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Individual and developmental differences in working memory across the life span

LISA JENKINS, JOEL MYERSON, SANDRA HALE, and ASTRID F. FRY
Washington University, St. Louis, Missouri

The effects of secondary tasks on verbal and spatial working memory were examined in multiple child, young adult, and older adult samples. Although memory span increased with age in the child samples and decreased with age in the adult samples, there was little evidence of systematic change in the magnitude of interference effects. Surprisingly, individuals who had larger memory spans when there was no secondary task showed greater interference effects than their age-mates. These findings are inconsistent with the hypothesis that age and individual differences in working memory are due to differences in the ability to inhibit irrelevant information, at least as this hypothesis is currently formulated. Moreover, our results suggest that different mechanisms underlie developmental and individual differences in susceptibility to interference across the life span. A model is proposed in which memory span and processing speed both increase with development but are relatively independent abilities within age groups.

How are individual and developmental differences in working memory related, and what can such differences tell us about the causes of variation in working memory, both within and between age groups? These important issues have sometimes been clouded by the variety of ways in which the term *working memory* has been used. This diversity in usage arises, in part, because of differences among the various disciplines involved in working memory research, ranging from neurobiology (e.g., Goldman-Rakic, 1995) to educational and cognitive psychology (e.g., Daneman & Merikle, 1996), each with its own conceptual history and current theoretical needs. The variety of definitions of working memory makes it necessary to begin by clarifying exactly how the term will be used in the present effort and by distinguishing our usage from other possible definitions.

For present purposes, the term *working memory* refers to a specific cognitive *function*: the ability to maintain access to items of information for short durations while the same or other information is processed or manipulated. Such usage may be contrasted with usage in which the term working memory refers to a particular *structure* (as in "information held in working memory"). However, it is potentially confusing to use the same term for both a function and a structure involved in that function, and therefore we will restrict ourselves to the former usage.

Even when researchers use working memory to refer to a specific function, they may differ with respect to the situations in which they think that function is used. For some researchers, working memory refers exclusively to situations in which there is an explicit secondary information-processing task. For others, the term also applies to situations in which there is no explicit secondary task. This is either because it is assumed that there is always some additional information that requires processing (even if the process involved is inhibition or suppression) or because it is assumed that merely maintaining information requires processing (e.g., covert rehearsal). For example, Baddeley (e.g., 1986, 1992) does not restrict working memory to situations in which there is an explicit secondary task but considers that simple word span tasks also exemplify the use of working memory. We will follow the latter usage and apply the term working memory to situations both with and without explicit secondary tasks.

Working Memory and Interference

Baddeley (1986, 1992) has proposed a multicomponent model of working memory that consists of three functionally independent subsystems: a phonological loop, which maintains speech-based information; a visuospatial scratchpad, which maintains nonverbal information; and a central executive, which coordinates cognitive operations. Much of the research devoted to testing and refining the subcomponents of Baddeley's model has focused on the phonological loop and the manner in which speech-based material is rehearsed (see Baddeley & Hitch, 1994, for a review). According to Baddeley and his colleagues, speech-based information is stored and refreshed using subvocal (i.e., covert) articulatory rehearsal (see Logie, 1995, for a discussion). Although the mechanisms involved in the rehearsal of visual and spatial information are not well understood, it has been suggested that imagery or eye movements may play a role in the mainte-

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nance of visuospatial information (for recent reviews, see Baddeley, 1992; Logie, 1995).

Experiments using dual-task procedures suggest that the phonological loop and the visuospatial sketchpad are independent subsystems. Performance on verbal working memory tasks is disrupted to a much greater extent by secondary verbal tasks than by secondary spatial tasks (Baddeley, Lewis, & Vallar, 1984), and performance on visuospatial working memory tasks is more disrupted by secondary visuospatial tasks than by secondary verbal tasks (Baddeley, Grant, Wight, & Thomson, 1975; Baddeley & Lieberman, 1980; Logie, 1986; Logie, Zucco, & Baddeley, 1990; Quinn & Ralston, 1986). However, in many studies (e.g., Baddeley, Grant, et al., 1975; Baddeley & Lieberman, 1980; Logie, 1986; Logie et al., 1990; Quinn & Ralston, 1986), it is unclear whether secondary tasks interfered with encoding, maintenance, or both. Recently, Hale, Myerson, Rhee, Weiss, and Abrams (1996) developed procedures for assessing the amount of interference that results from disrupting the maintenance of information after memory items have been successfully encoded. These procedures revealed completely selective interference by secondary tasks (i.e., secondary verbal tasks interfered with verbal working memory but did not interfere at all with spatial working memory, and vice versa; Hale, Myerson, et al., 1996, Experiment 1).

Age Differences in Working Memory

Research in which the effects of age on working memory was examined has revealed consistent age differences in working memory performance (see Craik & Jennings, 1992; Dempster, 1981; and Salthouse, 1994, for recent reviews). Several studies have demonstrated that children (Chi, 1976; Dempster, 1985; Hale, Bronik, & Fry, 1997; Kail & Park, 1994), adolescents (Dempster, 1985), and older adults (Salthouse, 1994) all have smaller memory spans than do young adults. Recent research suggests that, relative to young adults, both children and older adults show more pronounced age deficits in spatial memory than in verbal memory (Hale et al., 1997; Myerson, Hale, Rhee, & Jenkins, in press).

One plausible explanation for the observed age differences in working memory stems from research revealing a relationship between processing speed and working memory in children (Fry & Hale, 1996; Kail & Park, 1994) and in older adults (Salthouse, 1991; Salthouse, Kausler, & Saults, 1988). It is well established that both children (see, e.g., Hale, 1990; Kail, 1988) and older adults (see, e.g., Cerella, 1990, 1991) are generally slower information processors than young adults (see Cerella & Hale, 1994, for a review) and that both children and older adults show smaller working memory spans than do young adults. Indeed, age differences in working memory are minimal when processing speed is statistically controlled (Fry & Hale, 1996; Kail & Park, 1994; Salthouse, 1994). Although the mechanisms underlying the relationship between processing speed and working memory are not fully understood, it has been argued that faster processors may activate and covertly rehearse information more quickly than slower processors (Dempster, 1981; Salthouse, 1994).

Alternatively, Hasher and Zacks (1988) have suggested that age differences in working memory abilities result from deficits in inhibitory function. They argued that working memory involves not only the storage and manipulation of "information that is along the goal path," but also involves inhibitory mechanisms that prevent the entrance of "off-goal-path" information (Hasher & Zacks, 1988, p. 212). They hypothesized that age differences in working memory result from interference caused by older adults' decreased ability to inhibit irrelevant information. A similar suggestion has been offered regarding inhibitory deficits in children (Dempster, 1992; Tipper, Bourque, Anderson, & Brehaut, 1989).

Unfortunately, the interpretation of age differences in susceptibility to interference has been complicated by reliable age differences in baseline performance, as represented by memory span in the absence of interference from secondary tasks (Dempster, 1981; Hale et al., 1997; Kail & Park, 1994). These age differences in baseline working memory performance pose an analytical challenge when trying to determine the nature of interference effects across the life span. The present investigation was motivated, in part, by the idea that an analogous problem exists with respect to interference effects in individuals of the same age. Such individuals differ in both susceptibility to interference and baseline memory performance, and it is possible that examining individual differences in interference with working memory within age groups may shed light on the issue of how to evaluate age differences in interference effects. Accordingly, we conducted a meta-analysis of data from multiple child, young adult, and older adult samples that was designed to examine the interaction of individual and age differences in susceptibility to interference across the life span.[1]

THE META-ANALYSIS

The Studies

The present investigation took advantage of the fact that our laboratory has used the same basic procedures, with little or no modification, to assess working memory performance in multiple samples of children and adolescents, as well as young and older adults. Thus, the meta-analysis was able to combine data from seven studies by Hale and her colleagues in which school-age children (8-year-olds, 10-year-olds, and 12-year-olds), young adults (18- to 22-year-olds), and older adults (65- to 75-year-olds) were administered the digit span and location span working memory tasks first described in Hale, Myerson, et al. (1996, Experiment 1). Two of these studies (Hale & Jansen, 1994; Hale, Myerson, Faust, & Fristoe, 1995) were primarily concerned with processing speed and, hence, did not report the working memory data when originally published. On the basis of the data from the

Table 1
Number of Subjects in Each Age Group Whose Data Were Included in the Analyses by Study

	Age Group				
Study	8-Year-Olds	10-Year-Olds	12-Year-Olds	Young Adults	Older Adults
Fry and Hale (1996)					
Verbal	39	73	52	26	
Spatial	39	73	53	24	
Hale, Bronik, and Fry (1997)					
Verbal	19	20		22	
Spatial	19	20		21	
Hale and Jansen (1994)					
Verbal				19	
Spatial				18	
Hale, Myerson, Faust, and Fristoe (1995)					
Verbal				19	22
Spatial				18	23
Hale, Lawrence, Myerson, and Chen (1996)					
Verbal				23	30
Spatial				23	30
Hale, Myerson, Rhee, Weiss, and Abrams (1996)					
Verbal				27	
Spatial				28	
Myerson, Hale, Rhee, and Jenkins (in press)					
Verbal				17	19
Spatial				18	20

studies listed in Table 1, both verbal and spatial interference effects were examined in over 400 subjects. In both the verbal and the spatial domains, interference effects were measured as the difference between spans with and without secondary tasks.

In all the studies, subjects were exposed to at least four different conditions: digit span, no secondary task; digit span, verbal secondary task; location span, no secondary task; and location span, spatial secondary task. Examples of the stimuli and procedures are presented in Figure 1. For the no secondary task conditions, the subjects were shown a series of digits in a box or Xs in a grid, one by one. The subjects orally recalled the names of the digits in the order in which they were presented in the digit span task and marked the locations of the Xs on an empty grid in the location span task. For the verbal secondary task conditions, in addition to the memory requirements for the no secondary task condition, the subjects were required to indicate the color of each digit or X as it was presented by saying the color name aloud. For the spatial secondary task conditions, in addition to the memory requirements for the no secondary task condition, the subjects were required to indicate the color of each digit or X as it was presented by pointing to the matching color in the adjacent palette.

For all seven studies, the subjects initiated the presentation of each series of memory items by pressing a button on a response panel. The presentation of items within a series was computer controlled, and responses were recorded manually by the experimenter. For all conditions, each trial began with the presentation of a fixation square in the center of the screen until the subject pressed the *ready* button. Following a 250-msec delay, the items in a series were presented for either 1,250 or 1,750 msec, with a 250-msec interitem interval during which the screen was blank.[2] Immediately after all of the items within a series were presented, a recall signal was given. Testing for all conditions was conducted following the procedure used for the WAIS–R Digit Span subtest (Wechsler, 1981). That is, the subjects were exposed to two sets of series at an initial length (three items for the digit span and two items for the location span), and if at least one of the series was recalled correctly, the length of the series was increased by one. The experimenter discontinued testing when the subject failed to correctly recall two series of the same length. The order of presentation of the conditions was counterbalanced.

Working memory spans were based on the maximum series length for which at least one series was correctly recalled, without regard to performance on the preceding series. If both series were correctly recalled at the maximum length, the span was equal to that length. If only one series was correctly recalled at the maximum length, the span was equal to that length minus 0.5. Memory spans for each condition were calculated separately for each subject. Because the maximum number of digits and locations presented was 9 (in all the studies but Hale et al., 1997), individuals who could remember all 9 items when there was no secondary task might actually have had spans larger than 9. For such individuals, the resultant underestimation of their span would lead to underestimation of their interference effects. Therefore, individuals who had digit spans greater than 8.5 were not included in the analyses of verbal working memory. Similarly, individuals who had location spans greater than 8.5 were not included in the spatial working memory analyses. None of the subjects from the child samples were excluded for this reason; less than 10% of the young adult subjects and less than 3% of the older adult subjects were excluded.

Data Analysis

Mean verbal and spatial working memory spans, with and without secondary tasks for each study, are presented in Table 2. Mean working memory spans without secondary tasks and interference effects for each age group averaged across all studies are presented in Table 3. The upper left panel of Figure 2 depicts the mean verbal working memory spans with and without verbal secondary tasks. As was expected, verbal memory spans when secondary task performance was not required (unshaded bars) increased as the age of the child group increased. Verbal spans with a secondary task (shaded bars) also increased with the age of the child group. In adults, the older group showed smaller verbal memory spans both with and without a secondary task requirement than did the young adult group. In all the child and adult groups, verbal memory performance was substantially disrupted when the subjects were required to name the color of each letter as it was presented. When interference effects, were compared across the age groups, 8-year-olds showed the largest interference effects, whereas the 10-year-olds, 12-year-olds, young adults, and older adults all showed

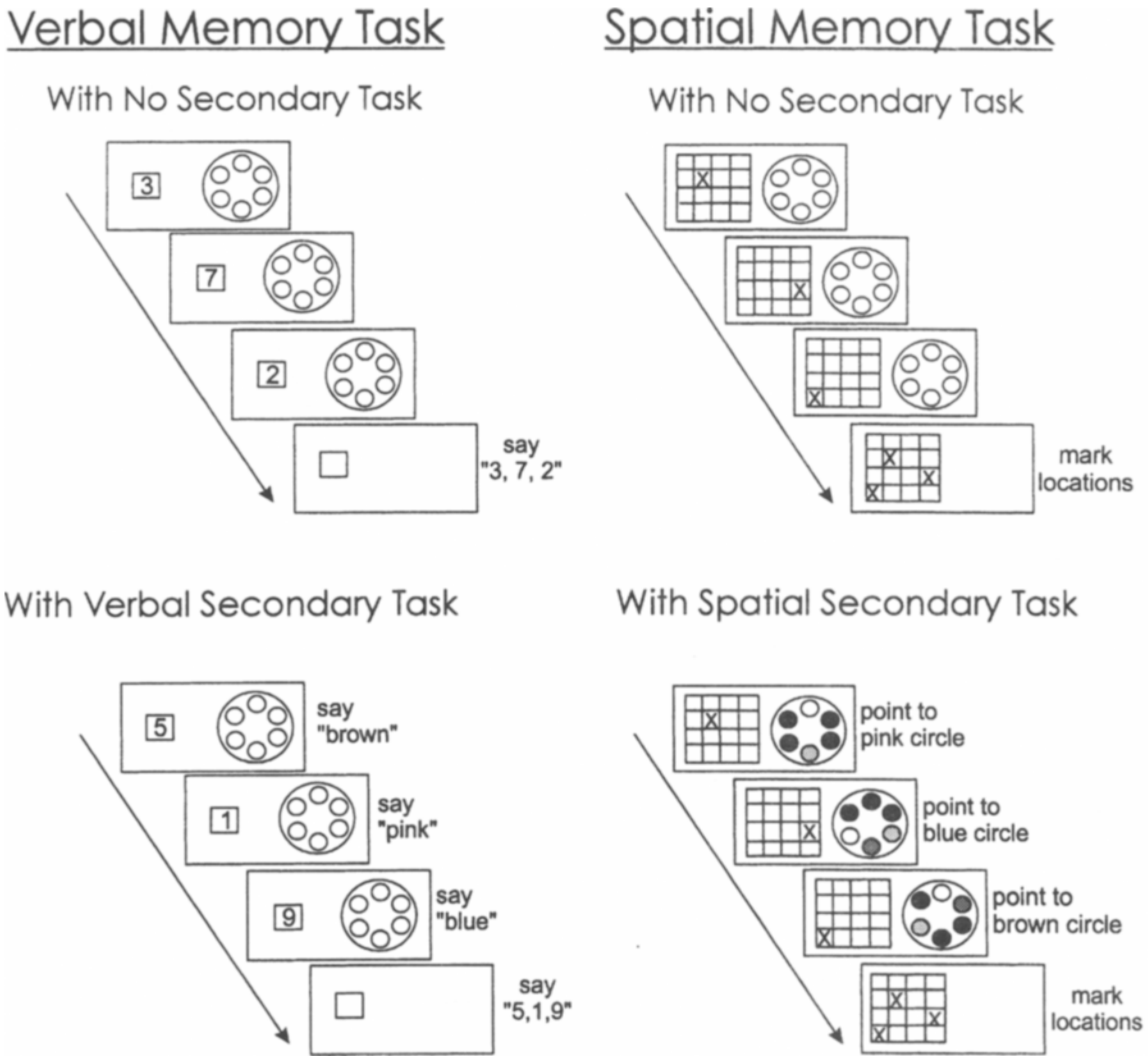

Figure 1. Examples of the stimuli and procedures for the conditions of each experiment. Time is indicated by an arrow, rectangles represent the computer display, and the correct primary task responses (as well as the secondary task responses, where applicable) are shown to the right of each rectangle.

approximately equivalent interference effects (upper right panel of Figure 2).

A similar pattern of results was obtained for the spatial working memory tasks. That is, spatial memory spans increased with the age of the child group and decreased with the age of the adult group, both when secondary task performance was not required and when it was required (lower left panel of Figure 2). In terms of interference effects, subjects of all ages showed substantial disruption in their memory for spatial locations when they were required to point to the color of each X as it was presented. As may be seen in the lower right panel of Figure 2, the 8-year-olds, 10-year-olds, 12-year-olds, and young adults all showed similar interference effects, whereas the older adults showed smaller interference effects than all the other age groups.

On the basis of the above results, we would conclude that there is virtually no change in interference from 10 to 20 years of age in either the verbal or the spatial domains. Moreover, there appear to be no *consistent* age differences (i.e., differences in both domains) in interference effects across the life span from 8 to 75 years of age. That is, although the 8-year-olds showed larger interference effects than any other age group in the verbal domain, they did not show larger interference effects in the spatial domain. Similarly, although older adults showed smaller interference effects than all other age groups in the spatial domain, they did not differ from the other groups in the size of their verbal interference effects.

The present results fail to reveal age differences in susceptibility to interference when the absolute size of interference effects is compared. An alternative approach to

Table 2
Mean Verbal and Spatial Memory Spans With and Without a Secondary Task (and Standard Errors) by Study

	Verbal Memory Span				Spatial Memory Span			
	Without Secondary		With Secondary		Without Secondary		With Secondary	
Age Group	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Fry and Hale (1996)								
8-year-olds	4.97	0.15	3.37	0.18	4.21	0.19	2.17	0.16
10-year-olds	5.60	0.14	4.45	0.14	4.73	0.11	3.00	0.14
12-year-olds	5.88	0.14	4.85	0.19	5.34	0.14	3.57	0.18
Young adults	6.98	0.22	6.02	0.22	6.75	0.26	4.46	0.32
Hale, Bronik, and Fry (1997)								
8-year-olds	4.66	0.19	2.61	0.14	3.89	0.21	1.82	0.26
10-year-olds	5.38	0.19	3.93	0.26	4.48	0.23	2.38	0.27
Young adults	6.84	0.22	5.80	0.22	7.12	0.26	5.05	0.33
Hale and Jansen (1994)								
Young adults	7.26	0.22	5.53	0.32	6.69	0.31	5.08	0.46
Hale, Myerson, Faust, and Fristoe (1995)								
Young adults	7.34	0.23	6.11	0.27	6.50	0.22	5.08	0.41
Older adults	6.57	0.27	4.80	0.34	4.67	0.25	3.15	0.16
Hale, Lawrence, Myerson, and Chen (1996)								
Young adults	7.28	0.21	6.02	0.23	6.00	0.31	4.50	0.34
Older adults	5.97	0.20	4.95	0.26	4.37	0.20	3.05	0.20
Hale, Myerson, Rhee, Weiss, and Abrams (1996)								
Young adults	6.85	0.19	5.26	0.21	6.27	0.25	4.16	0.28
Myerson, Hale, Rhee, and Jenkins (in press)								
Young adults	7.21	0.27	5.97	0.40	6.75	0.31	4.81	0.41
Older adults	6.50	0.27	5.05	0.35	4.55	0.23	3.23	0.18

Note—Table means include only those individuals whose memory spans were less than 9. As a result, the means reported here may not be equivalent to those reported in each of the seven published studies.

examining age differences in susceptibility to interference involves calculating interference effects as a proportion of memory span without a secondary task. When this is done, interference effects are larger in young children than in older children (e.g., 12-year-olds) and adults in both domains. However, there is nothing inherent in either the inhibition deficit or the speed accounts of age differences in working memory that justifies using proportions or any other transform of the data rather than absolute measures of the amount of interference.

As was noted in the introduction, when one compares interference in different age groups, one is comparing groups with different baseline levels of memory performance. In order to examine the role of age differences in baseline (without transforming the data), we tried comparing the interference effects of those subjects of different ages who had nearly equivalent memory spans when secondary tasks were not required. This comparison revealed clear age differences in interference between the matched groups: Verbal interference effects decreased systematically with the age of the child subgroup and increased with the age of the adult subgroup, and a similar pattern of results was obtained in the spatial domain.

The discrepancy between these results and those of the preceding analysis (which found no systematic age differences) raises an important new issue. An analysis that compares subgroups with equal baseline performance is really comparing subgroups of individuals who are systematically unrepresentative of their age groups, and the findings must be interpreted in light of this fact. For ex-

Table 3
Mean Memory Spans Without a Secondary Task and Mean Interference Effects (and Standard Errors) by Age Group

	Age Group									
	8-Year-Olds		10-Year-Olds		12-Year-Olds		Young Adults		Older Adults	
Task	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Verbal Working Memory										
Memory span	4.87	0.12	5.55	0.12	5.88	0.14	7.09	0.08	6.30	0.14
Interference effect	1.75	0.14	1.22	0.13	1.04	0.18	1.29	0.10	1.37	0.16
Spatial Working Memory										
Memory span	4.10	0.14	4.67	0.10	5.34	0.14	6.56	0.11	4.51	0.13
Interference effect	2.04	0.14	1.81	0.12	1.77	0.19	1.88	0.14	1.38	0.12

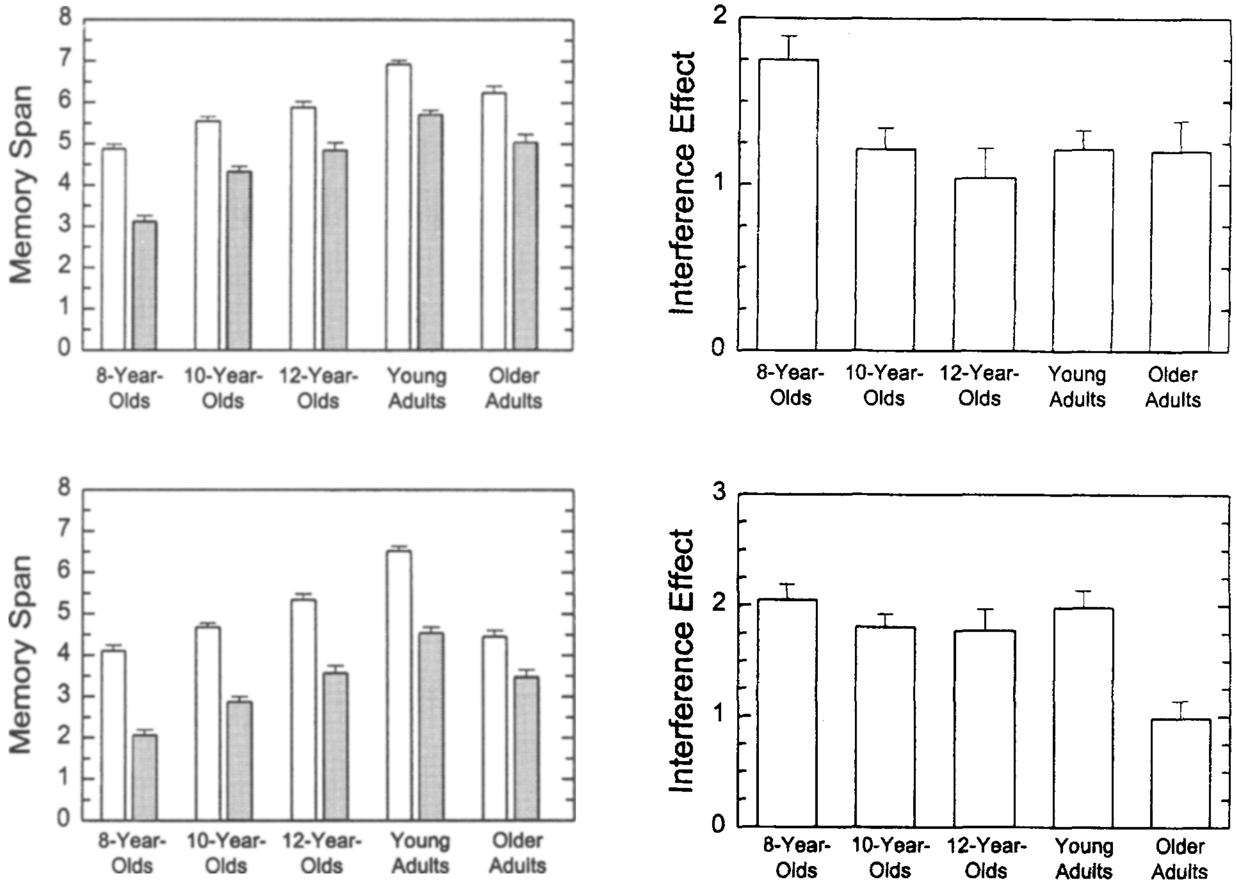

Figure 2. Mean memory spans (left panels) and interference effects (right panels) for 8-year-old, 10-year-old, and 12-year-old children, young adults, and older adults. Performance on verbal tasks is shown in the upper panels, and performance on spatial tasks is shown in the lower panels. Error bars indicate standard errors.

ample, we matched a subgroup of 8-year-olds with verbal spans of 4–5.5 with a subgroup of young adults with the same range of verbal spans. However, the subgroup of 8-year-olds was above average in span, relative to their peers, whereas the matched subgroup of young adults was below average in span, relative to their peers. Surprisingly, the subgroup of above-average 8-year-olds showed interference effects that were not only larger than those of the matched young adults but also larger than their peers. Also surprisingly, the subgroup of young adults with below-average spans showed interference effects that were not only smaller than those of the matched 8-year-olds, but also smaller than those of their peers. This may also be seen if one compares the datapoints for subgroups of approximately equal span in the absence of a secondary task in Figure 3.

Taken together, this pattern of results strongly suggests what would otherwise be a counterintuitive idea: Individuals with higher than average spans for their age show larger than average interference effects, and individuals with lower than average spans for their age show smaller than average interference effects. In order to rigorously evaluate this idea, we next proceeded to examine the pattern of individual differences within each group. In order to do this, subgroups were created within each age group on the basis of verbal and spatial spans in the absence of a secondary task: Subgroups consisted of individuals who had spans of 1–2.5, 3–4.5, 5–6.5, and 7–8.5 items. These ranges were selected so as to maximize the number of subgroups within each age group, while simultaneously distributing the total number of subjects in each age group as equally as possible across the subgroups.

We then compared interference effects for all of the different subgroups with *n*s greater than 5. The upper and lower panels of Figure 3 show verbal and spatial memory spans with secondary tasks for the different subgroups, plotted as a function of the subgroups' memory spans in the absence of secondary tasks. As may be seen, when young adults are compared with children and older adults of roughly equivalent span in the absence of a secondary task, the young adults have smaller interference effects. More importantly, however, interference effects increased with memory ability, as measured by span in the absence of interference in all the age groups. Within each age

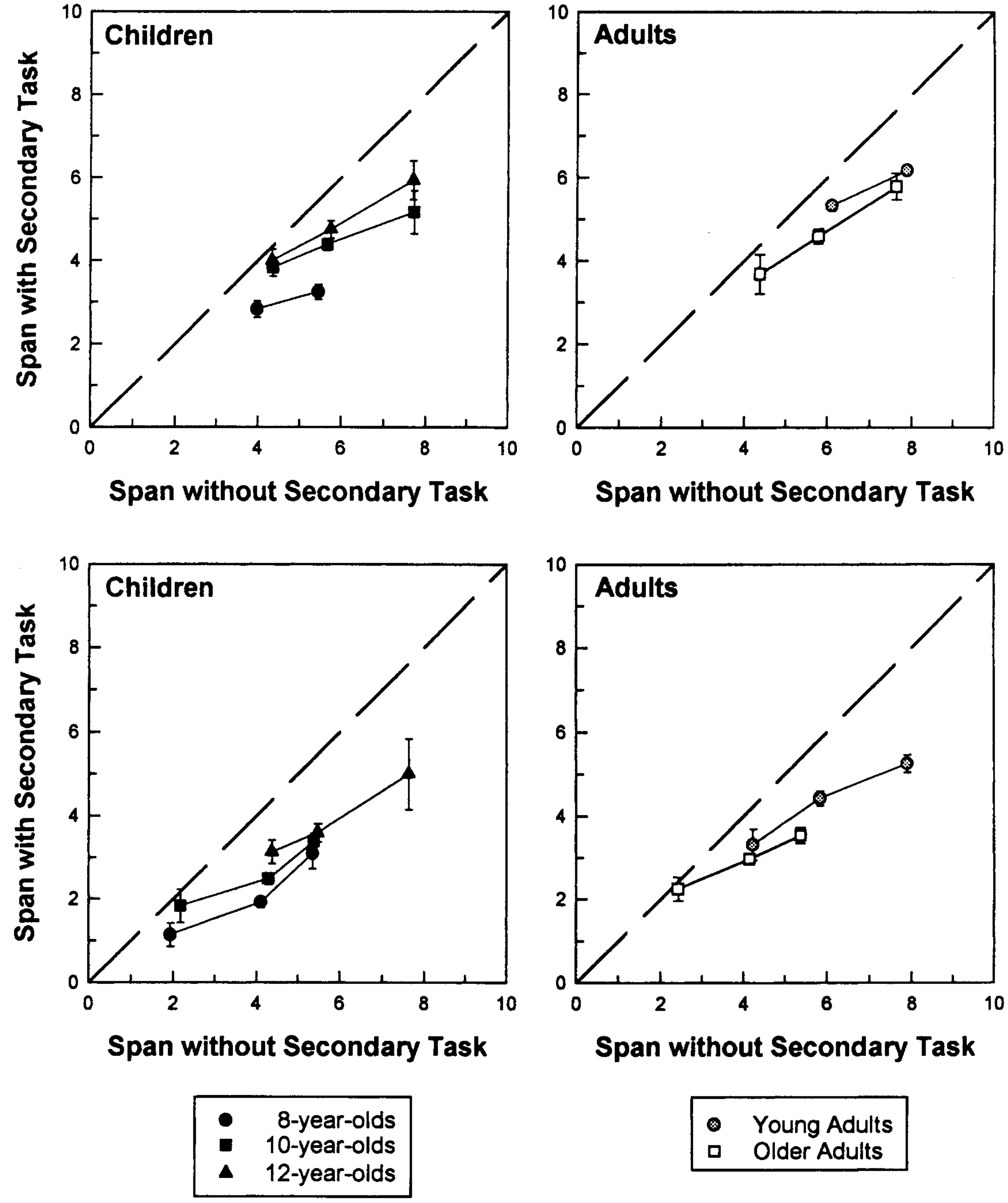

Figure 3. Memory span with a secondary task as a function of memory span without a secondary task in children (left panels) and adults (right panels). The upper panels show performance on the verbal tasks and the lower panels show performance on the spatial tasks. The dashed diagonal lines represent equality (i.e., if secondary tasks had no effect on memory, the data would fall along the diagonal, assuming perfect reliability for the measurement of span), and thus the vertical distance from the diagonal to the data points represents the size of the interference effects. Error bars represent standard errors.

group, interference effects were smallest for those with the smallest spans without secondary tasks and largest for those with the largest spans without secondary tasks. Remarkably similar patterns were observed for both verbal and spatial working memory.

Finally, we analyzed the data from the age group with the largest number of subjects (young adults: verbal *n* = 153, spatial *n* = 150). The large *n*s and wide range of spans in this group made it possible to use the techniques of correlational and regression analysis to examine more precisely the relation between the amount of interference and the size of an individual's memory span in the absence of a secondary task. The correlation between spans with and without a secondary task was significant for both verbal and spatial working memory tasks (verbal $r = .423$, spatial $r = .333$, both $ps < .0001$). Importantly, the slope of the regression of span with a secondary task on span without a secondary task was significantly less than 1.0 for both verbal and spatial working memory tasks (verbal slope = 0.501, $t = 5.70$; spatial slope = 0.421, $t = 5.91$; both $ps < .0001$), indicating that the size of the interference effect was an increasing function of span in the absence of a secondary task.

This may be seen clearly in Figure 4, which shows the verbal and spatial regression lines (upper and lower panels, respectively) based on all young adult subjects. In both plots, each point represents the mean and standard error for a subgroup of individuals with exactly the same span in the absence of a secondary task (e.g., either 5.5, or 6.0, or 6.5, etc.; subgroups with $ns < 5$ are not shown). Although, as may be seen, the magnitude of the interference effect tended to be larger for spatial working memory, the same overall pattern was observed in both domains. That is, individuals with larger spans in the absence of a secondary task suffered the most interference when performance of a secondary task was required.

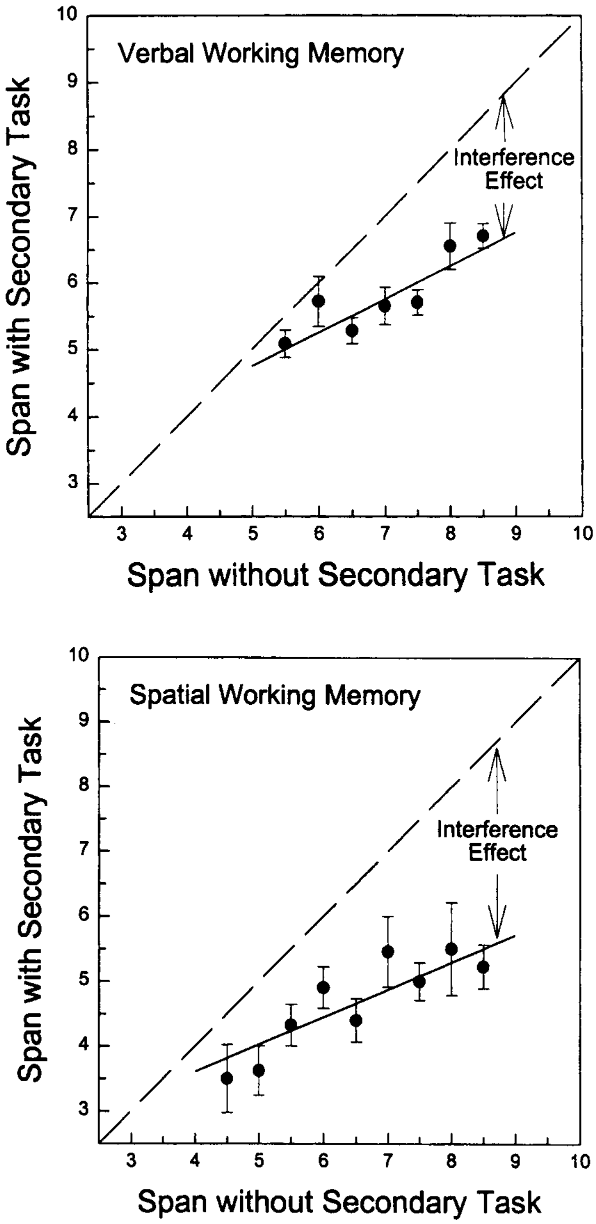

Figure 4. Memory span with a secondary task as a function of memory span without a secondary task in young adults. The upper panel shows performance on verbal tasks, and the lower panel shows performance on spatial tasks. In both panels, the solid lines represent the regression lines fit to all of the young adult data. The dashed diagonal lines represent equality (i.e., if secondary tasks had no effect, the data would fall along the diagonal, assuming perfect reliability for measurement of span), and, thus, the vertical distance from the diagonal to the data points represents the size of the interference effects. Error bars represent standard errors.

DISCUSSION

Collectively, the results of the present meta-analysis reveal two important findings about developmental and individual differences in susceptibility to interference. First, verbal and spatial spans measured in the absence of a secondary task increased with age in children and decreased with age in adults, but interference effects did not change systematically as a function of age at either end of the life span. Second, an examination of individual differences within each age group revealed that, in both the verbal and spatial domains, the subjects with larger spans showed larger interference effects than did their peers with smaller spans.

The finding of larger interference effects in higher span individuals, although counterintuitive, is reminiscent of findings regarding individual differences in the effect of secondary tasks on memory performance reported by Rosen and Engle (1997). These researchers found that when subjects were required to generate the names of members of a category (e.g., animals), high-span individuals were more affected by a concurrent load on working memory than low-span individuals. The primary task involved retrieval from long-term memory, and it is possible that the concurrent load interfered with the process of retrieval itself or that it interfered with the use of working memory in either the strategic control of retrieval or the evaluation of retrieved information.

In the present case, however, it is clear that the secondary task is interfering with the maintenance of information in working memory. The pattern of interaction between age and individual differences in the susceptibility of working memory to interference observed in the present analyses is not easily explained on the basis of existing theories of working memory, at least as they are currently formulated. These theories tend to focus on either age or individual differences in working memory and do not deal with the relationship between the two, or they tend to assume that age and individual differences are determined by the same mechanisms.

For example, differences in the ability to inhibit irrelevant information have been used by Dempster (1992) and Hasher and Zacks (1988) to explain age differences in working memory and by Engle (1996) to explain individual differences in working memory. It is possible that inhibition deficit theories might be able to explain the pattern of age and individual differences in interference effects (i.e., the general lack of age difference in interference effects and the larger interference effects in individuals with larger memory spans) if they incorporated additional assumptions. However, it is not obvious what such assumptions might be.

The difference in interference effects observed between low- and high-span individuals in the present data (as reflected in the slopes of the regressions in Figure 4) is undoubtedly exaggerated by measurement error. Although the reliability of the present measures was not determined directly, the digit span task was simply a computerized version of the Digit Span subtest from the WAIS–R (reliability is equal to or greater than .90 for both young and older adults of ages comparable to those in our sample; Psychological Corporation, 1997), and the location span test followed an analogous procedure. It is highly unlikely, therefore, that the true slope of the regression between span with a secondary task and span without a secondary task (i.e., the slope corrected for attenuation by measurement error) could be greater than 1.0, as is predicted by the inhibition deficit hypothesis.

Alternatively, other researchers have argued that differences in processing speed are the cause of differences in working memory performance. Some of these researchers have focused on the relation between age differences in speed and age differences in working memory (e.g., Dempster, 1981; Salthouse, 1996), whereas others have focused on the relation between individual differences in speed and individual differences in working memory (e.g., Miller & Vernon, 1992). A possible mechanism underlying the role of speed in both age and individual differences in working memory is suggested by the observation that the longer that words take to pronounce, the fewer that can be recalled. This is known as the word-length effect (Baddeley, Thomson, & Buchanan, 1975). The word-length effect is often interpreted as implying that the speed with which particular items can be rehearsed determines how many items can be remembered (e.g., Baddeley, 1986; Baddeley, Thomson, & Buchanan, 1975; but see Brown & Hulme, 1995). This idea may be extended to imply that any source of difference in rehearsal rate, whether it is attributable to characteristics of individual items or to age and individual variations, will affect working memory. Consistent with this idea, developmental differences in children's rehearsal rates are good predictors of developmental differences in memory span (Hulme, Thomson, Muir, & Lawrence, 1984; Kail & Park, 1994; Nicolson, 1981).

Like the inhibition hypothesis, the speed hypothesis may require additional assumptions in order to explain the present findings. In this case, however, it is more apparent what form these assumptions might take. Most current versions of the speed hypothesis tend to assume that information in working memory will decay in the absence of rehearsal. A number of researchers (e.g., Baddeley, 1986; Hulme et al., 1984; Schweickert & Boruff, 1986) have observed that the number of items that can be recalled in a verbal memory span task is approximately equal to the number of items that can be rehearsed in 2 sec. This is interpreted by Baddeley and others to mean that, in order for an item to be maintained, its trace must be refreshed at approximately 2-sec intervals. If this is so, when secondary tasks interrupt rehearsal, some items will be lost, and the amount lost will depend on both the rehearsal rate and the speed with which the secondary task is performed (i.e., the length of time that rehearsal is interrupted).

To see this, imagine an individual who can rehearse six items in 2 sec (i.e., three items per second) but cannot rehearse these items while performing a secondary task. Assume that performance on the secondary task interrupts rehearsal for 1 sec. There is now only 1 sec to rehearse items before they are lost, and only three items can be rehearsed in that time. The remaining three items will have gone 2 sec without rehearsal, and their trace strengths may have decayed to the point where the items are unrecoverable.

To see how individual and age differences may affect the amount of interference produced by a secondary task, recall that there are both individual and age differences in processing speed (see, e.g., Cerella & Hale, 1994; Hale & Jansen, 1994) and that there are individual and age differences in rehearsal rate as well (see, e.g., Kail & Park, 1994). At the group level, both processing speed and rehearsal rate increase with age during childhood and decrease with age in adulthood. However, the relationship between processing speed and rehearsal rate in individuals of the same age is not well established. Thus, it is unclear to what extent processing speed and rehearsal rate are independent abilities. Cowan and his colleagues (Cowan et al., 1998) have reported that, although retrieval speed and rehearsal rate both increase with age during childhood, these measures were uncorrelated within an age group. The present findings suggest that the same may be true for processing speed and rehearsal rate. If so, this could explain the present pattern of results.

Assume that processing speed governs the amount of time it takes to perform a secondary task. If the time it takes to perform a secondary task is relatively brief and highly correlated with rehearsal rate, it may be shown that individuals with different rehearsal rates will have more nearly equivalent interference effects. If, however, the time it takes to perform a secondary task is relatively independent of rehearsal rate, individuals with higher rehearsal rates will not only have larger spans, they will also show larger interference effects.

These two possibilities are illustrated in Figure 5, which shows two individuals, one with a span of 5 and one with a span of 9. It is assumed that the high-span individual can rehearse more items in the same amount of time than can the low-span individual, that trace strength decays exponentially (i.e., a constant proportion is lost per unit time), and that the rate of decay does not vary appreciably between individuals. The upper two panels show what would happen if the high-span individual took less time to perform a secondary task than the low-span individual (i.e., rehearsal rate and speed of secondary task performance are highly correlated). The lower two panels show what would happen if both the high- and the low-span individuals take the same amount of time to perform a secondary task (i.e., rehearsal rate and speed of secondary task performance are relatively independent).

As may be seen, when low-span individuals take more time to perform a secondary task than do high-span individuals, both low- and high-span individuals will show similar interference effects. In contrast, when low-span and high-span individuals take the same amount of time to perform a secondary task, the high-span individuals will show *larger* interference effects than low-span individuals. That is, the difference between the number of items recalled when there is no secondary task (i.e., secondary task duration equals zero) and when there is a secondary task will be larger for high-span individuals than for low-span individuals.

How does this apply to the present problem? The pattern of age differences is similar to that shown when processing speed and rehearsal speed are highly correlated (i.e., the pattern shown in the upper panels of Figure 5).

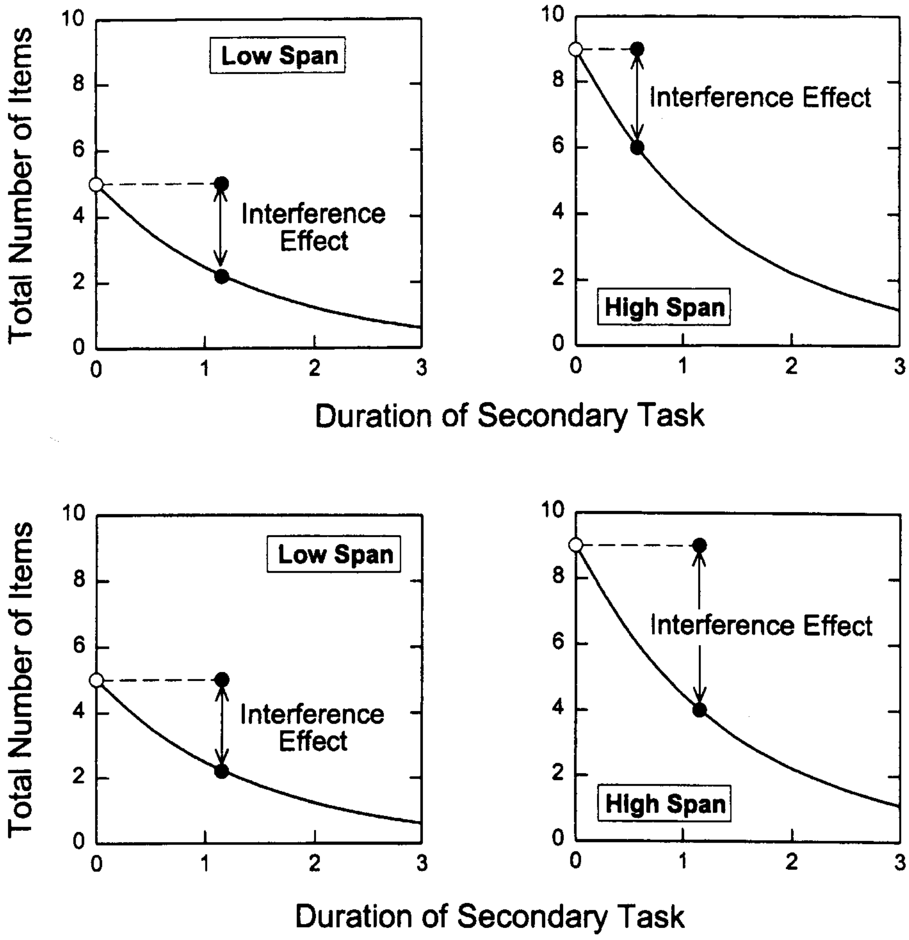

Figure 5. Schematic representation of the effects of rehearsal and processing speed on memory spans of low- and high-span individuals. The upper panels illustrate the relation between secondary task duration and size of the interference effect when rehearsal and processing speed are highly correlated; the lower panels illustrate the relation between secondary task duration and size of the interference effect when rehearsal and processing speed are relatively independent. The curved lines indicate the decay of information in working memory.

Children, young adults, and older adults all tend to show interference effects of approximately equivalent size, even though children and older adults have smaller spans than young adults. In contrast, the pattern of individual differences among like-aged individuals is similar to that shown when processing speed and rehearsal speed are relatively independent (i.e., the pattern shown in the lower panels). Individuals of a particular age with higher spans tend to show larger interference effects than individuals of the same age with lower spans. This suggests that developmental changes in rehearsal and processing speed occur in concert but that these changes do not modify the pattern of individual differences in rehearsal and processing speed.

For example, one child, Diane, may be faster at rehearsing than her age-mate, Jack, but the two do not differ appreciably in the rate at which they process information. Therefore, Diane will have a larger span in the absence of a secondary task and will show a larger interference effect. This is analogous to the comparison of low- and high-span individuals shown in the lower panels of Figure 5, because rehearsal speed is independent of processing speed in the case of Jack and Diane. As they approach adulthood, Jack and Diane will get faster at both rehearsing and processing, but Diane will remain the faster of the two at rehearsing, whereas there will still be no difference in their processing rates. Therefore, both Jack and Diane's spans will be larger when there is no secondary task, but Diane will still lose more items from working memory when there is a secondary task. However, the size of Diane's interference effect will not have changed appreciably from when she was younger. Although she can now rehearse faster, giving her more items to lose, she can also perform the secondary task faster.

Importantly, exactly the same will be true for Jack: His interference effect will also be largely unchanged because, again, the increase in processing speed will cancel out the increase in rehearsal rate. The change in Jack's (and Diane's) spans, both with and without a secondary task, is analogous to moving from that shown in the upper left-hand panel to that shown in the upper right-hand panel of Figure 5. This is because developmental changes in rehearsal speed and processing speed are highly correlated.

Although the preceding account adequately explains the present findings, it only holds if the time required to perform secondary tasks is short, relative to the time it takes for information in working memory to decay. Thus, a more rigorous test of these ideas will require actually measuring the amount of time it takes individuals to perform secondary tasks and the rate at which information decays. Measures of processing speed, rehearsal speed, and working memory should also be obtained from the same subjects. Finally, the reliability of all the measures should be assessed in order to determine the true relations between the various measures. For example, it is possible that the slope of the relation between spans with and without secondary tasks may turn out not to differ appreciably from 1.0, after correcting for measurement error. If so, this result would be consistent with the speed hypothesis as originally proposed (i.e., with the assumption that rehearsal and processing speed are different aspects of the same ability and, therefore, are highly correlated). There would then be no need to modify this hypothesis along the lines outlined above.

The need to examine the interrelations between various measures is heightened by the fact that, as Brown and Hulme (1995) have recently argued, the case for rehearsal speed as the determinant of memory span may have been overstated. These authors show that a simple model can account for the word-length effect without assuming the existence of covert rehearsal. In addition, they question other evidence that has been taken as support for a covert rehearsal process. Although Brown and Hulme focus on verbal working memory, the role of covert rehearsal in visuospatial working memory is also unclear. As a number of authors have pointed out (Fry & Hale, 1996; Hale, Myerson, et al., 1996; Logie, 1995), the nature of the mechanism underlying the rehearsal of visuospatial information, assuming that rehearsal is even involved, has never been firmly established.

Even if the covert rehearsal rate does not determine memory span in the absence of a secondary task, the present findings remain consistent with a speed hypothesis of age differences in working memory. This hypothesis predicts a correlation between processing speed and memory span and thus predicts relatively little age difference in interference effects. This is because, as was noted in the case of Jack and Diane, cognitive development in children is associated with faster performance on secondary tasks and larger memory spans, but the faster secondary task performance cancels out the increase in interference effect that would otherwise be associated with an increased span. The same argument, in reverse, applies to cognitive aging. However, the present findings are not consistent with a speed hypothesis of individual differences in working memory. This is because, within an age group, interference effects are actually larger in individuals with larger spans, implying that individuals with large and small spans take approximately the same amount of time to perform the secondary tasks.

Although the generalizability of the current findings remains to be determined, the characteristics of the database examined in the present meta-analysis suggest that the present findings regarding the interaction of age and individual differences in working memory are likely to prove highly reliable. One important characteristic is that both verbal and spatial working memory spans with and without secondary tasks were measured in the same individuals, using the same procedures. This made it possible to examine the covariation in span and the size of interference effects and minimized the noise that would otherwise occur with procedural variations. Two other important characteristics of the present database are the number of subjects and the extensive age range that was sampled: Data from over 400 individuals from five child and adult age groups, with at least 50 in each age group, were analyzed.

In summary, the present findings strongly suggest that the absolute amount of interference with working memory that results from secondary tasks does not change systematically as a function of age and that, at all ages, individuals with larger spans show larger interference effects than do their peers with smaller spans. What are the implications of these findings for the measurement of age differences in susceptibility to interference? Should mean interference effects of different age groups be compared directly, despite age differences in baseline performance, or should interference effects be compared after taking into account baseline differences?

Both of these approaches focus exclusively on age differences, yet the present results suggest that what is needed is research that directly examines the interaction of age and individual differences. If the speed hypothesis is correct, susceptibility to interference is the result of an interaction between the speed with which one processes secondary task information, on the one hand, and the size of one's memory span in the absence of interference, on the other. If memory span and processing speed are related, as the speed hypothesis assumes, an important question is whether the nature of this relationship changes with age. Consequently, studies that examine how both age and individual differences in memory span are related to differences in processing speed may be particularly important for clarifying our understanding of the nature of working memory.

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NOTES

1. Although the term *meta-analysis* is often applied to the statistical assessment of effect sizes from different studies, we use the term here in its more general sense to refer to "the quantitative assessment of the results of a group of studies on a given topic" (Rosenthal & Rosnow, 1991, p. 130).

2. Items were presented for 1,750 msec in all the studies but one (Hale, Myerson, et al., 1996). Comparisons between the data from this and the other studies revealed no difference in either the size of the interference effects or the overall pattern of results, although spans in the Hale, Myerson, et al. (1996) study tended to be slightly smaller.

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