CHAPTER FOUR

Working Memory

While simple qualitative conceptual models have proved very useful, one eventually reaches a point at which some form of detailed and preferably quantitative model is necessary if the concepts are to develop.

—Alan Baddeley (1994)

The previous chapter chronicled the development of the idea of separate memory stores, one devoted to memory for the short term and one for memory for the long term. In this chapter, we examine current views of short-term memory in some detail. The term *working memory* was first introduced by Miller, Galanter, and Pribram (1960, p. 65; see also Atkinson & Shiffrin, 1968, p. 92). It has long been used to reflect the idea that information often has to be retained briefly in a highly accessible state while performing cognitive tasks. One problem is that different researchers use the term in very different ways. Indeed, Kintsch, Healy, Hegarty, Pennington, and Salthouse (1999, p. 436) conclude that "it is rather difficult to identify a common core in terms of the phenomena under consideration" across theories that address working memory.

Three major uses of the term can be identified, however. Alan Baddeley's (1986) working memory is perhaps the single most influential current model of immediate memory. Although initially a theory of memory for the short term, it has been extended to other areas such as reading and language comprehension (see Gathercole & Baddeley, 1993). The second approach characterizes immediate memory as the subset of information that currently has a heightened state of activation (e.g., Cowan, 1988, 1993, 1995; Schneider & Detweiler, 1987; Shiffrin & Schneider, 1977). Although this view is quite similar to Baddeley's conception, there are several major differences. A third view (Engle, Kane, & Tuholski , 1999) uses the term *working memory capacity* to reflect attention rather than memory per se. In contrast to these various working memory views, we finish the chapter with a functional account of the same data, Nairne's (1988, 1990, 2001) feature model.

Baddeley's Working Memory

Alan Baddeley and his colleagues (see Baddeley, 1986, 2000; Baddeley & Hitch, 1974; Baddeley & Logie, 1999) have developed what is currently the most influential view of working memory. Part of their goal was to examine more closely the idea of immediate memory as a place where many basic cognitive operations are carried out—hence the name of the system. The modal model (discussed in the previous chapter) was seen as too limited and restrictive. In contrast, working memory is seen as the combination of a central executive—a controlling attentional mechanism—and a number of subsidiary slave systems (see Figure 4.1). The central executive coordinates activities within the slave systems, two of which have been studied extensively. (We will postpone discussion of the visuo-spatial sketch pad, which sets up and manipulates visual images, until the chapter on imagery.) The slave system known as the phonological loop will be of primary concern, as this is the system that handles the phenomena previously attributed to short-term store.

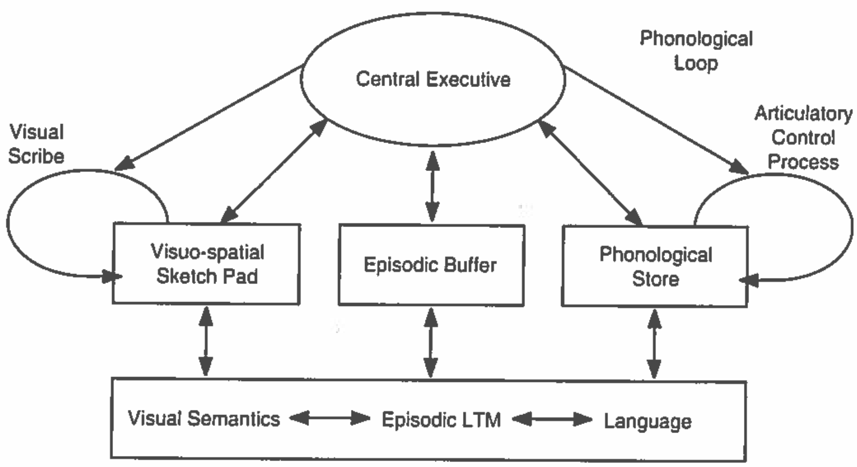

Figure 4.1 A schematic representation of Baddeley's working memory. The phonological loop is made up of the articulatory control process and the phonological store; the corresponding process and store for visuo-spatial information are the visuo-spatial sketch pad and the visual scribe. SOURCE: Based on descriptions from Baddeley (2000) and Baddeley & Logie (1999).

The Phonological Loop

The *phonological loop* has two main components: the phonological store and the articulatory control process. The *phonological store* is a memory store that can retain speech-based information for a short period of time. Unless rehearsed, the traces within the store are assumed to fade and decay within about 2 seconds, after which they are no longer usable. The second component is the *articulatory control process*, which is responsible for two different functions: It translates visual information into a speech-based code and deposits it in the phonological store; and it refreshes a trace in the phonological store, offsetting the decay process. One of the fundamental assumptions of working memory is that the articulatory control process controls subvocal rehearsal, which is analogous to overt rehearsal (saying the item out loud). The amount of verbal information that can be retained is therefore a trade-off between the decay rate (which is assumed to be fixed for a given type of item) and the covert rehearsal rate (which can vary). If rehearsal of a particular item does not occur within a certain amount of time, the memory trace for that item will have decayed too far to be usable. The phonological loop was designed to explain four basic findings: the phonological similarity effect, effects of articulatory suppression, the irrelevant speech effect, and the word-length effect (Baddeley, 1986, 1992a, 1994).

Phonological Similarity The *phonological similarity effect* refers to the finding that memory is worse for items that sound alike than for items that differ (Baddeley, 1966; R. Conrad, 1964; see Figure 3.1). The sequence PGTCD is harder to recall from memory than the sequence RHXKW because the items in the first sequence share similar sounds. The phonological similarity effect occurs for both visual and auditory presentation because, according to the working memory view, items are retained in a speech-based code in the phonological store. In this store, items interfere with other similar items through some as yet unspecified process (Baddeley, 1992b). If the items are presented aloud, then they have immediate access to the store because they are already in the appropriate, speech-based code. If the items are presented visually, however, they need to be translated into a phonological code by the articulatory control process. A strong prediction is that if we somehow prevent the visual items from being translated by the articulatory control process, then the phonological similarity effect should disappear for visually presented items because they cannot be translated into the appropriate code for deposit into the phonological store. One way of preventing translation is to have the subject engage in articulatory suppression, the second phenomenon that working memory was designed to account for.

Articulatory Suppression When subjects engage in *articulatory suppression* (Murray, 1968), they repeatedly say a word, such as *the*, over and over out loud. According to the working memory view, this activity occupies the articulatory control process, which is needed for both overt and covert articulation. Therefore, there should be no covert rehearsal using the articulatory control process during articulatory suppression. Without covert rehearsal, visual information cannot be translated into a phonological code and so cannot be placed into the phonological store; therefore, there should be no phonological similarity effect. Auditory items, however, have direct access to the phonological store; they do not need to be recoded. Because auditory information can enter the phonological store without the articulatory control process, there should still be a phonological similarity effect for auditory items when subjects engage in articulatory suppression.

Table 4.1 The proportion of items recalled correctly as a function of presentation modality, phonological similarity, and articulatory suppression

	Silent		*Articulatory Suppression*	
	Dissimilar	*Similar*	*Dissimilar*	*Similar*
Visual	0.93	0.73	0.57	0.58
Auditory	0.82	0.32	0.45	0.19

NOTE: With no articulatory suppression, dissimilar lists are recalled better than similar lists. With articulatory suppression, there is no phonological similarity effect for visual items, but the effect remains for auditory items. Note that articulatory suppression also greatly reduces overall performance.

SOURCE: From "Some Effects of Minimizing Articulation on Short-Term Retention," by L. R. Peterson and S. T. Johnson, 1971, *Journal of Verbal Learning and Verbal Behavior, 10*, 346–354. Copyright © 1971 Academic Press, Inc. Reprinted with permission.

The results from a study by Peterson and Johnson (1971) are shown in Table 4.1. In the silent condition, recall of the dissimilar items is better than recall of the similar items for both visual and auditory presentation. In the articulatory suppression condition, recall of dissimilar and similar items is equivalent for visually presented information, but there is still an advantage for dissimilar items for auditory information (Baddeley, Lewis, & Vallar, 1984; Estes, 1973; Levy, 1971; Longoni, Richardson, & Aiello, 1993; Murray, 1968; Peterson & Johnson, 1971).

The Irrelevant Speech Effect The third phenomenon that working memory was designed to account for is the *irrelevant speech effect*. Colle and Welsh (1976) had two groups of subjects recall visually presented consonants, but one group saw the consonants while some irrelevant speech was played in the background. Relative to the subjects in the quiet condition, subjects who heard irrelevant speech were not as successful in recalling the information. According to working memory, the phonemes from the irrelevant speech enter the phonological store and interfere with the information about the visually presented items. Given this explanation, we can make three predictions. First, articulatory suppression should remove the irrelevant speech effect because the articulation will prevent the visually presented items from entering the phonological store. Although the irrelevant speech can still enter the store, the to-be-remembered items will not. Second, because the basis is interference at the level of the phoneme, it should not matter whether the irrelevant speech is a single phoneme or a multisyllable word; what *is* important is the similarity of the phonemes in the irrelevant speech to the phonemes in the to-be-remembered items. Third, nonspeech items, such as tones, should not produce an irrelevant speech effect. Salamé and Baddeley (1982) confirmed these predictions.

The Word-Length Effect The fourth phenomenon that working memory was designed to account for is the *word-length effect*—the finding that short words (*man*, *dog*) are recalled better than long words (*gentleman*, *canine*). Mackworth (1963) first reported the high correlation between reading rate and memory span, but because she was interested primarily in identifying limits in iconic memory (or the *visual image*, as she termed it), she did not measure word length precisely. Nonetheless, over five experiments with a variety of stimuli, including pictures, letters, digits, and colors, she found that "the amount reported

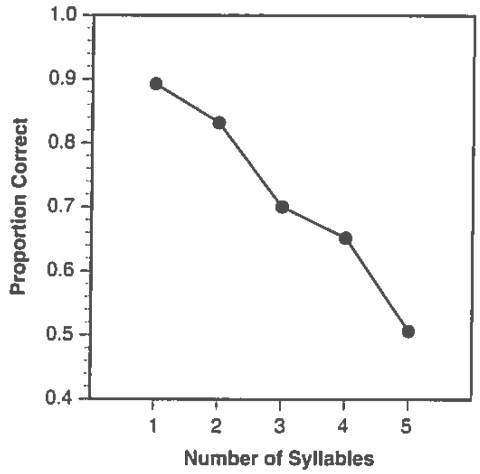

Figure 4.2 Proportion of words recalled correctly as a function of the number of syllables. SOURCE: From "Word Length and the Structure of Short-Term Memory," by A. D. Baddeley, N. Thomson, and M. Buchanan, 1975, *Journal of Verbal Learning and Verbal Behavior, 14*, 575–589. Copyright © 1975 Academic Press, Inc. Reprinted with permission.

was proportional to the speed of reporting the individual items" (Mackworth, 1963, p. 81). Watkins (1972) and Watkins and Watkins (1973) reported effects of word length as a function of modality and serial position in both free and serial recall. In all cases, words of one syllable were recalled better than words of four syllables, and the effect was also slightly larger for visually presented items than for auditory items.

Word length can be measured in two different ways. The *syllable-based word-length effect* refers to the finding that words with fewer syllables are recalled better than equivalent words that have more syllables. The stimuli were selected so that the only important difference was the number of syllables. Each list contained the name of an animal, a disease, a country, and so forth. For example, the one-syllable list contained *stoat, mumps, Greece, Maine,* and *zinc*, and the four-syllable list contained *rhinoceros, diphtheria, Australia, Alabama,* and *uranium*. Figure 4.2 shows the results: As the number of syllables in the words increased, the proportion of words that could be recalled decreased.

Baddeley, Thomson, and Buchanan (1975) also plotted their data in a different form, measuring the reading rate of their subjects (in words per second). When this measure is used, rather than just syllables, the relationship between the time to say a word and the ability to recall a series of items becomes even more striking. These results are shown in Figure 4.3, indicating a linear relationship between how long it takes to pronounce a word and the level of recall.

The explanation of the word-length effect, according to working memory, is that the number of items that can be immediately recalled depends on how often each item can be rehearsed subvocally by the articulatory control process. This process is used to refresh the decaying traces in the phonological store. The shorter the items (in terms of pronunciation time), the more items can be rehearsed before a particular trace decays.

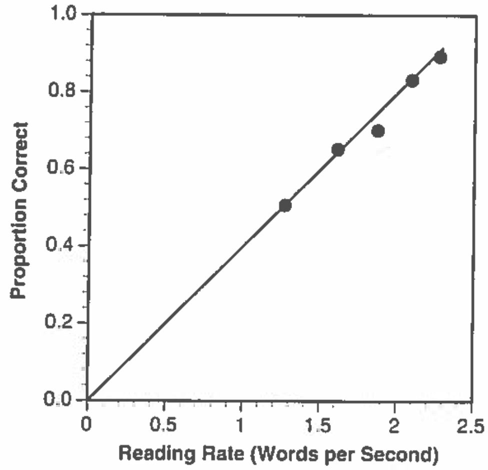

Figure 4.3 Proportion of words recalled correctly as a function of time required to read the words (in words per second).
SOURCE: From "Word Length and the Structure of Short-Term Memory," by A. D. Baddeley, N. Thomson, and M. Buchanan, 1975, *Journal of Verbal Learning and Verbal Behavior, 14*, 575–589. Copyright © 1975 Academic Press, Inc. Reprinted with permission.

Baddeley, Thomson, and Buchanan (1975) explored the effect of word length in terms of pronunciation time. They demonstrated that even when items are equated for meaning and word frequency, if one set of words takes less time to pronounce than another set, memory will be better for the shorter items. The stimuli from their Experiment 3 are reproduced in Table 4.4. This word-length effect is referred to as the *time-based word-length effect* because the only systematic difference between the words is the time needed to pronounce them (Cowan, Day, Saults, Keller, Johnson, & Flores, 1992).

The time-based word-length effect is captured by a very simple equation. One critical assumption is that overt pronunciation rate is correlated with the speed that the articulatory loop can support subvocal rehearsal. Given this assumption, the relationship between memory span, s, for verbal items of type i can be described as a linear function of pronunciation rate, r, and the duration of the verbal trace, t (Schweickert, Guentert, & Hersberger, 1990):

$$s_i = r_i t \tag{4.1}$$

Experimenters can measure both span, s in the equation, and pronunciation rate, r. They can then solve for the third variable, the duration of the trace, t. Perhaps the most compelling evidence supporting this view is the relative consistency of the estimated duration. As Schweickert and Boruff (1986) put it, "The mean of these trace duration estimates is 1.6 s. Considering the variety of methods for presenting the stimuli and measuring the spans and pronunciation rates, one is struck more by the agreement than by the differences" (p. 420). Because of the consistency of this finding, the word-length effect is seen as "the best remaining solid evidence in favor of temporary memory storage" (Cowan, 1995, p. 42).

Experiment *The Syllable-Based Word-Length Effect*

Purpose: To demonstrate the effect of word length on immediate serial recall

Subjects: Twenty subjects are recommended.

Materials: Table D in the Appendix contains eight short words and eight long words. Construct ten lists of five words each, using these words in a different random order for each subject. Each subject will need an answer sheet on which to write responses. It is useful to have five spaces marked for the subjects to write down the five responses.

Design: This is a within-subjects design, because each subject receives each level of the experimental condition, word length.

Procedure: Inform the subjects that this is an experiment on memory. Tell them that they will hear a list of five words and that they will be asked to recall the words in order. Read each list aloud at the rate of one word per second. As soon as the last word is read, the subjects should begin writing down their responses. For this experiment, serial recall is required. With serial recall, the subject must write down the first word first, the second word second, and so forth. If they cannot remember a word, have them write an X and proceed to the next word. They are not allowed to go back and change their responses. Allow about 20 seconds for recall, then read the next list.

Instructions: "This is an experiment on memory. I will read five words out loud, and then I would like you to recall them in order. Simply write the first word you heard in the first blank on your answer sheet, then write the second, and so on. It is important that you write the words in order. If you cannot remember a particular word, write an X in that blank and proceed to the next word. You are not allowed to go back and fill in a blank or change a response once you have written it down. Any questions?"

Scoring and Analysis: For each subject, count the number of words recalled in order for each word length and compute the average. A one-way analysis of variance with length as a repeated measure can be used to analyze the results.

SOURCE: Adapted from "Word Length and the Structure of Short-Term Memory," by A. D. Baddeley, N. Thomson, and M. Buchanan, 1975, *Journal of Verbal Learning and Verbal Behavior, 14*, 575–589.

This relationship, regardless of the underlying theoretical explanation, has important implications. For example, one component of many intelligence tests is a memory span task. Subjects are tested to see how many items—often digits—they can recall in order. Ellis and Hennelly (1980) showed that apparent differences in memory span and IQ between Welsh- and English-speaking subjects may be ascribed to the relatively longer time needed to say the Welsh digits compared to the English digits. The fact that it takes longer to pronounce the digits 1–9 in Welsh than in English reduces the number of items that can be recalled correctly. Bilingual Welsh-English speakers have higher memory spans and higher measures of intelligence when tested in English than when tested in Welsh. It appears that the language most optimized for digit span is Cantonese (cited in Naveh-Benjamin & Ayres, 1986), where the average digit span approaches nine or even more items, compared with seven for English.

One prediction of working memory's account of the word-length effect is that articulatory suppression should remove the effect for both auditory and visual items, because articulatory suppression prevents the items from being rehearsed with the subvocal articulatory control process. Baddeley, Thomson, and Buchanan (1975, Experiment 8) presented subjects with five-word lists for immediate serial recall. There were two word lengths (one and five syllables), two presentation modalities (auditory and visual), and two articulatory conditions (suppression and no suppression). According to the working memory view, articulatory suppression prevents subjects from registering visually presented items in the phonological store because the articulatory control process is not available. Although auditory items have automatic access to the phonological store, articulatory suppression prevents rehearsal of these items because the articulatory control process is not available. Baddeley, Thomson, and Buchanan observed appropriate effects of word length for the no suppression groups, but articulatory suppression eliminated the word-length effect *only* for the visual group; the effect of word length remained in the auditory modality with articulatory suppression group. Because articulatory suppression should remove the word-length effect regardless of presentation modality, the finding that the word-length effect remained for auditory items is problematic for the working memory view.

Baddeley (1986) argued that subjects may be rehearsing during recall, refreshing the decaying trace in the phonological store while simultaneously recalling items. This is more likely for auditory items because they are automatically registered in the phonological store and do not require conversion using the articulatory control process during presentation. If this is the case, then requiring articulatory suppression not only during presentation but also throughout recall should eliminate the word-length effect for auditory items. Baddeley, Lewis, and Vallar (1984, Experiment 4) conducted an experiment almost identical to Experiment 8 of Baddeley, Thomson, and Buchanan (1975). Five-item lists of auditory items were presented for immediate serial recall; the short words had one syllable and the long words had five syllables. The main difference was that whereas Baddeley et al. (1975) had subjects engage in articulatory suppression only during presentation, Baddeley et al. (1984) had subjects engage in articulatory suppression during both presentation and throughout the entire recall period. The data are summarized in Table 4.2. The word-length effect was present when suppression occurred only during presentation but was eliminated when suppression continued throughout the recall period. To the extent that subvocal rehearsal is prevented during both presentation and recall, there will be no word-length effect, just as working memory predicts (Baddeley, 1992a).

Another prediction concerns the interaction between word length, articulatory suppression, and phonological similarity. Articulatory suppression should remove the

Table 4.2 Percentage of short and long words recalled correctly as a function of two types of articulatory suppression

	Quiet	*Suppression Presentation Only*	*Quiet*	*Suppression Presentation and Recall*
Short	83.7	71.0	78.0	46.9
Long	62.0	53.7	61.0	41.7

NOTE: Articulatory suppression eliminates the word-length effect for auditory items only when it occurs during both presentation and recall.

SOURCE: Data in first and second columns from "Word Length and the Structure of Short-Term Memory," by A. D. Baddeley, N. Thomson, and M. Buchanan, 1975, *Journal of Verbal Learning and Verbal Behavior, 14*, 575–589. Copyright © 1975 Academic Press, Inc. Data in third and fourth columns from "Exploring the Articulatory Loop," by A. D. Baddeley, V. J. Lewis, and G. Vallar, 1984, *Quarterly Journal of Experimental Psychology, 36*, 233–252. Adapted with permission.

Table 4.3 The percentage of auditory items recalled correctly as a function of word length, phonological similarity, and articulatory suppression

	Silent		*Articulatory Suppression*	
	Dissimilar	*Similar*	*Dissimilar*	*Similar*
Short	86.2	63.2	52.0	25.0
Long	73.7	31.2	49.4	17.5

NOTE: With no articulatory suppression, dissimilar lists are recalled better than similar lists, and short lists are recalled better than long lists. With articulatory suppression, there is still a phonological similarity effect, but the word-length effect (52.0 versus 49.4 and 25.0 versus 17.5) is eliminated.

SOURCE: Data from Longoni, Richardson, & Aiello (1993).

word-length effect for both visual and auditory items, but it should remove the phonological similarity effect only for visual items, not for auditory items. We have discussed both of these findings separately. However, the working memory view predicts that, at the same time that articulatory suppression is removing the word-length effect, the phonological similarity effect should be removed for visual but remain for auditory presentation. The results from a study by Longoni, Richardson, and Aiello (1993) using auditory presentation are shown in Table 4.3.

The Episodic Buffer

One problem with early accounts of working memory is explaining how items are recalled at all when subjects engage in articulatory suppression. As the data in Tables 4.2 and 4.3 show, recall is still much higher than it should be if all rehearsal is prohibited. To address this problem, Baddeley (2000) added another system to working memory: the episodic buffer (see Figure 4.1). This component is designed to function as a "'back-up store' that is capable of supporting serial recall, and presumably of integrating phonological, visual and possibly other types of information" (Baddeley, 2000, p. 419). Given the newness of this concept, it has yet to be subjected to rigorous experimental tests.

It is possible that the episodic buffer may also alleviate some of the problems concerning the meaningfulness of stimuli. In the original account, items in the phonological store were treated as equivalent even when they varied in terms of meaningfulness. The problem for working memory was that meaningfulness is clearly an important factor in situations where working memory is invoked; for example, memory span is lower for nonwords than for words (Hulme, Maughan & Brown, 1991).

Critique of Working Memory

The major problem with working memory, particularly the phonological loop, is that recent data cast doubt on the trade-off between rehearsal and decay (see Nairne, 2002, for an extended discussion). At its core, working memory proposes that items decay unless refreshed via articulatory rehearsal. This idea, most clearly illustrated in the time-based word-length effect, serves as the heart of the verbal processing capabilities of the phonological loop.

Table 4.4 The top two rows show the short and long stimuli used by Baddeley et al. (1975); the bottom two rows show the short and long stimuli used by Lovatt, Avons, & Masterson (2000). Pronunciation times and percent recalled are from data reported by Lovatt et al. (2000).

Word Type	*Stimuli*	*Mean Pronunciation Time*	*Percent Recalled*
Short	*bishop, pectin, ember, wicket, wiggle, pewter, tipple, hackle, decor, phallic*	530 ms	70.7 %
Long	*Friday, coerce, humane, harpoon, nitrate, cyclone, morphine, tycoon, voodoo, zygote*	693 ms	65.5 %
Short	*button, tractor, whistle, spider, pencil, pocket, shovel, candle*	605 ms	60.7 %
Long	*pebbles, curtains, station, needle, branches, canoes, necklace, robot*	793 ms	65.1 %

Lovatt, Avons, and Masterson (2000, 2002) reported a series of experiments in which they examined recall of different sets of long and short words. One experiment used the same stimuli that Baddeley et al. (1975) had used and replicated the finding. However, a different set of words, also equated except for pronunciation time, yielded a negative or reverse word-length effect; if anything, the long words were recalled slightly better than the short words. Both sets of words, their mean pronunciation times, and the recall levels are shown in Table 4.4. Caplan, Rochon, and Waters (1992) have reported similar results with yet another set of stimuli. In their experiment, the short words took, on average, 546 ms to say and the long words took 720 ms. However, only 65.6% of the short words were recalled, compared to 76.4% of the long words. Neath, Bireta, and Surprenant (in press) report yet another set of words that vary in pronunciation time but do not produce a time-based word-length effect. Working memory unambiguously states that if an item takes longer to say, it will be recalled less well, yet these data show the opposite finding. It seems that the time-based word-length effect can be observed only with the original set of stimuli; there are now half a dozen sets of words that produce either no time-based word-length effect or even a reverse effect, but only one set that produces a positive result.

CogLab Experiment
http://coglab.wadsworth.com/experiments/MemorySpan/

A second problem concerns the interpretation of span data. Almost all of the key data come from a paradigm referred to as *immediate serial recall*. For example, memory span tests assess how many items of various kinds a person can recall correctly in order half the time. The resulting span is taken as providing critical evidence in support of a limited capacity system. Nairne and Neath (2001) reported an experiment in which the same general procedure was used: Subjects were presented with lists of items that varied in length from two to nine items and then were tested on their memory for the order. The results are shown in Figure 4.4.

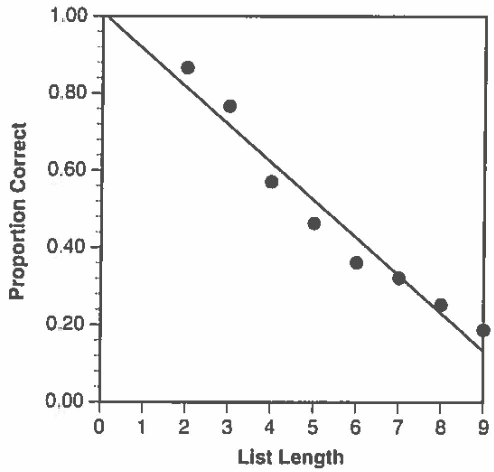

Figure 4.4 Long-term memory span: the proportion of items correctly recalled in order as a function of list length. There was a 5-minute delay between end of list presentation and recall.
SOURCE: Nairne & Neath (2001).

Just as other researchers had found, Nairne and Neath (2001) found that span for two-syllable words was approximately 5. However, they had delayed the memory test by 5 minutes, which is well beyond the capability of short-term or working memory. There are three possible interpretations.

First, Nairne and Neath measured the span of long-term memory using the same technique that is used to measure the capacity of short-term memory and found that the capacity limit is about four or five. If this is true, you should consider carefully what you store in long-term memory: You have only five slots available at any one time! A second interpretation is that neither the long-term memory span nor the short-term memory span techniques actually measure span. Rather, the capacity limit has to do with remembering items *in a particular order*. We examine this issue in detail in Chapter 13. A third possibility is that, at least within the working memory framework of Baddeley, performance on this task is supported by the episodic buffer. If so, then the buffer has a far smaller capacity than would otherwise be useful and necessary to explain performance on other tasks (see Baddeley, 2000).

Other problems with working memory include a continuing inability to explain precisely how items in the phonological store interfere (Baddeley, 1992b). Because there is no specific interference mechanism, the phonological similarity effect is not really explained. With regard to the irrelevant speech effect, several studies have been unable to replicate the key finding that the magnitude of the irrelevant speech effect is related to the phonological similarity between the relevant and irrelevant items (Jones & Macken, 1995; LeCompte & Shaibe, 1997). Moreover, it has been shown that pure tones disrupt serial recall (Jones & Macken, 1993; LeCompte, Neely, & Wilson, 1997), and thus the irrelevant speech effect may not require speech. Both of these findings contradict predictions of working memory (see also Martin, 1993; Neath, Farley, & Surprenant, 2003).

A second problem concerns several findings that involve presentation modality. Although working memory predicts some interactions involving presentation modality (for example, that articulatory suppression will eliminate the phonological similarity effect for visual but not auditory items), it does not explain the basic modality effect—the better recall of the final item in a list that is presented auditorily rather than visually (see Chapter 2). As another example, the syllable-based word-length effect is larger for visually presented items than for auditory items (Baddeley, Thomson, & Buchanan, 1975, Experiment 8; Watkins & Watkins, 1973), but working memory does not address this finding.

A third problem concerns exactly how the many subsystems of working memory, such as the phonological loop, the episodic buffer, and episodic long-term memory, interact. They need to interact to allow the model to handle findings (reviewed below) of influences of long-term memory on immediate serial recall, and also to explain where items are recalled from when subjects engage in articulatory suppression. With no detailed description of the process, it is difficult to see how this approach explains the data.

A final problem concerns how order information is retained. The majority of findings that working memory was designed to explain are observed using immediate serial recall. In these tests, subjects must not only recall the items, but must recall them in the correct order. Whereas the verbal version of working memory (e.g., Baddeley & Logie, 1999) does not explicitly state how order information is retained, some quantitative versions do. However, among these more specific models, three different accounts have been offered (Burgess & Hitch, 1999; Henson, 1998; Page & Norris, 1998).

Baddeley's version of working memory should be seen as an ongoing process in which the ideas are still being refined and more precisely specified. Given the complexity of the topic, it should not be surprising that a simple model does not fare well. It remains to be seen whether modifications can be made that will correct or resolve the problems mentioned here or whether quantitative versions, as Baddeley (1994) advocates, can be derived that give the model more precision in its operation and predictions.

Working Memory as Activation: The Embedded-Processes Model

The second current view of immediate memory is that it is a subset of information that is currently in a heightened state of activation (for example, Cowan, 1988, 1993; Shiffrin, 1993). This view is similar to Baddeley's (1986, 1994) working memory and is sometimes (confusingly) also called working memory. The main similarities between the two are the use of decay as the fundamental cause of forgetting over the short term and the role of immediate memory as the "place" where cognitive "work" is performed. The activation view differs from Baddeley's account in that (1) it does not divide immediate memory into separate subsystems, such as the visuo-spatial sketch pad or the phonological loop, and (2) it specifically includes a long-term memory contribution (Cowan, 1999). Indeed, some properties originally ascribed to working memory are now being relegated to long-term memory (see Cowan, 1999, pp. 81–82, for an example).

The activation view encompasses at least two different approaches. One has as its goal a simulation model and specifies in great detail how the proposed system operates (e.g., Schneider & Detweiler, 1987). The second approach favors simplicity: "It appears most efficient for the time being to try to stay near the most basic level of the hypothesis space until the fundamental issues are resolved, even though this results in a model too general to make specific predictions in many situations" (Cowan, 1995, p. 24). We shall examine the latter view, because the more complex versions (e.g., Anderson, 1983a; Schneider & Detweiler, 1987) can be seen as variants of the former. With the exception of providing many elaborations and subdivisions, the major difference between Anderson (1983a) and Cowan (1988) is that the former does not include sensory stores and omits mention of selective attention. The major difference between Schneider and Detweiler (1987) and Cowan (1988) is similarly the division into eight separate modules (visual, auditory, speech, lexical, semantic, motor, mood, and context), each of which is embedded in a connectionist network. Cowan's view, then, is a framework that has many possible instantiations.

In Cowan's (1999) embedded-processes model, the term *working memory* "refers to cognitive processes that retain information in an unusually accessible state" (p. 62). This view emphasizes that working memory is a set of processes that are contained within long-term memory. In Figure 4.5, the large box represents all of memory. A subset of the information in memory is in a temporarily heightened state of activation (labeled "Activated Memory"). A subset of this information is the current focus of attention and is the information that is available to conscious awareness. Thus, an item can be activated but not the focus of attention; all items that are in the focus of attention, however, are activated.

The sensory store retains items for only a few hundred milliseconds (see Chapter 2). Information in the sensory store that is activated can undergo both sensory and semantic processing. The central executive is a set of processes that are influenced by instructions and incentives. For example, a person will attend to a stimulus that is novel, to one that has personal significance, and to those that are important for the current task. The focus of attention is limited to approximately four unrelated items (Cowan, 2001); in addition to this item-based limit, there is a time-based limit on the activation of memory of approximately 10 to 20 seconds unless the item is reactivated.

Baddeley's (1986) version of working memory addresses only phonological and visuo-spatial forms of representations, but Cowan's (1999) view emphasizes other forms, including nonverbal sounds and tactile information. Temporarily activated items will decay over time and are also subject to interference from similar items. Items can remain in the focus of attention or in a heightened state of activation thgough rehearsal, but also through other processes. For example, searching through a list of items in memory can help reactivate them. Retrieval means having the items in the focus of attention at the time they are needed. If an item is in the focus of attention, recall is almost always successful. Retrieval of items that are not in the focus of activation can fail because of both decay and interference.

The embedded-processes model accounts for many of the effects described previously in a way that is similar to that of Baddeley's (1986, 2000) version of working memory. One area in which the embedded-processes model has a distinct advantage over Baddeley's version concerns long-term memory effects on immediate memory tasks. In Cowan's (1999) model, working memory is essentially activated long-term memory; thus, long-term memory is predicted to play a substantial role in short-term memory tasks. In contrast, Baddeley's original version of working memory allowed only the phonological loop to play a major role. The episodic buffer has recently been added, but its operation and interaction with the other systems are not yet well specified.

One common finding on many long-term memory tasks is that concrete words, such as *army*, are recalled better than otherwise equivalent abstract words, such as *amount*

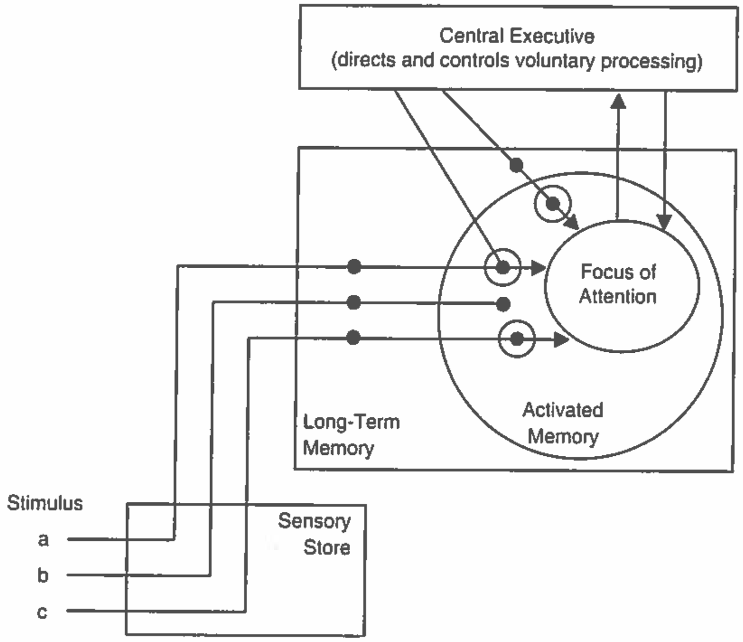

Figure 4.5 A schematic representation of the embedded-processes view of working memory. Long-term memory, activation, and the focus of attention all contribute to working memory. Stimuli a and b are unchanged items (they have been experienced before) and ordinarily would not attract attention. Stimulus a is selected for more elaborate processing, which requires some attention and the involvement of the central executive. Stimulus b is not selected, and although some features will be encoded, the resultant information will be less rich than for stimulus a. Stimulus c is a novel item, one that has not been seen before or recently, and so it attracts attention. SOURCE: Adapted from "Evolving Conceptions of Memory Storage, Selective Attention, and Their Mutual Constraints Within the Human Information Processing System," by N. Cowan, 1988, *Psychological Bulletin*, *104*, 163–191. Copyright © 1988 American Psychological Association. Adapted with permission of the author.

(Paivio, Yuille, & Madigan, 1968). The explanation of this concreteness effect is usually that concrete items have more forms of representation in long-term memory (Paivio, 1969; see Chapter 11) or more associates in semantic memory (Jones, 1988; see Chapter 10). Even though the concreteness effect has its locus in long-term memory, it is also observable on immediate serial recall tests and tests that measure memory span (Walker & Hulme, 1999). As a second example of long-term memory effects on short-term memory tasks, Roodenrys and Quinlan (2000) found that high-frequency words were recalled better on immediate serial recall tests than were low-frequency words.

The demonstration of long-term memory effects in working memory is most serious for memory span—the number of items that can be immediately recalled in order. Baddeley's (1986) version of working memory says that memory span is determined by

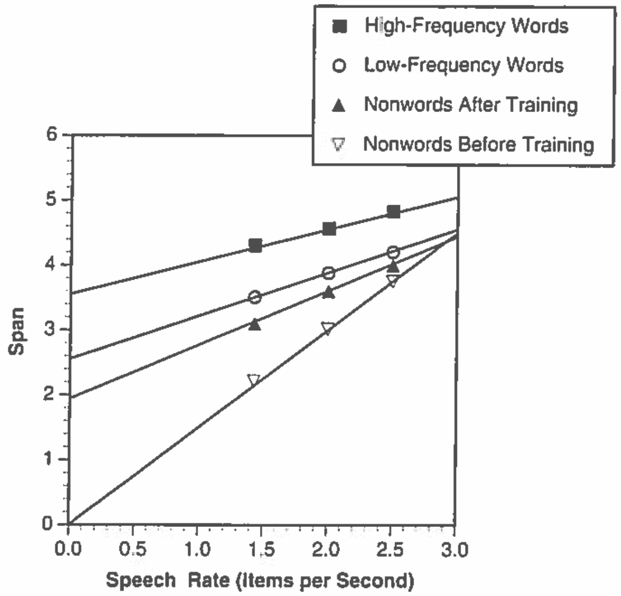

Figure 4.6 The relation between speech rate, which is assumed to be correlated with rehearsal rate, and memory span. If span is determined by decay offset by rehearsal, as in phonological loop models, then span should be 0 when the speech rate is 0. The data are hypothetical, but realistic.

how well rehearsal offsets decay within the phonological loop. If memory span is solely a function of pronunciation rate and the duration of the verbal trace, then when there is no rehearsal, span must be zero (Schweickert, Guentert, & Hersberger, 1990). When memory span is plotted as a function of speech rate (as in Figure 4.6) and the best-fitting line is calculated, the key issue is whether this line intercepts the y-axis at 0. Hulme, Maughan, and Brown (1991) did find an approximately zero intercept when they used nonwords (Italian words with subjects who knew no Italian), and both Brown and Hulme (1992) and Hulme, Roodenrys, Brown, and Mercer (1995) also found an approximately zero intercept for nonwords. However, all of these researchers found that when subjects became more familiar with the stimuli, the intercepts increased. Stuart and Hulme (2000) even found that familiarizing subjects with low-frequency words 24 hours prior to the memory span assessment improved subjects' performance.

When any stimuli other than unfamiliar nonwords are used, the predictions of the decay offset by rehearsal account are no longer accurate. There is clear evidence that information from long-term memory affects memory span. Span, then, is not be a pure measure of working memory (Nairne & Neath, 2001; Tehan & Lalor, 2000; Watkins, 1977).

A second advantage of the embedded-processes model over other versions of working memory is that it predicts that output time will have an effect on measures of span. For example, Cowan, Wood, Wood, Keller, Nugent, and Keller (1998) showed that subjects' articulation rates and the duration of pauses between items when recalling were not correlated with each other. However, both were related to span. Moreover, Dosher (1999;

Dosher & Ma, 1998) found that output time was a better predictor of recall than pronunciation time. This is readily accounted for by noting that searching through a set of items can help to reactivate them by bringing them into the focus of attention (Cowan, 1992). Thus, covert rehearsal during acquisition and search during retrieval can both maintain items and influence performance, with particular experimental factors determining the precise role each processes plays.

There are three main problems with this approach. First, the term *activation* is often not defined very precisely. Typically, researchers use operational definitions to specify what is meant by activation. For example, activation is usually defined by reference to a particular behavioral task; thus, Cowan (1993) offers one definition as "the temporary state of memory representations that would allow these representations to have a priming effect on subsequent stimuli" (p. 162). Although the concept has widespread acceptance, particularly for priming data, there are other explanations of priming (see Chapter 10). Some researchers suggest that activation corresponds to a pattern of activity across a subset of individual neurons. This suggestion runs into problems, however, as there are many instances in which the nervous system uses a change in the rate of firing, rather than activity versus no activity, to code information.

The second problem concerns the assumption of deactivation. Although the concept of decay within connectionist networks has been used without controversy (e.g., Rumelhart & McClelland, 1986), the concept has been vigorously and repeatedly rejected in the memory literature (McGeoch, 1932; Osgood, 1953; see Chapter 6). The main objection has been that time is not a causal agent: Iron rusts over time, but time does not cause rust, oxidation does. In memory, information appears lost over time, but time should not be given the causal role; some other activity (usually defined as interference) that unfolds over time should be the causal agent. The underspecification of how activated information becomes deactivated, and whether it can become inhibited, is a major omission in this view.

In defense of the activation view, its proponents (see Cowan, 1995, 1999, 2001) recognize some of these weaknesses and note that more development is necessary. It is conceivable that these problems may be solved or greatly mitigated with further theoretical work and more precise descriptions.

Working Memory Capacity

A lot of research has focused on working memory capacity—the extent to which a person can control and sustain attention in the face of interference and distraction. This capacity, which varies among individuals, reflects the ability to activate items in memory, to bring or maintain them in the focus of attention, and to ignore or disregard interfering items or distractions (Engle, Kane, & Tuholski, 1999). The reason for the interest in measures of working memory capacity is that they correlate highly with many cognitive tasks, including reading comprehension, language comprehension, spelling, vocabulary learning, writing, and reasoning (see Engle, Tuholski, Laughlin, & Conway, 1999). The assumption is that measures of working memory capacity reflect some ability that is fundamental to cognitive operations.

CogLab Experiment
http://coglab.wadsworth.com/experiments/OperationSpan/

Working memory capacity can be measured by a variety of tasks, including reading span (Daneman & Carpenter, 1980) and operation span (Turner & Engle, 1989). To measure a person's operation span, for example, subjects are asked to perform mathematical calculations and to remember the order in which a list of words was presented. They see a mathematical question, such as "Is $(4/2) - 1 = 1$?" and they are asked to respond yes or no. They then read a word, and then see another math question. After a series of problems and words have been presented, the subjects are asked to recall the words in order. For subjects who were more than 85% accurate in evaluating the math problems, the operation span is defined as the sum of sequence lengths recalled correctly. Thus, if a subject recalled a list of three words correctly in order, 3 would be added to the operation span score (see Conway & Engle, 1996).

For Engle (2001), working memory capacity is very different from capacity as used in discussions of short-term memory (i.e., 7±2) and also capacity as used in discussions of Baddeley's (1986) working memory (i.e., 2 seconds). Rather, it is about "limitations in the ability to use controlled processing to maintain information in an active, quickly retrievable state. . . . WM capacity is not about storage and processing but is about retention over a period in which there is distraction or shift of attention away from the stored information" (p. 301).

Individuals with larger working memory capacity (as measured by tasks such as operation span) are better able to ignore irrelevant but potentially distracting information. For example, Conway, Cowan, and Bunting (2001) had subjects participate in a *dichotic listening task*. In this task, subjects are asked to shadow (repeat out loud) everything they hear in one ear (referred to as the attended channel) and to ignore everything that is presented to their other ear (the unattended channel). The subjects chosen for this study were those who scored in the top 25% (high span) and the bottom 25% (low span) of the operation span task. Of key interest was the proportion of times each subject detected his or her own name when it was presented to the ear that was supposed to be ignored. Approximately 20% of the high-span subjects detected their name, compared to 65% of the low-spans. The idea is that with lower working memory capacity, the low-span subjects were less able to ignore the information in the unattended channel. In contrast, the high-span subjects, with more working memory capacity, were better able to block the distracting information (everything on the unattended channel) and so were less likely to hear their name.

The working memory capacity approach, then, is interested not so much in memory per se but rather in determining the components common over multiple tasks. Rather than emphasizing working memory as the place in which information is retained briefly in a highly accessible state while performing cognitive tasks, this view emphasizes the processing that is shared between different cognitive tasks.

The Feature Model

The feature model (Nairne, 1988, 1990) was designed to account for the major effects observed when memory is tested using immediate serial recall, including many of the phenomena described in Chapter 2, such as the recency effect, the modality effect, and the suffix effect, and phenomena described in this chapter, such as the phonological similarity effect and the effects of articulatory suppression. The model gets its name from the fact that items are assumed to be represented as a set of features, a common modeling assumption (Hintzman, 1991). In its simplest form, this assumption states that any item can be represented by a series of 1s, −1s, and 0s. As an analogy, think of a small black-and-white television set. If you look at the screen up close, you will find that each pixel can take on three values: black, white, or broken. The screen uses the same pixels to represent an ice hockey game, a debate, or a commercial. If you were to freeze the screen at any instant and write down the value of each pixel, you would be representing the information as a series of (mostly) 1s and −1s. The value of pixel number 824 is meaningless by itself; it does not tell you whether you are watching a sporting event or a disclaimer that not all plates go up in value. Rather, it is the ordered set of values that represents the particular display. In the feature model, then, no one feature in a vector is meaningful.

The feature model assumes that there are only two types of features. Modality-dependent features represent the conditions of presentation, including presentation modality; modality-independent features represent the nature of the item itself and are generated through internal processes, such as categorization and identification. This follows the distinction, proposed by the broad class of dual-coding models, between an abstract form of representation and a form that more closely represents the physical characteristics (e.g., Durlach & Braida, 1969; Fujisaki & Kawashima, 1970; Pisoni, 1973, 1975; see also Surprenant & Neath, 1996).

Regardless of whether you read the word *dog* silently to yourself or hear someone else say "dog," the modality-independent information will be the same. However, if you hear the word *dog*, the modality-dependent features may represent information such as the person's accent, whether the speaker is male or female, and so on. If you see the word *dog*, the modality-dependent feature may represent information such as whether the word is in upper- or lowercase, what color it is, and so on. Internally generated traces can contain only modality-independent features because there is no modality. There is abundant evidence for this assumption. For example, studies from the imagery literature show many differences between a percept arising from experiencing a stimulus directly and one that is created solely via internal processes (Crowder, 1989a; Nairne & Pusen, 1984; Suengas & Johnson, 1988; Surprenant, 1992).

The modality-dependent features are used to account for the effects previously attributed to echoic memory. Unlike other accounts that place the locus of echoic memory in a separate structure (Crowder & Morton, 1969), the feature model follows Watkins and Watkins (1980) in that modality-dependent information is viewed as just part of the memory representation.

The feature model also distinguishes between primary and secondary memory. Primary memory has no capacity limits, and items in primary memory do not decay. Rather, the major function of primary memory is to construct and maintain cues that may indicate which items were recently presented (see also Raaijmakers & Shiffrin, 1981). The feature model assumes that all memory is cue driven (see Watkins, 1979). The only loss of information from primary memory occurs from interference: Newly entering items can interfere with items that are already in primary memory. A simplifying assumption is that an item can interfere only with the immediately preceding item (see Figure 4.7). At the end of the presentation of a typical list, primary memory will consist of partially degraded traces. In the memory test, subjects must match the degraded primary memory traces with the appropriate intact trace in secondary memory.

For each partially degraded trace in primary memory, the subject tries to select an appropriate recall candidate by comparing the degraded trace with intact traces in the

Item Presented		Primary Memory
1	[+1 -1 +1 +1, +1 -1 +1 -1]	[+1 -1 +1 +1, +1 -1 +1 -1]
		[+1 0 0 +1, +1 0 +1 0]
2	[-1 -1 +1 -1, -1 -1 -1 -1]	[-1 -1 +1 -1, -1 -1 -1 -1]
		[+1 0 0 +1, +1 0 +1 0]
		[-1 0 +1 0, -1 -1 0 -1]
3	[+1 -1 -1 -1, +1 +1 -1 +1]	[+1 -1 -1 -1, +1 +1 -1 +1]
		[+1 0 0 +1, +1 0 +1 0]
		[-1 0 +1 0, -1 -1 0 -1]
		[+1 -1 0 0, +1 0 -1 0]
4	[-1 +1 -1 -1, -1 +1 +1 +1]	[-1 +1 -1 -1, -1 +1 +1 +1]

Figure 4.7 An example of what might happen when four items are presented, assuming perfect encoding and an overwriting probability of 1. The first four features represent modality-independent information, and the second four represent modality-dependent information. Item 1 is presented and is encoded accurately in primary memory. When item 2 is presented, any features in item 1 that overlap with features in item 2 are overwritten (set to 0). The same thing happens when item 3 is presented. Only the last item is completely intact. However, rehearsal can take place. This consists of generating an item, and a generated item can only contain modality-independent features. The rehearsed item(s) can overwrite the modality-independent features of the final item, but the modality-dependent features will remain intact.

secondary memory search set. Typically, the secondary memory search set will consist of items presented on the most recent list, but this is not necessarily always the case. For example, when the same to-be-remembered items are repeated on each list or if the items constitute a well-established group (such as the digits 1–9), the subject will use the appropriate secondary memory search group. However, when the to-be-remembered items come from a larger group (such as unique items on each trial), the search group is likely to be larger.

Even though a subject may have correctly matched a degraded primary memory trace with its intact secondary memory counterpart, the subject still may not produce the item. In general, subjects tend not to recall an item more than once, even if that item actually appeared more than once on the original list (see Hinrichs, Mewaldt, & Redding, 1973). The feature model includes this type of *output interference*. Suppose the subject is trying to find a match for primary memory trace number 2, but mistakenly selects from secondary memory the item that matches the fifth primary trace; the fifth item will be recalled (and scored as incorrect because it is in the wrong order). When it comes time to match primary memory trace number 5, the subject may select the appropriate secondary memory item. However, the subject has already produced this as a response and so is less willing to write this item down again.

Because the feature model is a computer simulation model, all details have to be specified completely. One detail that must be specified is how many features should be used. Items are assumed to have 20 modality-independent features; this number was picked solely to minimize the time required to run the simulation and has no other significance. However, it also turns out that the absolute number of features used is largely irrelevant because the rule that decides how similar two items are relies on the relative, not absolute, number of matching features.

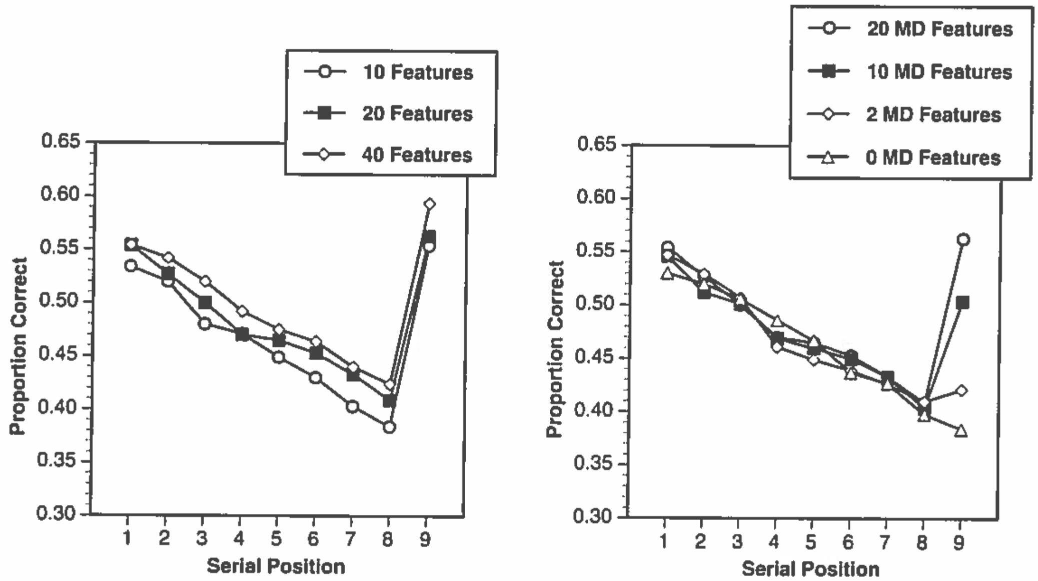

Figure 4.8 The left panel shows the proportion of items recalled correctly as a function of the number of features. The three lines show predicted performance (1) when there are 10 modality-independent and 10 modality-dependent features, (2) when there are 20 of each kind, and (3) when there are 40 of each kind. As the figure shows, there is almost no effect of increasing the absolute number of features. The right panel shows the effect of changing the number of modality-dependent features when the number of modality-independent features is held constant at 20.

The final assumption needed to get the model up and running is that different presentation modalities give rise to modality-dependent features that differ in terms of their discriminability. The key issue is how much a presentation modality differs from inner speech. It is assumed that the visual modality differs the least, the auditory modality differs the most, and other modalities, such as lip-read and mouthed, fall somewhere in between. The important assumption is that in the typical case, auditory presentation gives rise to modality-dependent features that are more useful in identifying the items that were presented than does visual presentation.

Within the model, the basic idea is the acknowledgment that primary memory traces do not exist in a vacuum; rather, they exist as part of a stream of ongoing mental activity (see Johnson & Raye, 1981; Nairne & McNabb, 1985). When interpreting a primary memory trace, the subject needs to discriminate the trace not only from other traces but also from traces that are generated internally. An extensive literature shows that visual presentation and subvocal rehearsal produce similar effects (for reviews, see Baddeley, 1986; Crowder, 1976). Thus, a visually presented item will be quite similar to an internally generated item. Because there is also evidence of differences between visually and auditorily presented items, we end up with a scheme in which auditory items have more modality-dependent features than do visual items, which in turn have more modality-dependent features than do internally generated items (Nairne, 1988, 1990; for further converging evidence, see Surprenant & Neath, 1996). The right panel of Figure 4.8

shows the effect of decreasing the number of modality-dependent features when the number of modality-independent features is held constant.

What makes the feature model seem complex is that it can simulate many different processes simultaneously. Fortunately, each individual process is simple and straightforward, and the key processes are precisely described using four simple equations (see Optional Chapter). To make things even simpler, the feature model exists as a computer program that can be used to make unambiguous predictions about what will and will not happen. An online version of the feature model that can run most of the simulations described in this chapter can be found on the Web at http://rumpole.psych.purdue.edu/models/FeatureModel.html.

Feature Model Operation

Each to-be-remembered item is made up of features. With auditory presentation, we assume there are 20 modality-independent features and 20 modality-dependent features, each of which is randomly set to a value of 1 or −1. These 40 features represent the first item presented. The second item presented also contains 40 features. Retroactive interference occurs, with features from item 2 overwriting features of item 1; specifically, if modality-independent feature number 5 of item 2 has the same value as modality-independent feature number 5 of item 1, then item 1's feature 5 is overwritten by replacing the original value with a value of 0. Then the third item is presented, then the fourth, and so on.

The final item is followed not by any external information but by rehearsal. Because subvocal rehearsal has, by definition, no modality-dependent information (there is no modality!), only the modality-independent features of the final item are subject to overwriting. At the end of list presentation, primary memory contains a trace of each of the items presented. In the typical case, these traces will be degraded because certain features will have been overwritten. The final item, however, will have its modality-dependent features intact.

The subject now tries to match each primary memory item with an intact secondary memory trace. If we are considering the case in which nine digits are presented in random order, the subject will limit the search to the representations of the nine digits in secondary memory. Beginning with the first item, each primary memory item is compared with all secondary memory items in the comparison set. In general, the secondary memory item with the fewest mismatching features will be selected as the candidate for recall. Thus, the secondary memory trace chosen as the response for a particular degraded primary memory trace will typically be that trace with the largest proportion of matching features, relative to the other choices currently available in the secondary memory search set.

Simulations Using the Feature Model

The Serial Position Function In the feature model, recall generally declines over serial positions because of output interference; this agrees with recent empirical data (Cowan et al., 2002). Items presented later in the list have a greater chance of being mistakenly recalled early on and so are less likely to be produced even if sampled. The pronounced recency effect seen in serial recall of auditory items arises because the modality-dependent features of the last list item are not subject to overwriting. Consequently, there will be extra information available to make a better match between a degraded primary memory item and the appropriate secondary memory item. To the extent that a presentation modality provides useful modality-dependent features (for example, tactile, lip-read, mouthed), there will be a modality effect (see the right panel of Figure 4.8). To the extent that a presentation modality does not provide useful modality-dependent features, there will not be a modality effect. Because visual presentation leads to very little useful extra information, recency effects are not seen with visual presentation and serial recall (LeCompte, 1992). Another way of reducing the usefulness of the modality-dependent information is to use homophones (such as *pear, pare, pair* or *pour, poor, pore*). When a list of auditory homophones is presented, there is no recency effect (Crowder, 1978a). According to the feature model, this is because the undegraded modality-dependent features of the final item will contribute almost no useful information for matching the degraded trace to the original item; the right panel of Figure 4.8 shows these effects. Standard auditory presentation uses 20 modality-independent and 20 modality-dependent features. Standard visual presentation uses 20 modality-independent and 2 modality-dependent features. If the 20 modality-dependent features are all set to be the same (as is the case with homophones), there will be no recency effect.

The Suffix Effect The suffix effect occurs whenever the modality-dependent features of the final item are overwritten. Two factors influence when this will occur: First, the suffix has to be perceptually grouped with the list items, and second, the stimulus has to have similar modality-dependent information. Thus, a speech suffix will overwrite some of the modality-dependent features of a list of speech items because these features are likely to be similar. Visual suffixes should have little or no effect on auditory list items, and physically similar suffixes should have far larger effects than semantically similar suffixes do (because the locus of recency lies in residual modality-dependent features). The less similar the suffix, the smaller the suffix effect (Morton, Crowder, & Prussin, 1971). If the suffix is grouped in with the list items, then there will also be a suffix effect on more than just the final items because of the increased search set (see Nairne, 1990). This approach has been used to explain the context-dependent suffix effect (see Neath, Surprenant, & Crowder, 1993), as well as modality and suffix effects that are observed in modalities with no apparent acoustic component, such as tactile (Nairne & McNabb, 1985; Watkins & Watkins, 1974) or mouthed or lip-read (Nairne & Crowder, 1982; Spoehr & Corin, 1978) stimuli. To simulate the suffix effect, an additional auditory item is presented but not recalled. Its modality-dependent features will overwrite some of the modality-dependent features of the last to-be-remembered item and will make performance roughly equivalent to a visual condition.

Grouping Effects The feature model can predict the appropriate modality-based grouping effects. When a temporal gap is inserted in a list, performance is enhanced for auditory items, but there is little or no effect on visual items (Frankish, 1985; Ryan, 1969). A temporal gap preserves the modality-dependent features of the item immediately preceding the gap in the auditory case; thus, the auditory condition can be conceived of as two (or more) smaller lists. The reduction in the search set size provides an overall increase in performance relative to the ungrouped condition, and the removal of overwriting of the modality-dependent features of each end-boundary item produces mini serial position functions (see Nairne, 1990, Figures 11 and 12). There is almost no advantage for visual items in a grouped list, because there are far fewer modality-dependent features to be preserved.

Phonological Similarity The feature model also accounts for the observation that phonological similarity impairs serial recall performance (Crowder, 1978). Within the model, the probability that a degraded cue will be matched to a particular secondary memory item is based on a ratio (see Equation O.33 in the optional chapter). The numerator is the similarity of the degraded cue in primary memory and the target in secondary memory. The denominator is the sum of the similarity between the cue and all the items. Any increase in similarity increases the value of the denominator relative to the numerator, resulting in overall worse performance.

Phonological similarity is simulated in the feature model by manipulating the number of overlapping features. On average, there will always be some similarity between adjacent items; phonological similarity is modeled by setting a minimum number of similar features. For example, in a control or phonologically dissimilar condition, each of the 20 modality-independent features is randomly set to be −1. Under these conditions, there will be some feature overlap, but it will be essentially random. In a phonologically similar condition, however, a certain number of features (for example, 13 out of the 20) are set to the same value—1, for example—and the remaining features (in this case, 7) are randomly set to −1. There will be at least 13 overlapping features, but some of the other 7 may also overlap.

Articulatory Suppression When subjects engage in articulatory suppression, they repeatedly say a constant item out loud. In the feature model, this is seen as adding noise to the memory trace of each individual item (see also Murray, Rowan, & Smith, 1988) through a process known as feature adoption. Some of the modality-independent features of the item being articulated will replace some of the modality-independent features of the cues in primary memory. Because articulatory suppression affects both auditory and visual items, articulatory suppression should affect only those features that both auditory and visual items share. Because articulatory suppression does not eliminate recall of items completely, it cannot be affecting all of the modality-independent features. Thus, articulatory suppression affects half of the modality-independent features. This has the net result of decreasing the sampling probability by decreasing the similarity of the cue in primary memory to the corresponding item in secondary memory.

Irrelevant Speech The feature model accounts for the effects of irrelevant speech in the same way as the effects of articulatory suppression, through feature adoption (Neath, 2000). Because articulatory suppression is active—the subject needs to articulate items at a particular rate—whereas irrelevant speech is passive, it is assumed that articulatory suppression requires extra resources or serves as a general distractor (see, e.g., Parkin, 1993a, p. 130) compared to irrelevant speech. The model therefore predicts that the magnitude of the disruption caused by articulatory suppression should significantly correlate with the magnitude of the disruption caused by irrelevant speech. This prediction has been confirmed (Neath, Farley, & Surprenant, in press).

Articulatory Suppression and Phonological Similarity As Nairne (1990) has demonstrated, the feature model produces the appropriate interaction between phonological similarity effects in the two modalities when tested with and without articulatory suppression. For visual items, the phonological similarity effect is eliminated because articulatory suppression eliminates the advantage that dissimilar items have: The features in the dissimilar items that helped the cue match with the appropriate target are replaced, through feature adoption, with features from the articulated item. Visual items have so few modality-dependent features that they add essentially no information that would be useful for matching the phonologically dissimilar traces relative to the phonologically similar traces. Auditory items, however, have many more modality-dependent features, and even though the modality-independent features of the dissimilar items have been subjected to feature adoption, there remain enough intact modality-dependent features in the phonologically dissimilar condition to give an advantage over the phonologically similar items.

Word-Length Effects The syllable-based word-length effect is implemented following an idea originally suggested by Melton (1963). The basic idea is that the more parts there are, the more opportunities there are to make a mistake. To take an extreme example, if you have a jigsaw puzzle with only 2 pieces, it is very difficult to put the pieces together incorrectly. In contrast, a 100-piece puzzle allows you to make far more mistakes in assembly. Just as a list can be divided into items, an item can be divided into segments.

The feature model assumes that words are made up of segments and that these segments have to be assembled at some stage during the recall process. For example, Caplan, Rochon, and Waters (1992) suggested that the segments could correspond to the phonological structure of the items and that the word-length effect arises when this information is being used in preparation for recall. The probability of making a segment error is the same for all segments; however, because long items have more segments than short items, there is more chance of making an error with a long than with a short item. Because word-length effects are seen with both visual and auditory presentation, segment assembly errors must affect modality-independent features.

Although some segments may undoubtedly be more critical than others to the identification of a particular item (e.g., Brown & Hulme, 1995), Neath and Nairne (1995) chose the simplifying assumption that any segment error will result in the same loss of information as any other. Regardless of the number of segment assembly errors, it seems likely that some information will remain, even if that information is only disassembled segments; thus, Neath and Nairne again chose a simplifying assumption that a segment assembly error affects half of the modality-independent features (see Neath & Nairne, 1995, for more details). The feature model predicts that there will be no difference in recall between two sets of equivalent words that differ only in pronunciation time (the so-called time-based word-length effect), which appears to be the case (Lovatt et al., 2000, 2002; Neath et al., in press). Word-length effects will be seen only when the short and long items vary in the number of segments.

Modality and Word Length Watkins and Watkins (1973) found that the recall difference between short and long visual items was greater than the difference between short and long auditory items. The feature model correctly predicts this finding of a larger word-length effect for visual items than for auditory items (see Table 4.6). The reason is straightforward: The word-length effect is implemented in the feature model as affecting only modality-independent features. Because auditory presentation results in more modality-dependent features than does visual presentation, the effects of a word-length manipulation will affect a smaller proportion of elements in a vector that represents an auditory item, other things being equal.

Table 4.6 The predicted interaction between presentation modality and word length

	Visual	*Auditory*
Short	0.433	0.478
Long	0.322	0.414
Difference	0.111	0.064

NOTE: The word-length effect is larger (there is a larger difference between recall of short and long words) for visually presented items than for auditory items. Values come from simulations using the feature model.

Articulatory Suppression, Phonological Similarity, and Word Length The strongest test of the feature model so far has been to see if it predicts the correct interactions among the various effects just modeled. For the most part, each main effect (word length, phonological similarity) has been modeled independently, and it could easily have been the case that when several effects were performed simultaneously within the model, it would produce inappropriate results. However, the model does predict the correct interactions. Table 4.7 shows the results of one such simulation in which the effects of word length, articulatory suppression, and phonological similarity are combined.

The silent/dissimilar condition is really the control condition, and the word-length manipulation has its effect by increasing the number of mismatches between corresponding primary and secondary memory traces. Because a long word is less likely to be assembled correctly, it is less likely to be matched correctly with the secondary memory trace. Comparing the silent/dissimilar with the silent/similar condition, the phonological similarity manipulation reduces performance by increasing the number of mismatching features between a primary memory trace and the correct secondary memory trace. The reason for this increase is that more overwriting will occur if all the items in the list are phonologically similar: Overwriting changes an element's value to 0, and the secondary memory traces do not contain any zeros. This effect is independent of the word-length manipulation; thus, word-length effects should be seen for both similar and dissimilar items.

Articulatory suppression is modeled by adopting some features from the item being said aloud. On average, these will differ from the original features in the to-be-remembered item, reducing the probability that an item will be sampled. This effect masks the word-length effect because so many features have already been changed by feature adoption that assembly errors are not detectable with standard stimuli.

Table 4.7 The predicted interaction between phonological similarity, word length, and articulatory suppression on recall of auditory items

	Silent		*Articulatory Suppression*	
	Dissimilar	*Similar*	*Dissimilar*	*Similar*
Short	0.608	0.412	0.496	0.321
Long	0.558	0.349	0.507	0.320

NOTE: Articulatory suppression eliminates the word-length effect but does not eliminate the phonological similarity effect. Similar items had a minimum of ten identical features, long items had ten segments, and short items had one segment. Compare with Table 4.4. Values come from simulations using the feature model.

Serial Recall The feature model predicts not only which items will be recalled well, but the type of errors that will be made (Neath, 1999a). This is due to the perturbation model, which will be discussed in detail in Chapter 13.

Long-Term Effects on Memory Span The feature model offers a natural extension to include the influence of long-term knowledge on memory span. For example, consider the finding that span is higher for concrete than abstract words. Both explanations (Paivio, 1969; Jones, 1988) suggest richer encoding, which is easily implemented by using a larger range of features. Using feature values of +1 and −1 is really the same as using feature values of +1 and +2. Thus, an abstract item might have features with values in the range of 1 to 2, whereas a concrete item might have feature values in the range 1 to 3.

Novel Predictions The feature model allows one to generate predictions in a very precise and unambiguous way. As one example, the model was run to assess the effect of articulatory suppression on the suffix effect. According to PAS (see Chapter 2), articulatory suppression should eliminate the suffix effect because the irrelevant items being articulated should fill up PAS and thus prevent any advantage for the last item in the control condition. According to the feature model, the effects of articulatory suppression and the suffix should be independent because articulatory suppression alters modality-independent features whereas the suffix alters modality-dependent features (see Figure 4.9). This prediction has been confirmed empirically (Surprenant, LeCompte, & Neath, 2000).

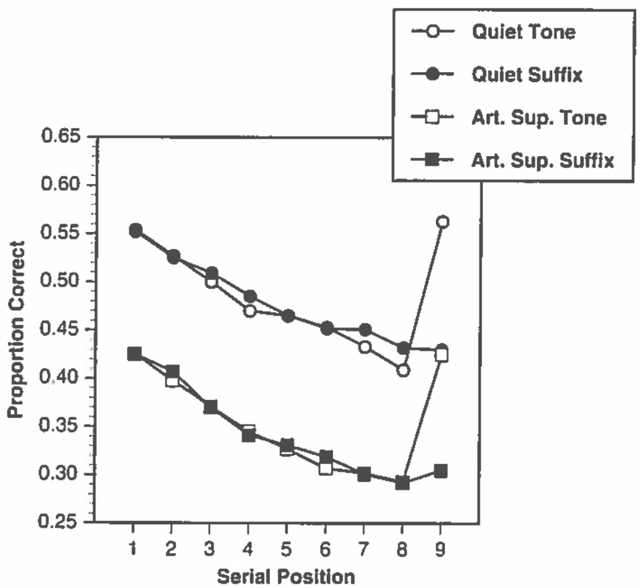

Figure 4.9 An example of a novel prediction of the feature model. Using the same parameter settings as for the previous simulations, the model predicts that a suffix effect will still be seen when subjects engage in articulatory suppression. The simulation models immediate serial recall of a list of nine digits presented auditorily and followed by either a tone or a suffix. Values come from simulations using the feature model.

Critique of the Feature Model

Although the feature model has had remarkable success in accounting for many of the basic phenomena observed when memory is assessed immediately, it has several weaknesses. The major problem with the feature model is that it does not include any specific process that models the passing of time. Many demonstrations have shown that increasing the time between the presentation of an item and recall can actually *increase* the likelihood of recall (e.g., Bjork, 2001; Glenberg, Bradley, Kraus, & Renzaglia, 1983; Neath & Crowder, 1990, 1996). Of course, there are also many demonstrations that increasing the time between presentation and test decreases the likelihood of recall. Because there is no role for time in the feature model, it cannot address these data.

A second major problem is that many experimental manipulations cannot be modeled. For example, the model addresses only serial recall, not free recall or recognition. A third problem is that the model oversimplifies the task facing the subjects: In the model, only one list is being recalled, whereas most experiments ask subjects to recall multiple lists.

The feature model does have some distinct advantages over working memory, whether Baddeley's (1986, 1994) version or Cowan's (1988, 1999) embedded-processes model. First, the feature model can address effects at different serial positions, including modality and suffix effects observable with auditory as well as tactile or olfactory stimuli, whereas the working memory and activation views cannot. Second, it can readily explain the absence of time-based word-length effects, as described above, whereas working memory has to predict that they will occur. Perhaps the most important advantage, however, is that the feature model is a precise statement of what happens during the study and retrieval process. The predictions are unambiguous because the model provides numbers that are easily compared. By this means, it also provides a check on human reasoning. It is quite easy to make an error when working through a complex set of predictions (such as those concerning the interactions among modality, word length, phonological similarity, articulatory suppression, and serial position), and it is very useful to have a computer double-check the line of reasoning.

Chapter Summary

The majority of theories currently used to explain immediate memory phenomena are based on Baddeley's (1986) "working memory" and focus on the phonological loop. This part of working memory was designed to explain the effects of word length, phonological similarity, irrelevant speech, and articulatory suppression and also to explain the interactions among these variables. Although there are many versions of the model (Martin, Shelton, & Yaffee, 1994; Miyake & Shah, 1999; Richardson, 1996), almost all maintain that some form of decay occurs and that this imposes a fundamental limit on the amount of information that can be retained. However, there is relatively little current empirical support for decay (Nairne, 2002; see also Chapter 6). Cowan's embedded-processes model views working memory as activated long-term memory, and so long-term memory is predicted to play a substantial role in short-term memory tasks. This view, although new and still incomplete, nicely handles the many results showing such long-term memory effects. It remains to be seen whether the concepts of activation and deactivation (which seems a lot like decay) can gain much empirical support. The working memory capacity approach emphasizes attention more than memory but retains many working memory components.

The feature model differs from the above views in that it does not use the concept of decay; rather, memory performance is made worse by interference. It can account for all of the phenomena that Baddeley's working memory was designed to account for, and it has predicted new findings, including that the suffix effect remains even when subjects engage in articulatory suppression. It is also the only view that directly addresses modality effects. The major problems with the feature model are that it does not include in any way the passage of time and that it has not yet been applied to as many different experimental paradigms as working memory. It remains to be seen whether the feature model can be successfully extended.