Speed of processing: a developmental source of limitation

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IN ANY SUBPOPULATION that does not perform at the level of adults, whether in reading, memorizing, or problem solving, there are two general sources of limitation. The first possible source is inadequate knowledge, including the inefficient use of strategic knowledge. The second source is more structural in nature, relating to either the capacity of working memory or the general speed with which individuals process information. The locus and sources of a more limited speed of processing deficit, as manifested by a given subpopulation, are the concerns of this article. Although our example is drawn from the subpopulation of normal children, the logic of our analyses is applicable and generalizable to other subpopulations, as long as there is no apparent brain damage.

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EVIDENCE OF CAPACITY AND SPEED LIMITATIONS

That children have a more severe limitation in functional memory capacity has been apparent for decades. For example, children have a smaller digit span than adults. The number of digits that a 5-year-old can recall is usually four, whereas adults can recall about seven. Children’s more limited recall is general and applies to all domains, such as words, random forms, and color names.

This apparent deficit in the memory performance of normal children need not necessarily imply that there is an actual structural deficit in the size of working memory (Chi, 1976), because it is difficult to untangle actual structural deficit from an inability to deal with the limitation. Thus it has been possible (though difficult) to control for other aspects of adult superiority (such as greater knowledge and more efficient use of strategies) and to obtain results that do not show an adult advantage (Chi, 1977a; Lindberg, 1980; Nicolson, 1981). In any case, the debate about whether children actually do have a smaller capacity is not completely resolved at the moment (Pascual-Leone, 1978; Trabasso, 1978; Trabasso & Föllinger, 1978).

That children process information at a slower rate has also been a general developmental finding (Chi, 1977b; Wickens, 1974). Children have been found to be slower in memory scanning, simple and choice reaction time (Fairweather & Hutt, 1978), naming (Kirsner, 1972), and visual search (Bisanz & Resnick 1978), to name a few examples. Several factors have been considered to affect processing speed: use of different strategies (Chi, 1977b) and attention and motivational variables (Wickens, 1974).

Although both capacity and speed have been demonstrated independently to be more limited in younger than older children, these two factors may actually reflect a single underlying structural deficit, because there is a consistent relationship between the speed of processing and the capacity of working memory in adults. This relationship is elegantly demonstrated in the inverse linear relation between the speed for scanning a short list of items in working memory (the Sternberg task) and memory span for different materials (Cavanagh, 1972): the longer the span, the faster the scan. A similar linear relationship has been demonstrated for memory span and reading rate in adults (Baddeley, Thomson, & Buchanan, 1975).

The reciprocal relation between speed of processing and functional capacity has been noted again recently by Case, Kurland, and Goldberg (in press) and Nicolson (1981) where explicit developmental comparisons have been made. Replications of Baddeley et al.’s (1975) study indicate a linear relation between memory span and reading rate that is independent of age for the ranges of 8 to 12 years (Nicolson, 1981) and 3 to 6 years (Case et al., in press). Taken together, these studies clearly point to the increase in processing efficiency as the source of developmental difference in memory tasks but not necessarily to the capacity of working memory.

LOCUS OF SPEED LIMITATION

Given that children show a deficit in the speed of processing, is this limitation specific to a particular stage of processing, or is it general to all stages? And furthermore, when a slower speed of processing is manifested in children, is this due to an inherent slowness in the speed of processing (perhaps related to a physiological source), or can alternative interpretations be offered?

Following Sternberg (1966), Smith (1968), and others, we divide information processing into four component stages. External information is first encoded; it makes contact with existing knowledge in memory to produce
recognition. Once the stimulus is recognized (or activated in semantic memory), activation can spread along pathways to related nodes in memory (Anderson, 1976). The activated stimulus node can also be manipulated. This second stage, manipulation, may involve comparison (as in the Sternberg task) or name retrieval (the name code of the activated node needs to be retrieved) or semantic category judgment (identify the category to which the stimulus item belongs), and so on. After an operation of some kind is performed, a decision is made about its outcome. In the Sternberg memory scanning task, for example, each comparison of the target stimulus with the memory set produces a decision about whether the target is present or absent from the memory set. Once a decision is reached, signals are sent to the appropriate effector muscles (the third stage, response selection), and a motor response (the fourth stage) is made.

Hence, a latency response is basically decomposed into four sequential stages: encoding or recognition, manipulation and decision, response selection, and response execution. We assume a sequential nature in the stages of processing for the sake of interpretation, although in reality some stages may overlap, and others may proceed in parallel. Stage independence is merely an adequate way to conceptualize different internal processes.

Encoding or recognition time

The time it takes children and adults to encode information is commonly measured by a tachistoscopic recognition task, in which subjects are asked to identify a target when it is exposed for a brief duration. We attempt, in all cases, to restrict our interpretation only to those findings that are uncontaminated by other factors, such as short-term memory capacity or strategic usage. Although many studies using this recognition under limited exposure task show age differences in the speed with which information is recognized, one might still be able to conclude that when the task is simplified and strategy usage is controlled, there is a minimal difference between children and adults in the speed of encoding.

It is suggested here that minimal differences between children and adults in the speed of encoding exist when only one simple stimulus is being encoded. However, as soon as any complexity is introduced, either through multiple stimuli or longer maintenance of the stimulus, significant age differences occur. To illustrate this, in the following four studies, the

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stimuli used became progressively more complex, and the age differences also increased. The simplest task required subjects to perceive the orientation of a T. Adults required 98 msec to perceive the orientation of a T correctly 100% of the time, whereas second graders needed 127 msec (Gummerman & Gray, 1972). Using more complex stimuli, Welsandt, Zupnick, and Meyer (1973) found that adults needed 76 msec (with a mask) to perceive a letter above the 50% criterion, whereas 5-year-olds needed 125 msec. For familiar faces, Chi (1977a) found that adults needed 25 msec, whereas 5-year-olds needed 140 msec. Finally, for unfamiliar, more complex stimuli, such as random shapes, Munsinger (1965) exposed each form for only 5–18 msec for adults but 80–400 msec for 5-year-olds.

Adults’ superiority in the speed of encoding can also be discerned when multiple stimuli are to be maintained or when a delay is
interjected before recall. For example, when four geometric forms are presented with an interjected delay of 150 msec, adults can recall 3.5 forms, whereas 5-year-olds can recall only 1.5 forms (Haith, Morrison, Sheingold, & Mindes, 1970). In fact, when the array increases to six forms, adults' recall increases to around four items, whereas the 5-year-olds' recall never exceeds two items (Morrison & Haith, 1976). However, no age differences were observed at a short delay of 50 msec. Both adults and 5-year-olds have an estimated capacity of 7–8 items (Morrison, Holmes, & Haith, 1974; Sheingold, 1973).

The superior recall of adults at longer delays and the minimal age differences in the speed of encoding a simple single stimulus suggest that nonstructural factors, such as strategy usage, may come into play to facilitate the maintenance of multiple items in memory during retrieval. But the actual speed of encoding a single stimulus is not particularly deficient in young children.

**Mental manipulation time**

In the second stage of processing, information is assumed to be manipulated in active memory. The hope here is to find pure measures of elementary operations that are not contaminated by other factors. An elementary operation is an irreducible process such as compare, match, find next, and so on (Chase, 1977). Evidence from two tasks are provided below to see whether the speed of performing a mental operation increases with age: the Sternberg (1966) memory scanning task and Shepard's (Cooper & Shepard, 1973) mental rotation task.

**Sternberg memory scanning task**

This task was designed to estimate the amount of time required to compare an encoded stimulus (the target) with items in active memory (the memory set). The subject's task is simply to determine the presence or absence of the target in the memory set, which can vary from one to six items. Reaction time is a linearly increasing function of the set size, and the slope indicates the time used to make one comparison. The suitability of this task for estimating a mental operation derives from the fact that encoding and movement time can be partialled out of the scanning rate estimate, since they basically influence the intercept and not the slope.

The majority of the studies using this paradigm have found basically no developmental differences in the scanning rate in the age range from 5 years to adult, using stimuli such as digits (Bracey, 1969; Harris & Fleer, 1974; Keating & Bobbitt, 1978, Experiment 3; Maisto & Baumeister, 1975), familiar line drawings (Baumeister & Maisto, 1977; Hoving, Morin, & Konick, 1974), and nonalphanumeric symbols (Silverman, 1974).

The two studies that have found clear developmental differences using digits (Herrmann & Landis, 1977) and letters (Naus & Ornstein, 1977, Experiment 1) differ from the other studies in factors such as practice (Baumeister & Maisto, 1977; Harris & Fleer, 1974) and strict criterion of performance expectation (Hoving et al., 1974). Also, both of these studies used a fixed set procedure, which may have enabled the older subjects to recode the memory set by categories and has been shown to benefit older children more (Naus & Ornstein, 1977, Experiment 2).

In any case, the implication from this set of studies is clear: When they have to, and under optimal conditions (sufficient practice and not fatigued), children can manipulate information in active memory just as efficiently as adults, at least as measured by the Sternberg scanning task. However, as soon as the task becomes more difficult, then an interaction occurs in which the older children's and adults' speed of processing becomes significantly faster than the younger children's. This pattern of
interaction is consistent with our analyses of the data from the encoding studies listed earlier.

**Mental rotation**

Mental rotation, as the term implies, is the ability to rotate a stimulus object in memory. Its major distinction from the previous task lies in its spatial nature. Despite earlier notions that children younger than 7 to 8 years of age are incapable of coordinating the movements of different parts of an object in imagery (Piaget & Inhelder, 1971), it is now known that children as young as 5 years can mentally rotate objects. However, the question here is the proficiency level.

The mental rotation task is chosen because by varying the extent of rotation, one can again use additive logic and linear regression to determine the rate of rotation. Thus age comparisons without the contamination of response selection or motor time can be made. The task consists of deciding whether two geometric forms are the same or not, with one of the pair rotated anywhere from 0 to 180 degrees. Reaction time is a linear function of the angular discrepancy between the pair of stimuli, with the rate of rotation being its slope.

Two sets of developmental findings are available. First, both Marmor (1975) and Childs and Polich (1979; using a slight variant of the task) found no age differences in the slope between the third graders and adults. Although Marmor did not run adult subjects, her third graders rotated panda bear-like forms at the rate of 7 msec/degree, which is analogous to some of the rotation rates of adults, as found by Cooper and Shepard (1973), even though a direct comparison cannot be made. Although Marmor wishes to conclude that there may not be age differences beyond age 8 years, the 5-year-olds in her study definitely had a steeper slope, on the order of 15 msec/degree of rotation. Furthermore, Kail, Pellegrino, and Carter (1980) also found age differences between 8-year-olds (who rotated at the rate of 7 msec/degree) and adults (at the rate of 4 msec/degree). Hence there are discrepant findings here that need to be resolved.

The assumption that adults are capable of using more clever strategies with increased task complexity is again a possible interpretation. For example, adults can profit from advanced warning with respect to the stimulus and its orientation and exhibit an essentially flat slope (Childs & Polich, 1979; Cooper & Shepard, 1973), but third and fifth graders cannot take advantage of such cueing. Likewise, Kail et al. (1980) suggested that the children use different processing strategies, such as rotating the whole objects rather than just the subcomponents essential for comparison. Alternatively, adults may be able to rotate the objects holistically, whereas children may have to rotate each component individually. These strategic differences would affect only the speed of rotation, not the linearity of the slope. Uncovering such differences requires more detailed explorations (Just & Carpenter, 1976), and developmental data are not yet available.

In sum, the data cited in this section across the two tasks all have the same general pattern: (a) age differences are found in some cases but not others; (b) when age differences do occur, and if the investigators do further exploring, they tend to find strategic differences; and (c) age differences usually become more pronounced when the task becomes more complex.

**Response selection and decision time**

The primary concern of this and the next section is the partitioning of the time that is generally estimated by the intercept into two components: response selection and motor
execution (or movement) time. One can safely assume at this point that across all of the studies mentioned in the previous section, the intercept estimate is higher for the younger age groups, even in the studies that report no developmental differences in slopes. So the question here is: Which of these times (response selection and motor execution) develops with age? (Although the intercept also includes the encoding time, it is assumed from the analyses in the first section that encoding time does not develop significantly for simple stimuli.)

In the decomposition of a reaction time, it was assumed in the previous section that the slope measures not only the mental manipulation time but the decision time as well. Hence at the termination of a scan (consisting of a series of mental comparisons), a positive or negative decision has been reached. Likewise, when the rotation is terminated, a decision has been reached with respect to the same or different judgment. For the three studies to be reported below, the technique used for estimating response selection time also has embedded in it the decision time. However, since we prefer to conclude from the mental comparison studies that there are no age differences in the slope, it must be assumed that the decision component is invariant with age as well. Thus any variability in the technique of estimating response selection time will have to be attributed to response selection per se and not the decision time.

Surwillow (1977) compared children’s time to make a choice response (pushing one of two buttons depending on a high or low tone) versus a simple response (pushing a single button when a tone sounds). The difference between the two reaction times is taken to be the amount of time it takes to process one bit of information. The data show very clear developmental trends in that the response time decreases with increasing age, from ages 5 to 17 years. Keating and Bobbitt (1978, Experiment 1) arrived at the same result, using subjects in the age range of 9 to 17 years. Finally, Fairweather and Hutt (1978) examined choice reaction tasks with two, four, and eight alternatives (corresponding to 1, 2, and 3 bits of information). Plotting reaction time against the number of choices shows that the slope gets shallower as children get older. To reiterate, the response times measured in these experiments incorporate both a decision component and the response selection component. Since it has already been assumed that decision time in the mental comparison tasks is constant, it would have to be concluded from this set of studies that the source of the age differences lies in the response selection time. Such an interpretation is also favored by Fairweather and Hutt (1978).

Perhaps some insight can be gained into the source of the young child’s difficulty in selecting a response (that is, choosing the appropriate effector muscles for movement) by drawing on some neurophysiological evidence. When the motor response is simple (such as controlled contraction of a single muscle), the young child (ages 3–12 years) is able to perform fine neuromuscular control equal to that of an adult (Simard, 1969). However, when complexity is introduced, the 4-year-olds tend to utilize more muscle groups and demonstrate higher levels of activity in those muscle groups, when compared with 8-year-olds, even though the overt performance (electromyogram patterns) is similar. On more complex tasks, younger children are at an even greater disadvantage. When a young child attempts to integrate two movements (such as maintenance of posture and throwing), different electromyogram (EMG) patterns exist between 4-, 6-, and 8-year-olds (Simard, 1969; Williams, in press; Williams, Balon, Fisher, & Tritscher, 1978). The 4- and 6-year-olds respond with far more widespread and higher levels of EMG activity in involved muscle groups than is evident for 8-year-olds.
These neurophysiological data indicate that children approach novel movement by choosing to use different muscle groups than adults use to accomplish a task, therefore quite possibly causing a time delay in responding. Hence response selection may indeed be a source of developmental differences.

Execution time

The last component in a latency that must be considered developmentally is execution time, which is also embedded in the intercepts in the tasks used in the previous sections. Perhaps the most direct way to measure execution time itself is through tasks measuring simple reaction time. It is well documented that simple reaction time decreases steadily with increasing age (Goodenough, 1935; Jones, 1937; Pierson & Montove, 1958; Surwillo, 1977), although the decrease in simple reaction time (from 311 msec for 9-year-olds to 233 msec for 17-year-olds) is less dramatic than the reduction in two-choice reaction time (from 729 msec for 9-year-olds to 467 msec for 17-year-olds; Keating & Bobbitt, 1978).

At least two sources can be considered for the systematic decrease. The smaller source of difference, we speculate, is the child’s inability to remain attentive (Wickens, 1974), coupled with the adult’s greater ability to maintain set in anticipation of a stimulus (Day, 1978; Potter, 1975). Furthermore, not only are children less able to profit from set, they are also more distracted by irrelevant cues and information than are adults (Strutt, Anderson, & Well, 1975; Smith, Kemler, & Aronfreed, 1975). Also, young children appear to benefit from expected events and to be hurt by unexpected events to a greater extent than adults (Kerr, 1979; Kerr, Blanchard, & Miller, 1980).

A second and possibly more potent source of age differences is the motor component. The fact that motor performance in general improves with age suggests that simple reaction time may predominantly be accounted for by movement time, since the execution of a movement constitutes a large portion of the simple reaction time task.

The degree to which information processing variables (set, decision time, selection, and response time) or neurophysical maturation (nerve fiber size difference, increased myelination) affect reaction time has been investigated by fractionating reaction time into premotor and motor time. Premotor time is the time from stimulus onset until the first nerve impulse reaches the muscle unit, and motor time is the time from the arrival of the first impulse at the muscle until sufficient motor units are recruited to initiate movement. Therefore, motor time is related to the physical state of the nerves and, hence, to neurophysical maturation, whereas premotor time is dependent upon information processing. For adults and older individuals, the data seem quite clear: Age differences do not exist in the motor time (physiological degeneration of the nerves) but in an increased premotor time (Botwinick & Thompson, 1966a, 1966b; Che- 

Chema, Thomas, Ward, and Groppel’s (1978) study illustrates the independent effects of premotor and motor time in a simple reaction time task across age, comparing EMG recordings for reaction time of the jaw, hand, and foot. The authors argue that if the difference in reaction time were due to increased neurological development or degeneration, then changes in the premotor time for the jaw muscle should be proportionately smaller than for the leg, due to differences in the lengths of the nerve pathways. In studies of 7-, 11-, 25-
and 65-year-olds, however, this was not the case, indicating that overall changes in reaction time are due to information processing rather than neurophysiological changes. Similarly, other studies indicate that young children's ability to perform simple motor acts, such as tapping a finger, is no different from that of adults (Kerr, 1975; Salmoni & Pascoe, 1978). It is only more complex tasks that produce developmental differences. Thus it seems clear that simple motor execution time (which includes motor time and the time to accomplish the actual movement) is not an important developmental factor.

OVERCOMING LIMITATIONS

Since children often process information at a slower speed than adults, it has been suggested that the capacity of working memory is more limited. However, since the capacity of working memory is inversely related to the speed of processing, it is thought that a more limited speed of processing may be the source of deficit, causing inferior performance in many memory and problem-solving tasks.

To explore the sources of children's inferior speed of processing, latency data were considered. By decomposing a reaction time into four stages (encoding, manipulation, response selection, and response execution), attempts were made to isolate the stage at which deficits were the most reliable, and the nature of this deficit was explored. It was tentatively concluded that the major retardation in the speed of processing for children occurs at the response selection stage.

Another consistent pattern emerging is that complexities always seem to hinder children's performance more than adults'. There may be several reasons. First, as soon as the task becomes more complex, there are greater opportunities to use different strategies and approaches to the task. Second, as soon as a stimulus gets more unfamiliar, one has to be concerned with the structure of the semantic network. Perhaps the lesser density and lesser strength of a child's semantic network of nodes and links impair the rapidity with which pathways and nodes can be activated (Chi & Koeske, in press). These handicaps could simulate a structural limitation that is related to either the speed of processing or memory capacity. However, because these limitations can be overcome with greater experience (Chase & Ericsson, 1981; Chi, 1978), we prefer to view the apparent limitations as functional in nature and not structural.

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