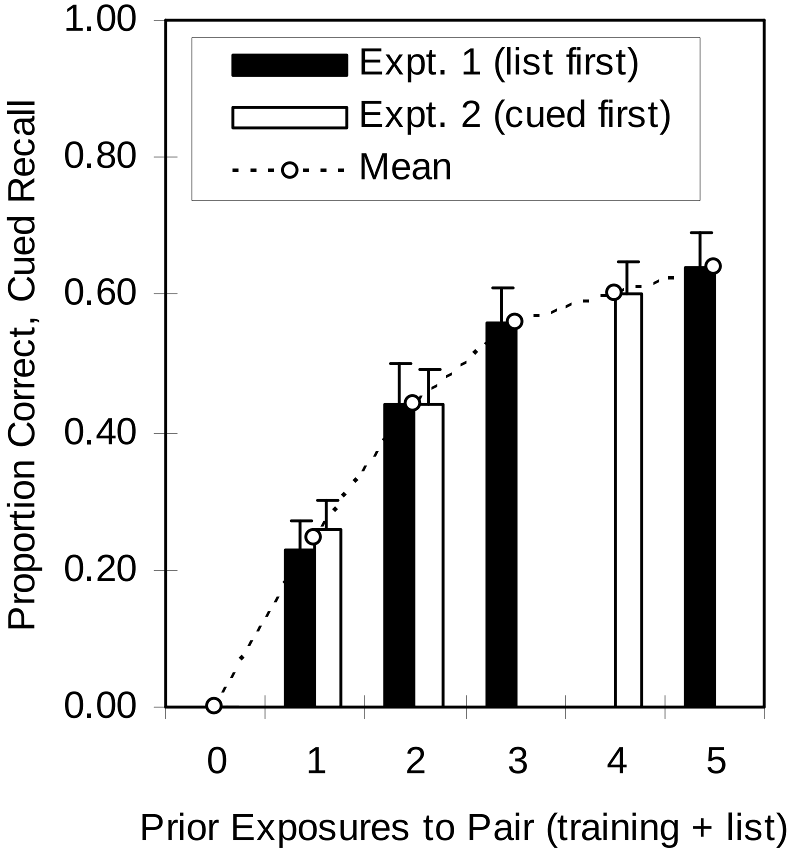

Figure 3. The cued-recall results of Cowan et al. (2004), redrawn to show the proportion correct as a function of the total number of prior presentations of each pair, including presentations received either in training itself (in both experiments) or in a serial-recall task when it came before cued recall (in Experiment 1 only). The number of presentations that preceded cued recall was 0, 1, 2, or 4 in Experiment 2 (white bars) because of training presentations of the pair, whereas it was 1, 2, 3, or 5 in Experiment 1 (black bars) because of the additional contribution of a list presentation before cued recall. Notice the smooth learning function. Error bars are standard errors.

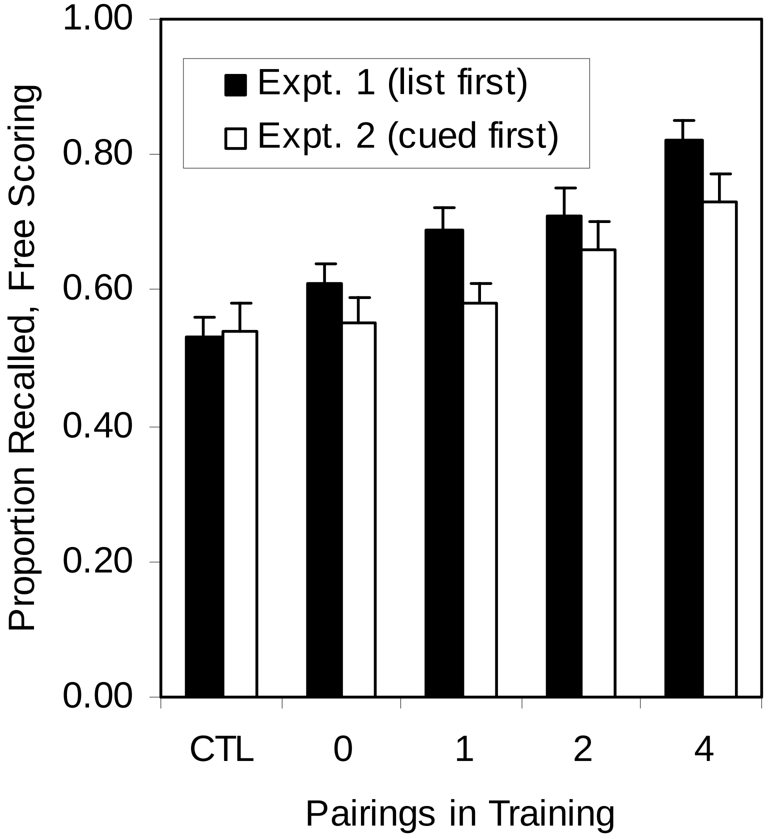

Figure 4. The proportion of words correctly recalled within lists in Cowan et al. (2004) in each training condition, with credit given for each recalled word regardless of the serial position in which it was recalled (free scoring). CTL = unstudied-control condition. The list-recall task was presented either before cued recall (Experiment 1, black bars) or after cued recall (Experiment 2, white bars). Error bars are standard errors.

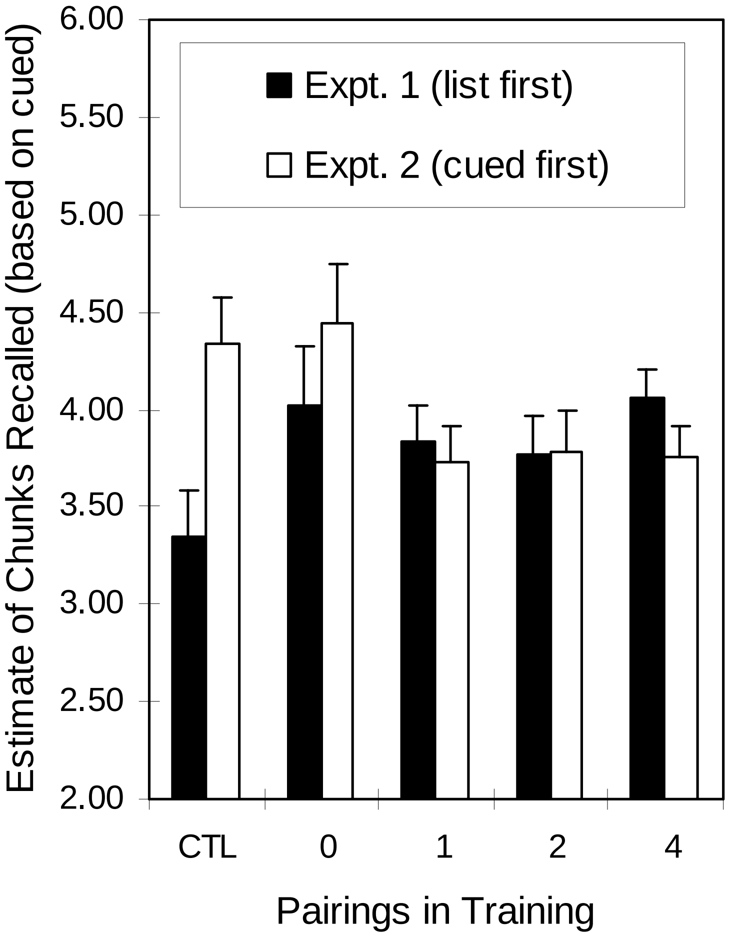

Figure 5. Number of chunks per list recalled in each training condition by participants in Cowan et al. (2004). CTL = unstudied-control condition. The list-recall task was presented either before cued recall (Experiment 1, black bars) or after cued recall (Experiment 2, white bars). The chunks were estimated here under the assumption that the proportion correct in cued recall in a particular training condition mirrors the proportion of pairs forming 2-item chunks in lists. Error bars are standard errors. There are reasons to believe that the most valid capacity estimate occurs in Experiment 1 for the 0- through 4-pairing conditions (see text).