

Research Article

Rethinking Speed Theories of Cognitive Development

Increasing the Rate of Recall Without Affecting Accuracy

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ABSTRACT—*Researchers have suggested that developmental improvements in immediate recall stem from increases in the speed of mental processes. However, that inference has depended on evidence from correlation, regression, and structural equation modeling. We provide counterexamples in two experiments in which the speed of spoken recall was manipulated. In one experiment, second-grade children and adults recalled lists of digits more quickly than usual when the lists were presented at a rapid rate of two items per second. In a second experiment, children received lists at a rate of one item per second; half the children were trained (successfully) to speak their responses more quickly than usual, at a rate similar to adults' usual rate. Recall accuracy was completely unaffected by either of these response-speed manipulations. Thus, although response rate is a strong marker of an individual's maturational level, it does not appear to determine the accuracy of immediate recall. These results have important methodological and theoretical implications for human development.*

The length of word lists that can be recalled verbatim immediately after they are presented, or short-term memory span, increases as children mature (Bolton, 1892). This increase is important because memory span indexes intelligence and mental maturation (Sattler, 1992). Researchers have proposed that span grows because of increases in the speed of mental processing (Cowan et al., 1998; Fry & Hale, 1996; Kail & Park, 1994; Kail & Salthouse, 1994). However, the evidence for this account has been limited to correlations between memory span and the speed of speech (and results from related approaches,

including regressions and structural equation models). In the two experiments reported here, we managed to increase children's speed of spoken recall dramatically, but, counter to speed-of-processing accounts, found no accompanying improvement in short-term memory.

One account of how processing speed could affect serial recall stems from evidence that individuals recall as many stimuli as they can recite in about 2 s (Baddeley, Thomson, & Buchanan, 1975; Hulme & Tordoff, 1989; Schweickert, Guentert, & Hersberger, 1990). The assumption is that temporary memory representations are lost within about 2 s unless covert rehearsal refreshes them quickly enough; recitation speed is presumably an estimate of covert rehearsal speed. Representations might also be lost while recall of the list is under way, which would place a premium on recall speed (Cowan et al., 1992; Doshier & Ma, 1998; Hitch, Towse, & Hutton, 2001).

Consider, though, that a relation between a speed variable and a memory variable need not reflect an effect of speed on memory, though that hypothesis is attractive. A famous counterexample is found in orienting tasks. The speed of decision for words in different orienting tasks shows a linear relation with later recognition of those words. Nevertheless, manipulations that equated the speeds of several orienting tasks did not eliminate the effects of those tasks on later recognition of the words (Craik & Tulving, 1975).

One way to go beyond the correlation between processing speed and short-term memory is to examine spoken responses in the recall task as a measure of processing speed and to speed up these spoken responses in children, to see if there are commensurate improvements in recall. It has proven infeasible to train children to increase an overt speech counterpart to covert rehearsal, in which a few words are repeated as quickly as possible (Hulme & Muir, 1985). However, until now, there has been no attempt to speed up recall responses, which differ from overt rehearsal in that recall is ordinarily attempted at the participant's preferred pace, with no demand for speed.

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We sped up recall by presenting some of the lists to be recalled (by children and adults) at a rapid pace (Experiment 1) and simply by instructing children to recall quickly (Experiment 2).

EXPERIMENT 1

Previous manipulations of presentation rate have yielded inconsistent effects on recall accuracy (cf. Engle & Marshall, 1983; Murray & Roberts, 1968; Sarver, Howland, & McManus, 1976). However, studies have not examined whether the rate of presentation influences the rate of recall. If it does, it is possible to examine whether the accuracy of recall is also influenced. The simple prediction from a speed theory is that faster recall should lead to commensurately better recall (e.g., Cowan et al., 1992; Doshier & Ma, 1998).

Consider, however, that memories might be reactivated during interitem gaps during presentation (Baddeley, 1992; Barrouillet, Bernardin, & Camos, 2004) or recall (Cowan, 1992). Barrouillet et al. found that what was important for recall was the proportion of the presentation time in which the subject was free to concentrate on the memoranda as opposed to distractors. From this perspective, slower rates of recall would not necessarily produce poorer performance because decay could be at least partly offset by additional reactivation occurring between items.

Method

Subjects

The subjects were 18 second-grade children (5 female, 13 male; mean age = 102.11 months, $SD = 3.62$) and 18 college students (13 female, 5 male; mean age = 262.53 months, $SD = 60.71$).

Apparatus and Stimuli

Subjects were tested individually in a sound-attenuated chamber. A computer was connected to audiological headphones and to a microphone mounted on the monitor. Responses were saved digitally for later timing analyses.

The main visual stimuli were the digits 1 through 9, presented individually in the center of the computer monitor in a 30-point Helvetica font (0.75 cm high) for 0.4 s. The sounds were the digits 1 through 9 spoken in a male voice, digitally recorded on the computer and played through the headphones at an intensity ranging from 77 to 82 dB(A). The duration of the sounds ranged from 223 to 394 ms ($M = 327$ ms). Stimuli were presented at three different paces: 0.5 s/item (i.e., 2 items/s), 1 s/item (1 item/s), and 1.5 s/item (0.67 items/s).

Different portions of the session were signaled by a dark rectangle (7.4 cm wide \times 2.4 cm high) with a colored border. A yellow border served as a ready signal for 1 s. Then the border changed to red while the set of to-be-recalled stimuli was presented. When the presentation modality was visual, printed digits were presented in the center of the rectangle defined by the red border for 0.4 s. When the presentation was acoustic, the

red-bordered rectangle was left empty during the presentation of spoken digits. The recall signal, which was presented 500 ms after the onset of the last list item, was the border turning green; this change in color was accompanied by a 100-ms, 440-Hz, triangular-wave tone. As the response was spoken, it was recorded on a clipboard by an experimenter seated behind the subject. The experimenter then typed responses into the computer after each list recall was completed.

Procedure

Children received a book and a \$10 reward for participating, whereas adults received credit toward successful completion of their introductory psychology course. Each subject took part in two test sessions on separate days. One session was for spoken lists and the other was for printed lists, with the order counterbalanced across subjects. Each session included three phases, one for each presentation rate. (The three rates were presented in a Latin square order.) The instruction for each trial was to wait until the list ended and then repeat the digits aloud in the order in which they had been presented, "as fast or as slow" as the subject thought best; the subject was told not to talk during a trial except to repeat the list.

Each phase of the experiment began with a span-determination test for that particular rate and presentation modality. Four trials were presented at each list length, beginning with lists of three digits; list length increased by one until the subject made a mistake on all four trials at a given length. The longest length at which at least one list was recalled correctly was taken as that subject's span. Each span-determination test was followed by a postspan sequence of 12 additional lists at the same presentation rate. These trials comprised, in random order, 4 trials at a length equal to the just-determined span, 4 trials at a length one item shorter (span - 1), and 4 trials at a length two items shorter (span - 2). This postspan procedure provided information about memory performance and verbal response rates with the difficulty level comparable for all subjects. Altogether, each subject received six span-determination tests (for spoken and printed lists at three presentation rates) and 72 postspan test trials (12 per span type).

Timing Analysis

The spoken response for each trial was saved in a separate computer file and analyzed later with a waveform editing program allowing each utterance to be measured with millisecond accuracy. The rater highlighted the relevant segment of the sound file on an oscillographic display on the computer monitor and then listened to the highlighted segment to verify its beginning and ending points. Reliability (Cronbach's α) for the total duration of response was .91 (calculated for the postspan data with trials within a subject alternately assigned to three subsets).

Trials in which the response contained an error were not used for timing analyses. Consequently, only short lists had enough

trials for these analyses. Trials with three-item lists were used for the span-determination task, and trials with a list length two less than span were used for the postspan task. In previous studies of response timing in short-term recall (Cowan, 1992; Cowan et al., 1994, 1998; Hulme, Newton, Cowan, Stuart, & Brown, 1999), we focused on interword pauses to examine the details of retrieval processes. In the present study, however, our intent was to examine relations between recall response rate and performance. Therefore, the key timing measure was the rate of recall, defined as the number of items divided by the time between the end of the stimulus list and the end of the response.

Results and Discussion

The results are summarized in Figure 1. The clear result is that the presentation-rate parameter influenced the rate of recall, but had no effect at all on either memory span or the postspan level of recall. Notice that the span measure was quite precise (with small error bars) and was grossly different for children and adults, even though it was unaffected by presentation rate.

These observations were born out by inferential statistics. An analysis of variance (ANOVA) of recall rates in the span-determination test was conducted with age group as a between-subjects factor and presentation modality (auditory or visual)

and presentation rate (2, 1, or 0.67 items/s) as within-subjects factors. Recall speeds for auditory and visual lists did not differ overall. The rate of recall was slower in children ($M = 1.50$ items/s, $SEM = 0.08$) than in adults ($M = 1.74$ items/s, $SEM = 0.08$), $F(1, 34) = 4.89, p < .05, \eta_p^2 = .13$. More important, the rate of recall was fastest with a presentation rate of 2 items/s ($M = 1.75$ items/s, $SEM = 0.06$), and slower with presentation rates of 1 item/s ($M = 1.58$ items/s, $SEM = 0.06$) and 0.67 items/s ($M = 1.54$, $SEM = 0.07$). The main effect of presentation rate was significant, $F(2, 68) = 8.36, p < .001, \eta_p^2 = .20$. Newman-Keuls pair-wise post hoc tests indicated that the fastest presentation rate resulted in significantly faster recall than either of the other two presentation rates, which did not differ. Only interactions with presentation rate are relevant to the hypotheses, and therefore only these interactions are reported in this article. However, there were no such interactions in the present analysis of recall rates in the span-determination test.

A comparable analysis of memory span yielded no effect of presentation rate. This analysis yielded only main effects of age group, $F(1, 34) = 45.42, p < .001, \eta_p^2 = .57$, and modality, $F(1, 34) = 35.25, p < .001, \eta_p^2 = .51$. Children had lower spans than adults ($M = 5.44$ vs. 7.32 , $SEM = 0.20$ in each case), and span for spoken lists ($M = 6.69$, $SEM = 0.14$) exceeded span for printed lists ($M = 6.07$, $SEM = 0.16$).

In one condition (lists spoken at the fastest rate), children's rate of recall (1.73 items/s, $SEM = 0.12$) was nearly the same as adults' rate (1.79 items/s, $SEM = 0.10$), yet children's span (6.06, $SEM = 0.25$) was well below adults' span (7.56, $SEM = 0.25$).

In an analysis of the rates of recall of lists two items below span in the postspan trials, the results were for the most part similar to those for recall rates in span-determination trials. Recall was slower in children ($M = 1.45$ items/s, $SEM = 0.09$) than in adults ($M = 1.91$ items/s, $SEM = 0.09$), $F(1, 33) = 14.04, p < .001, \eta_p^2 = .30$, and it slowed down as the presentation rate slowed (M s = 1.80, 1.62, and 1.63 items/s for rates of 2, 1, and 0.67 items/s, respectively; SEM s = 0.06, 0.07, and 0.07), $F(2, 66) = 9.05, p < .001, \eta_p^2 = .22$. (One adult had no postspan timing data because of a recording problem and was omitted from the postspan analyses.) Newman-Keuls tests showed that, as in the span-determination data, response rates were significantly faster in the fastest presentation condition than in the two slower presentation conditions, which did not differ from one another. Unlike the analysis of recall rates in the span-determination procedure, though, the analysis of postspan recall rates showed an interaction of presentation rate and presentation modality, $F(2, 66) = 5.36, p < .01, \eta_p^2 = .14$. The decrease in response rate as a function of decreasing presentation rate was more pronounced for spoken lists (response rates: 1.86, 1.62, and 1.59 items/s) than for printed lists (response rates: 1.74, 1.63, and 1.66 items/s).

In the analysis of the proportion of postspan lists recalled correctly, only list length had a significant main effect, $F(2, 66)$

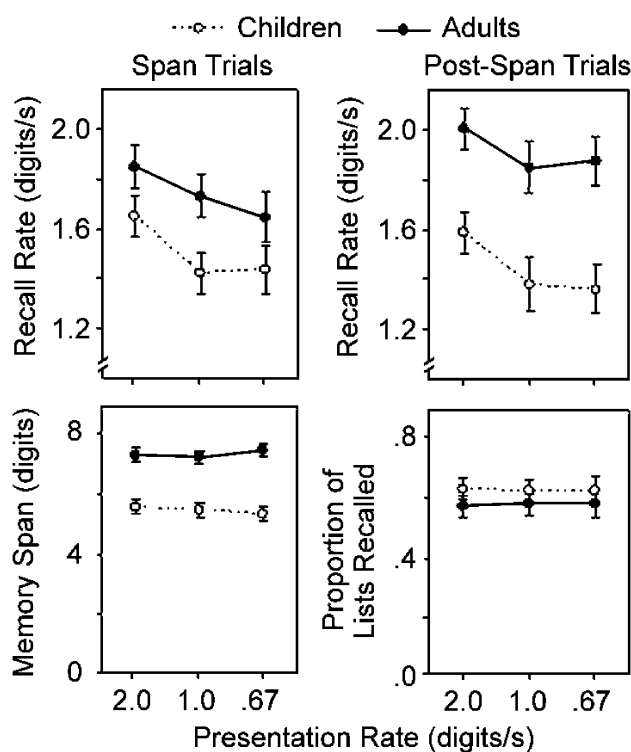


Fig. 1. Performance of children and adults in Experiment 1 as a function of the three presentation rates. The graphs at the top present recall rates in the span-determination task for three-word lists (left) and in the postspan task for lists two items below span (right). The graphs at the bottom show mean memory spans (left) and the proportion of trials recalled correctly in the postspan period (right). Error bars indicate standard errors.

= 199.97, $p < .001$, $\eta_p^2 = .86$. Recall was correct for .34 of span-length lists ($SEM = .03$), .63 of lists one below span ($SEM = .03$), and .82 of lists two below span ($SEM = .02$). The absence of an effect of age was expected, given that list lengths were adjusted for ability. There were no effects of presentation rate.

In sum, for both age groups, in both span-determination and postspan trials, presentation rate had a strong effect on response rates, but no effect on immediate memory performance.

Finally, to obtain more insight into developmental improvement in span, after the experiment we asked each subject how he or she had recalled the digits. Most of the adults (16 of 18) alluded to some sort of grouping strategy, whereas only 2 of the 18 children did so, a difference highly significant by Fisher's exact test. This suggests that memory development could result at least partly from improved strategies (cf. Flavell, Beach, & Chinsky, 1966; Ornstein, Naus, & Liberty, 1975). It is noteworthy, however, that age differences in capacity for spoken lists can be observed even in a situation in which rehearsal and strategies during presentation are infeasible because the spoken lists are unattended during presentation (Cowan, Nugent, Elliott, Ponomarev, & Sauls, 1999).

EXPERIMENT 2

Experiment 1 showed that a manipulation in the stimulus presentation rate greatly affected the timing of recall, but nevertheless did not influence recall accuracy. This result rules out the possibility that the accuracy of recall is a direct result of the recall rate. However, another possibility remains. Perhaps it is the response speed relative to the stimulus speed that matters. This could be the case, for example, if rapidly presented lists lose their temporal distinctiveness in memory more quickly than do slowly presented lists (Nairne, 2002; Neath & Surprenant, 2003). To assess this possibility, we conducted a second experiment with children. In this experiment, lists were presented at a rate of one item/s, and in a critical block of trials, half of the children were instructed to repeat the items as quickly as possible. This procedure is reminiscent of the training procedure of Hulme and Muir (1985) except that they attempted to train the rapid, overt recitation of small groups of words, and were largely unsuccessful. Our attempt to train children to hasten responses in the recall task itself was, in contrast, highly successful.

Method

Subjects

The subjects were 38 second-grade children (20 females and 18 males; mean age = 96.95 months, $SD = 4.11$) who did not participate in Experiment 1.

Procedure

The procedure was the same as in Experiment 1 with three exceptions: First, the digit stimuli were always presented in the

auditory modality at a rate of one item/s. Second, the entire basic procedure, in which span determination was followed by a postspan test, was repeated three times in successive phases of the experiment. Third, the children were randomly divided into two groups of 19, who received different instructions in Phase 2. In Phase 1, the instruction for all subjects was to repeat the lists at whatever speed seemed best. In Phase 2, half the children were instructed to speak their responses as quickly as possible without making errors, and the other half were given the same instruction as in Phase 1. In Phase 3, we again asked all children to speak at whatever speed seemed best to them, so that we could observe any aftereffects of the manipulation in Phase 2.

Two scorers measured the same 100 trials, and the interscorer correlation for total response durations was .99. Reliability (Cronbach's α) calculated from the postspan data (divided into three subsets) was .95.

Results and Discussion

Figure 2 shows the results, including recall rates and accuracy in the span and postspan trials, measured in the same way as in

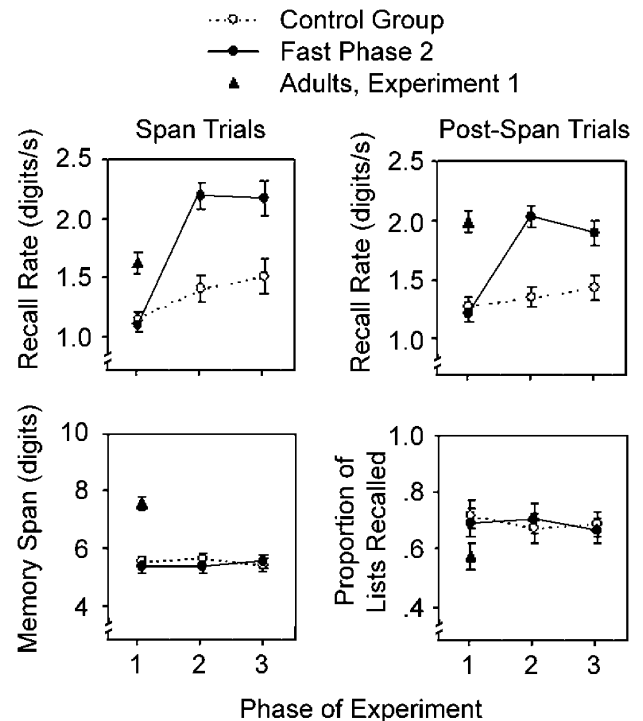


Fig. 2. Performance of children in Experiment 2 as a function of the three phases of the experiment. During Phase 2, half of the children were instructed to speak as quickly as possible, without making errors ("Fast Phase 2"), and the other half were instructed to speak at the rate that seemed best to them (control group). The graphs at the top present recall rates in the span-determination task for three-word lists (left) and in the postspan task for lists two items below span (right). The graphs at the bottom show mean memory spans (left) and the proportion of trials recalled correctly in the postspan period (right). The unconnected points show adults' means from the comparable condition in Experiment 1 (spoken lists presented at a rate of one item/s). Error bars indicate standard errors.

Experiment 1. It is clear that responses sped up in Phase 2 among children instructed to recall quickly in that phase, and that these children's responses remained fast in Phase 3, even though rapid speaking was no longer required. For purposes of comparison, Figure 2 also presents the results for adults in the comparable condition of Experiment 1 (presentation rate of one item/s). The figure shows that the instructions were so successful that children sped up to an adultlike rate of recall. Nevertheless, this speedup was not accompanied by an increase in performance levels (Fig. 2, bottom panels).

Inferential statistics on the children's data verified these observations. An ANOVA of recall rate in the span-determination trials, with instructions as a between-subjects variable and with experimental phase as a within-subjects variable, indicated an overall advantage for the group instructed to speak quickly in Phase 2, $F(1, 36) = 16.03$, $p < .001$, $\eta_p^2 = .31$, and an advantage for Phases 2 and 3 over Phase 1, $F(2, 72) = 38.93$, $p < .001$, $\eta_p^2 = .52$. However, these main effects are not meaningful. What is important is the interaction of instruction group with experimental phase, $F(2, 72) = 12.53$, $p < .001$, $\eta_p^2 = .26$. Newman-Keuls tests showed that the instruction groups differed in recall rates in Phases 2 and 3 (i.e., after instructional differences had been introduced), but not in Phase 1 (baseline performance). In contrast, a comparable analysis of digit span showed no differences between the instructional groups or experimental phases.

The analysis of postspan recall rate (for lists two items below span) yielded the same effects: inconsequential main effects of instruction group, $F(1, 36) = 11.71$, $p < .001$, $\eta_p^2 = .25$, and experimental phase, $F(2, 72) = 33.61$, $p < .001$, $\eta_p^2 = .48$, modified by a critically important interaction of these variables, $F(2, 72) = 20.00$, $p < .001$, $\eta_p^2 = .36$. Newman-Keuls tests again showed that the instruction groups differed in Phases 2 and 3, but not in Phase 1. A comparable ANOVA of the proportion of trials correct yielded no effects.

In sum, then, simply instructing children to recall quickly was sufficient to achieve a dramatic increase in response speed, but with no accompanying change in short-term memory performance.

GENERAL DISCUSSION

We manipulated recall speed in two ways and related it to recall accuracy, in two immediate memory experiments. In Experiment 1, we found that adults and children repeated lists much more quickly when the lists were presented rapidly (2 items/s) than when they were presented more slowly. Yet there was no effect of presentation speed on recall accuracy.

There is some question as to why the manipulation of presentation speed in Experiment 1 altered recall speeds. The increase in recall speed does not appear to reflect a simple imitation process, inasmuch as recall speeds did not differ significantly between the presentation speeds of 1 item/s and

0.67 items/s. It is uncertain why lists presented at the rate of 2 items/s were recalled more quickly than slower lists. The rapid lists may have been perceived as having no interword pauses, and that perception may have been imitated in responses. Many theories might predict that such a connected representation of the words would lead to superior recall, but that was not the case.

In Experiment 2, we found that children could be taught to repeat lists at speeds much faster than they ordinarily use in immediate recall. The striking outcome was again that this speedup did not improve recall accuracy at all (or impair it, either), an effect in keeping with the findings reported by Lewandowsky, Duncan, and Brown (2004). This outcome runs counter to what would be expected if the key constraint on recall is decay of a temporary memory representation that is strictly time limited (e.g., Cowan et al., 1992; Doshier & Ma, 1998), although it still could be accounted for with a decaying temporary memory if, between words recalled, periods of rehearsal (Baddeley, 1992) or reactivation (Cowan, 1992) can renew the memory trace. Note that this stability of recall accuracy, despite different recall speeds, was obtained with no changes in the stimulus presentation rate in this experiment. This rules out the possibility (which arose in Experiment 1) that what is important for recall accuracy is the ratio between the speeds of stimulus presentation and response.

This research has strong implications for development. From previous research on various tasks, it is clear that developmental changes in the speed of processing co-occur with developmental changes in immediate memory ability and in many other cognitive skills (Cowan et al., 1998; Fry & Hale, 1996; Kail & Park, 1994; Kail & Salthouse, 1994; Salthouse, 1996). Given the success of structural equation models to predict immediate memory performance from processing speed generally or from verbal speed in particular, it has been appealing to speculate that speed moderates the accuracy of recall. For example, in one study (Cowan et al., 1998), two separate speed measures (the maximal speed of overt recitation of subspan lists and the speed of the spoken recall response) did not correlate with one another, but together accounted for 87% of the age-related variance in digit spans within a structural equation model. Cowan et al. proposed that whereas recitation speed reflects the efficiency of a verbal rehearsal process (cf. Baddeley, 1992), recall speed might reflect the efficiency of a lexical search process. Now, however, the reason for the correlation between recall speed and accuracy must be reexamined, given that speeded responses did not improve recall in the present study. More broadly, inasmuch as conceptions of rehearsal speed and other processing speeds as mediators of cognition have depended on similar arguments, the causal properties of these other types of processing speed also must be called into question.

This is not the first study demonstrating that processing speed can be a marker of maturation without being a causal variable. Basak and Verhaeghen (2003) examined the ability of young and

elderly adults to enumerate sets of items in an array, a task executed rapidly for small set sizes, inasmuch as several items can be apprehended concurrently (the *subitizing range*), but more slowly for larger set sizes (the *counting range*). Within the range of one to three items, response times increased as a function of set size 1.5 times as quickly in elderly adults as in younger adults. However, it turned out that the subitizing range included fewer items in elderly subjects. Consequently, their responses in the range of one to three items were more likely to include a mixture of subitizing and counting processes. An analytic model showed that neither the subitizing speeds nor the counting speeds of young and elderly adults differed—just the subitizing ranges differed. This result is in keeping with a theoretical view in which capacity, rather than speed, may be the primary cause of change in working memory across the life span (cf. Cowan, 2001; Cowan et al., 1999).

One must still ask why process times strongly index subjects' developmental levels. One possible explanation is that if a task is difficult for any reason, the subject may keep trying for a while. For example, if an item is in working memory with a relatively low activation level, the decision process may be difficult, and therefore the response will be slow. However, such an account cannot explain the present finding that immediate memory responses can be speeded up without a loss in mnemonic capability. Perhaps recall speed theoretically is constrained by mnemonic factors such as the speed of memory search (Cowan et al., 1998), but if so, individuals apparently carry out those search processes at a more leisurely pace than the maximum speed of which they are capable. Response speeds may serve as markers of development not because they reflect individuals' maximal processing speeds, but, rather, because they indicate what speeds the individuals find comfortable. We increased rates both by using stimuli that naturally elicit faster rates (Experiment 1) and by asking for faster rates (Experiment 2), yet neither of these manipulations affected memory performance.

It remains possible that speed failed to affect recall because speedy recall and slower recall punctuated by reactivation processes can be equally successful (e.g., Cowan, 1992). However, the present results demonstrate that the speed hypothesis, stating that correlations between speed and memory reflect effects of speed on memory, must be assessed with great caution (cf. Conway, Cowan, Bunting, Theriault, & Minkoff, 2002).

Acknowledgments—This work was supported by National Institutes of Health Grant R01 HD-21338.

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(RECEIVED 11/4/04; ACCEPTED 1/5/05;
FINAL MATERIALS RECEIVED 1/17/05)