problem it poses for traditional chaining theory, in *Quantitative Analyses of Behavior: Discrimination Processes*, M.L. Commons, R.J. Herrnstein, and A.R. Wagner, Eds. (Ballinger, Cambridge, MA, 1984).

10. H.S. Terrace, Chunking during serial learning by a pigeon: I. Basic evidence, *Journal of Experimental Psychology: Animal Behavior Processes, 17*, 81–93 (1991); M.R. D'Amato and M. Colombo, Representation of serial order in monkeys (*Cebus apella*), *Journal of Experimental Psychology: Animal Behavior Processes, 14*, 131–139 (1988); K.B. Swartz, S. Chen, and H.S. Terrace, Serial learning by rhesus monkeys: I. Acquisition and retention of multiple four-item lists, *Journal of Experimental Psychology: Animal Behavior Processes, 17*, 396–410 (1991).

11. B.O. McGonigle and D. Neapolitan, *Serial learning in children*, manuscript submitted for publication (1994).

12. M.R. D'Amato and M. Colombo, Serial learning with wild card items by monkeys (*Cebus apella*): Implications for knowledge of ordinal position, *Journal of Comparative Psychology, 15*, 252–261 (1989).

13. S. Chen, K. Swartz, and H.S. Terrace, *Knowledge of ordinal position of list items in rhesus monkeys*, manuscript submitted for publication (1994).

14. S. Chen, K. Swartz, and H.S. Terrace, *Serial learning in the monkey II: The emergence of a trial and error strategy during the mastery of successive lists*, manuscript submitted for publication (1991).

15. P.E. Bryant and T. Trabasso, Transitive inferences and memory in young children, *Nature, 232*, 456–458 (1971).

16. B.O. McGonigle and M. Chalmers, Are monkeys logical? *Nature, 267*, 355–377 (1977); B.O. McGonigle and M. Chalmers, Monkeys are rational! *Quarterly Journal of Experimental Psychology, 45B*, 189–228 (1992).

17. M. Harris and B.O. McGonigle, Modelling transitive inference, *Quarterly Journal of Experimental Psychology, 47B*, 319–348 (1994).

18. B.O. McGonigle and M. Chalmers, The selective impact of question form and input mode on the symbolic distance effect in children, *Journal of Experimental Child Psychology, 37*, 525–554 (1984).

19. B. Inhelder and J. Piaget, *The Early Growth of Logic in the Child* (Routledge & Kegan Paul, London, 1964).

20. M. Chalmers and B.O. McGonigle, *An experimental analysis of size seriation skills in children*, manuscript submitted for publication (1994).

21. B.O. McGonigle and M. Chalmers, *An Experimental Analysis of Ordering Skills in Children*, Economic and Social Science Research Council Project Grant Report (British Library, London, 1993).

22. B.O. McGonigle and C. De Lillo, *The spontaneous regulation of strategies in a spatial search task by* Cebus apella, manuscript submitted for publication (1994).

23. B. St. Johnston, *From transitive inference to exhaustive search: Towards self-regulatory models of developmental processes*, unpublished doctoral dissertation, Edinburgh University, Edinburgh (1994).

24. S. Sternberg, S. Monsell, and C.E. Wright, The latency and duration of rapid movement sequences: Comparisons of speech and typewriting, in *Information Processing in Motor Control and Learning*, G.E. Stelmach, Ed. (Academic Press, New York, 1978).

Mechanisms of Verbal Short-Term Memory

Nelson Cowan

A fundamental concept in cognition is that only a small amount of information can be kept in mind at a particular moment. William James[1] labeled this phenomenon "primary memory," which is now commonly called "short-term memory." These terms have been used in contrast to "secondary" or "long-term" memory, which refer to the much larger amount of information saved in the brain for later retrieval. Most psychologists consider short-term memory to be important in much of cognition, playing a key role in the "working memory" system that holds onto the information needed for comprehension and problem solving.[2]

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Yet the empirical support for short-term memory as a distinct mechanism has been weak enough that many psychologists have doubted the concept. Across many years, researchers have debated whether memory tests over short and long periods of time tap into different processes, or whether instead the results of all memory experiments can be described by a unitary set of rules that is valid regardless of the delay imposed between the stimulus presentation and memory test.[3] According to the unitary memory hypothesis, for example, remembering a phone number for a few seconds is accomplished by the same rules of learning as memorizing and later reciting the Pledge of Allegiance.

Though the passage of time would cause forgetting according to either hypothesis, the proposed mechanisms of forgetting differ. Both hypotheses allow that the passage of time can remove the subject from the context in which the information to be recalled was encountered originally. However, the unitary memory theorists rely on that sort of principle exclusively to explain forgetting, whereas the short-term memory theorists assume in addition that a transient representation of some aspects of stimulation, such as the detailed sensory and phonetic properties of spoken words, exists but is lost within several (up to about 30) seconds, unless the transient representation is renewed before that time through some sort of rehearsal. This review discusses recent research that supports the short-term memory hypothesis in the verbal domain and describes relatively specific ways in which short-term memory might operate.

FINDINGS FROM SPAN AND SUPRASPAN RESEARCH TRADITIONS

Most of the evidence for verbal short-term memory storage has come from two basic types of procedures: span and supraspan. In memory span procedures, lists of unrelated verbal items are to be recalled immediately after their presentation. The lists increase in length until sub-

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jects no longer can recall them, and the longest lists correctly recalled serve as approximate indicators of short-term memory capacity. In supraspan procedures, the subject is also asked to recall lists of unrelated verbal items, but more items are presented on each trial than the subject can recall. Researchers have found that the most recent items on the list are more likely to be recalled than items earlier on the list (the *recency effect*). Some investigators have taken this phenomenon to reflect a contribution of short-term memory, though this specific conclusion has been questioned rightfully, as I explain later.

Verbal memory span experiments have revealed an intriguing, brief time limit in recall. Specifically, given a particular subject and stimulus set, the mean span is roughly equal to the largest amount that the subject can pronounce, speaking quickly, in about 2 s. This relation has been obtained across variations in the subject's age, in the language, and in the length of words in the list to be recalled.[4]

Alan Baddeley explained this linear relation between speech rate and memory span by positing an articulatory-loop mechanism in short-term recall.[5] According to this account, a phonological representation of each list item is stored in short-term memory automatically, but fades within 2 s unless it is refreshed through covert verbal rehearsal. It is assumed that the faster one can pronounce the items, the faster one can rehearse them covertly and, therefore, the more items one can rehearse in a repeating loop without losing the short-term representation. This type of account depends inevitably on the assumption that there is a distinct mechanism for short-term (transient) memory storage.

Unlike memory span procedures, supraspan procedures allow investigations of the pattern of errors across serial positions. For 10 or more years, it was thought that the privileged recall of the most recently presented items in a list indicated a contribution of a separate short-term memory mechanism. A finding taken to support that account was that the recency effect was eliminated when a period of distracting activity (lasting, e.g., 20 s) separated the list and the recall periods. The usual interpretation was that the interposed activity allowed the short-term representation of the list items to decay.[6]

This view of supraspan experiments has been disproved by studies using a "separated-item" testing procedure. In that procedure, there is a period of distracting activity not only after the last list item, but after each list item. Despite the final distracting period, which should disrupt short-term storage, the recency effect is obtained with this procedure.[7] Accounts of these results typically favor a unitary mechanism that is common to immediate and separated-item recall, such as the enhanced temporal distinctiveness of the final items in a list.[8]

There is much left to reconcile between the two views. The unitary memory theorists have not provided an alternative account of the linear relation between speech rate and memory span that could operate without a transient storage mechanism. The short-term memory theorists, for their part, have not proven that a particular model of span tasks is correct and have not demonstrated that short-term storage is needed to explain the results of supraspan tasks. However, recent research with both span and supraspan tasks shows that short-term memory exists, and reveals some of its mechanisms.

SHORT-TERM MEMORY LOSS DURING VERBAL OUTPUT DELAYS

In the conventional form of the articulatory-loop theory, the existence of a short-term memory store can only be inferred indirectly. A correlation between articulatory rate and memory span is accounted for with a proposed causal relation between covert rehearsal speed and memory span, and rapid covert rehearsal is assumed to be helpful because it counteracts short-term memory loss. However, recent studies suggest that there may be more direct ways of observing short-term memory loss and its role in processing during spoken recall.

Though short-term memory may be lost while the subject is silently receiving the list to be recalled, because of a limit in covert rehearsal speed,[5] my colleagues and I[9] demonstrated that short-term memory is lost also while the subject is recalling the list aloud. While the first word is being repeated, the other words cannot be rehearsed and may be forgotten; while the second word is being repeated, the remaining words may be forgotten; and so on. Our demonstration was a detailed analysis of the *word-length effect*, the well-known finding that words in a list can be recalled more successfully when they are phonologically shorter and therefore can be pronounced more quickly.[4] We hypothesized that short words are advantageous for recall not just because they can be rehearsed more quickly than longer words, but also because short words do not impose as much of a delay in overt verbal recall.

In our study, which used a supraspan procedure, each printed list could begin with either short or long words and, independently, could end with either short or long words. At the end of each list presentation, there was a cue signaling a forward or a backward order of recall. To the extent that the word-length effect occurs because of forgetting during verbal responding, the length of whatever words are to be recalled first should be more important than the length of words to be recalled later (because the words recalled earlier delay the recall of a larger number of additional words than do those recalled later).

The results, shown in Figure 1, were as predicted. For the recall of the entire list, the word lengths that mattered most (producing significant effects within a recall order) were the lengths of the words that were to be recalled early on (i.e., the first words in the list for forward recall and the last words in the list for backward recall).[9] The data suggest that word length modulated memory loss largely during overt recall, and not only during input and covert rehearsal. During overt spoken recall, moreover, memory loss can be examined in some detail.

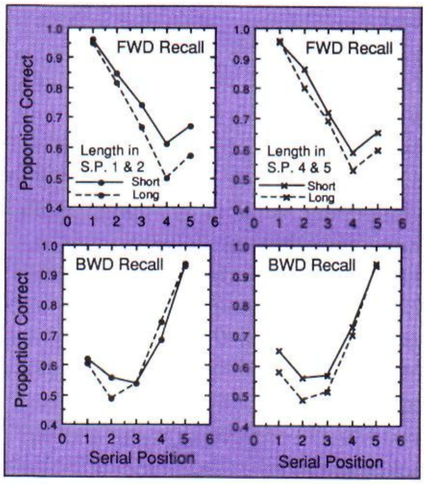

Fig. 1. Proportion correct as a function of the length of words in the first two (left-hand panels) and the last two (right-hand panels) of five serial positions (S.P.). Results are shown separately for forward recall (top panels) and backward recall (bottom panels). The length of the third (middle) word varied randomly within each condition, and there were filler lists to prevent subjects from detecting a pattern. Length effects were significant only for the length of words in whichever half of the list was to be recalled first (top left and bottom right panels). Data from Cowan et al.[9]

DIRECT SUPPORT FOR THE SHORT-TERM MEMORY CONCEPT

The word-length effect, unlike many of the phenomena that traditionally had been taken to reflect a contribution of short-term memory, never had been examined using a separated-item technique, so that was our next step. Our version of the short-term memory hypothesis attributes the word-length effect largely to greater short-term memory loss during spoken recall when longer words are pronounced. According to our hypothesis, the word-length effect should not occur if there is a filled delay at the end of the list, such as the one imposed in the separated-item procedure, because the delay should result in the dissipation of all information in short-term storage, leaving no short-term memory to decay subsequently during spoken recall. The word-length effect should not occur with this procedure because performance should reflect only the retrieval of information saved in long-term memory. In contrast to this hypothesis, unitary memory theorists could expect word-length effects in separated-item recall similar to those obtained in immediate recall, given that these theorists have placed great importance on the fact that results for separated-item recall so far have resembled the results of immediate recall.

We tested these predictions recently in an experiment[10] using backward recall and manipulating word length separately in the first and second halves of the list. With a separated-item procedure, the advantage for short words was not obtained, whereas with an immediate-recall procedure, it was. These results reconfirm that there is a process, presumably short-term storage, that can be used only in immediate-memory tasks. The word-length effect depends on such a short-term process rather than on unitary principles that apply to any kind of memory test regardless of the time periods involved.

MECHANISMS OF SHORT-TERM MEMORY LOSS AND REACTIVATION

In the supraspan task, the clues to underlying mental processes are simply the failures in recall. Using the span task, however, it is possible to gain further clues to mental processes from the timing of correctly recalled lists. Recently, my colleagues and I have taken this less-traveled route.[11] We set out to distinguish between two models of short-term memory loss during the recall period in a span task, shown in Figure 2. In the first model, memory is lost steadily throughout the recall period, as several researchers have assumed. In the second model, memory loss occurs only while the subject is pronouncing an item in recall. Then, during interword pauses in the recall period, something happens to refresh the short-term memory representations of some items. The evidence to date suggests that the second model is correct and, further, that the covert process during interword pauses in recall may be a rapid memory search undertaken to determine which item is to be pronounced next.

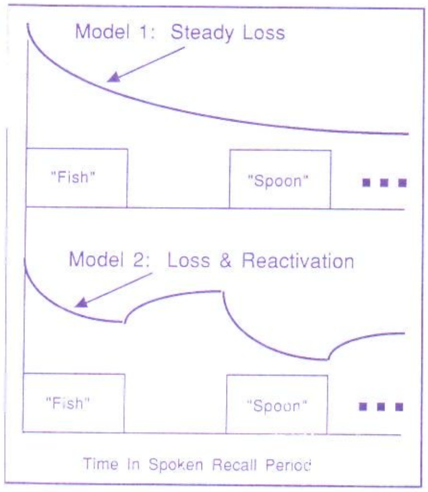

Fig. 2. Two possible models of short-term memory loss during the spoken recall period in a memory span task: steady memory loss (top panel) and loss during words, with reactivation during pauses (bottom panel). After Cowan.[11]

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According to the steady-loss model, the basis of individual differences in memory span presumably is that some subjects can speak more quickly during recall than others, and thus can recall more items during the fixed, limited period of short-term memory availability. Our work with children ages 4 through 8 appears to contradict this account, however.[11] Correct spoken recall was not at all limited to a fixed, 2-s period. Instead, subjects with different memory spans recalled their span-length lists at comparable rates of about 1 s for each correctly recalled item, resulting in longer lasting recall for more capable subjects. Older children *can* speak more quickly than younger ones, but they do not do so in the recall task. Thus, these data lend support to the loss-and-reactivation model of short-term memory.

Further clues to the processing taking place during the recall period came from examining the duration of word responses and interword pauses in recall.[11] First, in the subjects tested (children ages 4 through 8), though the number of syllables in each word in the list affected the durations of words spoken in recall, the number of syllables did not affect the durations of subjects' interword pauses in recall. Given the seemingly ubiquitous finding of word-length effects whenever verbal rehearsal is used, the absence of word-length effects on interword pauses suggests that the covert processes carried out in the pauses generally do not include rehearsal, at least not in the age group studied. Instead, a more rapid memory search process may be carried out. Previous studies of memory search focusing on adults' reaction times in reporting whether a probe item appeared in a short list also failed to obtain word-length effects.[12]

Second, in our studies, a subject's memory span was found to bear no relation to the duration of words in the subject's spoken recall,[11] in contrast to the clear effect of the length of stimulus words on word durations in the responses. However, subjects with higher memory spans had shorter interword pauses in the recall of lists of a particular length. Moreover, for a given subject, the pauses were shorter within shorter lists than within longer lists. To illustrate these relations, Figure 3 shows some data from the two studies in which interword pauses in verbal recall were examined.[11] Data Bars A and B are from my study of individual differences in recall for monosyllabic words in 4-year-olds. Interword pauses within the responses to three-word lists were longer in subjects for whom this was the span length (A) than in more advanced subjects for whom this was one word below span (B). Data Bars C and D are from a developmental study, averaged here across lists of monosyllabic, bisyllabic, and trisyllabic words. The pauses were longer for 4-year-olds recalling their span-length lists (C) than for 8-year-olds recalling lists that were of a similar mean length but one word below their span (D). For data bars reflecting below-span list lengths (B and D), the Xs above the bars show how long interword pauses were for the same subjects in span-length lists. Clearly, though interword pauses increased with list length, for a particular list length, the pauses were shorter in more capable or older children. Such effects on interword silent intervals might be attributed to a speedup in covert processes that is known to occur as children mature.[13]

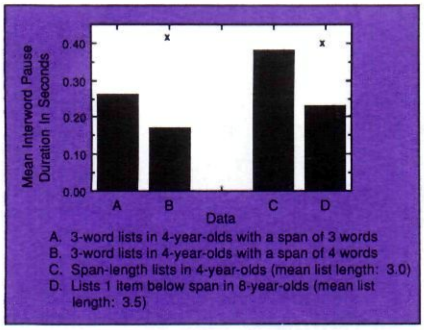

Fig. 3. Effects of individual differences, age, and list length on interword pauses in spoken recall. For a particular list length, subjects who had a lower span (A and C) made longer interword pauses than subjects who had a higher span (B and D). The *X* marks above Data Bars B and D indicate the mean lengths of interword pauses for those same subjects in span-length lists. The variables shown in this figure did not affect the durations of words during recall, whereas the number of syllables in each word affected word durations but not interword pauses. Data Bars A and B from Cowan;[11] Data Bars C and D from Cowan et al.,[11] collapsed across lists of short, medium, and long words.

In sum, whereas the original articulatory-loop model assumed that word-length and age effects on memory span both work by modulating the speed of covert rehearsal, the output timing research indicates that the mechanisms of age and word-length effects cannot be identical. Word length affects the duration of words in the recall response, whereas age affects instead the duration of interword pauses.

We are not yet sure what processes take place during interword pauses. However, the literature provides clues. Measures of the timing of verbal responses in experiments conducted by Saul Sternberg and his associates[14] resemble the studies I have discussed so far, but with adult subjects only, subspan lists only, and the requirement to speak as quickly as possible. A large number and variety of such experiments produced results suggesting to Sternberg that while responding, subjects conduct a rapid memory search between words to determine which word to say next, but that the search includes all items in the list, even items that have been recalled already. For example, as the number of items in the list increased, interword periods became longer, but the durations of the internal portions of words did not change. (In Sternberg's study, the interword period for the word pair "copper, token," for example, would be defined as the period including the "–er" of "copper" and the "t–" of "token," and the internal portions would be the remaining parts of the response.) In addition, interword durations were constant across serial positions. In all of these respects, the results appear to agree with our own results in the span task.

The processes that affect memory during the spoken recall period in memory span tasks, in children at least, are consistent with the bottom panel of Figure 2 and a working model that might be summarized as follows. The length of stimulus words affects how much time passes, and therefore how much of short-term memory is lost, while words are spoken during recall. The subject's mnemonic capability helps to determine how quickly or efficiently memory search can occur during silent pauses in recall, and this memory search may, as a useful byproduct, reactivate some items in short-term memory; faster reactivation in more capable or older subjects would prolong short-term memory activation in these subjects, and thus can explain why their span-length recall responses last much longer than those of less capable or younger subjects.

I must caution that the effects described here are likely to be based on only some of the mental processes available to subjects to carry out short-term memory tasks. The effects occur most reliably when the stimuli on each trial are drawn from a small set and recall in the correct serial order is required. Even under such circumstances, though, there are some few subjects who may be able to circumvent the short-term memory mechanisms I have discussed by using special strategies, such as rapidly forming semantic associations to reorganize the materials to be recalled.[15]

CONCLUSIONS

There is a set of phenomena specific to short-term memory procedures that cannot be explained by unitary rules that have been proposed to apply to all memory tasks. These phenomena include the effects of word length and age: Longer words allow more loss of information from short-term memory not just by slowing the rate of covert rehearsal, but also by slowing the rate of overt spoken recall. Older subjects are able not just to rehearse more, but also to search through memory more efficiently, decreasing the length of pauses in recall and possibly increasing the rate of refreshment of items in a short-term store. The unitary memory concept cannot explain these findings easily because they depend on the specific amount of time in which stimulus information can be lost from short-term memory, and not only on more general factors such as the temporal distinctiveness of stimuli.

Given that there is a fundamental human limitation in short-term memory and in skills that rely on it, it is important to know what causes the limitation. Recent research demonstrates that, although a unitary set of rules describing learning is important, a special, short-lived memory representation also plays an important role.

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Notes

1. W. James, *The Principles of Psychology* (Henry Holt, New York, 1890).

2. J. Cantor, R.W. Engle, and G. Hamilton, Short-term memory, working memory, and verbal abilities: How do they relate? *Intelligence, 15,* 229–246 (1991); R.H. Logie, K.J. Gilhooly, and V. Wynn, Counting on working memory in arithmetic problem solving, *Memory & Cognition* (in press).

3. For the two-process view, see N. Cowan, Activation, attention, and short-term memory, *Memory & Cognition, 21,* 162–167 (1993). For the unitary view, see R.G. Crowder, Short-term memory: Where do we stand? *Memory & Cognition, 21,* 142–145 (1993).

4. C. Hulme and V. Tordoff, Working memory development: The effects of speech rate, word length, and acoustic similarity on serial recall, *Journal of Experimental Child Psychology, 47,* 72–87 (1989), and references therein.

5. A.D. Baddeley, *Working Memory* (Clarendon Press, Oxford, 1986).

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

7. R.A. Bjork and W.B. Whitten, Recency-sensitive retrieval processes in long-term free recall, *Cognitive Psychology, 6,* 173–189 (1974); R.L. Greene, Sources of recency effects in free recall, *Psychological Bulletin, 99,* 221–228 (1986). Greene also describes certain other effects that previously had been attributed to the contribution of a short-term storage mechanism.

8. R.G. Crowder, *Principles of Learning and Memory* (Erlbaum, Hillsdale, NJ, 1976); A.M. Glenberg and N.C. Swanson, A temporal distinctiveness theory of recency and modality effects, *Journal of Experimental Psychology: Learning, Memory, and Cognition, 12,* 3–15 (1986).

9. N. Cowan, L. Day, J.S. Saults, T.A. Keller, T. Johnson, and L. Flores, The role of verbal output time in the effects of word length on immediate memory, *Journal of Memory and Language, 31,* 1–17 (1992); for a convergent result, see L.A. Henry, The effects of word length and phonemic similarity in young children's short-term memory, *Quarterly Journal of Experimental Psychology, 43A,* 35–52 (1991).

10. N. Cowan, N.L. Wood, and D.N. Borne, Reconfirmation of the short-term storage concept, *Psychological Science, 5,* 103–106 (1994).

11. N. Cowan, Verbal memory span and the timing of spoken recall, *Journal of Memory and Language, 31,* 668–684 (1992); N. Cowan, T. Keller, C. Hulme, S. Roodenrys, S. McDougall, and J. Rack, Verbal memory span in children: Speech timing clues to the mechanisms underlying age and word length effects, *Journal of Memory and Language, 33,* 234–250 (1994).

12. W.G. Chase, Does memory scanning involve implicit speech? in *Attention and Performance VI,* S. Dornic, Ed. (Erlbaum, Hillsdale, NJ, 1977), and references therein.

13. S. Hale, A global developmental trend in cognitive processing speed, *Child Development, 61,* 653–663 (1990), and references therein.

14. S. Sternberg, C.E. Wright, R.L. Knoll, and S. Monsell, Motor programs in rapid speech: Additional evidence, in *Perception and Production of Fluent Speech,* R.A. Cole, Ed. (Erlbaum, Hillsdale, NJ, 1980), and references therein.

15. S. Della Sala, R.H. Logie, C. Marchetti, and V. Wynn, Case studies in working memory: A case for single cases? *Cortex, 27,* 169–191 (1991).

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