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Effects of Adult Age on Structural and Operational Capacities in Working Memory

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Eight experiments were conducted in which young adults and older adults were asked to report the latest value of 1 of several continuously changing numeric or spatial variables. Accuracy of reporting the current value of the target variable was lower with increases in the number of potentially relevant variables and with increases in the number of required processing operations. Young and older adults exhibited similar effects of the number of potentially relevant variables (hypothesized to be sensitive to the structural capacity of working memory) and of the number of required processing operations (hypothesized to be sensitive to the operational capacity of working memory), but older adults were generally less accurate than young adults.

Working memory is generally distinguished from earlier notions of short-term memory by an emphasis on the simultaneous storage and processing of information in working memory, as opposed to a concern primarily with the storage of information in short-term memory (e.g., Baddeley, 1986; Craik & Rabinowitz, 1984; Daneman & Carpenter, 1980). It has recently been suggested (cf. Carpenter & Just, 1989; Salthouse & Mitchell, 1989) that working memory may have at least two distinct capacities, structural and operational, with the former referring to capacity in terms of "the number of distinct informational units that can be remembered at any given time" and the latter to capacity in terms of "the number of processing operations that can be performed while still preserving the products of earlier operations" (Salthouse & Mitchell, 1989, p. 18).

Carpenter and Just (1989) and Salthouse (1982) have proposed analogies to clarify the contrast between static or structural, and dynamic or operational, capacities. A hospital was used as the basis of the analogy by Carpenter and Just, with static capacity likened to the number of surgical theaters and dynamic capacity interpreted in terms of the number of surgical operations that can be performed in a given period. Salthouse (1982, p. 180–181) contrasted the structural capacity of a banquet hall, expressed as the maximum number of diners that could be accommodated at a single time, with the operational capacity of a fast-food restaurant, as reflected by the number of meals that could be served in a specified period. With respect to working memory, the key distinction in both analogies is between capacity expressed as the maximum number of items that can be remembered and capacity reflected in terms of the amount of processing performed between input and output of the to-be-remembered information.

Despite the presumed importance of operational factors in working memory, relatively little attention has been paid to the processing aspects of it. That is, most measures proposed to assess working memory evaluate the maximum number of items that can be remembered (i.e., storage capacity) while the subject is carrying out specified processing, such as reading sentences (Daneman & Carpenter, 1980), counting dots (Case, Kurland, & Goldberg, 1982), or performing arithmetic (Salthouse, Mitchell, Skovronek, & Babcock, 1989). A unique aspect of the current studies is that the dynamic or operational aspects of working memory were investigated in addition to the static or structural aspects. That is, experimental manipulations consisted of varying either the number of distinct variables to be considered (a manipulation hypothesized to be informative about the structural capacity of working memory) or the number of processing operations that must be performed (a manipulation assumed to be informative about the operational capacity of working memory).

Figure 1 illustrates the sequence of events in trials in the numeric (A) and spatial (B) versions of the new experimental tasks. Each column represents the events in a single trial, and each frame within a column corresponds to a successive display on the computer screen. Darkened lines in the figure indicate the quadrants that are displayed on the computer screen. Initial values are displayed in the relevant quadrant in the first frame or frames of the display. The following frames indicate the type of transformation to be performed and the variable on which that transformation is to be applied (i.e., in which quadrant). For example, in the numeric example with three variables and three operations, the initial values of each quadrant are displayed in the first 3 screens (i.e., 6, 7, and 4). The remaining three frames indicate that the subject should add 5 to the current value in the upper right quadrant, subtract 4 from the current value in the upper left quadrant, and finally subtract 1 from the current value in the upper right quadrant. The ??? indicates that the current value of the variable in that quadrant of the display is to

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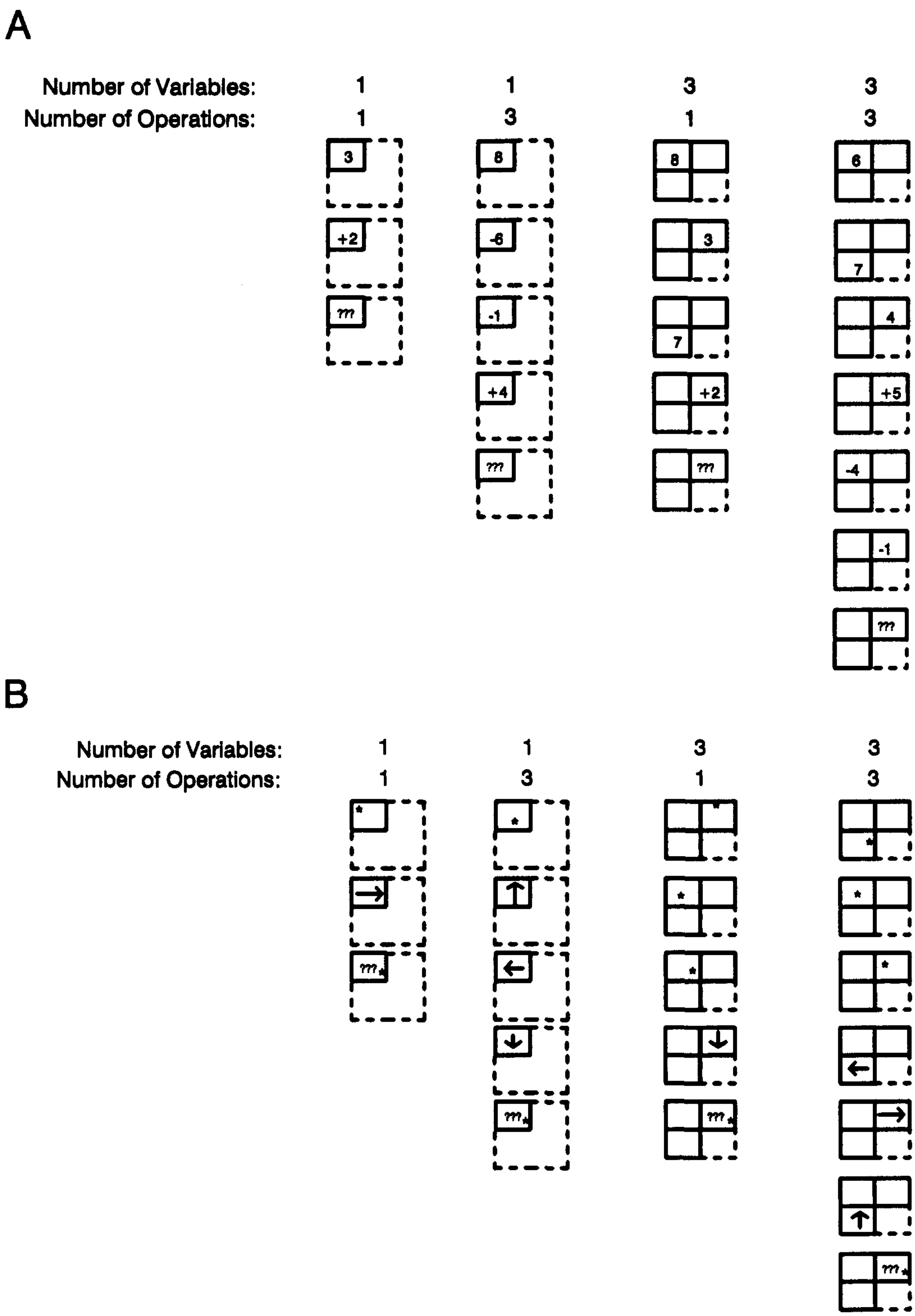

Figure 1. Illustration of the sequence of displays within a trial for different numbers of potentially relevant variables and different numbers of required processing operations. (The columns in panel A represent trials in the numeric version of the task, and those in panel B represent trials in the spatial version of the task.)

be reported. In this example, the correct response would be 8 (i.e., 4 + 5 − 1 = 8).

The spatial version of the task, portrayed in panel B of Figure 1, is similar to the numeric version of the task in that the initial locations of the asterisk in each quadrant are displayed, followed by frames indicating how the position of each asterisk should be transformed. The arrow in each frame indicates the direction and amount (signified by the length of the arrow) in which the subject should mentally move the asterisk. As in the numeric version of the task, the ??? indicates that the current value of the variable (in this case, the position of the asterisk) in that quadrant should be entered. Arrow keys on the computer keyboard could be used to move the symbol in the probed quadrant to the position it would occupy after being moved in the direction and by the amounts indicated by the arrows in that quadrant.

Notice that the numeric and spatial versions of the tasks are formally equivalent, in the sense that both can involve the presentation of one to four variables (in separate quadrants of the display screen), both allow the variables to be subjected to different numbers of transformations, and in both the variables are distinguished by the quadrant in the screen in which they appear. The transformations in the numeric task were always one-dimensional in that the value of the variable was either increased or decreased by a specified amount. Two-dimensional transformations were possible in the spatial task because the asterisk position could be moved by varying amounts along either the horizontal or the vertical dimensions. The manipulations of the number of variables and the number of processing operations, and the theoretical distinction between structural capacity and operational capacity that these manipulations are intended to assess, nevertheless appear quite similar in the two versions of the task.

An initial study involving only young adults was conducted (a) to explore the feasibility of the tasks, (b) to investigate correlations between the measures from the numeric and spatial versions of the task, and (c) to determine the correlations between these measures and established measures of cognitive abilities. A total of 50 male college students performed both the numeric and spatial versions of the tasks, using procedures very similar to those to be described in Experiments 1 and 2. The subjects also performed nine paper-and-pencil tests intended to assess higher order cognitive functioning. Four of the tests (Paper Folding, Surface Development, Form Boards, and Cube Comparisons) were assumed to assess spatial visualization ability, three (Letter Sets, Shipley Abstraction, and Raven's Progressive Matrices) were postulated to assess inductive reasoning ability, and two (Number Comparison and Finding As) were presumed to assess perceptual speed.

The major results from this preliminary study were that the reliabilities of the performance measures from the experimental tasks were respectable (i.e., .87 for the numeric task and .84 for the spatial task) and that the correlation between the measures in the two tasks was significantly greater than 0 (i.e., r = .42). The correlations between the average error in the experimental tasks and composite cognitive ability scores from the paper-and-pencil tests were also moderate, with numeric and spatial correlations of −.47 and −.30 for the reasoning composite, −.31 and −.18 for the spatial visualization composite, and −.08 and .04 for the perceptual speed composite. It therefore appears that the two new working memory measures have at least some common aspects and that these aspects may be important for reasoning and spatial visualization abilities but not for the ability of perceptual speed. Larson and Saccuzzo (1989) have also reported moderate correlations between scores on psychometric cognitive tests and a task (counters) similar to the ones we used in requiring continuous updating of the status of multiple variables. Both sets of results are thus consistent in suggesting that dynamic or operational aspects of working memory may influence the effectiveness of cognition even when the amount of information to be remembered is well within the static or structural limits of working memory.

The results from the preliminary study were considered sufficiently encouraging to warrant systematic investigations of the effects of adult age on the hypothesized structural and operational capacities of working memory. The primary investigative procedure consisted of tests of interactions between age and manipulations assumed to be sensitive to either structural or operational capacities of working memory. All of the experiments were conducted in pairs, with one experiment involving the numeric task and the other the spatial task. Experiments 1 and 2 were designed to investigate structural capacity by manipulating the number of potentially relevant variables presented on each trial. The remaining experiments focused on operational capacity by manipulating the number of processing operations intervening between the initial presentation and the probe of the target variable, and they varied only with respect to the duration of stimulus presentation.

General Method

The sequence of displays within a trial was similar to that illustrated in Figure 1. Each display contained information relevant to a single variable, either the initial value or the operation to be performed, and was presented for a constant duration. Separate variables were presented in distinct quadrants of the screen, with the upper left quadrant used on trials when only one variable was presented, the upper quadrants used with two variables, the upper quadrants and the lower left quadrant used with three variables, and all four quadrants with trials involving four variables.

Responses in the numeric task consisted of typing in a number, between 0 and 9, thought to represent the latest value of the target variable (i.e., the variable in the quadrant in which the ??? probe appeared). Responses in the spatial task consisted of using the arrow keys on the computer keyboard to move the displayed asterisk to the latest position of the asterisk in the target quadrant. When satisfied with the response, the subject pressed the ENTER key on the computer keyboard to register the response and pressed it again to initiate the next trial. There was no time limit in the response phase of the trial, although subjects were encouraged to work rapidly as well as accurately.

Responses in the numeric task were scored in terms of absolute accuracy, whereas those in the spatial task were evaluated in terms of distance from the correct target position in a 10 × 10 Cartesian coordinate system. For example, if the true position of the target variable was $X = 4$ and $Y = 6$ but the subject placed the symbol in position $X = 2$ and $Y = 5$, then the score for that trial would be 2.24 (i.e., the square root of the sum of the square of [4 − 2] and the square of [6 − 5]).

Because of the large number of statistical comparisons across the eight experiments in the project, an alpha level of .01 was adopted for all significance tests. Except where explicitly noted, the same patterns of statistical significance would have been evident with a .05 alpha level.

Experiment 1

As noted in the preceding section, the primary purpose of Experiment 1 was to investigate the possibility of age differences in the structural capacity of working memory with numeric material. The rationale was that if the structural capacities of older adults are smaller than those of younger adults, then older adults should exhibit greater increases in errors with increases in the number of potentially relevant variables that must be considered on a given trial. The hypothesis of age differences in structural capacity therefore leads to the prediction of an interaction between age and the number of potentially relevant variables.

Because of an impression in the preliminary study that subjects were more accurate when they actively rehearsed the latest value of each variable, we were also interested in the effects of instructing subjects to use an active rehearsal strategy. Approximately half of the individuals in each age group therefore received standard instructions, and half received special instructions in which they were encouraged to repeat the latest value of each variable after every processing operation.

To determine whether all subjects could perform the task when no processing operations were required, a control task was also administered in which no processing operations were necessary. We expected that little or no errors would be made in this version of the task because the only requirement was to examine the sequential display of four digits and then to report the value of the digit in the probed quadrant.

Method

Subjects. Forty-four young adults were recruited from college classrooms, and 40 older adults were recruited from newspaper advertisements and referrals from other participants. Details about the demographic characteristics of the samples are summarized in Table 1.

Procedure. All subjects received the following sequence of trial blocks with the numeric tasks: four variables and no processing operations, one variable with a randomly selected (within a range of 5 to 10) number of processing operations, and four variables with a randomly selected (within a range of 5 to 10) number of processing operations, followed by the same conditions in the reverse order. Trials in the block with no processing operations consisted of displays of the initial value of the variables followed immediately by the probe requesting the current value of the target variable. A moderately large number of processing operations were required on the experimental trials to ensure that the task was sufficiently difficult to provide a sensitive test of structural capacity. It was also considered necessary to have a randomly selected number of operations to introduce enough uncertainty to discourage strategies based on anticipating the number of operations presented on a given trial. The first block of trials in each experimental condition contained 15 trials, with 12 trials presented in the second block. The initial 5 trials in the first block and the initial 2 trials in the second block were considered practice and were not analyzed.

Twenty-one of the young adults and 20 of the older adults received additional instructions emphasizing the importance of actively rehearsing the current value of each variable after a change in any of the variables. An example of cycling through the changing rehearsal set was described, and subjects in the active rehearsal group were encouraged to use this strategy to enhance their performance.

Results and Discussion

Mean error proportions for young and older adults as a function of the number of variables are displayed in Figure 2. The initial analysis conducted on the data summarized in Figure 2 was an Age (young and old) × Instructions (standard and active rehearsal) × Number of Variables (1 and 4) × Number of Operations (5–6, 7–8, and 9–10) analysis of variance (ANOVA). Neither the main effect of instructions nor any of its interactions were significant (i.e., all Fs < 1.0). Mean error proportions in the trials with four variables and 5–10 required operations were for young adults, standard instructions = .49 and active rehearsal instructions = .45 and for older adults, standard instructions = .70 and active rehearsal instructions = .70. The nearly complete absence of an effect of instructions suggests either that most subjects were already using an active rehearsal strategy even without special instructions or that the instructional manipulation was too weak to have induced a substantial change in the way in which the task was performed. In either case, however, the results indicated that the instructions manipulation had little effect, and therefore subsequent analyses are based on data collapsed across the two levels of the instructions manipulation.

An ANOVA with age, number of variables, and number of operations revealed significant effects of age, $F(1, 82) = 21.37$, $MS_e = 0.14$; number of variables, $F(1, 82) = 313.29$, $MS_e = 0.09$; and number of processing operations, $F(2, 164) = 8.38$, $MS_e = 0.02$, but no significant interactions. The interactions of Age × Number of Operations and Age × Number of Variables × Number of Operations did not approach significance (i.e., both Fs < 1.0). However, the results displayed in Figure 2 suggest that different patterns of effects were evident with one and four variables, and the interactions of number of variables and age, $F(1, 82) = 6.23$, $MS_e = 0.09$, and number of variables and number of processing operations, $F(2, 164) = 4.59$, $MS_e = 0.02$, just failed to reach the .01 significance level. Even if these statistical interactions had been significant at the adopted criterion level, however, it is important to note that they would have been difficult to interpret because of the existence of an obvious measurement floor for the error measure in the one-variable condition.

It is also apparent in Figure 2 that older adults were less accurate than the young adults at reporting the value of the probed variable even when there were no intervening operations. The implications of this significant age difference, $t(82) = -4.86$, is considered in the General Discussion section.

Experiment 2

The purpose of Experiment 2 was similar to that of Experiment 1 in that age differences in structural capacity were to be investigated by manipulating the number of potentially relevant variables. The experiments differed with respect to the version of the task that was presented, with the current experiment involving the spatial task instead of the numeric task used in Experiment 1.

Method

Subjects. Independent samples of adults were obtained from the same sources described in Experiment 1. Characteristics of the samples are summarized in Table 1.

Table 1
Sample Characteristics in the Eight Experiments

Experiment	n	Gender (% female)	Age (years) M	Age (years) SD	Education (years) M	Education (years) SD	Health rating[a] M	Health rating[a] SD
1								
Young	44	59	20.3	2.5	14.2	1.8	1.68	0.8
Old	40	48	66.0	6.2	15.2	1.8	1.68	1.0
2								
Young	40	50	20.1	2.0	13.8	1.2	1.30	0.6
Old	27	48	65.9	5.4	15.0	2.7	1.81	0.8
3								
Young	44	34	19.6	1.8	14.0	1.3	1.61	0.8
Old	30	53	64.0	6.2	15.9	2.0	1.73	0.9
4								
Young	41	54	19.9	1.5	13.3	1.0	1.32	0.6
Old	30	53	65.2	4.6	15.8	2.2	1.60	0.7
5								
Young	43	35	19.9	2.4	13.8	1.2	1.65	0.8
Old	40	48	65.4	9.4	15.7	2.6	1.80	0.9
6								
Young	42	43	19.7	1.2	14.2	1.2	1.50	0.1
Old	39	46	67.1	5.3	15.2	2.5	1.59	0.1
7								
Young	43	40	19.6	1.5	13.9	1.3	1.47	0.8
8								
Young	42	29	20.3	1.9	14.2	1.2	1.31	0.6

Note. Although the age differences were significant ($p < .01$) in amount of education in Experiments 3, 4, and 5 and in the self-reported health status variable in Experiment 2, neither the education nor the health variable was significantly correlated with performance in the experimental tasks in either age group in any experiment.
[a] 1 = *excellent*, 5 = *poor*.

Procedure. The procedure in this experiment was similar to that used with the numeric task in Experiment 1, with the following differences: (a) The spatial task was used instead of the numeric task; (b) no instructional manipulation was used; and (c) a total of six experimental conditions were administered with either 0 or 5–10 processing operations and one, two, or three variables.

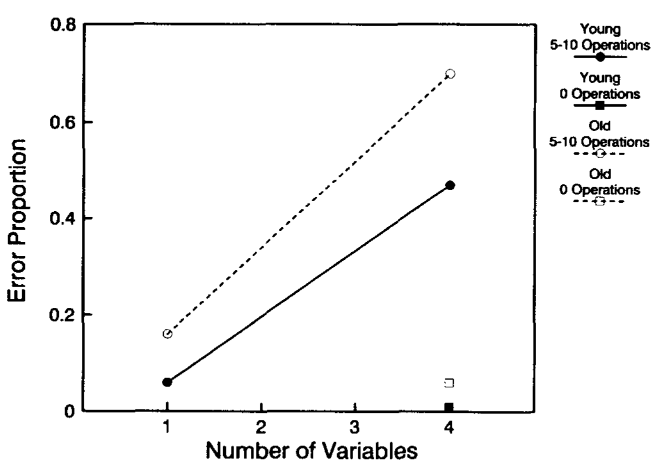

Figure 2. Error proportions for young and older adults in the numeric task as a function of the number of potentially relevant variables, Experiment 1. (The mean standard errors for the displayed data points were as follows: Young adults, 0 operations = .006, 5–10 operations = .029; older adults, 0 operations = .008, 5–10 operations = .027.)

Results and Discussion

Mean error magnitudes for young and older adults as a function of the number of potentially relevant variables are displayed in Figure 3. An initial ANOVA with age (young and old), number of variables (1, 2, and 3), and number of processing operations (5–6, 7–8, and 9–10) revealed that the main effects of age, $F(1, 65) = 2.51$, $MS_e = 5.69$, and of number of processing operations, $F(2, 130) = 2.23$, $MS_e = 0.060$, were not significant and that the main effect of number of variables was significant, $F(2, 138) = 47.93$, $MS_e = 1.17$. None of the interactions were significant (all Fs < 1.6).

Parallel Age (young and old) × Number of Variables (one, two, and three) ANOVAs were next conducted on the measures with 0 processing operations and with 5–10 processing operations. The number-of-variables effect was significant with both measures, $F(2, 130) = 172.77$, $MS_e = 0.07$, for 0 operations, and $F(2, 130) = 52.61$, $MS_e = 0.33$, for 5–10 operations, but the interaction of Age × Number of Variables was not significant for either measure (i.e., both Fs < 1.0). The main effect of age was significant for the measure with 0 operations, $F(1, 65) = 15.30$, $MS_e = 0.23$, but not for the measure with 5–10 operations, $F(1, 65) = 2.78$, $MS_e = 1.92$. Because it is apparent in Figure 3 that the absolute magnitude of the age differences was

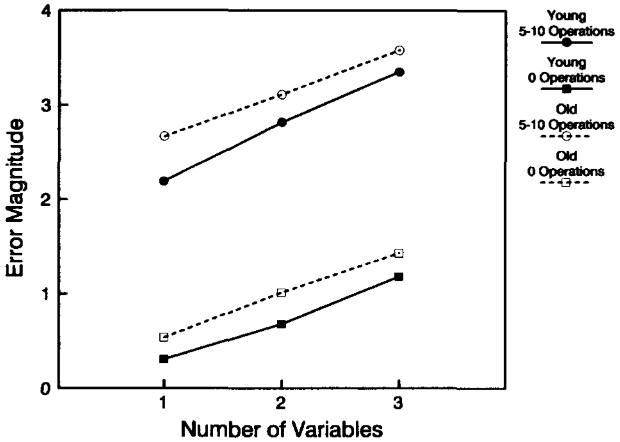

Figure 3. Error magnitudes for young and older adults in the spatial task as a function of the number of potentially relevant variables (Experiment 2). (The mean standard errors for the displayed data points were as follows: Young adults, 0 operations = .050, 5–10 operations = .150; older adults, 0 operations = .071, 5–10 operations = .163.)

similar with 0 and with 5–10 operations, the discrepancy in statistical outcomes is almost certainly attributable to greater interindividual variability with 5–10 operations.

The results of Experiments 1 and 2 suggest that young and older adults do not differ with respect to structural capacity for either numeric or spatial information. Increasing the number of variables that had to be remembered resulted in significantly greater errors for both young and older adults, and thus it appears meaningful to refer to structural limitations even when the tasks involved only one to four variables. However, the discovery that young and older adults exhibited very similar increases in error proportions or error magnitudes as the number of potentially relevant variables increased implies that the capacity of this structural system is not markedly different across the range from about 20 to 70 years of age.

Experiment 3

The purpose of Experiment 3 and of all of the remaining experiments was to investigate possible age differences in operational capacity of working memory by examining the effects on the performance of young and older adults of varying the number of processing operations that had to be performed on each trial. The number of variables was therefore kept constant (at four for the numeric task and at two for the spatial task), whereas the number of required operations ranged between zero and five. The reasoning was that if older adults have a smaller capacity for carrying out processing operations than young adults have, then they would be expected to exhibit larger increases in errors as the number of required processing operations increased. The hypothesis of age differences in operational capacity therefore leads to the prediction of an interaction between age and the number of required processing operations. The Age × Number of Operations interactions were not significant in Experiments 1 and 2, but this may have been attributable to weak effects of the number-of-operations manipulation in the range of 5–10 operations. A range of 0–5 operations was therefore used in this experiment and in all subsequent experiments to minimize this potential problem.

Method

Subjects. New samples of adults who had not participated in any of the previous experiments were obtained from the same sources described in Experiment 1. Characteristics of the samples are summarized in Table 1.

Procedure. The experimental session consisted of subjects performing one practice block of 5 trials, followed by three experimental blocks of 35 trials each. All trials involved four variables and were similar to those of the numeric task of Experiment 1 except that the number of variables was held constant at four and the number of processing operations on a trial was randomly varied between zero and five.

Results and Discussion

Mean error proportions for young and older adults as a function of the number of required processing operations are displayed in Figure 4. An Age × Number of Operations ANOVA revealed significant effects of age, $F(1, 72) = 17.97$, $MS_e = 0.19$, and number of operations, $F(5, 360) = 97.36$, $MS_e = 0.01$, but no interaction, $F(5, 360) = 2.09$, $MS_e = 0.01$.

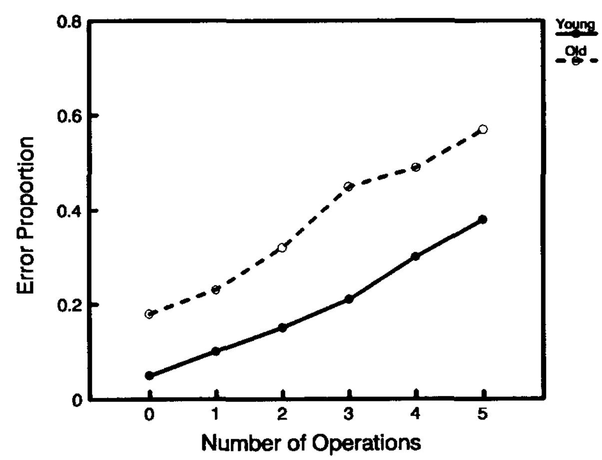

Figure 4. Error proportions for young and older adults in the numeric task as a function of the number of required processing operations (Experiment 3). (Mean standard errors for the displayed data points were .028 for young adults and .041 for older adults.)

Experiment 4

Experiment 4 was identical to Experiment 3 except that the spatial task was substituted for the numeric task, and all trials had two variables instead of four variables. Only two variables were presented to avoid the possibility of functional ceilings with the measure of error of spatial position.

Method

Subjects. New samples of subjects, none of whom had participated in any of the previous experiments, were obtained from the same sources described earlier. Characteristics of the samples are summarized in Table 1.

Procedure. As just noted, the same procedure as that used in Experiment 3 was followed in this experiment. The only differences were that the task involved spatial rather than numeric information, and every trial had two variables instead of four.

Results and Discussion

Mean error magnitudes for young and older adults as a function of the number of required processing operations are displayed in Figure 5. An Age × Number of Operations ANOVA revealed significant effects of age, $F(1, 69) = 26.04$, $MS_e = 3.10$, and number of operations, $F(5, 345) = 98.12$, $MS_e = 0.22$, and a significant interaction of age and number of operations, $F(5, 345) = 4.11$, $MS_e = 0.22$. Inspection of Figure 5 suggests that the interaction might be attributable to smaller age differences occurring in trials with no processing operations. Consistent with this interpretation, the Age × Number of Operations interaction was not significant (i.e., $F < 1.0$) when the analysis was repeated after excluding the data from the zero-operations trials.

The results of Experiments 3 and 4 indicate that, with the possible exception of trials involving spatial information and no processing operations, young and older adults exhibited nearly parallel effects of the number of required processing operations. To the extent that sensitivity to the number of processing operations that must be performed reflects the operational capacity of working memory, therefore, these results suggest that there are apparently little or no age differences in operational capacity for either numeric or spatial information.

Experiments 5, 6, 7, and 8

There were two primary purposes of Experiments 5 through 8. One purpose was simply to provide a wide range of performance levels in both young and older adults to allow analyses of

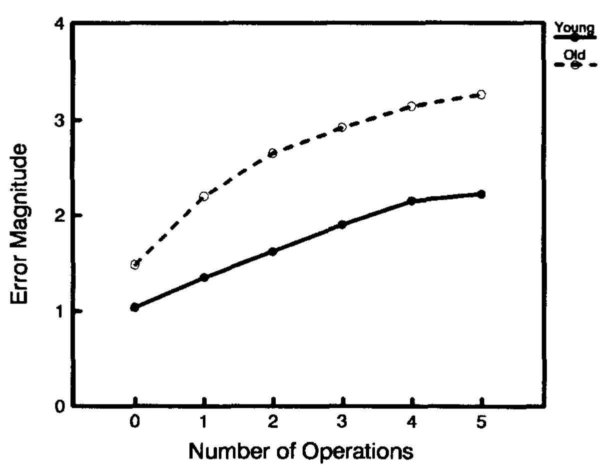

Figure 5. Error magnitudes for young and older adults in the spatial task as a function of the number of required processing operations (Experiment 4). (Mean standard errors for the displayed data points were .122 for young adults and .164 for older adults.)

the effects of the number of required processing operations when the two groups were matched on average level of performance. These analyses were considered potentially informative because both the presence and the absence of statistical interactions are often easier to interpret when the groups to be compared have average levels of performance in the same region of the measurement scale (cf. Chapman & Chapman, 1973). The use of analysis of covariance (ANCOVA) procedures to statistically equate the mean level of performance, together with the larger sample sizes created by pooling subjects across experiments, was therefore expected to provide a more powerful test of the Age × Number of Operations interaction hypothesized to reflect age differences in operational capacity.

The second purpose of Experiments 5 through 8 was to investigate the effects of stimulus presentation duration on the functions relating number of processing operations to error proportion or error magnitude. Experiments 5 and 6 were identical to Experiments 3 and 4 except that the duration of each stimulus display was increased from 2 s to 4 s. To extend the range of stimulus durations, Experiments 7 and 8 involved stimulus presentation durations of 1 s with samples of young adults only. No older adults were tested with the 1-s durations because we assumed that this condition might prove too frustrating for many of them to perform.

The manipulations of stimulus duration were expected to be informative because at least three distinct patterns could emerge with variations in the time of stimulus presentation, and each has implications for how the observed levels of performance might be interpreted. For example, one possible outcome of altering stimulus presentation duration is that there is no effect on performance in the sense that virtually identical functions relating number of operations to performance might be evident with each presentation rate. A finding of this type would seemingly imply that all of the presentation times were sufficient for the execution of all relevant processes. Note that the level of performance need not be perfect to support this inference; a conclusion that performance is limited by factors other than presentation time seems warranted if there is little or no variation in performance as a function of stimulus presentation duration.

A second possible effect of varying the duration of stimulus presentation is that the overall level of performance might shift without altering the nature of the relation between the number of required operations and performance. A discovery that the effects of additional time were independent of the number of processing operations would imply that the intercept of the function was altered, presumably by influencing the effectiveness of encoding the initial values of the variables.

The third potentially interesting effect of varying the stimulus presentation duration is a change in the magnitude of the relation between the number of operations and performance. This type of shift in the slope of the function would imply that the variations in presentation duration affect something associated with each processing operation. The additional time might allow the operations to be executed more successfully, or it might allow better preservation of the products of previous operations, perhaps by means of more effective or extensive rehearsal.

Method

Subjects. New samples of subjects, none of whom had participated in any of the previous experiments, were obtained from the same sources described earlier. Characteristics of the independent samples of adults participating in these experiments are summarized in Table 1.

Procedure. The basic procedure was identical to that in Experiments 3 (for the numeric task used in Experiments 5 and 7) and 4 (for the spatial task used in Experiments 6 and 8) except for the stimulus presentation duration. Experiments 5 and 6 had presentation durations of 4 s, and Experiments 7 and 8 had presentation durations of 1 s. An additional modification in Experiments 5 and 6 was that two blocks of 15 trials each with no processing operations were presented immediately before and after the experimental trials.

Results and Discussion

Figures 6 (numeric task) and 7 (spatial task) illustrate the results of the manipulations of stimulus presentation duration across Experiments 3 through 8. Three analyses were conducted on the data summarized in each figure: an Age × Number of Operations × Stimulus Duration ANOVA on the data with 2-s and 4-s stimulus durations and then separate Number of Operations × Stimulus Duration analyses on the data available in each age group (i.e., 1, 2, and 4 s for young adults and 2 and 4 s for older adults). The initial ANOVA on the data from the numeric task revealed significant main effects of age, $F(1, 153) = 47.82$, $MS_e = 0.17$; number of operations, $F(5, 765) = 156.37$, $MS_e = 0.01$; and stimulus duration, $F(1, 153) = 15.23$, $MS_e = 0.17$, and significant interactions of age and number of operations, $F(5, 765) = 12.78$, $MS_e = 0.01$; number of operations and stimulus duration, $F(5, 765) = 11.34$, $MS_e = 0.01$; and age, number of operations, and stimulus duration, $F(5, 765) = 3.36$, $MS_e = 0.01$. The three-factor ANOVA on the data from the spatial task revealed significant main effects of age, $F(1, 148) = 29.94$, $MS_e = 33.33$, and number of operations, $F(5, 740) = 230.56$, $MS_e = 0.22$, and a significant Age × Number of Operations interaction, $F(5, 740) = 10.34$, $MS_e = 3.33$.

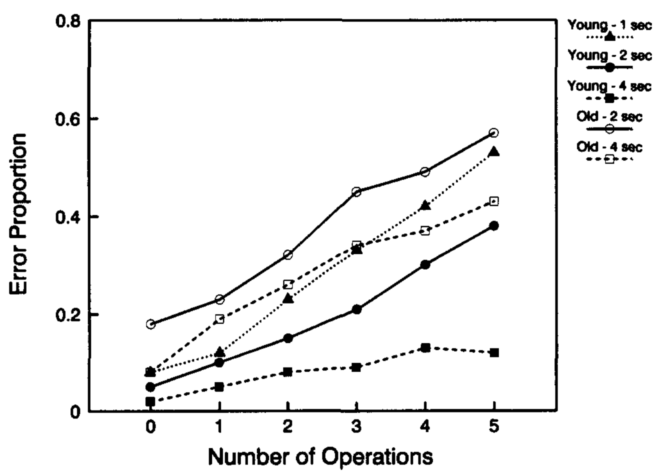

Figure 6. Error proportions for young and older adults in the numeric task as a function of stimulus duration and of the number of required processing operations (Experiments 3, 5, and 7). (Mean standard errors for Experiment 5 were .013 for young adults and .038 for older adults. The mean standard error for young adults in Experiment 7 was .024.)

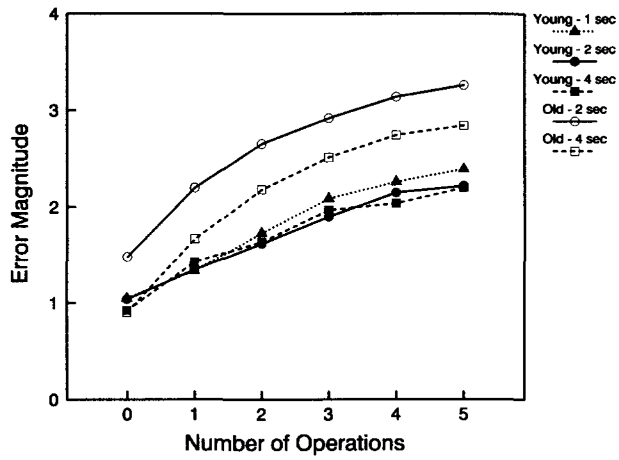

Figure 7. Error magnitudes for young and older adults in the spatial task as a function of stimulus duration and of the number of required processing operations (Experiments 4, 6, and 8). (Mean standard errors for Experiment 6 were .142 for young adults and .131 for older adults. The mean standard error for young adults in Experiment 8 was .121.)

The results of the analyses based on data within each age group are easiest to describe by reference to Figures 6 and 7. First, consider the results for the young adults with the numeric task. It can be seen in Figure 6 that increasing the duration of stimulus presentation resulted in a reduction in the slope of the function relating number of required operations to proportion of errors. This visual impression is supported by the existence of significant main effects of stimulus duration, $F(2, 127) = 27.71$, $MS_e = 0.10$, and number of operations, $F(5, 635) = 164.44$, $MS_e = 0.01$, and a significant Duration × Number of Operations interaction, $F(10, 635) = 21.62$, $MS_e = 0.01$. As discussed earlier, this pattern is consistent with the interpretation that the additional time influences the processes associated either with more effective execution of the processing operations or with more successful preservation of the products of earlier operations while executing other operations.

A different pattern was evident among the older adults; increasing the presentation duration from 2 to 4 s appeared to result in a slight reduction in the overall proportion of errors, but with the same general relation between number of required operations and proportion of errors. This impression was supported statistically by a significant effect of number of operations, $F(5, 340) = 87.23$, $MS_e = 0.02$, but nonsignificant effects of stimulus duration, $F(1, 68) = 3.53$, $MS_e = 0.26$, and of the Duration × Number of Operations interaction, $F(5, 340) = 1.49$, $MS_e = 0.02$. According to the interpretations discussed earlier, this pattern suggests that the additional time may have influenced processes unrelated to the number of required operations and possibly those concerned with more effective encoding of the initial values of the variables.

The older adults exhibited the same pattern in the spatial task of an increase in stimulus duration leading to greater overall accuracy, but with no change in the slope of the function relating number of operations to error magnitude. That is, the main effects of stimulus duration, $F(1, 67) = 7.43$, $MS_e = 2.98$, and number of operations, $F(5, 335) = 116.24$, $MS_e = 0.29$, were both significant, but their interaction was not, $F(5, 335) = 0.34$, $MS_e = 0.29$.

No effect of stimulus duration was evident in the spatial task for the young adults. The number-of-operations effect was significant, $F(5, 610) = 195.74$, $MS_e = 0.15$, but neither the main effect of stimulus duration, $F(2, 122) = 0.26$, $MS_e = 3.42$, nor its interaction with number of operations, $F(10, 610) = 1.16$, $MS_e = 0.15$, was significant. One can infer that all of the processes required to perform at the observed level were accomplished by the young adults within the minimum interval of 1 s.

The varying patterns of stimulus duration effects suggest that young and older adults may have been operating at different positions relative to their respective temporal limits in the two tasks. These different patterns might be associated with differences in the speed with which young and older adults can carry out the necessary processing operations. Regardless of their source, however, their existence can complicate the interpretation of interaction patterns. That is, the possibility that the number-of-operations effect may depend on the mean level of performance (whether that in turn is determined by factors related to rate of processing or by other processes) implies that inferences may be misleading if young and older adults are contrasted at a single, arbitrarily selected stimulus duration. A more desirable procedure consists of examining the effects of the number of required processing operations across several different values of presentation duration and then attempting to abstract the true effects of the manipulation of interest after adjusting for differences in mean level of performance associated with variations in presentation duration. ANCOVAs were therefore conducted on the pooled data from Experiments 3, 5, and 7 for the numeric task and on the pooled data from Experiments 4, 6, and 8 for the spatial task. These analyses used mean performance across all levels of the number-of-operations manipulation as the covariate and then specifically focused on the interaction of age and number of operations with the covariate-adjusted error measures.

The analysis based on the pooled data from the numeric task revealed that the Age × Number of Operations interaction was not significant, $F(5, 985) = 1.12$, $MS_e = 0.01$. The interaction was significant on the pooled data from the spatial task when all of the data were included, $F(5, 955) = 6.42$, $MS_e = 0.19$, but it was not significant when the data from zero operations were omitted, $F(4, 764) = 1.65$, $MS_e = 0.18$.

Age differences were also significant in Experiments 5 and 6 on the control tasks in which no processing operations were required. The mean errors averaged across the two blocks of trials in the numeric task were 0.01 for young adults and 0.07 for older adults, $t(81) = -4.86$, and 0.58 for young adults and 0.93 for older adults, $t(79) = -3.83$, in the spatial task.

General Discussion

The major results of these experiments are that the magnitudes of the age differences seem to be largely independent of both the number of potentially relevant variables and the number of required processing operations. In terms of our theoretical constructs, these results imply that young and older adults are similar in both structural and operational capacities of working memory.

The inference of similar structural capacities is based on the nearly parallel effects for young and older adults of the number of potentially relevant variables in Experiments 1 and 2. The evidence leading to the inference of similar operational capacities is more complicated because the results of Experiments 3 through 8 indicate that the effect of the number of required processing operations may depend on the duration at which the stimuli are presented. Moreover, different patterns of duration influences were evident across the two age groups and the two tasks. The number-of-operations effects were assumed to be easier to interpret when the mean level of performance was equated in young and older adults, and thus an ANCOVA was conducted to adjust for differences in average level of performance. No Age × Number of Operations interaction was evident in these analyses, at least when the zero-operations data were excluded from the spatial task, and thus it appears that young and older adults were also equivalent in terms of operational capacities of working memory.

The generally similar effects of the number of required processing operations in young and older adults, together with the presence of sizable age differences in the performance measures when no processing operations were performed, strongly suggest that the source of the age differences in these tasks is not related to the amount of required processing. This finding is surprising in view of earlier results by Salthouse (1987) and Salthouse and Mitchell (1989) in the context of a spatial integration task. In the previous studies, young and older adults exhibited parallel reductions in performance with increases in the number of line segments in a composite pattern (suggesting equivalent structural capacities), but older adults had greater decreases in accuracy as the number of required integration operations increased (leading to the inference of different operational capacities). Our a priori expectation, therefore, was that the functions relating errors to amount of processing in the present experiments would be steeper for older adults than for young adults.

However, the current results appear consistent with the findings of several recent projects. For example, Babcock and Salthouse (1990) reported two experiments in which the performance of young and older adults was compared across memory tasks presumed to vary in their concurrent processing requirements. In line with the findings of the present studies, Babcock and Salthouse found that the age differences in memory performance remained invariant across tasks with quite different processing requirements. Gick, Craik, and Morris (1988) and Morris, Gick, and Craik (1988) also found that young and older adults were equally affected by increases in the complexity of tasks presumed to involve working memory. Complexity in their projects was manipulated by a concurrent memory requirement (both studies), and by the necessity of having to process sentences while remembering words (Gick et al., 1988). In neither study did these manipulations significantly interact with the age variable. Older adults were reported to have more difficulty than young adults with negative as opposed to positive sentences in both studies, but this effect may not be attributable to limitations of processing in working memory because sizable age differences in sentence verification accuracy were apparent even when those decisions were made without any concurrent memory load. It is therefore not clear whether the presence of larger age differences with negative sentences than with positive sentences reflects an effect of additional processing in working memory or is simply a consequence of greater confusion regarding negative sentences on the part of older adults.

One possible resolution of the apparent discrepancy between the earlier spatial integration studies (i.e., Salthouse, 1987; Salthouse & Mitchell, 1989) and the current studies is that older adults may be deficient relative to young adults in a processing component related to stimulus encoding, but once the information is encoded it is preserved equally well across successive processing operations by both young and older adults. The discovery in Experiments 1, 2, 5, and 6 that older adults were less accurate than young adults even when no processing operations were required is consistent with this hypothesis, as is the finding of nearly parallel effects of additional processing operations for young and older adults. Age differences may have been apparent in the spatial integration studies because each additional operation in those tasks required the encoding and integration of another distinct stimulus.

An alternative interpretation is that age differences in operational capacity exist only when the operations change the internal representation in the direction of becoming more complex or more abstract. In the current studies, each operation resulted in the replacement of the previous stimulus with another stimulus of the same level of complexity or abstraction. In the spatial integration tasks, however, each operation alters the nature of the internal representation by requiring that a more complex stimulus be synthesized and preserved. Age differences in operational limits may therefore be evident only when the operations result in a representation that incorporates more discrete parts or is at a higher level of abstraction.

Both of these interpretations suggest that a key factor influencing the magnitude of adult age differences in working memory tasks is the nature of the processing operations that must be performed while information is being preserved. Systematic investigation of the effects of different types of processing operations on the working memory performance of young and older adults therefore seems to be a productive direction for future research.

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