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Short-term memory limitations in children: Capacity or processing deficits?

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This paper evaluates the assertion that short-term memory (STM) capacity increases with age. Initially an analysis is made of the STM system in terms of its parameters and control processes. No evidence was found that can suggest conclusively that either the capacity or the rate of information loss from STM varies with age. On the other hand, substantial evidence exists to show that the processing strategies used by adults are unavailable or deficient in children. Furthermore, considerable differences in the contents and complexity of the long-term memory (LTM) knowledge base (semantic and recognition networks) can produce grossly different STM performance between age groups. The second half of this paper reviews three STM-related paradigms—memory span, serial probed recall, and recognition under limited exposure—that have consistently shown performance deficits in children. These deficits are explained in terms of the lack of proper control processes (or processing strategies), as well as an impoverished LTM knowledge base rather than a limitation in STM capacity.

This paper evaluates the commonly held view that short-term memory (STM) storage capacity increases with age. Many investigators have invoked a "capacity increase" as an explanation of quantitative differences in performance between adults and children on a variety of STM-type tasks, and interpretations based on a capacity increase concept have become quite pervasive. It is often difficult, however, to assess precisely what authors mean when they use the word "capacity." It is crucial, therefore, that the notion of capacity increase be clarified.

There are at least two interpretations of the capacity increase concept. The first interpretation uses capacity in merely a descriptive, or empirical, sense. Consider, for example, the following quotation from the 1975 *Annual Review of Psychology*: "The current year was very exciting for investigators of children's memory. Only a few studies were directed primarily at demonstrating correlations of children's memory capacity with their age—an already well-established fact. Most of the studies reported were directed toward a clearer specification of the impact of children's cognitive skills on their memory capabilities" (Hetherington & McIntyre, 1975, p. 97). Here, capacity is equated with behavior, that is, performance on memory tasks. It is empirically true that older children and adults recall more items than younger children. Invoking a capacity increase, however, does not explain this finding; it merely restates it, since a performance increase means a capacity increase in this sense.

The second interpretation of the concept of a capacity increase uses the word capacity to refer to hypothetical "slots" in memory. According to the slots notion, a capacity increase would mean that the number of slots increases (Case, 1974; McLaughlin, 1963; Pascual-Leone, 1970). However, it is not always clear that those who equate the term slots with capacity necessarily imply that the number of slots increases when they propose a capacity increase. The need for further clarification is exemplified in the following quotation: "An alternate explanation points to age-related changes in absolute storage capacity in the verbal short-term memory system which accounts for age-related changes in immediate memory span performance beyond those attributable to rehearsal" (Frank & Rabinovitch, 1974, p. 405). In this case, it is unclear whether the authors meant a change in the number of slots or, alternatively, an increase in the size (or "capacity") of each slot. This distinction betwen the number and size of slots will be elaborated upon later. In this paper, the term *capacity* is conceived of in terms of slots. Further, *capacity increase* will be used to refer to an increase in the *number* of slots in STM.

The first part of this paper will deal with an analysis of the memory system, which will serve as a theoretical framework. The discussion begins with the basic parameters of STM; capacity and rate of information loss. That is, the capacity of STM (or the number of slots) is a parameter to be estimated, and in order to address

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the question of a capacity increase, this parameter needs to be estimated developmentally. Numerous obstacles are encountered in such an endeavor, and these will be treated. Attempts to estimate the rate of information loss from STM have been more successful, and several converging methods all indicate an invariant rate of loss across ages. The discussion, then, focuses on the effects of having differential long-term memory (LTM) knowledge bases between age groups. In addition, apparent differences occur in the acquisition and use of mnemonic strategies (or control processes) that are indispensable to adults for maintaining information in STM.

Following this analysis of the memory system, the second part of this paper treats some of the empirical data which have demonstrated consistent deficits in children's performance on STM-related tasks. The intention in this second part is to show that the increase in performance with age (a) need not imply a similar increase in the capacity of STM, (b) can be explained in terms of developmental changes in the use of control processes, and (c) can also be accounted for by the difference in complexity of the knowledge base.

AN ANALYSIS OF THE MEMORY SYSTEM

Short-Term Memory Structure

Short-term memory is here conceived as being composed of a limited number of slots (Atkinson & Shiffrin, 1968; Newell & Simon, 1972). (Although no assumptions are made here about how these slots are organized, it is clear that the structure of STM has important consequences for rehearsal and retrieval of ordered information.) The contents of each slot can best be viewed as composed of one chunk of information (Simon, 1974). That is, once a chunk of information has been recognized, all information relevant to that chunk may be placed in one slot in STM if it needs to be further attended to (Laughery, 1969). Thus, there is no limit to the size of each chunk. Alternatively, one can view the contents of STM as symbols that serve strictly as pointers to designated entries in LTM (Gilmartin, Newell, & Simon, 1976). Again, in this framework, the size of each entry that the pointer designates may be limitless. The limitation occurs in the number of slots that can contain pointers.

Short-term memory can be characterized by either one of two parameters, depending on whether loss from STM is conceived of as decay or displacement. If loss is due to decay, then it becomes important to determine whether inadequate performance reflects a faster decay of information from STM.There is no evidence to support a faster rate of information loss from STM for younger children than for older children. Flavell, Beach, and Chinksky (1966) found similar retention at 0 and 15 sec within each age group of 5-, 7-, and 10-year-olds. This may have resulted, however, from a floor effect for the 5-year-olds, that is, they remembered so little (of the seven items presented) at the 0 interval that there was no room to forget. On the other hand, for the older groups, this task may not have been sensitive enough to measure forgetting, because the subjects were able to rehearse during the retention interval, thus producing equivalent recall at both intervals (ceiling effect).

To eliminate floor and ceiling effects, Belmont (1972) first determined the memory span for colors for age groups ranging from 8-year-olds to adults. The number of colors to be retained was then set at one below their span. Recall was assessed at 4-, 8-, and 12-sec filled retention intervals. The number of colors recalled decreased with increasing retention interval for all age groups, and there was no interaction between age and retention interval. This suggests that the rate of loss from STM is independent of age.

Some other indirect evidence for a lack of a difference in the decay function can be extracted from serial probed recall studies (to be elaborated later). Basically, one can regard the number of stimulus cards intervening between presentation and probe as a rough measure of retention interval. Although younger children always make more errors at every serial position than adults or older children, the slope of the forgetting curve (starting from the recency portions) is almost identical between age groups, beginning with children as young as 5 years (see Hansen, 1965; McCarver, 1972).

Another acceptable measure of STM loss is the rate of proactive inhibition (PI) buildup across trials in a Brown-Peterson paradigm. In all the developmental research on PI release, the rate of PI buildup is always uniform across age groups, except when the distractor task differs in difficulty for subjects of different ages. This suggests that the rate of information loss is the same across age groups (see Kail & Levine, 1976).

Thus, it can be concluded tentatively that loss from STM, if occurring through time decay, cannot explain the differential amount of recall between older and younger children in tasks such as memory span and serial probed recall. However, this conclusion does not preclude the possibility that poorer recall in young children could be due to displacement from a smaller STM. In fact, there seems to be some evidence, from both the adult and developmental literature, to support the notion that STM loss does occur through displacement rather than decay. For example, a study with adults has shown that the amount of intervening material is a greater determinant of STM loss than time alone (Shiffrin, 1975).

The two models of STM loss (decay vs. displacement) lead to different predictions concerning STM performance with varied presentation rates. According to the decay model, since items are lost from STM over time if rehearsal is prevented, slower rates of presentation should induce more loss. According to the displacement model, however, varying the rate of stimulus presentation should have no effect on total recall if there is no rehearsal or interfering task imposed between presentations and recall. Since children younger than age 7 seldom rehearse (Daehler, Horowitz, Wynns, & Flavell, 1969), the displacement model predicts that presentation rate should have little effect on their recall. According to the decay model, however, slow rates of presentation should result in poorer recall than fast rates of presentation. Although the Murray and Roberts (1968) study was not designed to discriminate between these two models, the data show that, for 7-year-olds, there was no difference between recall of lists visually presented at 1 digit/sec and recall of lists visually presented at 3 digit/sec, supporting the displacement theory. (However, 10-year-olds recalled more at the slow rates, which implies that recall is contaminated by rehearsal in the slower rates for 10-year-olds.)

Hence, in general, it seems preferable to consider loss from STM as due to displacement. We now return to the original question: Does the capacity of STM, in terms of a displacement buffer model, increase with biological maturation? To decide whether or not STM capacity grows, one must first determine what the capacity is for adults. This question is currently unresolved. Short-term memory span has variously been estimated to be about seven by Miller (1956), six by Spitz (1972), five by Simon (1974), and three to four by Broadbent (1975); these estimates further depend on (a) the criterion used, (b) the task used to tap this capacity, and (c) the definition of a chunk. According to Broadbent (1975), if one elevates the criterion used to determine the span, then memory span can be considerably reduced. For example, a strict criterion of perfect recall 100% of the time would produce a span of three items, irrespective of types of material. The type of task used to tap memory span can also shed light on the capacity of STM (Broadbent, 1975). For example, in a task such as running memory span (Pollack, Johnson, & Knaff, 1959), only a lag of three to four digits can be kept track of accurately by adults. Likewise, in serial probed recall, only the last three items can be recalled significantly more accurately than the middle position items (Bernbach, 1967). However, for tasks involving a continuous stream of events, the question arises whether the reduced capacity is the true capacity, or whether it merely appears reduced because capacity is taken up by processing other aspects of the task. The final factor, the definition of a chunk can also cloud the estimate of adults' true capacity. For example, should the true adult capacity be determined by their span for digits (about eight) or by their span for nonsense syllables (about three).

The definition of a chunk is also the single most important factor that can confound span measurement developmentally. For example, can one truly state that adults' digit span is twice as long as 5-year-olds' when pairs of digits can obviously constitute one chunk of information for adults but not for children?

One approach taken by theorists who do believe in a constant capacity assumption is to attempt to find tasks that are essentially strategy free. A task that is strategy free and draws on that portion of semantic memory that is comparable between age groups should not be sensitive to developmental changes (Brown, 1975; Flavell, 1970). Unfortunately, most tasks that have been classified as strategy free and have been successful at being insensitive to developmental trends tend to involve a recognition paradigm, such as judgment of recency (Brown, 1973) and the continuous recognition paradigm (Brown & Scott, 1971). It is not clear at the moment that a recognition (vs. recall) paradigm taps information stored in STM. For example, in the continuous recognition paradigm, the number of items recognized far exceeds the limits of STM (Shepard, 1967).

Although there has been no study which shows that memory span is comparable between children and adults, Chi and Klahr (1975) have shown that the span of apprehension is the same between adults and 5-year-olds, even though children subitize at a slower rate than adults. Span of apprehension, or subitizing, has often been defined as the number of discrete objects (in this case, dots) that can be apprehended in a single perception. Although the precise nature of subitizing is still unclear [see Klahr & Wallace (1976) for one view of the underlying processes], the evidence that adults and children have the same apprehension span of three is certainly consistent with Miller's (1956) suggestion of a common underlying capacity.

To summarize: The outcome of this section shows that there is no reason to believe that the basic STM parameters of capacity and rate of information loss are different between children and adults. The next section is concerned with the control processes and the role they play in differentiating performance between children and adults.

Control Processes

Control processes are viewed as "transient phenomena under the control of the subject" (Atkinson & Shiffrin, 1968, p. 106). Because they are not permanent features of memory, it is proposed that they are acquired strategies. A strategy is simply a set of decision processes in LTM concerning what actions to perform on information in STM (Gilmartin, Newell, & Simon, 1976). Once a strategy is acquired, it is still necessary to learn when to execute it. This section will point out the differences in control processes between children and adults. Four types of control processes will be mentioned: rehearsal, naming, grouping, and recoding.

Rehearsal. Rehearsal in general can be viewed as an iterative process by which materials in STM are continually attended to in a serial fashion. The rehearsal process has several characteristics. First, it appears to be under the subject's conscious control. Second, it is somewhat analogous to implicit speech, at least for verbal materials, because acoustically confusable materials will slow up rehearsal, as does syllabic word length (Chase, in press; Clifton & Tash, 1973). Depending on the type of material, rehearsal can proceed at about the rate of 250 msec/item. It is also possible to rehearse in the visual modality, such as by generating images of the stimulus materials, in which case the rate is much slower, about 500 msec/letter (Kroll, Kellicut, & Parks, 1975; Weber & Bach, 1969). Third, rehearsal takes time. Hence, according to adult models, rehearsal cannot take place unless there is time, such as between stimulus presentations or between presentation and recall, and so on.

Most models of rehearsal view the rehearsal mechanism as a process of reperception to maintain materials in STM (e.g., Gilmartin, Newell, & Simon, 1976; Laughery, 1969). In addition to maintaining information in STM, rehearsal has also often been deemed necessary for consolidation. When two or more items in STM are rehearsed together for a certain length of time, a new entry (association) can be formed in LTM composed of the items that were rehearsed together. This newly consolidated entry will then require only one STM location to represent that entry in the future.

Although rehearsal has been viewed as an indispensable process for retaining information in STM, it has generally been found that children do not begin to engage in spontaneous rehearsal until after age 5 (Daehler et al., 1969). This absence of rehearsal at age 5 can be demonstrated in several ways by the lack of: (a) primacy effects in serial position curves (Cole, Frankel, & Sharp, 1971; Kingsley & Hagen, 1969); (b) interitem pause times during acquisition (Belmont & Butterfield, 1971); (c) labial movements (as measured by electromyographic recordings) during periods of retention (Locke & Fehr, 1970); and (d) acoustic confusions during recall (Conrad, 1971; Hayes & Rosner, 1975).

The fact that lack of rehearsal produces inferior performance in young children has been documented in several tasks. For example, the amount recalled can be shown to be correlated directly with the amount of rehearsal. Keeney, Cannizzo, and Flavell (1967) have induced nonrehearsers (6- to 7-year-olds) to rehearse, and were able to obtain the same amount of overall recall as other 6- to 7-year-olds who do rehearse. Conversely, if one could find 9- to 10-year-old nonrehearsers, then their recall performance should not be significantly superior to 6- to 7-year-old nonrehearsers, assuming everything else is equal.

How does the rehearsal process develop with age? It is postulated that the acquisition of rehearsal is a three-stage learning process. The first stage consists of the proper assembling of the rehearsal process. The lack of such a process has traditionally been labeled as a production deficiency (Flavell, 1970). The second stage consists of learning when to execute the process. Recall that rehearsal is a time-dependent process, that is, the subject may engage in rehearsal only if there is time left between stimulus presentations. Given that there is time available, whether or not the rehearsal process is executed is at the discretion of the subject. For example, Keeney et al. (1967) have shown that children who have been taught the rehearsal process will often abandon it given the appropriate situation. That is, they still have not acquired the decision rule concerning cues that should initiate the rehearsal process. Furthermore, Hagen, Hargrave, and Ross (1973) showed that induced rehearsers will rehearse only if they are prompted by the experimenter. This again confirms the hypothesis that children must learn the appropriate moment to elicit the rehearsal process. The third stage of rehearsal acquisition consists of correct execution of the existing process. For example, Ornstein, Naus, and Liberty (1975) have shown that children sometimes fail to execute their rehearsal process correctly, that is, they rehearse each item separately rather than cumulatively in groups.

If rehearsal is indeed acquired through learning, the relevant question then is why do training studies fail to elevate children's recall performance to adults' (or older children's) level? (See Belmont & Butterfield, 1971.) One unsatisfactory response is simply to accuse experiments of deficient training procedures. That is, it is quite conceivable that training studies often fail to train all three stages of rehearsal acquisition. However, a more plausible answer may lie in the rate of rehearsal. That is, assuming that the rate of information loss from STM is constant between children and adults, the utility of rehearsal (which serves to reactivate decaying traces) is defeated if children are retarded in the rate with which they can reactivate their STM traces.

Naming. Naming will be defined here as attaching a verbal label to a visual stimulus. Theoretically, naming can be differentiated from rehearsal because stimuli can activate multiple codes (e.g., visual, semantic) and these codes can be rehearsed independently of deriving the name of the stimulus. In the developmental literature, it has often been suggested that the lack of verbal rehearsal in young children is a result of a deficient naming process (the implicit assumption being that naming is a prerequisite for verbal rehearsal). However, there exist fairly explicit data showing that children at age 5 do spontaneously name the input stimuli, but they do not rehearse. With regard to the former statement, Locke and Fehr (1970) have shown that if sets of three pictures are presented for later recall to 4- and 5-year-olds, one can observe labial and nonlabial electromyographic tracings during the picture presentation, but not during the subsequent rehearsal period.

The reason most investigators have associated a lack of rehearsal with a deficient naming mechanism is that the data often show that 5-year-olds who have been taught explicitly to label or name each stimulus as it is presented in a serial probed recall task usually manifest better overall recall (Bernbach, 1967). However, if one looks at the serial positions at which such improvements occur, the label group exhibits a slight improvement in the primacy positions and large improvement in the last two recency positions (Bernbach, 1967; Keely, 1971; Kingsley & Hagen, 1969; Siegel & Allik, 1973). The improvement in the last two recency positions is understandable if one assumes that the most recent items reside in a precategorical acoustic store (PAS) when subjects overtly name them. Hence, forcing subjects to overtly label the stimuli merely produces acoustic and articulatory representations for storage in STM and in PAS, but labeling need not necessitate rehearsal. The slight improvement observed in the primacy positions attributed to labeling can be a function of attentional rather than mnemonic processing, for better performance at the primacy positions can be obtained whether the supplied labels are relevant, such as color names to color patches, or irrelevant, such as animal names to color patches (Bush & Cohen, 1970).

A direct test of whether labels initiate rehearsal or control attention could be inferred from Brooks' data (Note 1). He used several kinds of labels of pictorial stimuli in a recognition task where a child has to merely say whether a picture is "old" (already seen) or "new." Recognition improved for all kinds of labels, such as congruous vs. incongruous phrases. The chances of rehearsing lengthy unfamiliar phrases can be immediately ruled out, especially in children as young as 3½.

To summarize: The evidence is very strong that young children do explicitly name visual stimuli when they are presented. However, the presence of naming does not necessitate subsequent rehearsal, assuming that naming is a precursor to verbal rehearsal. That is, the lack of rehearsal cannot be attributed to a lack of naming.

Grouping and recoding. Grouping is a process whereby subjects actively parse a lengthy string of stimuli into subgroups. Grouping serves many functions, mostly organizational (Bower, 1972). Adults typically group a string of inputs into groups of threes for ease of rehearsal (Cavanagh, 1976; Wickelgren, 1964). Grouping can also occur for inputs other than temporal or linear arrays. In quantification of random dot patterns, for example, Klahr (1973) suggested that adults appear to group the entire pattern into smaller subgroups of dots and then quantify each subgroup.

We have already seen how adults often actively group a string of inputs during stimulus acquisition (Belmont & Butterfield, 1971), whereas children do not. The effect of grouping is so powerful for adults that the effect of repetition disappears when the same string of digits is regrouped into a different group structure (Bower & Winzenz, 1969). Adults also benefit from experimenter-manipulated grouping, whereas children do not, at least not until they are in second grade (Harris & Burke, 1972; McCarver, 1972).

Another type of grouping (other than by temporal or spatial properties) is by category membership. Liberty and Ornstein (1973) were able to train fourth graders to sort words into the same categories as adults, and vice versa. They then obtained some improvement in free recall by children forced to sort according to the adult's pattern and some impairment in recall by adults forced to categorize according to the children's pattern. Hence, one could say that grouping in general can be a learned strategy.

A closely related control process that is also under conscious control is recoding. Recoding essentially is an active process by which the subject searches the contents of STM to see whether or not the concatenation of two or more internal symbols in STM (grouping)–either by pronounceability or meaningfulness–will result in one recognizable unit or chunk in LTM. If so, this one entry retrieved from LTM will replace the two or more symbols in STM. Thus, in this sense, recoding can conserve space in STM. Recoding is different from consolidation in the following way: In order to recode, the recognizable chunk must already exist in LTM, whereas consolidation is the formation of a new chunk in LTM.

There appears to be no study which shows that children actively recode two or more stimuli into a single chunk. This may be a bit difficult to demonstrate because children's chunks in LTM are still so rudimentary that larger chunks do not yet exist. However, there is one study showing that children can, through 78 days of practice, increase their digit span from 4.3 to 6.4 (Gates & Taylor, 1925). It is possible that recoding has taken place here, especially since, after 4½ months of no practice, their digit span dropped back to around 4.

Recoding, as in the case of rehearsal, can also be seen as a time-dependent process. That is, if there is time available between items during presentation or between presentation and recall, adult subjects can (and usually do) engage in recoding (Laughery, 1969). This model of recoding appears not to apply to children. But in this case, it is not clear whether it is because they do not possess the strategy for recoding or because there are very few sets of stimuli which children are capable of recoding.

In general, the section on control processes suggests that young children are deficient in their use of mnemonic strategies to help code and maintain information in STM. The ability to use control processes develops with age, and this is probably accomplished through learning.

Long-Term Memory Knowledge Base

In addition to the inadequate use of mnemonic strategies, another major difference that must be mentioned between children of different ages lies in the contents of long-term memory (LTM), especially the complexity of the knowledge base (semantic network). The knowledge base of a younger child can be limited in three ways. The first is the *absence of a recognizable chunk*. This difference has often been characterized in the literature as whether one class of stimuli is familiar or unfamiliar to a given subject. For example, a visual stimulus such as a letter could be totally unfamiliar to a 5-year-old because the recognition network for that letter is totally absent.

The second way that a younger subject's knowledge base can be deficient is in terms of the *size of a chunk*. This difference is often expressed in the literature as the degree of familiarity. That is, a visual word could be one chunk of information for adults but more than one chunk for a child who is familiar only with the letters composing that word. Hence, one could say that a word is more familiar to an adult than to a child. A clearer example is the following: For an expert chess player, a chunk could consist of a pattern with as many as six pieces, whereas a novice might have a chunk of only two pieces (Chase & Simon, 1973). In this sense, greater familiarity means that the size of a chunk is bigger.

A third difference between a limited vs. a rich knowledge base in LTM is the number of associations, pathways, or test branches leading to a chunk. In the present paper, this difference will be referred to as the *accessibility of a chunk*. This developmental difference in the accessibility of a chunk can be quantified in many ways. One simple method of measuring richness of LTM associations is through the amount of clustering in free recall. It has typically been found that clustering for verbal materials increases as a function of age (Moely, Olson, Halwes, & Flavell, 1969; Neimark, Slotnick, & Ulrich, 1971; Rossi, 1964; Willner, 1967).

Another way of quantifying differences in accessing the LTM knowledge base is through the amount of time it takes to recognize and retrieve the name of a recognizable chunk. For example, 5-year-olds required twice the time needed by adults to name a number that is presented visually (Mackworth, 1963; Morin & Forrin, 1965). However, in order to accept this difference in naming latency as evidence of inaccessibility rather than of some intrinsically slower speed of responding in young children, one must be able to show that for materials that are more accessible to younger children, naming speed is faster. For example, a reversal can be obtained between children and adults on the amount of name-retrieval time for stimulus materials that are differentially familiar to each age group: It takes first graders 100 msec longer to read a word than to name a picture (Norton, 1972), whereas it takes adults longer to name pictures than to read words (Fraisse, 1968; Potter & Faulconer, 1975). Although these results (they need to be replicated within a single study) do not imply that children can actually name pictures faster than adults, they do suggest that young children's discrimination nets are more elaborate for pictures than for words. Another piece of evidence suggesting that latency in name retrieval reflects the accessibility or the complexity of the LTM knowledge base is revealed in a study by Carroll and White (1973). They found that naming latencies were faster for objects that were learned at an earlier age (according to subjective introspection) than those learned at a later age.

Hence, in general, it can be concluded that naming latency differences between age groups do reflect the complexity of the semantic network around a particular chunk of information, rather than a retarded rate of information processing in younger children. This difference in the accessibility of a chunk can produce substantial deficits in the speed of recognition, as well as in subsequent manipulation of a stimulus. Investigators who are interested in adult semantic memory, however, have begun to show that the underlying LTM structures can be revealed by differential facility with categorization. Rosch (1973), for example, has shown that central instances of categories are classified faster than peripheral instances (e.g., robin-bird vs. chicken-bird). A similar mapping is proposed here between naming or identification latencies and familiarity. That is, the internal structure of a chunk can determine the speed with which it is accessed. It is imperative for experimental paradigms that manipulate familiarity as a variable developmentally to take into consideration familiarity in this third sense, in terms of the accessibility of a recognizable chunk.

In sum, thus far three major points have emerged: First, there is no direct evidence to suggest that the underlying capacity (in terms of slots) of STM is either constant or variable with age. Second, developmentally, children of different age groups differ in their use and availability of mnemonic strategies. Third, three ways have been distinguished in which contents of LTM can differ among individuals, as well as between age groups. These differences are: absence vs. presence of a recognizable chunk, size of each chunk, and accessibility of a chunk. It will be aruged in the remaining part of the paper that the latter two factors, rather than a limitation in the capacity per se, can account for the major variances in STM performance between age groups.

TASKS THAT DEMONSTRATE STM DEFICITS AND ALTERNATIVE INTERPRETATIONS

Three paradigms that typically have demonstrated STM deficits in children will be briefly sketched. The general conclusion arising from each paradigm is that quantitative deficits in STM performance in children could be caused by a smaller STM capacity, although very few investigators specify exactly what they mean by the precise nature of capacity increase. Even though such an interpretation is parsimonious, there is no hard evidence to support such a hypothesis. Most of the data are descriptive in the sense that they illustrate the performance level of certain age groups. The intention of this section is to show that there exist many alternative factors that could produce the performance deficits. In order to understand the difference in performance level between age groups, it is necessary to consider the more fundamental processes that comprise the more complex tasks. Hence, in the following section, each task and its basic results will be outlined, and at least one variable or process that could very well produce the major quantitative difference in performance will be isolated.

Table 1
Memory Span for Different Types of Material as a Function of Age

	Types of Material			
	Digit	Letter	Concrete word	Geometric figures
5-year-olds	4.3	3.69	4.3	4.15
Adults	7.98	7.21	5.86	5.31
Ratio	1.86	1.95	1.36	1.28

Note–Data are from Brener, 1940; Crannel and Parrish, 1957; Gates and Taylor, 1925; Hurlock and Newmark, 1931.

Memory Span

The most straightforward data to consider when one talks about STM deficits in children is digit span. There is typically a 2:1 ratio in digit span between adults and 5-year-olds (see Table 1).

Digit span is typically measured by presenting lists of varying lengths of digits, either aurally or visually. The subject then immediately recalls the lists in serial order, either by written or spoken output. Recall is scored as correct if every digit is recalled in the appropriate order. Digit *span* is then the longest length that the subject can recall correctly 50% of the time. Various methods of scoring can be used, but all correlate highly. Four factors–stimulus familiarity, grouping, speed of encoding, and LTM retrievel–will now be considered as potential contributors to the adult-child difference in span, as opposed to a STM capacity difference.

Familiarity. In the previous section (under LTM Knowledge Base), three forms of familiarity were distinguished. To reiterate, a stimulus is *familiar* (presence vs. absence of a chunk) if it constitutes one recognizable chunk of information. Further, a stimulus can be more or less familiar (size of a chunk) to a given subject depending on its codability. For example, to all chess players, each chess piece is a familiar stimulus. However, to chess masters, the chess pieces are more readily codable into larger patterns than to novice players. In this sense, the chess pieces are *more* familiar to chess masters than to novices. Finally, a stimulus (such as a familiar face) can be differentially accessible to different subjects, even though it is equally familiar (in the sense of recoding) to all subjects.

It is postulated here that the shorter digit span for children may reflect their familiarity with digits in terms of chunk size and, as a result, their inability to recode, rather than their STM capacity (Olson, 1973; Simon, 1974). Another demonstration of the effect of a lesser degree of familiarity with a set of stimuli is shown by Boswell (Note 2), who manipulated familiarity by using different orders of approximation to English as stimuli for a memory span task. Using second graders and adults, she found the item span (irrespective of order) for fourth-order approximation to English to be about 4.5 for adults and 2.7 for 8-year-olds. (These estimates of span were extracted from her graphs.) Fourth-order approximation to English is more familiar to adults than children, since adults are more familiar with sequential dependencies and probabilities of English language. Accordingly, a difference of 1.8 letters was observed in the span. However, for zero-order approximation to English, where familiarity has less advantage for adults, the difference in item span between adults and 8-year-olds dropped to 1.0, almost a 2:1 reduction in span difference.

The hypothesis that the large digit span of adults reflects the degree of familiarity of a type of material can be further confirmed by examining memory spans for other types of materials. Table 1 shows adults' and children's memory spans for different types of material. Adult memory spans vary with types of material, reflecting their familiarity, whereas children's spans remain fairly constant.

Grouping. Another factor that can influence adults' performance in a serial ordered recall task like digit span is grouping. Adults often actively parse a string of digits, whereas children do not. One way of tapping this parsing strategy is to measure the interitem pause times during acquisition. Belmont and Butterfield (see Figure 2 of 1971) found pause times for adults to peak after every third item, whereas children's pause times did not show such a consistent trend. When a grouping strategy is used by adults, there is a marked improvement in digit span as they master increasingly larger groups (Martin & Fernberger, 1929). Adults can also benefit from experimenter-manipulated groupings (Bower, & Winzenz, 1969), whereas young children may not. McCarver (1972) grouped his stimuli by spatial cues into pairs and obtained facilitation with fourth graders and adults, but not with kindergartners or first graders. Harris and Burke (1972) grouped digits spatially into threes and found some facilitation with second graders and marked facilitation with fourth graders.

An alternative way of tapping younger children's deficiencies in grouping can be found in the correlation between category clustering (during free recall) and digit span performance. Kail (Note 3) found that, for third graders, the correlation between clustering and digit span was .15 (not significant), whereas the correlation for fourth graders was .34 (significant at the .05 level). This suggests that there may exist a greater tendency to apply strategies such as clustering and grouping in diverse tasks in older children.

Why do adults (but not young children) actively group a string of inputs and benefit from such grouping? It appears that the purpose of parsing is to facilitate rehearsal. Adults prefer to rehearse digits in groups of three (Cavanagh, 1976; Wickelgren, 1964). Since young children do not generally rehearse anyway, there is no need for them to parse a string of inputs into subgroups. Furthermore, if children (third graders) do rehearse, they tend to rehearse each item individually as opposed to groups of threes, as eighth graders do (Ornstein, Naus, & Liberty, 1975).

Speed of encoding. Speed of encoding is an additional factor intertwined with stimulus familiarity which can also affect memory span performance. That is, there is an abundance of evidence to suggest that the speed with which adults can identify a stimulus is faster than children (e.g., Gummerman & Gray, 1972; Welsandt, Zupnick, & Meyer, 1973). This faster speed of identification seems to be a function of stimulus familiarity (the evidence will be presented later). The fact that adults can encode a class of stimuli faster than children suggests that once the stimuli are properly encoded, adults have more time to process the stimuli in the sense of manipulating them in STM for a more efficient recall.

Following are two pieces of evidence which suggest quite conclusively that memory span performance varies with age as a function of the speed of encoding. First, Boswell (Note 2) found that, given a 50-msec exposure duration with 16 letters to encode, adults still recalled a greater number of letters than did 8-year-olds, even though in a 50-msec exposure, mnemonic strategies could not have played a major role in creating a differential amount of recall.

Although the level of recall was not of prime concern to Boswell (Note 2), it seems clear in view of the differential speed of encoding for letters between children and adults (Welsandt et al., 1973) that adults' advantage in recall may derive from their superior speed of encoding. Boswell also found a significant interaction between age and exposure duration with respect to the number of letters recalled. That is, adults asymptoted in the amount of information they gained from increasingly longer exposures (such as from 100 to 200 msec), whereas 8-year-olds continued to gain information with increasing exposure durations. This suggested that adults' recall performance is not limited by the speed of encoding in the short exposure duration, whereas encoding time can have a larger influence on children's recall performance.

Second, a study by Chi (in press) showed that, in general, the limitations on a memory span performance may lie in processes prior to short-term memory retrieval. That is, Chi found that not only memory span for faces exhibits a 2:1 ratio between adults and 5-year-olds, but also the amount of time needed to encode a familiar face and the amount of time needed to retrieve the name of a face (after partialling out response times) exhibit a 2:1 ratio. In other words, for familiar stimuli such as faces of classmates, young children required more than twice the amount of time to identify a face as did adults. This suggests that children's recall performance is usually limited not only by the lack of mnemonic skills (mentioned previously), but also by the speed of encoding. The implication is that if adults were not twice as efficient at encoding (so as to permit more time for subsequent processing in STM), then perhaps their recall performance in a memory span task would not be so greatly superior to those of children's. When Chi (in press) controlled the amount of available processing time for adults and children by cutting exposure time in half for adults, adults could not recall any more faces than children. These results suggest that memory span performance may be very much under the control of time-dependent perceptual and coding processes.

LTM retrieval. A fourth factor that can also contribute toward span differences between age groups is LTM retrieval. This factor is related to rehearsal as a means of consolidating or storing information in LTM. Craik (1968) conceptualized the typical memory span task as follows. If STM has unlimited capacity, recall should be perfect as memory set size increases. However, if STM has a limit of n items and recall is strictly from STM, then recall should be perfect for set sizes up to n, with less than perfect recall with set sizes increasing beyond n. However, the true adult capacity of STM will be obscured, if, with set size increasing beyond n, adults can retrieve more items from LTM. This conceptualization is compatible with serial position data, which always show a significant primacy effect, indicating that these items were retrieved from LTM (Murdock, 1972). If it is assumed that the primacy effect was due to more frequent rehearsal of the initial items (Rundus & Atkinson, 1970), then it makes sense to suggest that children's memory span will reflect only their true capacity, since no additional items will be retrieved from LTM due to the lack of rehearsal. The implication of this analysis is that adults' memory span has been elevated through LTM retrieval and, hence, their span score does not reflect their STM capacity; whereas children's span score may indeed be an indicant of their STM capacity.

The adaptation of Craik's (1968) analysis to developmental data has some support from Chi's (in press) results. Chi found that adults can perfectly recall only three familiar faces in a memory span task. However, their recall does increase with increasing set size beyond three, suggesting that beyond three faces, adults are relying on retrieval from LTM. Five-year-olds, on the other hand, do not show an increase in recall with increasing set size. They cannot recall more than two familiar faces, regardless of the set size. Furthermore, for unfamiliar faces where names are not available for rehearsal, adults' recall performance no longer increases with increasing set size beyond three. This suggests that when verbal rehearsal is prevented by not having available verbal labels, adults can no longer retrieve information from LTM.

In sum, the evidence reviewed in this section suggests that memory span performance can be contaminated by several factors which tend to produce superior performance on the part of adults and inferior performance on the part of children. The consequence of these factors–stimulus familiarity, grouping, speed of encoding, and LTM retrieval–is a different internal representation of the same external task for adults vs. children.

Serial Probed Recall

A second task which has been widely used to study STM in children is serial probed recall. It was introduced by Atkinson, Hansen, and Bernbach (1964), and its popularity arises from the nature of the task, which tends to sustain children's attention. Usually, a sequence of eight pictures is shown to the subject, one at a time. As soon as a card is presented, it is laid face down in a row in front of the subject. After all eight cards have been shown, a probe card is presented, and the subject's task is simply to turn up the card that matches the probe. If the subject makes an error, he is usally allowed to make another choice. The eight cards could be selected, either with or without replacement, from a larger pool, although sampling without replacement gives better performance (Keely, 1971). The dependent variable is the proportion of correct responses made at each serial position.

Results obtained from adults exhibit the typical serial position curve, with prominent primacy and recency effects (Phillip, Shiffrin, & Atkinson, 1967). There are two characteristics of children's (ages 4, 5) results that are distinctly different from those of adults. First, children make errors across all serial positions as compared to adults, and the proportion of errors decreases with increasing age. Second, the proportion of correct responses at a given position is a decreasing function of the number of items intervening between presentation of the item and its test for recall. That is, there is not a striking primacy effect with children (Atkinson, Hansen, & Bernbach, 1964; Hansen, 1965).

The finding of primary concern to the capacity hypothesis is the first one, namely, that 5-year-olds make more errors across every serial position compared to older age groups or adults. In Siegel and Allik's (1973) results, for example, the overall percentage of correct recall for adults was 76%, as compared to 47% for 5-year-olds.

One interpretation of these data centers on the difference in rehearsal strategies between adults and children. Rundus and Atkinson (1970) have shown explicitly that a direct relationship exists between amount of rehearsal and amount of free recall of verbal materials for adults, and there is extensive literature showing that young children do not spontaneously rehearse (Flavell, 1970; Hagen, 1971). Thus, a simple explanation of the depressed performance of young children in the serial probed recall task is that they are less likely to rehearse. The lack of primacy effects in the children's data (Cole, Frankel, & Sharp, 1971; Kingsley & Hagen, 1969) further supports this interpretation. In McCarver's (1972) data using the serial probed recall task, it was strikingly evident that most of the increase in performance from 5-year-olds to adults occurred in the primacy portions, whereas no obvious increase in recency performance was observed. Furthermore, Kingsley and Hagen (1969) were able to show that a significant primacy effect can be obtained if children are induced to rehearse. Finally, Keeney, Cannizzo, and Flavell (1967) found an overall improvement in recall in children who were induced to rehearse. The evidence is therefore substantial that the normally obtained difference in performance between children and adults on the serial probed recall task is due in large part to a difference in processing (rehearsal) strategies.

It should, of course, be stressed that any one factor alone cannot totally eliminate the adult-child difference. Belmont and Butterfield (1971), for example, found that 13-year-olds still obtain greater accuracy over the primacy positions than 9-year-olds in a letter serial probed recall task, even though both groups were using identical rehearsal strategies. However, some other processes must also contribute to 9-year-olds' deficit (perhaps inefficient retrieval), because their fastest correct latencies in response to the primacy positions were considerably longer and increased substantially more across these positions than the 13-year-olds.

It should also be pointed out, however, that other studies have found significant primacy effects in young children (ages 4, 5) especially if one partials out children's response bias. That is, it has been found that children tend to make more choices (about 54%) in the center positions (4 and 5) as compared to the end positions (Donaldson & Strang, 1969). When one corrects for this bias, a primacy effect emerges (Calfee, 1970). Related to the idea of unequal distribution of choices is the possible difference in criterion levels for different serial positions. Keely (1971) used the d' measure as an index of the strength of memory because it is independent of criterion. She varied the stimulus materials with respect to ease of labeling and found consistent primacy effects for all age groups (4, 8, 14), although the primacy effects did increase with age. Other reanalyzed studies (Atkinson et al., 1964; Calfee, Hetherington, & Waltzer, 1966) all show persistent primacy effects.

The finding of a significant primacy effect, however, raises an immediate dilemma, namely, why should young children exhibit a primacy effect when they obviously do not appear to rehearse? Siegel, Allik, and Herman (1976) have shown that the primacy effect exhibited in young children (ages 6, 7) is a function of the spatial (rather than temporal) component of the task. In other words, the superior performance on the primacy (as well as recency) positions arises from the additional cues provided by the spatially "end" positions, rather than from rehearsal per se. This conclusion was derived by mismatching the temporal and spatial positions during presentation.

Unfortunately, exactly the opposite conclusion was drawn by Spitz, Winters, Johnson, and Carroll (1975), using the same paradigm with 8-year-olds. Spitz et al. found the primacy and recency effects from cues provided by the temporal order of presentation. Perhaps the difference in the two studies lies in the method of response used. Siegel et al. (1976) used a probe technique, while Spitz et al. (1975) used a free recall response.

In sum, the existence of primacy effects in young children cannot be attributed to the same processes as in adults and older children. In other words, adults can manifest primacy effects as a result of both rehearsal and spatial (or temporal) cues, whereas children's primacy effects can arise strictly from the spatial (or temporal) cues. This difference in the underlying processes can perhaps explain why primacy effects are not a consistent finding in young children.

The fact that primacy effects can arise from two separate processes in adults may explain their elevated overall recall performance in a serial probed recall task. In both the Spitz et al. (1975) and Siegel et al. (1976) studies, no comparison was made with adults to see if the difference in the amount of recall between children and adults would approach a minimum when the spatial and temporal positions were not congruent. It is not difficult to suppose that adults can virtually ignore the spatial locations by learning a serial list and maintaining it via rehearsal when the temporal order and spatial order are congruent. Upon presentation of the probe, adults can locate its positions by first finding the item in the verbal list, and then finding the corresponding spatial location from the direct mapping between temporal and spatial order. Indeed, both Mandler and Anderson (1971) and Healy (1975) have shown that for adults spatial recall was impaired when the order of presentation was random. Children, on the other hand, may be doing something entirely different. Instead of learning interitem associations and rehearsing them, children may be associating items to spatial locations, as Atkinson et al. (1964) have suggested. In this case, children's recall performance should not be impaired if the spatial positions are not congruent with the temporal positions.

Recognition Under Limited Exposure

A third paradigm where children's STM performance has been deficient is recognition under limited exposure. Haith, Morrison, Sheingold, and Mindes (1970) showed that, if the total exposure duration is held constant at 150 msec and the number of geometric forms presented is increased from one to four, adults recalled (by pointing) about 3.5 geometric forms, while 5-year-olds recalled only about 1.5 forms. They surmised that such findings reflect "a striking limitation on children's visual STM capacity" (p. 464). Here is another instance of a 2:1 difference in recall between adults and 5-year-olds.

To explain such results, Haith (1971) ruled out the possibility of a difference between adults and children in the speed of processing the icon. From the following two results, they claimed that recognition or encoding time is just as fast in 5-year-olds as adults. First, Haith, Morrison, and Sheingold (1970) showed that adults can recognize a single geometric figure with greater than 50% accuracy with a 10-msec exposure duration, and 5-year-olds with a 20-msec exposure duration. They concluded that there were no gross differences betwen 5-year-olds and adults in their speed of recognition. However, this result must be interpreted with caution. Because no backward mask was used to terminate the persistence of the visual icon (Sperling, 1960), it could have been the case that children continued to process the visual icon considerably longer than adults. In a second study by Liss and Haith (1970), using both a backward and forward mask, 5-year-olds and adults could differ by as much as 30 msec, after partialling out the effect of forward masking, in the amount of exposure they needed to process even such simple stimuli as a horizontal vs. a vertical bar. On the basis of these and other studies, Haith (1971) ruled out the possibility of greater processing efficiency on the part of adults to explain their greater recognition score.

It may be agreed on a theoretical basis that the speed of encoding should not be different between adults and young children, or at least that the differences observed should be minimal, as Liss and Haith (1970) have suggested. However, a minimal difference in the amount of time needed by children and adults to process simple stimuli such as a horizontal vs. a vertical bar does not imply that gross differences in encoding speed would not be observed for complex stimuli. If gross differences are observed in complex stimuli, then a difference in the speed of encoding could easily be postulated as a potential source of limitation, instead of what initially appears to be a STM limitation.

The following is a list of studies illustrating that the difference in encoding speed between adults and children increases as the stimuli become more complex and unfamiliar. In the Gummerman and Gray (1972) study, for example, fairly simple stimuli were used and, hence, minimal differences were found. Adults and children were asked to perceive the orientation of a T, given 80 msec exposure followed by a mask. Adults were correct 81% of the time, whereas second graders perceived it correctly 63% of the time. This error data can be converted to an estimate of latency. This would imply that adults would have needed approximately

98 msec to perceive the orientation of a T correctly 100% of the time, and second graders would require 127 msec. Under these terms, results are very similar to the Liss and Haith (1970) results, where they observed a 30-msec difference in deciding the orientation of a bar. However, when more complex stimuli are used, such as letters, Welsandt et al. (1973) found that adults could perceive a letter well above the 50% level at an interstimulus interval of 76 msec followed by a mask, while 5-year-olds required 125 msec. For even more complex (but still familiar) stimuli such as faces of classmates, Chi (in press) found that adults needed about a 25-msec exposure duration to recognize one face, whereas 5-year-olds required 140 msec. For even more complex stimuli, such as random shapes, in order to obtain approximately equal recognition accuracy, Munsinger (1965) exposed each form for only 5-18 msec for adults, but 80-400 msec for 5-year-olds.

The only study which apparently agrees with Haith's (1971) original assumption that there is no difference in the speed of encoding is Blake's (1974). She presented one, two, or four geometric forms for a 15-msec duration for adults and a 30-msec duration for 4-year-olds, followed by a mask at variable interstimulus intervals. She found no difference in the speed of encoding one stimulus, but a significant difference between age groups for stimulus arrays of more than one stimulus. The lack of a significant difference in the speed of processing one stimulus can be explained by the failure to control stimulus onset asynchrony. That is, for every target array, 4-year-olds received an exposure duration that was 15 msec longer than adults. This extra 15 msec was probably sufficient to enable children to perceive one stimulus as accurately as adults, but not two or more. It is suggested here that what appears to be a memory deficit in a task, such as recognition under limited exposure, may actually be a deficit in the speed of encoding the stimuli.

In summary, three paradigms have been cited as representing studies which demonstrate STM deficits in children. In each case, it was pointed out that these deficits could be the result of inefficiencies in children's processing. There was substantial evidence to indicate that such factors as familiarity, rehearsal strategies, recognition time, grouping, recoding, and their interactions could all play a significant role in causing poorer memory performance in STM-type tasks in children.

Three further points should be made here. First, many other tasks besides the three mentioned also show poorer memory performance by children. Some of these are modifications of the paradigms already cited, such as running memory span (Frank & Rabinovitch, 1974), and others are totally different, such as dichotic listening (Friedrich, 1974; Inglis, Ankus, & Sykes, 1967). It is hoped that a consideration of the underlying information processing mechanisms will apply to all such memory-dependent tasks. Second, it should be stressed that many other factors can also influence children's behavior to produce inferior performance, such as motivational factors, ability to maintain set (Elliott, 1970), and task comprehension (Meacham, 1972). Third, although the factors that have been isolated here (rehearsal, stimulus familiarity, grouping, recoding, etc.) have typically been implicated in STM-type tasks, it is proposed here that these and similar types of fundamental processes can probably account for performance competencies in Piagetian tasks (Chi, Note 4). Increasingly large numbers of studies have begun to investigate alternative processes that can contribute to Piagetian task performance as well. For example, attentional factors can determine whether or not a child can successfully pass a conservation task (Gelman, 1969); knowledge of differential amounts of experience can effect performance at the formal stage of operations (Siegler & Liebert, 1974); and skill at quantification (Chi & Klahr, 1975) can also effect performance in Piagetian tasks where quantities are used, such as conservation of number, class inclusion, and so on (Klahr & Wallace, 1973).

SUMMARY AND CONCLUSION

The question of whether the capacity of STM increased with age was addressed in this paper. The paper was divided into two major portions. The first part was concerned with the STM structure and its control processes, as well as with differences in LTM knowledge base between age groups. In particular, an attempt was made to show that no evidence suggests directly that the parameters which characterize STM, such as capacity and rate of information loss, are significantly different between age groups. On the contrary, there is ample evidence to suggest that one of these parameters, namely, the rate of information loss, is invariant across age. However, substantial differences can be observed in the utilization and acquisition of control processes such as rehearsal, grouping, and recoding, as well as differences in the contents of LTM.

In the second half of this paper, an analysis of a few STM tasks where extensive developmental research has been conducted was presented. These tasks have typically shown that children's performance is deficient when compared to adults', and these deficiencies suggest a STM capacity limitation. From an analysis of these tasks, it appears that the two major factors mentioned in the first half of this paper—differential use of mnemonic strategies and differential LTM knowledge base—are better predictors of performance deficits than STM capacity per se.

In conclusion, it is suggested that what appears to be a STM capacity limitation in children is actually a deficit in the processing strategies, as well as a deficit in processing speeds. Both of these deficiencies result from a limited LTM semantic and recognition knowledge base, which presumably improves with age through cumulative learning.

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