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Covert Processes and Their Development In Short-term Memory

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TABLE OF CONTENTS

Introduction [centered heading]

Immediate, serial verbal recall could be viewed as one of the simplest tasks used by investigators of cognition and intelligence. On every trial, a list of items is presented to the subject, who is supposed to reproduce that list verbatim. The correct response is the same as the stimulus. What could be simpler? It would be tempting to try to account for performance in the task in an equally simple manner. How would that account go? Perhaps we have an internal recording of the sensory impression of the list items, along with a verbal output process that can convert the sensory impression back into spoken or written words; or perhaps each sensory impression is immediately converted into a motor plan and the motor plans are retained in a memory store, in order, until the list ends and the response can begin.

Notice that even these maximally simple accounts of performance rely on mental processes that cannot be observed directly (e.g., in these accounts, a sensory-to-motor conversion process and either sensory or motor memory storage). Such "covert" mental processes can be studied indirectly, however, through attempts to draw inferences about what must occur in the brain and mind to account for performance across a variety of test conditions. Our thesis is that progress has been made recently in understanding the covert mental processes that take place in short-term memory tasks, though we still have far to go for a complete understanding. Unfortunately for inquiring minds, human performance does not appear to be as simple as the possibilities sketched above; but it does appear reasonably orderly.

In the present chapter, we will focus on recent progress in understanding immediate, serial recall tasks involving both verbal and visual stimuli. The organization of the chapter is by the specific covert processes, which will be discussed one at a time although, in reality, multiple covert processes appear to operate together to produce an adequate response. We believe that the mnemonic processes underlying this seemingly simple sort of task actually may be important in a much broader variety of problem-solving activities.

The list of processes that we will examine is not exhaustive, but we have attempted to include the processes that have attracted researchers' attention the most. These include 1) stimulus recoding, 2) speech articulatory processes, 3) short-term memory search, and 4) the retrieval of information from long-term memory as support for immediate memory performance. We will rely on previous literature reviews where we can, allowing us to focus on what we consider to be some key findings and controversial points within the research literature.

Throughout the chapter, we also will consider how these covert processes may account for developmental and individual differences in immediate recall. The emphasis is on normal childhood development, but with some evidence from learning disabilities and adult aging considered, also. If differences in recall can be related to other abilities, that can help us eventually to determine what the causal variables underlying immediate recall may be. The developmental and individual-difference research reflects back on our basic process knowledge and informs it considerably.

Near the chapter's end we will ask how well a simple, general factor, the overall speed of processing, accounts for an individual's level of ability in immediate recall tasks. We will conclude with a consideration of future directions for research on covert processes in short-term memory.

Stimulus Recoding [centered heading]

Within the confines of the immediate, serial verbal recall task, one can present stimuli in the form of spoken words, printed words, or pictures. One can require a spoken response, a written response, or some form of manual response. At some point, the subject must decode the incoming stimulus and re-encode it in terms of the planned response modality, at least when the stimulus and response modalities differ. We refer to the decoding and re-encoding processes together as stimulus "recoding."

There are several reasons why the nature and timing of the recoding process logically could influence recall. Subjects could differ in how difficult it is for them to recode the materials, which could affect (a) the fidelity of the recoding process, or (b) the amount of various processing resources that must be taken away from strategic mnemonic activities in order to accomplish that recoding. Subjects also could differ in (c) the degree to which they have the foresight to do the recoding at convenient points in the trial, with less able subjects therefore forced to do the recoding at later, less opportune points. (We do not know, at present, what points would be inopportune.) A final possibility is that (d) there is some choice in how to recode and that the ideal route involves going through some intermediate coding modality, not directly from the stimulus modality to the response modality.

Spoken Responses to Spoken Lists [left-justified heading]

One cannot readily convert a spoken stimulus into a spoken response without going through an intermediate, abstract code. Consider how difficult it is, for example, to repeat a single word spoken in a foreign language, especially one with a phonology that is very different from that of one's own language. Familiarity with the phonemes helps one repeat them accurately, and familiarity with the lexical item greatly helps one recall the sequence of phonemes. These effects occur presumably because a spoken word activates phonological and lexical codes in long-term memory.

It seems quite likely that some sort of internal recoding is needed, therefore, even in the case of spoken responses to spoken lists. However, the recoding differences might be expected to be smaller than in the case of written or pictorial stimuli, for which the initial stimulus encoding is more complex. A written word needs to be read and a picture needs to be interpreted in light of one's world and lexical knowledge; and individuals differ greatly in the amount of knowledge. The recoding differences also might be expected to be larger in the case of a written response, for which a knowledge of spelling is needed. The difficulty of a manual response would depend on what coding cues are being responded to manually (e.g., written versus pictorial response choices). In any case, it seems likely on an a priori basis that there would be individual and age-related differences in the speed and accuracy with which internal recoding could proceed.

A study by Case, Kurland, and Goldberg (1982) was seminal in bringing a concern about recoding into the immediate recall literature. Their subjects (children aged 3 and 6 years, and adults) received a test of memory span for spoken lists composed of subsets of the words star, ball, fish, shoe, tree, chair, and cup (which, presumably, all the children knew). They also received a test in which isolated spoken words were presented and the subject was to repeat each word as quickly as possible. The correlation between span and the mean identification time (defined as the time between an isolated word and the onset of the response) was -.74. When age was partialled out, the correlation remained significant at -.35.

It should be pointed out that the repetition task demonstrates age and individual difference effects in recoding, but it is not clear what the critical covert processes are. The critical difference could be either in attaching a lexical identity to the spoken input, or in creating and initiating a motor plan based on that lexical identity. As an excellent review of the relevant literature (Henry & Millar, 1993) indicates, the results typically have been interpreted as evidence of the former. The measure is termed "identification time" even though the time of response planning also is included in the estimate.

It also is important to note that one must continually take seriously the caveat that correlations cannot be interpreted as clear evidence of causation. Henry and Millar (1991) attempted to examine the causal role of identification times by controlling for them. The subjects were children 5 and 7 years of age. An identification time measure similar to that of Case et al. (1982) was used to produce a set of stimuli for each subject, such that the identification times were matched across subjects and across ages. Despite a completely successful match for familiar, monosyllabic words, older children's mean span (4.13) was significantly higher than that of younger children (3.29). At the very least, this suggests that identification time is not the sole causal factor in developmental changes in memory span.

What alternative account of the correlation between identification time and span can be found? It seems quite unlikely that short-term memory skills play a critical role in carrying out the identification- time task. Therefore, the remaining hypothesis is that a third factor (or set of factors) underlies the variance common to span and identification time tasks. For example, the time it takes to identify an item might be correlated, though imperfectly, with the time it takes to carry out other processes that are more directly relevant to memory span performance. This type of hypothesis has been prevalent in recent research and will be discussed later in the chapter.

Tasks Involving Stimuli or Responses in Other Modalities [left-justified heading]

The recoding considered so far is the minimal recoding necessary when the stimuli and responses both are in the same, spoken modality. Additional recoding processes may be necessary when they differ in modality. Aside from the obvious developmental increase in reading and writing ability in childhood, facility with verbal labelling is known to increase with age (Henry & Millar, 1993). Consequently, whenever the stimuli are pictorial in nature and verbal responses are required, young children's performance may be limited by their verbal labeling abilities.

The recent work of Hitch and his colleagues is quite consistent with this proposed factor. The results obtained in several studies (Hitch, Halliday, Schaafstal, & Schraagen, 1988; Hitch, Halliday, Dodd, & Littler, 1989; Halliday, Hitch, Lennon, & Pettipher, 1990; Hitch, Halliday, Schaafstal, & Heffernan, 1991) suggest that children below the age of 7 years do not consistently use labels for pictorial stimuli. In all of these studies, stimuli were presented in either pictorial or spoken form, and spoken responses were required. There were specific disadvantages for younger children that occurred only with the pictorial stimuli, suggesting that the difficulty was in converting these stimuli to a verbal form.

Role of phonological similarity and word length effects. [paragraph run-in heading]

Rather than relying solely upon developmental differences in memory span, which could be attributed to many different factors, the studies by Hitch and his colleagues, cited above, focused on the well-established "phonological similarity" and "word length" effects. The phonological similarity effect is the finding that short-term memory performance is less accurate for lists of words that are phonetically similar to one another than for dissimilar lists (Conrad, 1964). The effect is much smaller in very young children (Conrad, 1971; Hulme, 1984), which has been interpreted to mean that items are confused with one another in phonological storage or during retrieval from storage for recall (e.g., Baddeley, 1986). The applicability to picture recall in children is that the phonological similarity effect should not occur if the subject has not recoded the stimuli into a phonological form.

The word length effect is the finding that short-term memory performance is less accurate for lists composed of phonetically longer words (Baddeley, Thomson, and Buchanan, 1975; Baddeley, 1986). Given that this effect is abolished when articulation is suppressed during both the reception of the list and written recall (Baddeley, Lewis, & Vallar, 1984), it has been assumed that the word length effect reflects the contribution of articulatory activity to recall, and that longer words permit more forgetting while words are being articulated covertly during the presentation of the list (Baddeley, 1986) or overtly in the spoken response (Cowan et al., 1992; Henry, 1991). Similar to the phonological similarity effect, the applicability to picture recall in children is that the word length effect should not occur unless a phonological recoding of the stimuli is undertaken at some point.

All of the experiments by Hitch and his colleagues cited above included conditions in which the stimuli consisted of line drawings, and they all required a spoken response. Hitch et al. (1988) found that visual similarity between the drawings impaired recall in 5-year-old children but not 10-year-old children, as would be expected if only the older children recoded the stimuli into a verbal form. Hitch et al. (1989) investigated word length effects at various ages in childhood and found them in children as young as 4 years when the stimuli were spoken, but not until 8 years when the stimuli were line drawings. This finding again suggests that only the older children recoded the line drawings into a verbal form, permitting the word length effect to occur. Halliday et al. (1990) used an articulatory suppression task (repeating a word over and over during the recall task) to prevent any covert articulation. This eliminated the phonological similarity and word length effects in the recall of line drawings in 11-year-olds, and reduced their performance to the level of 5-year-olds without articulatory suppression. Finally, Hitch et al. (1991) found that 5-year-old children produced word length effects and phonological-similarity effects when they were required to label line drawing stimuli during their presentation, but not when the children remained silent during the presentation. All of these findings are consistent with an interpretation in which young children convert the pictures to a phonological form (and therefore yield phonological similarity and word length effects) only if they are instructed or encouraged to do so.

In the above research, visual materials might be recoded primarily because of the requirement of verbal recall. However, Schiano and Watkins (1981) found phonological similarity and word length effects for pictures in adults, even though the response was nonverbal: Subjects were to select the pictures presented from a larger deck, and were to place the selected pictures in the correct serial order.

A developmental study by Hulme, Silvester, Smith, and Muir (1986), basically modelled after the one by Schiano and Watkins (1981), contradicts the findings of Hitch and his colleagues regarding the abilities of young children. In the Hulme et al. study, each stimulus picture was overturned after its presentation and, after the list was presented, a complete set of pictures was revealed. The subject was to match each overturned picture to the corresponding picture in the response set. The pictures had names that were monosyllabic on some trials and multisyllabic on other trials. A length effect was obtained in the youngest children tested (4-year-olds), even when the pictures were not labelled at the time of their presentation (Experiments 2 and 3). The third experiment also showed that the length effect was abolished with articulatory suppression during presentation of the list.

It is not yet clear why the studies with young children are discrepant. The response modes differ, but one would think that the use of a nonverbal response by Hulme et al. (1986) would, if anything, discourage labelling of the picture stimuli. One potentially relevant factor is that Hulme et al. (1986) did not use a span procedure, but instead presented three items per trial to the 4- and 5-year-old subjects. However, Hitch et al. (1991) also used 3-item sets with 5-year-olds, with a spoken response, and they did not find a length effect in these subjects (even though the overall level of recall was higher than Hulme et al. obtained).

Hulme et al. (1986, Experiment 2) attempted to detect children's articulatory movements during the presentation of unnamed pictures, and found that naming occurred in 4-year-olds on about 73% of those trials. Perhaps the amount of naming was greater than in other studies. However, it remains unclear what factor accounts for the difference in the likelihood of 4-year-olds to name pictures. In any case, it seems likely that word length effects and phonological similarity effects for pictorial stimuli occur only if the subject recodes the pictures into a verbal form, and that this verbal recoding is at least somewhat less readily accomplished across a variety of stimuli by young children.

These conclusions in turn lead to a more fundamental statement. It is not the stimuli or the responses per se that primarily govern the nature of immediate recall performance. Instead, it is the nature of the internal memory codes that is critical. To the extent that very different kinds of stimuli and responses are converted to comparable mental codes (e.g., to a phonologically based code), then they are processed in a comparable manner during the recall task. Cowan and Saults (in press) pursued this notion further, discussing the variety of sensory, phonological, orthographic, and semantic codes that can be formed for verbal stimuli and used in combination.

The act of verbal recoding cannot apply to all pictorial stimuli, as there are sure to be visual stimuli too complex for that type of recoding to be accomplished adequately. The strategies and covert processes used in retaining more complex visual stimuli have been examined in other studies (e.g., for a review see Baddeley, 1986), but we will treat them as beyond the scope of the present chapter.

Speech Articulatory Processes [centered heading]

The above discussion indicates that at least older children and adults verbally label picture stimuli and tend to rely on that recoding of the stimuli in recall, even when the response mode is nonverbal. As yet, we have not suggested why this might be the case. One good reason, however, is that verbal recoding may allow more efficient covert articulatory rehearsal of the material to be recalled than would be the case if the material were not verbally recoded. Subjects may use rehearsal, for example, to retain the serial order of stimuli.

This notion of covert articulatory rehearsal is the cornerstone of a predominant account of short-term memory performance (e.g., Baddeley, 1986; Gathercole & Baddeley, 1993). For example, in this account it was suggested that the word length effect stems largely from rehearsal, because the effect is abolished if articulatory suppression is required during both the presentation and the written recall of word lists (Baddeley et al., 1984). The basic idea is that timely rehearsal is needed to refresh a decaying representation of the list items before it is too late (within about 2 seconds of the previous presentation or rehearsal of the item), and that longer words are recalled more poorly because they take longer to rehearse. In contrast, the account of the phonological similarity effect does not depend on the notion of rehearsal. Instead, it assumes that similar items are confused in the act of retrieval from phonological storage.

We will present a critical appraisal of the role of covert rehearsal within this theoretical framework. Then we will examine consequences of developmental and individual differences in the speed of rehearsal and overt articulation.

Critical Appraisal of the Role of Covert Rehearsal [left-justified heading]

Within the general constraints of the model of short-term memory developed by Baddeley (1986, and this volume), it need not be the case that word length effects occur totally because of memory decay during covert rehearsal. Another possibility is that memory could decay while words are pronounced during verbal responding. Longer words take longer to pronounce in recall, thereby allowing more time for the memory of other words to decay.

Cowan et al. (1992) obtained strong evidence that at least some of the effect of word length can result from the duration of overt verbal recall. They presented lists of words visually, following each word by a cue to recall the words either in the forward or the backward order. Adults were to repeat each list aloud following the cue. There were four types of list: those composed of short words, those composed of long words, those beginning with short words but ending with long words, and those beginning with long words but ending with short words. The finding was as predicted according to a recall delay factor. Only the length of words to be recalled first made a difference, and the length of those words affected performance throughout the list. Presumably, this occurred because the length of words to be recalled first determined the length of the delay before recalling the remaining words. However, the results did not rule out the possibility that rehearsal is important also.

Henry (1991) showed that both rehearsal and recall delay are important factors to consider in understanding developmental changes in memory span. She tested phonological similarity and word length effects for spoken lists in children, using a verbal response on some trials and a nonverbal response, pointing to pictorial representations of the words, on other trials. With a verbal response, both 5- and 7-year-olds yielded phonological similarity and word length effects. However, with a pointing response, only 7-year-olds yielded these effects. This suggests that events taking place during the recall period are the main (or only) factor underlying the effects in 5-year-olds, whereas covert rehearsal is an additional factor in 7-year-olds. It appears from this research that rehearsal is important in recall, though it may not play the central role that Baddeley (1986) suggested for it.

Of course, Henry (1991) is not alone in demonstrating that young children generally do not engage in covert rehearsal. Two recent reviews (Gathercole & Hitch, 1993; Henry & Millar, 1993) together do an excellent job of summarizing evidence for this. However, the impact of Henry's study is to resolve a contradiction between the fact that word length effects are obtained with spoken stimuli in children too young to rehearse (e.g., Hitch et al., 1989) and the supposition that word length effects result from rehearsal processes.

Another account of the word length effect also has been offered. Caplan, Rochon, and Waters (1992) suggested that it might originate in the phonological complexity of words and their effect on the speech planning process. In two previous studies (Baddeley et al., 1975; Cowan et al., 1992) the word length effect was obtained even with short and long word lists matched for the number of phonemes and syllables, but differing in the necessary time for pronunciation. Caplan et al. questioned the adequacy of the match between words in the study of Baddeley et al. In experiments in which Caplan et al. used new sets of words matched for phonemes and syllables, no word length effect was obtained. However, it is important to realize that Caplan et al. had subjects respond by pointing to pictures representing the words. Perhaps a portion of the word length effect can be obtained when the lists are matched for phonemes and syllables, but only because of delays in pronouncing the longer words during recall, given a verbal response. It may well be the response modality, rather than inadequacies in previous stimulus sets, that accounts for the difference in the findings. In support of this account, Avons, Wright, and Pammer

(1994) found that word length effects were much smaller in probed recall (in which the output processes cannot operate) than in serial recall. In a serial, spoken recall task, the stimuli of Caplan et al. might well yield a word length effect after all.

It can be concluded that rehearsal is one factor in immediate verbal recall, though clearly not the only covert process that matters.

The Speed of Covert Rehearsal [left-justified heading]

Baddeley et al. (1975) found a correlation between subjects' rate of speech, when asked to speak as quickly as possible, and their short-term memory ability. They also found that subjects took longer to pronounce long words, to an extent that was commensurate with the reduction in short-term memory performance for the longer words. Across individuals and words, a particular individual could recall about the same number of words of a particular type that he or she could pronounce in about 1.5 - 2.0 seconds. The theoretical account (further described in Baddeley, 1986) was that subjects use an "articulatory loop" mechanism in which the list of words is rehearsed in a repeating loop. Each item rehearsal can take place only if the phonological representation of the item still remains in short-term memory, which is said to be the case if less than the critical duration (1.5 - 2 seconds) has elapsed since the last rehearsal of that item. Therefore, the individual will be able to recall about as many words as can be rehearsed in 1.5 - 2 seconds, an amount that is estimated by the speeded speech task. A study by Landauer (1962) supports the basic contention that speeded overt speech is a reasonable estimate of the rate of covert speech.

Other researchers have found that age differences in recall can be accounted for by the rate of rehearsal. For example, Hulme and Tordoff (1989) found this in a study examining memory span for short, medium, and long words in children of three ages (4, 7, and 10 years). A plot of speech rate task performance against memory span resulted in approximately a straight line across the nine condition means.

There is much less of this type of research on development throughout adulthood, but the articulatory loop hypothesis is strengthened to the extent that adult development also is consistent with it. Kynette, Kemper, Norman, and Cheung (1990) obtained speech rate differences commensurate with span differences in young versus elderly adults. A simple account of these data would state that the rate of rehearsal increases with age in childhood and decreases with adult aging, and that this rate of rehearsal accounts for age differences in short-term memory performance.

This account appears to conflict, however, with the general finding that children under the age of about 7 years do not use covert rehearsal. How can the rate of rehearsal account for recall, given that the regression line extends down to subjects who do not use rehearsal?

Two recent studies have found that if one looks at performance within a group of 4-year-olds, the expected correlation between individuals' speech rate and memory span does not emerge. Gathercole, Adams, and Hitch (1994) found no significant correlation within 4-year- olds, but a significant correlation within a group of adults. Cowan, Keller et al. (1994) found a correlation that was opposite of the expected within 4-year-olds (i.e., slower speech rates in subjects with better memory span), though the correlation was as expected in 8-year-olds. Thus, rate of rehearsal cannot entirely explain the correlations between speech rate and memory span across ages and materials, and cannot be the sole causal factor underlying effects of various factors on memory span.

The Role of Overt Pronunciation [left-justified heading]

In line with the findings of Henry (1991) and Cowan et al. (1992) mentioned above, perhaps the important factor is not rehearsal, but rather the amount of time it takes subjects to pronounce items in spoken recall. This hypothesis states that subjects should only be able to recall words within about a 2-second period because the phonological representation of any unrecalled items would have decayed from short-term memory by that time. (A weaker form of the hypothesis states that there is some fixed duration of memory decay, but not necessarily close to 2 seconds). According to this type of hypothesis, speeded pronunciation correlates with span, not because it estimates rehearsal speed, but because it provides an estimate of the relative durations of words as they are spoken during the recall period. This hypothesis remains generally compatible with the articulatory loop mechanism proposed by Baddeley (1986), and was proposed by Schweickert and Boruff (1986). It appears to be supported by a study of digit span in Chinese and American adults (Stigler, Lee, & Stevenson, 1986) showing that the recall period for span-length lists lasted roughly 2 seconds on the average. It takes less time to say the Chinese digits, so more digits were included in the 2-second recall period when subjects were tested in Chinese.

If the recall duration limit hypothesis were universally true, and if we assume that the rate of memory decay is comparable across subjects, then we would expect subjects of any level of ability to limit their recall to a comparable period. However, Cowan (1992) measured the duration of recall in 4-year-olds and found results that are discrepant with those expectations. More capable subjects took longer to produce their responses. In fact, the duration of recall varied from an average of less than 2 seconds for the children with the shortest spans to over 5 seconds for the children with the longest spans. Rather than a monotonically decaying memory representation, one would have to assume that some items are reactivated during the recall period, allowing more capable subjects to speak for longer without letting the memory representations lapse. Thus, it does not appear that either covert or overt articulatory speed factors, or both together, are sufficient to account for memory span. Another potential factor, the speed of short-term memory search, is discussed below.

Short-term Memory Search [centered heading]

We have an apparent contradiction between the findings of Stigler et al. (1986), suggesting that word length differences across languages affect span and the duration of each item in recall, but not the total duration of the recall period, and the findings of Cowan (1992), suggesting that individual differences in ability affect span and the total duration of the recall period, but not the duration of each item in recall. Could it be that word length effects and individual differences in ability work through different mechanisms? There are reasons to believe so, and to suspect that a second mechanism playing an important role may be some sort of short-term memory search.

Providing evidence for the different mechanisms, Cowan, Keller et al. (1994) examined memory span for short (monosyllabic), medium (bisyllabic), and long (trisyllabic) words in 4- and 8-year- olds, using a spoken response, and measured the duration of each word and each interword silent period in the correct responses, using a speech waveform editor on a microcomputer. An interesting outcome of that study was a dissociation between the speech-timing correlates of word length effects and age effects. Word length affected the duration of words in the response, as one would expect (with means of 0.52 sec for short words, 0.60 sec for medium words, and 0.75 sec for long words), but it had no effect on the duration of interword silent periods. However, age affected the duration of silent periods in the response. For correct responses to lists of a particular length, older subjects had significantly shorter interword silent periods, and much shorter preparatory periods, than younger subjects did. For example, the preparatory intervals in span-length lists were an average of 1.75 seconds long in 4-year-olds, versus 1.16 seconds in 8-year-olds. Age had no effect, however, on the duration of words in the response. Older subjects were shown to be capable of saying words more quickly than younger subjects, but they did not do so in the response periods of the span task.

The data seem compatible with the hypothesis that the processes that are common during silent intervals in the response may not include covert rehearsal. If covert rehearsal were prevalent during those periods, then the length of words should have had an effect on the duration of silent periods, which was not the case.

A process that may be more prevalent during the silent intervals is memory search. Subjects might have to search through the short-term memory representation in order to determine which word to say next. Similar to the absence of word length effects on the duration of silent periods in the memory response (Cowan, Keller, et al., 1994), effects of word length on memory search were not observed in the probe task devised by Sternberg (1966), in which subjects must quickly indicate whether a probe item was present or absent from a list presented previously (Chase, 1977; Clifton & Tash, 1973).

The idea that memory must be searched before the overt repetition of elements in a list can take place is not brand new. A similar idea was proposed by Sternberg, Monsell, Knoll, and Wright

(1978). They required subjects to repeat lists of various lengths as rapidly as possible upon receiving a start signal. As the list length increased, the preparatory interval increased and the rate of pronunciation (in items per second) decreased. An essential aspect of the account offered for these effects was that subjects search through a representation of the entire list every time another item is to be pronounced. As list length increased, there would be more items to process during each interval between items, explaining the response slowdown that occurs with longer lists.

Analogous to the findings of Sternberg et al. (1978), Cowan, Keller et al. (1994) found that the preparatory interval and rate of pronunciation in correctly repeated lists within the span task both depended on the list length, with longer preparatory intervals and slower pronunciation rates occurring for lists one below span than for span-length lists. The preparatory interval was, on the average, 1.24 seconds for lists at the subject's span length, versus only 1.04 seconds for lists of a length one below span. The rate of speech can be calculated (on the basis of mean word duration plus mean interword pause) as 1.02 seconds/word at span, versus only 0.84 seconds/word at one below span. Extending the effect of list length downward, in Cowan's (1992) larger sample of 4-year-olds who were to repeat lists of monosyllabic words, the rate of speech was significantly faster for lists two below span than for lists only one below span.

The type of memory search for lists to be recalled may not be the same as the type that occurs in a rapid pronunciation task. However, in both cases, one reason for proposing that a covert process such as memory search is carried out on each list item repeatedly, between items, is to account for the finding that the recall rate is dependent on the number of list items.

Sternberg, Wright, Knoll, and Monsell (1980) conducted a more detailed analysis of speech responses. They divided each response sequence into inter-word and intra-word periods. For example, if the response sequence included the two- word series "copper, token," then the period including the "-er" of copper and the "t" of token was taken to be the inter-word period, with the other segments representing intra-word periods. That analysis showed that the stimulus list length affected the duration of inter-word periods but not intra-word periods. Somewhat analogously, in spoken responses within the memory span task, Cowan, Keller et al.

(1994) found that list length affected inter-word pause durations in the response (0.38 seconds for span-length lists, versus 0.22 seconds for lists one below span) much more than word durations (0.64 versus 0.62 seconds, respectively). In both cases, apparently a list-length-dependent covert process takes place primarily during the periods between words. In both cases, that covert process could be some type of short-term memory search.

Now the discrepancy between the effects of word length (Stigler et al., 1986) and individual and age differences (Cowan, 1992; Cowan, Keller et al., 1994) on the timing of spoken responses in the span task can be explained. According to the articulatory loop theory (Baddeley, 1986), both word length and age effects are assumed to occur because these variables affect the rate of covert rehearsal. However, we have seen that word length and age have dissociable effects on response timing. One possible revised interpretation is that word length directly affects the duration of spoken words in the response, and therefore the amount of memory decay during the response period; whereas age affects the speed of a covert process such as memory search, and therefore affects the efficiency with which items can be retrieved (and perhaps reactivated) during silent periods in the response.

The mechanisms may be similar in the realm of adult aging. Salthouse and Coon (1993) presented younger and older adults with lists of printed digits and letters for immediate recall through keystroke responses, and the timing of responses was analyzed. Consistent with the results of Cowan, Keller et al. (1994), they observed the biggest age difference in response timing in the preparatory intervals. Response timing was correlated with recall across individuals, and more general speed-of-processing measures accounted for most of this common variance (anticipating a theme to be discussed at the end of the present chapter).

The results of several investigators thus suggest that age across the life span may affect short-term memory ability through a change in the rate of covert, mnemonically-related processes. Indirect evidence points to memory search as one such important process.

Retrieval of Information from Long-term Memory [centered heading]

One well-motivated modification of the articulatory loop theory is that long-term memory representations of the items might assist in the performance of a short-term memory task (see Brown & Hulme, this volume). For example, lexical knowledge might be used to reconstruct a complete memory representation when only partial knowledge of the item remains in short-term phonological storage (e.g., see Schweickert, 1993).

Hulme, Maughan, and Brown (1991) showed how the contribution of long-term memory storage in short-term memory tasks might be observed. In one experiment, memory span and maximal articulatory rate were measured for short, medium, and long English words and nonsense words conforming to English phonology. When the two measures were plotted against one another using the group means for each of the word lengths, the functions across item lengths were linear, with the same slope for words and nonwords but with a higher Y-intercept for words.

To understand the implication of this result, consider first what the articulatory loop theory (Baddeley, 1986, and this volume) would predict. Assume that the duration of short-term memory is T seconds (T 2 seconds, according to previous findings). If subjects can articulate the items in a stimulus set at an average rate of R items/second, then the subjects should be able to recall on the average (T x R) of those items. Thus the plot of memory span across materials with different speech rates should follow the equation: $Memory_i = T \times R_i$, where i is the particular item set. Identical slopes for words and nonwords would be expected assuming that T is the same for both sets. (A similar argument could be made even if the measured articulation rate is indicative of the rate of a larger set of mnemonically relevant processes, as proposed for example by Cowan, Keller, et al., 1994.)

The theory also would predict that, for materials yielding a pronunciation rate of zero there should be no memory; the Y-intercept should be zero. If the Y-intercept of the linear function is above zero, this indicates that some factor other than the articulatory loop contributes. Hulme found a Y-intercept of about 1 item for nonwords versus about 2.5 items for words. The difference was attributed to lexical knowledge that exists for words only.

There have been several applications of the Hulme et al. (1991) method, with varying outcomes. Roodenrys, Hulme, and Brown (1993) found a marginally significant difference in the intercept in 6-year-olds versus 10-year-olds, though far more of the age difference was accounted for by the lower position of the younger children along the regression lines as predicted by the articulatory loop theory. Although they interpreted the intercept difference as indicating the contribution of long-term memory, the graph shows that a nonsignificant difference in slope could have contributed to that pattern. When the slopes differ, there may be no simple, clear-cut interpretation within an articulatory loop framework. However, the results suggest to us that long-term memory may have given an advantage to the older subjects, beyond what the articulatory loop theory would predict, only for the long words. Another example of a data set that includes differences in slope is seen in the difference between children with and without severe learning difficulties (Hulme & Mackenzie, 1992).

An example of a data set that is more ideally suited to the Hulme et al. (1991) type of analysis (because there are no slope differences) is a study by Hulme, Lee, and Brown (1993) comparing normal adults to those with Alzheimer-type dementia. The patients had a function with a slope similar to the normal subjects, but with a slightly lower intercept (suggesting poorer use of long-term memory) and lower placement along the regression lines (suggesting slower articulatory processes).

Another approach to observing the effect of long-term memory is to manipulate factors that theoretically should influence the use of long-term memory but not articulatory processes. For example, Bourassa and Besner (1994) found that the imageability of the items to be recalled affected short-term memory performance (see also Cowan, Wood, & Borne, 1994).

To summarize, it is clear at this point that information in long-term memory plays a role in short-term memory tasks. Researchers have just begun to develop the tools necessary to determine the nature of this long-term memory contribution.

What Factors May Determine the Effectiveness of Covert Processing? [centered heading]

We have shown that a number of covert processes are influential in short-term verbal recall, and that the use of those processes changes markedly with age. We conclude with a discussion of what factors may determine the effectiveness of a subject's covert processing.

The question of the ultimate causes of individual differences obviously is beyond the current state of knowledge and can be addressed only speculatively. There may be myriad individual differences in the component skills that can be used in short-term memory performance, as well as myriad differences in preferred strategies. Some progress has been made, however, in discerning one factor that operates across individuals as a function of age. Specifically, there is considerable evidence that the speeds of multiple processes change together as a function of age and that this global speed of processing factor is critical in many cognitive tasks. If short-term memory ability can be viewed as one instance of the larger question of why operations change in speed with development, the conception of short-term memory becomes a more parsimonious one.

On most speeded tasks, age differences are substantial: Speed increases throughout childhood and adolescence, reaches a peak in young adulthood, and declines slowly thereafter. Considerable evidence now supports the position that a global mechanism, or perhaps a few mechanisms, limit(s) the speed with which children and older adults process information, relative to young adults (Cirella and Hale, 1994; Kail and Salthouse, 1994). The mechanism is not specific to particular tasks or domains but is, instead, a fundamental characteristic of the information-processing system.

Two lines of evidence involving children and older adults are consistent with this conclusion. One line is based on the method of statistical control. If two measures reflect a common age-related mechanism, then statistical control of the variance in one of the measures should greatly reduce the age-related variance in the other. According to this logic, if a global mechanism is responsible for age-related change in processing speed, then statistical control of one measure of processing speed should substantially reduce age effects in other measures. If, instead, each speeded process changes with age at a unique rate, then statistical control of one speeded measure should have a relatively small impact on the magnitude of age-related variance on other measures. In general, for children and older adults, age-related differences in speeds of various mental processes typically are attenuated by approximately 70 to 90 percent when the variance associated with performance on a paper-and-pencil measure of perceptual speed is eliminated (Kail & Salthouse, 1994). This result is readily reconciled with the notion of a substantial general component to the development of processing speed, but not with the view that processing speed can be explained entirely in terms of task-specific mechanisms.

Another line of evidence is based on a relation that is often found between young adults' reaction times (RTs) on the one hand and children's and older adults' RTs on the other. If children execute all cognitive processes more slowly than young adults by some constant factor, then children's RTs should be equal to adults' RTs multiplied by that constant. That is, children's RTs should increase linearly as a function of RTs from corresponding experimental conditions for younger adults. The same prediction would hold for older adults.

The general prediction of a linear increase is upheld, both for children and for older adults (Cirella and Hale, 1994; Kail and Salthouse, 1994). Furthermore, the rate of increase, which indicates the constant by which RTs for children and older adults differ from young adults' RTs, changes systematically with age. It drops rapidly during childhood and more slowly during adolescence, and then increases gradually throughout adulthood (Cirella and Hale, 1994; Kail and Salthouse, 1994).

Findings like these, along with results derived from the method of statistical control, point to the conclusion that some sort of mechanism that is not specific to particular tasks limits the speed with which children and older adults process information. Of course, the impact of such a global mechanism is particularly salient on speeded tasks but it need not be restricted to those tasks. To the contrary, much cognitive processing is temporally limited; processing must occur in a finite window of time or it fails. Consequently, the speed of processing may be critical whenever the rate of stimulation or pacing of responses is controlled externally, or, more generally, whenever a number of activities must be completed in a fixed period. In these instances, slow processing speed in children or older adults may result in reduced performance because these individuals are less likely than young adults to complete the necessary components of task performance in the time allotted.

Memory represents one domain in which performance may be particular sensitive to age-related changes in processing speed. Recall the evidence discussed earlier concerning the articulatory loop hypothesis in which, across a variety of experimental conditions and ages, recall increases linearly as a function of articulation rate. Perhaps age-related change in articulation rate is, itself, a reflection of global developmental change in processing speed. Increased processing speed with age would yield more rapid articulation, which, in turn, would yield more accurate retention. (A similar case could be made for the dependence of other mnemonically relevant covert processes, such as memory search, on global processing speed.)

Figure 1 shows this general framework for the factors of global speed and articulation. The effects of age on memory might be mediated entirely by the highlighted path that runs from age to processing speed to speech articulation rate and then to memory (Path 1-4-6). However, other paths are also possible. Age might have direct effects on rate of articulation (Path 2), perhaps reflecting an age-related increase in the familiarity of information to be remembered. Moreover, processing speed might have direct effects on memory (Path 5) in addition to those mediated by speech articulation rate. For example, age-related change in processing speed might also lead to more rapid initial encoding of stimuli, independent of the rate with which they are subsequently rehearsed. Finally, if global and specific processing speeds cannot account for all of the age-related variation in memory span, then age would be linked directly to span (Path 3).

[insert Figure 1 here]

This framework was evaluated by Kail and Park (1994), who tested 7- to 14-year-olds and adults. To assess processing speed, subjects completed the Identical Pictures and Number Comparisons tasks, two measures of perceptual speed derived from the French Kit; to measure rate of articulation, subjects were timed as they repeated sets of 3 letters or 3 digits aloud; and finally, digit and letter spans were assessed in the standard way.

The key results concern analyses of the paths that link the constructs in Figure 1. Consider, first, direct links to memory. As expected from work on the articulatory loop hypothesis, the path linking memory and speech rate was significant. Processing was linked significantly to speech rate but not to memory. This indicates that the impact of processing speed on memory was mediated entirely by increases in rate of articulation. However, the link between age and memory remained significant. This link means that other age-related variables not included in the general framework play a mediating role in the age-memory span relation.

In sum, the findings support the view that processing speed contributes to developmental change in memory. Processing speed may well have some interesting links with other forces that are important in the development of memory, at least during childhood. First, consider memory strategies. Much of the impact of processing speed may well be mediated by memory strategies. More rapid processing means that overt rehearsal or mental imagery or other deliberate mnemonics are more effective because subjects accomplish more in a fixed period of time. Turning to task-relevant knowledge, here, processing speed may well work differently. Increased processing speed may be a consequence of greater task-relevant knowledge. Subjects can access highly familiar stimuli in long-term memory more rapidly than less familiar stimuli and this is independent of age-related change in global processing speed. It still must be kept in mind also that the exact mechanisms accounting for childhood development, adult development, and various types of deviance may well be different from one another.

Future Directions [centered heading]

The articulatory loop model by Baddeley (1986) has served as a convenient framework to tie findings together and motivate research. Some of the new processing factors that, as a result of that research, are now thought to make a difference (e.g., memory search; the involvement of long-term memory) must be explored further. However, it is our conviction that if these new factors are to contribute to our understanding of working memory, they sooner or later must be tied together into a new simple framework, similar to the articulatory loop model in intent, though probably not in exact substance.

There certainly are ways to continue to learn about each factor. For example, consider the potential role of memory search. Whereas Cowan and his colleagues have shown that there are systematic effects of age and list length on the duration of silent pauses between words within the immediate verbal recall of lists, the exact nature of processing within those pauses remains uncertain. Do these pauses relate strongly to subjects' ability to conduct memory searches, as the account of Cowan et al. (1994) implies, or not? To what extent is it true that subjects who search more quickly can recall more? Answers to these questions appear to be on the horizon.

We now know that information in long-term memory influences short-term memory performance, but the way in which it operates is far from certain. Long-term lexical memory may contribute by helping the subject to interpret the identity of a partly-faded phonological trace. Another possibility is that subjects use long-term memory to form an episodic record of the list that is completely separate from the phonological short-term memory of the articulatory loop model. Whenever the phonological store proved inadequate to retrieve an item, there would be the option to check for the item's identity in the abstract episodic record. There is interesting work to be done here.

Finally, the newer covert variables have yet to be explored within the statistical control approach. Perhaps the application of that approach would be premature until more is known about the new variables. Age differences in these variables have been examined usefully, but individual differences are still unexplored. There appear to be tremendously large differences between children within an age on memory span and on various processes that may contribute to it, despite the systematic nature of age differences.

One major question that needs to be addressed within the statistical control approach is the extent to which the various specific covert processes are merely manifestations of a common, global processing speed, and the extent to which different personal profiles of abilities exist. For example, is it possible to be very slow on memory search and very quick on covert articulation? Is there any one measure of global speed that is unbiased, or is any measure at best one of a number of imperfectly-correlated abilities? Ultimately, it is not any one task that will prove central to our understanding of covert processes in short-term memory. It is the task analysis that is central.

References

Avons, S.E., Wright, K.L., & Pammer, K. (1994). The word-length effect in probed and serial recall. Quarterly Journal of Experimental Psychology, 47A, 207-231.

Baddeley, A.D. (1986). Working memory. Oxford: Clarendon Press.

Baddeley, A.D. (This volume). Working memory.

Baddeley, A., Lewis, V. & Vallar, G. (1984). Exploring the articulatory loop. The Quarterly Journal of Experimental Psychology, 36A, 233-252.

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

Bourassa, D.C., & Besner, D. (1994). Beyond the articulatory loop: A semantic contribution to serial order recall of subspan lists. Psychonomic Bulletin & Review, 1, 122-125.

Brown, G., & Hulme, C. (This volume). Nonword repetition, short-term memory, and word age-of-acquisition: A computational model.

Caplan, D., Rochon, E., & Waters, G.S. (1992). Articulatory and phonological determinants of word length effects in span tasks. Quarterly Journal of Experimental Psychology, 45A, 177-192.

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

Chase, W.G. (1977). Does memory scanning involve implicit speech? In S. Dornic (ed.), Attention and performance VI. Hillsdale, NJ: Erlbaum. (pp. 607-628)

Clifton, C., & Tash, J. (1973). Effect of syllabic word length on memory-search rate. Journal of Experimental Psychology, 99, 231-235.

Conrad, R. (1964). Acoustic confusion in immediate memory. British Journal of Psychology, 55, 75-84.

Conrad, R. (1971). The chronology of the development of covert speech in children. Developmental Psychology, 5, 398-405.

Cowan, N. (1992). Verbal memory span and the timing of spoken recall. Journal of Memory & Language, 31, 668-684.

Cowan, N., Day, L., Saults, J.S., Keller, T.A., Johnson, T., & Flores, L. (1992). The role of verbal output time in the effects of word length on immediate memory. Journal of Memory & Language, 31, 1-17.

Cowan, N., Keller, T., Hulme, C., Roodenrys, S., McDougall, S., & Rack, J. (1994). Verbal memory span in children: Speech timing clues to the mechanisms underlying age and word length effects. Journal of Memory & Language, 33, 234-250.

Cowan, N., & Saults, J.S. (in press). Memory for speech. In H. Winitz (ed.), Human communication and its disorders, Vol. 4. Timonium, MD: York Press.

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

Gathercole, S.E., Adams, A.-M., & Hitch, G.J. (1994). Do young children rehearse? An individual-differences analysis. Memory & Cognition, 22, 201-207.

Gathercole, S.E., & Baddeley, A.D. (1993). Working memory and language. Hove, U.K.: Erlbaum.

Gathercole, S.E., & Hitch, G.J. (1993). Developmental changes in short-term memory: A revised working memory perspective. In A.F. Collins, S.E. Gathercole, M.A. Conway, & P.E. Morris (Eds.), Theories of Memory. Hove, U.K.: Erlbaum.

Halliday, M.S., & Hitch, G.J., Lennon, B., & Pettipher, C. (1990). Verbal short-term memory in children: The role of the articulatory loop. European Journal of Cognitive Psychology, 2, 23-38.

Henry, L.A. (1991). The effects of word length and phonemic similarity in young children's short-term memory. Quarterly Journal of Experimental Psychology, 43A, 35-52.

Henry, L.A., & Millar, S. (1991). Memory span increase with age: A test of two hypotheses. Journal of Experimental Child Psychology, 51, 459-484.

Henry, L.A., & Millar, S. (1993). Why does memory span improve with age? A review of the evidence for two current hypotheses. European Journal of Cognitive Psychology, 5, 241-287.

Hitch, G. J., Halliday, M. S., Dodd, A., & Littler, J. E. (1989). Development of rehearsal in short-term memory: Differences between pictorial and spoken stimuli. British Journal of Developmental Psychology, 7, 347-362.

Hitch, G.J., Halliday, M.S., Schaafstal, A.M., & Heffernan, T.M. (1991). Speech, "inner speech," and the development of short-term memory: Effects of picture-labeling on recall. Journal of Experimental Child Psychology, 51, 220-234.

Hitch, G.J., Halliday, S., Schaafstal, A.M., & Schraagen, J.M.C. (1988). Visual working memory in young children. Memory & Cognition, 16, 120-132.

Hulme, C. (1984). Developmental differences in the effects of acoustic similarity on memory span. Developmental Psychology, 20, 650-652.

Hulme, C., Lee, G., & Brown, G.D. (1993). Short-term memory impairments in Alzheimer-type dementia: Evidence for separable impairments of articulatory rehearsal and long-term memory. Neuropsychologia, 31, 161-172.

Hulme, C., & Mackenzie, S. (1992). Working memory and severe learning difficulties. Hove: Erlbaum Associates, Ltd.

Hulme, C., Maughan, S., & Brown, G.D.A. (1991). Memory for familiar and unfamiliar words: Evidence for a long-term memory contribution to short-term memory span. Journal of Memory and Language, 30, 685-701.

Hulme, C., Silvester, J., Smith, S., & Muir, C. (1986). The effects of word length on memory for pictures: Evidence for speech coding in young children. Journal of Experimental Child Psychology, 41, 61-75.

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

Kail, R., & Salthouse, T. A. (1994). Processing speed as a mental capacity. Acta Psychologica, 86, 199-255.

Kail, R., & Park, Y. (1994). Processing time, articulation time, and memory span. Journal of Experimental Child Psychology, 57, 281-291.

Keller, T.A., & Cowan, N. (in press). Developmental increase in the duration of memory for tone pitch. Developmental Psychology.

Kynette, D., Kemper, S., Norman, S., & Cheung, H. (1990). Adults' word recall and word repetition. Experimental Aging Research, 16, 117-121.

Landauer, T.K. (1962). Rate of implicit speech. Perceptual & Motor Skills, 15, 646.

Roodenrys, S., & Hulme, C. (1993). The development of short-term memory span: Separable effects of speech rate and long-term memory. Journal of Experimental Child Psychology, 56, 431-442.

Salthouse, T.A., & Coon, V.E. (1993). Influence of task-specific processing speed on age differences in memory. Journal of Gerontology: Psychological Sciences, 48, P245-P255.

Schiano, D.J., & Watkins, M.J. (1981). Speech-like coding of pictures in short-term memory. Memory & Cognition, 9, 110-114.

Schweickert, R. (1993). A multinomial processing tree model for degradation and redintegration in immediate recall. Memory & Cognition, 21, 168-175.

Schweickert, R., & Boruff, B. (1986). Short-term memory capacity: Magic number or magic spell? Journal of Experimental Psychology: Learning, Memory, and Cognition, 12, 419-425.

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

Sternberg, S., Monsell, S., Knoll, R.L., & Wright, C.E. (1978). The latency and duration of rapid movement sequences: comparisons of speech and typewriting. In G.E. Stelmach (ed.), Information processing in motor control and learning. NY: Academic Press.

Sternberg, S., Wright, C.E., Knoll, R.L., & Monsell, S. (1980). Motor programs in rapid speech: Additional evidence. In R.A. Cole (ed.), Perception and production of fluent speech. Hillsdale, NJ: Erlbaum.

Stigler, J.W., Lee, S.-Y., & Stevenson, H.W. (1986). Digit memory in Chinese and English: Evidence for a temporally limited store. Cognition, 23, 1-20.

Figure Legends

Figure 1. Possible links between age, global speed of processing, speech rate, and memory span.

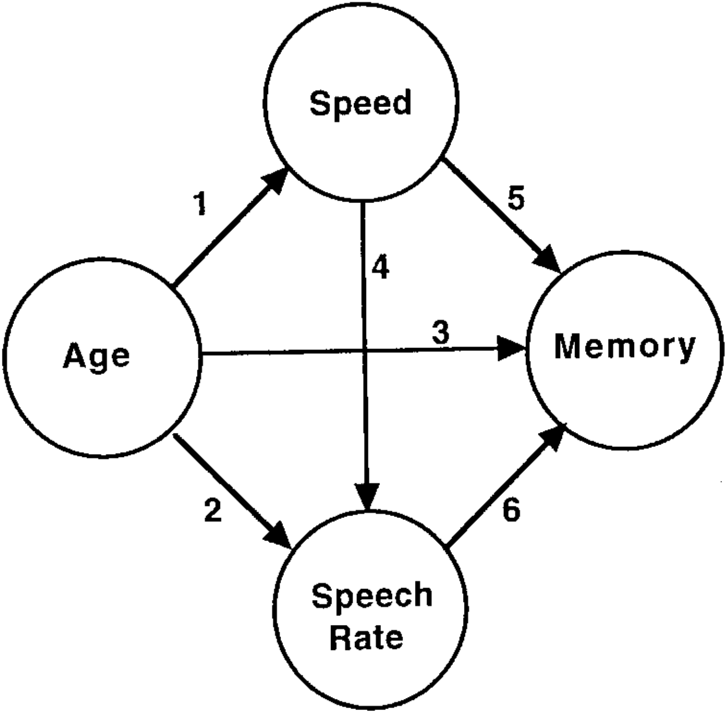

FIG. 2.1. Possible links between age, global speed of processing, speech rate, and memory span.