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Influence of processing speed on adult age differences in working memory *

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Two studies are reported in which adults ranging from 18 to 80 years of age performed tasks designed to measure working memory functioning and perceptual comparison speed. The results from both studies indicated that statistical control of the measures of perceptual comparison speed greatly attenuated the age-related variance in measures of working memory even when working memory was assessed under self-paced conditions. Additional results in the second study supported the hypothesis that the speed influence was manifested in the rate of activating information rather than in the rate at which it was lost as a function of time or other processing.

Several recent projects have found strong evidence that the speed with which relatively simple perceptual and cognitive operations can be performed is apparently an important factor in the negative relation between measures of working memory performance and chronological age across the range from about 18 to 80 years (Salthouse 1991; Salthouse and Babcock, in press). Working memory in these projects was measured with two tasks, computation span and listening span, and speed was measured with two perceptual comparison tasks, one involving pairs of letters and the other pairs of line patterns. The working memory tasks, which are described in more detail in Salthouse and Babcock (in press), required the research participant to remember as many digits or words as possible while also answering arithmetic problems or sentence comprehension questions. The perceptual comparison speed tasks required decisions about whether two

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Table 1
Results from four earlier studies investigating age, perceptual comparison speed, and working memory.

Study	Sample size	R^2 for age when considered alone	R^2 for age after control of speed
Salthouse and Babcock (in press)			
Study 2	233	0.211	0.007
Salthouse (1991)			
Study 1	221	0.292	0.050
Study 2	228	0.254	0.014
Study 3	223	0.208	0.012

sets of letters or two patterns of line segments were the same or different.

There are now four studies in which these same four tasks have been administered to samples of between 221 and 233 adults ranging from 18 to 80 years of age. Results of these studies, expressed in terms of the R^2 associated with age in the prediction of a composite measure of working memory before and after statistical control of a composite measure of perceptual comparison speed, are summarized in table 1. Notice that the proportion of age-related variance in the working memory measure ranged from 0.208 to 0.292 when considered alone, but it was reduced to between 0.007 and 0.050 after partialling out the variance associated with perceptual comparison speed. The consistency with which this result has been obtained across several independent samples suggests that the phenomenon is reliable, although its generality and the responsible mechanisms have yet to be determined.

The research to be reported in this article was designed to investigate two hypotheses about the role of speed in the relations between age and working memory. One hypothesis concerns the possibility that the influence of speed might be restricted to group-administered testing situations in which all tasks, and not merely those intended to assess speed of performance, are presented in a paced format with a limited time available for responding. The second hypothesis is more specific, and concerns the question of whether speed exerts its influence primarily by affecting the rate at which relevant information is activated, or by altering the rate at which it is lost as a function of time or other processing.

Study 1

The initial study was an attempt to replicate the basic phenomenon under conditions in which there is no obvious temporal component to the working memory tasks. That is, unlike the group-administered studies described above, in this study the working memory tasks were presented on a computer and research participants were allowed to spend as much time as desired inspecting each to-be-remembered item and later attempting to recall the target items. The stimulus materials were identical in content to those used earlier, but they were presented visually on a computer screen instead of orally by the examiner, and research participants were allowed to proceed at their own pace in both the stimulus presentation and recall phases of the task.

Two new perceptual comparison tasks were also used in this study to explore the generality of the speed-mediation phenomenon. One of the tasks was a computer-implemented version of the Wechsler Adult Intelligence Scale – Revised (Wechsler 1981) Digit Symbol Substitution Test, and the other was a choice reaction time variant of that test in which decisions were based on pairs of digits rather than pairs of digits and symbols. Both tasks had different response requirements than the paper-and-pencil tasks used to measure perceptual speed in the previous projects (i.e., key presses instead of writing the letters S or D), and at least the choice reaction time version (the Digit Digit task) can be assumed to have little or no memory involvement.

The primary prediction in this study was that the earlier results would be replicated in the form of substantial attentuation of the age-related differences in a composite working memory measure after statistical control of a composite perceptual comparison speed measure.

Method

Subjects

Ninety young adults (45 males and 45 females) and 90 older adults (43 males and 47 females) performed the two speed tasks and two working memory tasks before participating in an experiment concerned with age differences in either matrix reasoning or integrative reasoning. Young adults participated in partial fulfillment of a course requirement, and older adults, who were recruited from newspaper advertisements and various community organizations, received a nominal payment for their participation. The mean age of the young adults was 20.1 years ($sd = 1.2$), and that of the older adults was 63.5 years ($sd = 7.1$). Self-rated health on a scale ranging from 1 for excellent to 5 for poor averaged 1.5 ($sd = 0.7$) for young adults, and 1.8 ($sd = 0.8$) for older adults. The mean years of education reported by the participants was 14.1 ($sd = 1.1$) for young adults and 15.0 ($sd = 2.3$) for older adults. These characteristics indicate that the study participants had moderately high levels of education, and generally reported themselves to be in good to excellent health.

Procedure

All four tasks were performed on a computer and presented in the same order (Digit Symbol, Digit Digit, Reading Span, and Computation Span) for every research participant. The Digit Symbol task involved the same digit–symbol pairings as in the Digit Symbol Substitution Test from the WAIS-R, but the displays consisted of the code table and a single digit-symbol pair. The code table remained constant across trials but the digit–symbol pair changed from trial to trial. On one-half of the trials the digit–symbol pair was correct according to the code table, and on one-half it was incorrect. Responses were to be made, as quickly as possible, by pressing the '/' key on the keyboard if the digit–symbol pair was correct, and by pressing the 'Z' key on the keyboard if the pair was incorrect. The Digit Digit task was identical except that the symbols were replaced by digits. The code table was therefore uninformative because decisions could be based on the physical identity of the pair of digits. In both tasks there were 18 practice trials (2 for each digit) followed by 90 test trials (10 for each digit). Accuracy feedback was provided after each response.

The two working memory tasks involved the same materials (i.e., to-be-remembered words and digits, and contextual sentences and arithmetic problems) as in the earlier studies (Salthouse 1991; Salthouse and Babcock, in press), but all materials were presented on a computer screen at a pace controlled by the research participant. Trials in the reading span task involved the presentation of a sentence accompanied by a short question with three alternative answers. After typing in the number designating the correct answer to the question, any key could be pressed to present the next sentence. This sequence continued until the designated number of sentences had been presented, at which time the word RECALL was displayed and the examinee was instructed to type the last word from each sentence. As much time as desired was allowed to enter the recall responses, and provision was made to change one's response before registering it and proceeding to the next trial. Trials in the computation span task were similar but involved the presentation of arithmetic problems and memory for the last digit in each problem.

Spans in each task were determined by the highest number of items remembered correctly, while also successfully answering the relevant questions, on at least two of the three trials for a given sequence length. In other words, both the processing (question answering) and storage (recall) requirements had to be satisfied in order to be assigned a non-zero span. The task was terminated when errors were made on either the processing or storage aspect of the task on more than one trial for a given sequence length. A practice series with trials containing up to three items was presented before the test trials in each task in order to ensure that the participants clearly understood what they were supposed to be doing.

Results and Discussion

Because accuracy was greater than 95% in the two speed tasks, performance in the Digit Symbol and Digit Digit tasks was summarized in terms of the median sec per response. As described above, performance in the working memory tasks was represented by the span reflecting the largest number of items remembered correctly while also performing without errors on the required processing (i.e., answering sentence comprehension questions or solving arithmetic problems). Correlations for these measures, as well as for the composite measures created by averaging z-scores for the two speed measures and the two working memory measures, are displayed in table 2.

Table 2
Correlations among major variables, study 1 ($n = 180$).

Variable	1	2	3	4	5	6	7
1 Age	×	0.81	0.60	−0.50	−0.42	0.75	−0.53
2 DS		×	0.74	−0.43	−0.44	0.93	−0.50
3 DD			×	−0.33	−0.27	0.93	−0.35
4 CSpan				×	0.50	−0.40	0.87
5 RSpan					×	−0.38	0.87
6 Speed						×	−0.45
7 WMem							×
Mean	41.8	1.55	0.66	3.56	2.62	0.00	0.00
SD	22.4	0.48	0.21	2.33	1.67	0.93	0.86

Note: All correlations are significantly ($p < 0.01$) different from zero.
DS is median time in sec per response in computer-administered Digit Symbol task;
DD is median time in sec per response in computer-administered Digit Digit task;
CSpan is span in the computation span task;
RSpan is span in the reading span task;
Speed is a composite speed measure derived by averaging the z-scores of the DS and DD measures;
WMem is a composite working memory measure derived by averaging the z-scores of the CSpan and RSpan measures.

Two points should be noted about the values in table 2. The first is that the age correlations are all substantial, indicating that relative to young adults, older adults had slower performance on the speed tasks and lower scores on the working memory tasks. These values are undoubtedly inflated relative to what would have been obtained with a continuous age distribution because the variance associated with middle-aged adults is omitted, but the general pattern is quite similar to that found in previous studies (Salthouse 1991; Salthouse and Babcock, in press). The second interesting feature of the data in table 2 is that the two measures intended to represent the same construct are moderately correlated with one another. That is, the two perceptual speed measures were correlated 0.74, and the two working memory measures were correlated 0.50. The latter value is not particularly large, but it is in the same range as the values observed between similar tasks in the earlier group-administered studies (i.e., 0.49, 0.55, 0.63, and 0.62 for the four studies cited in table 1).

In light of the moderate correlations between the two speed measures and between the two working memory measures, and because of a desire to emphasize construct-relevant variance rather than task-specific variance, composite scores were created by averaging the z-scores for the two speed tasks and for the two working memory tasks. Two sets of regression analyses were then conducted to predict working memory performance both in the composite measure, and in the measures from each task. An initial analysis merely examined the proportion of age-associated variance in the working memory measure when age was the only predictor in the regression equation. The second analysis involved entering the composite speed

Table 3
Hierarchical regression results in the prediction of working memory, study 1.

	WMem			CSpan			RSpan		
	R^2	Incr. R^2	F	R^2	Incr. R^2	F	R^2	Incr. R^2	F
Age	0.279		69.02 [a]	0.245		57.81 [a]	0.176		38.07 [a]
Speed	0.206		51.15 [a]	0.164		38.46 [a]	0.146		31.66 [a]
Age	0.287	0.081	19.96 [a]	0.247	0.083	19.74 [a]	0.186	0.040	8.80 [a]

[a] $p < 0.01$.

Note: Entries in the first column indicate the cumulative R^2 after the varible in that row and the immediately preceding row have been included in the regression equation. Entries in the second column indicate the increment in R^2 associated with the variable in that row, and F-values in the third column refer either to the increment in R^2 where present or to the cumulative R^2.

measure in the regression equation prior to age, thereby removing the variance in working memory associated with speed before examining the influence of age-related effects. Results of the analyses are summarized in table 3.

It is clear from the entries in table 3 that the previous findings were replicated by the discovery that a large proportion of the age-related variance in measures of working memory was attenuated by statistical control of measures of perceptual comparison speed. Moreover, the magnitude of the R^2 values before and after control of speed, 0.279 and 0.081, are very similar to those reported earlier (cf. table 1) despite substantial differences in the tasks and the use of extreme groups rather than a continuous distribution of ages. Because the variance associated with age was still significantly greater than zero after statistical control of speed, not all of the age-related effects on working memory in these samples can be attributed to the influence of perceptual comparison speed. However, for the present purposes it is not the absolute value of the residual age-related variance that is important, but rather the relative reduction produced by statistical control of the index of speed, which with these data was nearly 71% (i.e., $100 \times [0.279 - 0.081]/0.279$).

The results of this study therefore confirm and extend the findings of the earlier studies investigating the role of perceptual speed on the relation between age and working memory. Based on the current results, it can be inferred that the phenomenon of a mediational influence of processing speed on adult age differences in working memory is relatively robust, and not an artifact of group-administered procedures or particular measures of perceptual comparison speed.

Study 2

In the discussion of their results, Salthouse and Babcock (in press) suggested that working memory might be conceptualized as corresponding to the amount of information that is simultaneously active in the processing system. From this perspective, therefore, individual differences in working memory could originate because of differences in the rate at which information is activated, or in the rate at which it dissipates. At least with respect to individual differences associated with increasing age in the adult years, Salthouse and Babcock proposed that the critical factor was the rate of activating information and not how quickly it was lost as a function of time or other processing operations.

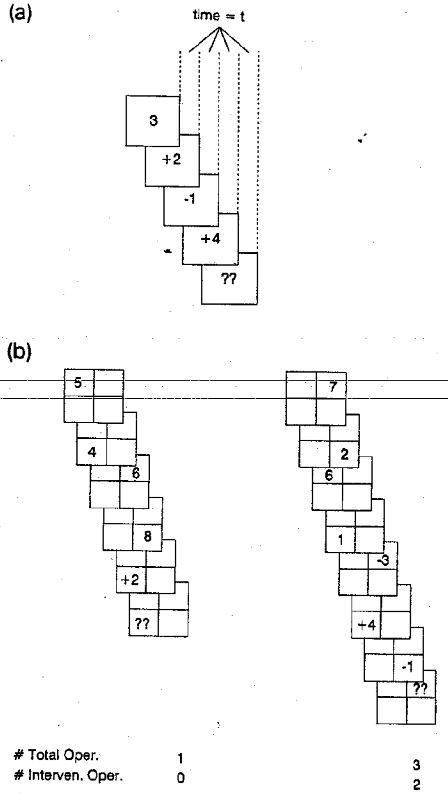

Fig. 1. (a) Illustration of the sequence of displays in a trial in the Duration Threshold task. (b) Illustration of the sequence of displays in trials in the Keeping Track task.

The primary purpose of this study was to investigate the Salthouse and Babcock hypothesis by attempting to measure both the time required to carry out relevant processing, and the rate at which information is forgotten or otherwise lost. In order to maximize correspondence with the working memory tasks used in this project, new tasks were designed to measure processing time and information loss rate with the same materials and operations as those used in the computation span task. Schematic illustrations of the tasks are presented in fig. 1. Fig. 1a portrays the sequence of displays used in the task designed to assess the individual's processing duration threshold. Notice that each trial consists of a display of an initial digit followed by three arithmetic operations and a request to enter the latest value of the digit after performing the displayed operations. In the illustrated example the correct response would be 8 because $3+2-1+4=8$. The duration of the stimulus displays was adjusted according to a threshold procedure to determine the minimum time needed to carry out the relevant processing. This duration was assumed to provide an estimate of the time required to perform the processing required in the computation span working memory task.

Fig. 1b illustrates the sequence of displays in the task designed to assess the individual's rate of information loss. Each trial began with the display of an initial value of a variable in each of four quadrants of the screen, and this was followed by displays of arithmetic operations to be performed on the variable in the corresponding quadrant. After a total of 0 to 5 operations, a target quadrant was designated and the latest value of the variable from that quadrant was to be entered. Because all of the arithmetic operations are very simple when performed in isolation, the primary source of difficulty in this task is in maintaining the products of earlier operations during the performance of new operations. It is in this respect that the task can be considered to assess the ability to preserve information in working memory.

This same basic task was recently examined in several studies by Salthouse et al. (1991), where young and old adults were found to have nearly parallel functions relating error proportion to total number of operations. The procedure employed in the current study differed in two respects from that used in the Salthouse et al. (1991) studies. First, the duration of each screen display was determined by the individual's own duration threshold rather than using the same duration for all research participants. And second, the analyses examined error proportion both as a function of the total number of operations, and as a function of the number of operations intervening between the last change of the target variable and its test. This distinction can be clarified by reference to fig. 1b. The sequence of displays on the left involve one operation (+2), but there are no intervening operations because the last change of the variable in the lower left quadrant occurred in the display immediately preceding the recall probe. The sequence of displays on the right represent a total of three operations (−3, +4, and −1), but only two of those (+4 and −1) intervene between the last change of the target variable (in the upper right quadrant) and its test. This distinction between the total number of operations presented in the trial and the number of operations intervening between the last change in the target and its test is potentially important because the latter variable may be the most relevant to the preservation of information.

To summarize, participants in this study performed the four tasks from the previous study as well as tasks specially designed to measure the speed of carrying out relevant processing, and the rate at which information is lost over time and subsequent processing. The primary predictions are that the earlier results will be replicated with respect to the attenuation of the age relations in working memory after statistical control of the perceptual speed measures, that the measure of the time to perform the relevant processing will be positively associated with age and with the perceptual speed measures but negatively associated with the working memory measures, and that the measure of information loss will be unrelated to either age or working memory.

Method

Subjects

Participants in this study consisted of 100 adults between 18 and 80 years of age recruited primarily from newspaper advertisements. Forty-seven of the participants were females. The sample contained 37 individuals between 19 and 40 years of age, 42 individuals between 41 and 60 years of age, and 21 individuals between 61 and 80 years of age. The mean health rating (on the same 5-point scale described earlier) was 1.5 with an age correlation of 0.21, and the mean years of education was 15.2 with an age correlation of 0.04. None of the results described below were substantially altered by including health rating or years of education as a covariate, and consequently these variables were ignored in the subsequent discussion.

Procedure

The Digit Symbol, Digit Digit, Reading Span and Computation Span tasks were identical to those used in study 1. The order of tasks for all participants was Digit Symbol, Digit Digit, Reading Span, Computation Span, Duration Threshold, and Keeping Track.

The Duration Threshold task is illustrated in fig. 1a. Presentation time for the first four displays in each trial, that is, the initial value and the three arithmetic operations, varied from trial to trial, but the display containing the question marks always remained visible until terminated by the registration of a response. A double random staircase procedure was used in the threshold determination with one sequence starting at a duration of 2 sec and the other starting at a duration of 0.2 sec. In both sequences the duration of the displays in the next trial decreased by 0.01 sec after every correct response, and increased by 0.01 sec after every incorrect response. The sequence was terminated after six reversals of duration, and the average duration across the last three trials of that sequence served as the estimate of the duration threshold. The two sequences were randomly intermixed so that the thresholds were at least partially independent. The correlation between the duration thresholds for the two sequences was 0.62, which resulted in an estimated reliability of 0.77 for the average threshold after boosting the correlation between the two estimates by the Spearman-Brown formula.

The Keeping Track task consisted of a practice block of 5 trials followed by three blocks of 35 trials each. The duration of the stimulus displays was set at a value equal to twice the average duration threshold achieved by the individual in the Duration Threshold task. Each trial involved the presentation of zero to five operations, followed by question marks in one of the quadrants indicating that the value of the variable in that quadrant should be reported. The procedure used for determining the number and type of operations to be presented on a trial selected the total number of operations first, the number of operations on the target variable next, and finally the number of operations intervening between the last change of the target and its requested recall. Approximate averages per trial for each type of operation were 2.5

for the total operations, 1.3 for target operations, 0.9 for intervening operations, and 0.3 for other operations (i.e., those on non-target variables before the last target operation). Because of the method used to determine number and type of operations, the number of total operations was correlated approximately 0.45 with the number of intervening operations.

Results and Discussion

Dependent variables for the perceptual comparison speed and working memory tasks were the same as those described in study 1. As noted above, the dependent variable in the Duration Threshold task was the average (in sec) of the duration thresholds from the two sequences in the double random staircase procedure. The primary dependent variables in the Keeping Track task were measures of the influence of different types of operations on the proportion of errors. One variable was the regression coefficient for the effect of total number of operations, and the other was the regression coefficient for the number of intervening operations. The coefficient for the total number of operations was determined in a regression equation with total number of operations as the only predictor, and the coefficient for number of intervening operations was determined in a regression equation with number of intervening operations, number of target operations, and number of other operations as predictors. Both regression analyses were based on the 105 trials administered to each research participant.

Correlations among age and the dependent measures are displayed in table 4. It can be seen that, as in study 1, the correlations were moderate between the two perceptual speed tasks (0.82) and between the two working memory tasks (0.59). It is also apparent that the two measures of information loss rate were correlated 0.67, suggesting that they are measuring similar properties. Because of the moderately high correlation, and because the coefficient for total number of operations can be assumed to be more reliable in that it is based on a greater range of values, it was used as the index of information loss rate in subsequent analyses.

In accordance with the Salthouse and Babcock (in press) hypothesis, the correlations with age were significantly ($p < 0.01$) different from zero for the Duration Threshold measure, but not for either information loss measure. Moreover, the direction of the non-significant age relations indicate that, if anything, increased age was associated with smaller rates of information loss. It should also be noted that the correlations between the perceptual speed measures and the Duration Threshold measure were in the moderate to large range (i.e., 0.48 and 0.62). This suggests that common factors are probably involved in both types of tasks, despite considerable differences in the nature of the required processing.

Another means of investigating the effects of age and working memory on performance in the Keeping Track task involves examining the magnitude of the correlation coefficients as a function of the total number of required processing operations. These data are presented in fig. 2. Note that although the mean proportion of errors increases nearly monotonically with more operations, there is no consistent trend for the magnitude of the correlations with age or with working memory to vary as a function of the number of required operations. These results provide additional confirmation of the lack of a relationship between age and rate of information loss because if a relation were evident it should be manifested in an increase in the size of the correlations when more operations were required.

Results of the hierarchical regression analyses used to predict working memory performance are summarized in table 5. Two points should be noted about the entries in this table. First, observe that the earlier results are replicated in the finding that the R^2 associated with age was substantially reduced after statistical control of the perceptual comparison speed measures (i.e., from 0.146 to 0.014 with the composite working memory measure). And second, note that the attenuation of the age-related variance appears greater after statistical control of the measure intended to reflect the time to activate information (i.e., a reduction in R^2 to 0.054 with the Duration Threshold measure) than after control of the measure intended to reflect rate of information loss (i.e., a reduction in R^2 to 0.114 with the regression coefficient for total number of operations in the Keeping Track task).

Table 4
Correlations among major variables, study 2 ($n = 100$).

Variable	1	2	3	4	5	6	7	8	9	10
1 Age	×	0.70	0.61	−0.36	−0.32	0.45	−0.17	−0.12	0.69	−0.38
2 DS		×	0.82	−0.40	−0.40	0.62	−0.31	−0.19	0.95	−0.45
3 DD			×	−0.30	−0.37	0.48	−0.24	−0.12	0.95	−0.37
4 CSpan				×	0.59	−0.39	0.32	0.12	−0.37	0.89
5 RSpan					×	−0.31	0.19	0.04	−0.40	0.89
6 Thresh						×	−0.26	−0.01	0.58	−0.39
7 Total Op.							×	0.67	−0.29	0.29
8 Interv. Op.								×	−0.16	0.09
9 Speed									×	−0.43
10 WMem										×
Mean	45.0	1.58	0.71	3.27	2.30	0.41	0.09	0.07	0.00	0.00
SD	17.4	0.47	0.19	2.45	1.53	0.23	0.05	0.05	0.95	0.89

Note: Correlations with absolute values exceeding 0.25 are significantly ($p < 0.01$) different from zero.

DS is median time in sec per response in computer-administered Digit Symbol task;
DD is median time in sec per response in computer-administered Digit Digit task;
CSpan is span in the computation span task;
RSpan is span in the reading span task;
Thresh is the average duration threshold in sec for performing arithmetic operations;
Total Op. is the regression coefficient for the influence of number of processing operations in the multiple regression equation predicting error proportion;
Interv. Op. is the regression coefficient for the influence of number of intervening operations in the multiple regression equation predicting error proportion;
Speed is a composite speed measure derived by averaging the z-scores of the DS and DD measures;
WMem is a composite working memory measure derived by averaging the z-scores of the CSpan and RSpan measures.

General discussion

Before discussing the conclusions implied by the present results it is useful to summarize the rationale underlying the statistical control procedure. The hypothesis based on earlier research is that age-related influences on working memory consist of a large effect mediated by a slower rate of information processing, and a relatively small direct, or not speed-mediated, effect. The optimal means of investigating this hypothesis would be to manipulate rate of processing in adults of different ages, and then to compare their performance in tasks assessing working memory. Unfortunately, because it does not appear feasible to alter speed of information processing within the nervous system, statistical control procedures must be used to attempt to artificially equate people of different ages with respect to the index of processing speed. These techniques are relatively crude because they only control or remove the variance in the speed index that is linearly related to the variance in the working memory measure. However, they do provide a method of estimating the degree to which age-related influences on working memory overlap with, or are common to, speed-related influences. That is, the age-related variance in working memory can be partitioned into a component uniquely associated with age, in the sense that it is independent of the speed influence, and into a component in common with speed. To the extent that the former component is small relative to the latter component, then it can be inferred that some aspect of speed is involved in the relation between age and working memory. Statistical control procedures are not informative about the mechanisms responsible for the relations

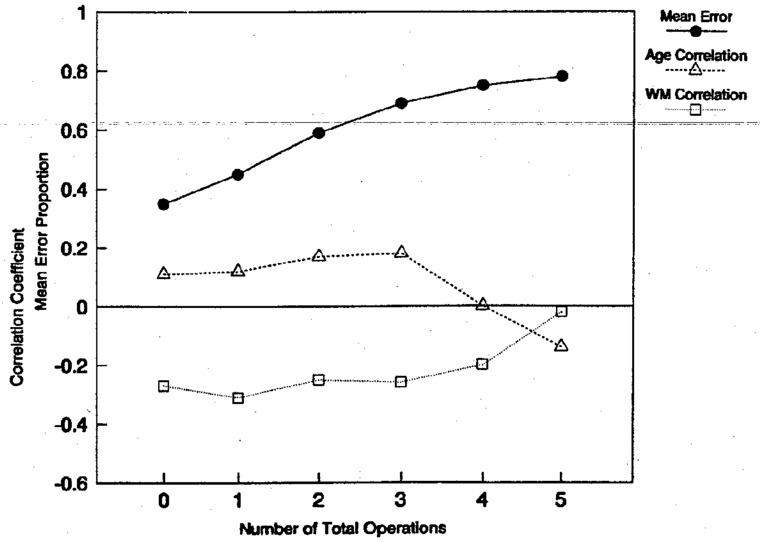

Fig. 2. Mean proportion error, and correlations with age and working memory, as a function of the number of total operations, study 2.

Table 5
Hierarchical regression results in prediction of working memory, study 2.

	WMem			CSpan			RSpan		
	R^2	Incr. R^2	F	R^2	Incr. R^2	F	R^2	Incr. R^2	F
Age	0.146		1678 [a]	0.131		14.76 [a]	0.103		11.24 [a]
Speed	0.187		22.64 [a]	0.135		15.59 [a]	0.163		18.94 [a]
Age	0.201	0.014	1.69	0.158	0.023	2.60	0.166	0.003	0.42
Total Op.	0.083		10.01 [a]	0.103		12.44 [a]	0.037		4.14
Age	0.197	0.114	13.78 [a]	0.199	0.096	11.73 [a]	0.123	0.086	9.41 [a]
Thresh	0.154		18.85 [a]	0.153		18.46 [a]	0.096		10.78 [a]
Age	0.208	0.054	6.55	0.197	0.044	5.27	0.137	0.041	4.67
Speed	0.187		23.20 [a]	0.135		16.25 [a]	0.163		18.92 [a]
Thresh	0.217	0.030	3.77	0.183	0.048	5.71	0.171	0.008	1.00
Age	0.228	0.011	1.34	0.200	0.017	2.12	0.174	0.003	0.32
Thresh	0.154		19.15 [a]	0.153		18.36 [a]	0.096		11.14 [a]
Speed	0.217	0.063	7.82 [a]	0.183	0.030	3.59	0.171	0.075	8.78 [a]
Age	0.228	0.011	1.34	0.200	0.017	2.12	0.174	0.003	0.32

[a] $p < 0.01$.

Note: Entries in the first column indicate the cumulative R^2 after the varible in that row and the immediately preceding rows have been included in the regression equation. Entries in the second column indicate the increment in R^2 associated with the variable in that row, and F-values in the third column refer either to the increment in R^2 where present or to the cumulative R^2.

CSpan is span in the computation span task;
RSpan is span in the reading span task;
Thresh is the average duration threshold in sec for performing arithmetic operations;
Total Op. is the regression coefficient for the influence of number of processing operations in the multiple regression equation predicting error proportion;
Speed is a composite speed measure derived by averaging the z-scores of the DS and DD measures;
WMem is a composite working memory measure derived by averaging the z-scores of the CSpan and RSpan measures.

between age and speed and between speed and working memory, but they do yield evidence relevant to the existence of those relations.

The results of these studies support two major conclusions. The first is that the phenomenon of a mediating effect of perceptual comparison speed on the adult age differences in working memory is apparently quite robust, and evident even when speed is assessed with reaction time measures and working memory is assessed under self-paced conditions. The results of studies 1 and 2, summarized in tables 3 and 5, indicate that, as was the case with the earlier group-administered studies, the age-related variance in composite measures of working memory is reduced by 70% or more after statistical control of composite measures of perceptual comparison speed.

The second major conclusion from these studies is that the processes responsible for the relations among age, speed, and working memory seem to involve the speed at which relevant information can be activated, and not the rate at which information decays or is displaced. Evidence for this conclusion derives from the discovery in the second study that the correlations between age and the duration threshold measure used as an index of activation time were statistically significant, but those between age and the coefficients reflecting the change in error proportion with additional operations were not significant. The lack of a systematic increase in the magnitude of the age correlations with additional operations in fig. 2 is also consistent with the inference that there are little or no age-related differences in the ability to preserve previously activated information.

Additional support for this conclusion about the differential effects associated with age on the activation and dissipation of information comes from other types of research. For example, many studies have reported that young and old adults are similar in the functions relating recall or decision accuracy to the number of intervening items in continuous recognition tasks (e.g., Craik 1971; Erber 1978; Ferris et al. 1980; Flicker et al. 1989; LeBreck and Baron 1987; Lehman and Mellinger 1986; Poon and Fozard 1980; Wickelgren 1975), and to the amount or duration of interfering activity in Brown-Peterson tasks (e.g., Charness 1981; Dobbs and Rule 1989; Keevil-Rogers and Schnore 1969; Kriauciunas 1968; Puckett and Lawson 1989; Puckett and Stockburger 1988; Ryan and Butters 1980; Talland 1967). As in the present Keeping Track task, these results suggest that young and old adults do not differ in the rate at which information availability is lost.

There have also been a number of studies examining relations between memory performance and the time required to activate or establish representations of verbal items. For example, Kynette et al. (1990) and Salthouse (1980; also see Salthouse and Kail 1983) found that older adults were slower at naming or subvocally rehearsing relevant items than young adults, but that the two groups exhibited similar relations between the speed of activating information and performance on memory tasks involving that material. Thompson and Kliegl (1991) have also reported high correlations (i.e., -0.75 in young adults and -0.79 in older adults) between recall accuracy and encoding times derived by determining the minimum stimulus duration necessary to achieve 50% correct responses. The apparent implication from results such as these is that adults of different ages vary primarily in the speed with which they can establish or activate representations, and not in the nature of the function relating activation speed to memory performance.

A key question in light of the current conceptualization of adult age differences in working memory concerns the nature of information activation. That is, if one accepts the argument that a large proportion of the adult age differences in working memory may be attributable to age-related reductions in the speed of activating information, it then becomes meaningful to inquire as to exactly what is meant by information activation. Unfortunately, only vague speculations can be offered on this issue at the present time. For example, information activation could consist of creating a recurring pattern of electrical activity in interconnected neural circuits, or it might involve the construction of appropriate symbolic descriptions. Still another possibility is that information activation corresponds to the outcomes of whatever transformations are produced by processing operations. Regardless of what is involved in establishing a stable representation, however, it appears that the speed of that process may be a key factor in the age-related reductions in working memory observed in these and other studies.

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