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Structural and Operational Capacities in Integrative Spatial Ability

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Four experiments were conducted to explore a distinction between *structural capacity*, the maximum number of informational units that can be temporarily stored, and *operational capacity*, the number of processing operations that can be executed while simultaneously preserving the products of earlier processing. The results, from a synthesis task requiring the integration of successively presented line segments into a composite stimulus, revealed that there were little or no age differences in structural capacity but large age differences favoring young adults in operational capacity. An attempt was also made to determine how much earlier information was available after each additional processing operation, but equivocal results precluded a definitive conclusion about the exact nature of the age differences in operational capacity.

Perceptual closure or synthesis tasks require an individual to identify or recognize a stimulus that is presented in an incomplete or fragmented form. Results from both psychometric (e.g., Gestalt Completion—Basowitz & Korchin, 1957; Salthouse & Prill, 1988; and Wasserstein, Zappulla, Rosen, Gerstman, & Rock, 1987; Hooper Visual Organization Test—Botwinick & Storandt, 1974; Cerella, DiCara, Williams, & Bowles, 1986; Ludwig, 1982; Mason & Ganzler, 1964; and Potvin et al., 1981; Form Boards—Demming & Pressey, 1957; Heston & Cannell, 1941; and Weisenburg, Roe, & McBride, 1936; and Wechsler Object Assembly—Wechsler, 1958, 1981) and experimental (e.g., Danziger & Salthouse, 1978; Dirken, 1972; Salthouse, 1988a, Salthouse & Prill, 1988; Verville & Cameron, 1946; Wallace, 1956) procedures indicate that increased age is associated with poorer performance in tasks of this type.

Two possible sources of age differences in closure or synthesis tasks were recently investigated by Salthouse (1987): (a) reduced capacity for temporarily storing spatial information and (b) diminished ability to execute synthesis or integration operations. The major findings of the three experiments in the Salthouse (1987) study were, first, that differences in decision accuracy between young and old adults remained constant across increases in the number of discrete line segments composing the composite stimulus but, second, that the accuracy of older adults declined more than that of young adults as the segments of the stimulus were distributed across a greater number of separate frames and, consequently, more integration operations were presumably required to synthesize the composite stimulus. These results were interpreted as suggesting "that aging is associated with a reduction in the efficiency or effectiveness of processing operations, but [that it] does not alter the quantity of information that can be handled in each operation" (Salthouse, 1987, p. 259). It was also proposed that a potentially fruitful way of conceptualizing age differences in certain cognitive tasks is in terms of variables affecting the construction and maintenance of internal representations. On the basis of the results reported, Salthouse (1987) hypothesized that aging might be associated with a "weakening of the quality or durability of the internal representations but having relatively little effect on the informational capacity of each representational unit" (p. 259).

The previous suggestions are obviously not the only ones that could be proposed, however, and an alternative way of viewing the pattern of results reported by Salthouse (1987) is in terms of a distinction between *structural capacity* and *operational capacity*. That is, structural capacity might refer to the number of distinct informational units that can be remembered at any given time, whereas operational capacity could indicate the number of processing operations that can be performed while still preserving the products of earlier operations. The results summarized earlier suggest that these two types of capacity are differentially sensitive to age, with structural capacity remaining relatively invariant across adulthood and operational capacity appearing to decline with increased age.

The structural–operational distinction is preferred at the present time because it not only encompasses the previous distinctions but it also seems to have the potential of providing a greater integration with results from other areas of cognitive aging. That is, referring to the informational capacity of representational units, or to the quantity of information that can be temporarily stored, as structural capacity is simply a change in terminology from the previous usage. The notion of operational capacity is new, but it relates to the efficiency or effectiveness of operations because those properties are determined, at least in part, by how well the products of past operations are maintained during processing. Operational capacity also relates to the quality and durability of internal representations because representations are necessarily less stable if the construction or strengthening of one portion (by means of current processing operations) is achieved only at the expense of the weakening of other portions (through the loss of previously available information).

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Moreover, because operational capacity seems to be very similar to the concept of working memory, the structural–operational distinction may facilitate integration with research using working memory as an explanatory construct. The key characteristic of both operational capacity and current conceptions of working memory (e.g., Baddeley, 1986; Case, 1985; Daneman & Carpenter, 1980) is simultaneous storage and processing. As noted earlier, operational capacity clearly incorporates these aspects because it is defined as the ability to preserve the products of earlier processing operations while executing new processing operations.

Because the usefulness of any of these distinctions is proportional to the amount of supporting evidence, a major purpose of the present research is to replicate the evidence leading to the distinction between structural and operational capacity in spatial synthesis tasks. Once confirmed, the focus will shift toward attempting to identify the factors contributing to the existence of age differences in operational capacity.

Four separate experiments were conducted, but the basic methods were very similar in each, and thus the common aspects will be described before proceeding to the detailed description of each experiment.

General Method

Subjects

All of the research participants were male students (young adults) or male alumni (older adults) of Georgia Institute of Technology, a relatively select university with a technically oriented curriculum. Summary characteristics of the samples of 24 different individuals in each age group in each experiment are reported in Table 1. As can be seen, participants generally evaluated their own health status as between very good and excellent, with 98% of all individuals in each age group reporting themselves to be in at least average health. The vision measure represents a crude threshold for determining the laterality of a line presented on a video display screen in order to ensure that all participants had adequate visual acuity. On each trial a line was displayed that extended either to the left or to the right of the center of the screen. The task for the participant was to indicate, with a key press, which direction the line extended on that trial. The line length was reduced by 1 pixel unit when 7 or more trials out of 10 were correct, and a threshold was determined when 4 or more trials out of 10 were incorrect at a given line length, or when the minimum value of 1 unit was reached. The Digit Symbol score is simply the number of items correctly completed in the Digit Symbol Substitution subtest from the Wechsler Adult Intelligence Scale–Revised (Wechsler, 1981). The age differences in this measure are very similar to those reported in many previous studies and thus suggest that the current samples are typical of those participating in other investigations of cognitive aging phenomena.

Procedure

A microcomputer was used for the presentation of stimuli and the monitoring of responses. The stimuli were composed of line segments between adjacent dots in an invisible 4 × 4 matrix. All of the segments were connected to one another in the composite stimulus and in the stimulus fragments presented in each separate frame. (See Salthouse, 1987, for an illustration of sample stimuli.) The comparison stimulus in *same* trials was the composite of the line segments from each frame, whereas that in *different* trials was the composite stimulus after alteration of the positions of two of the line segments.

Table 1
Descriptive Characteristics of Research Participants

Characteristic	Experiment 1	2	3	4
Age (in years)				
Young				
M	19.7	19.5	19.3	20.2
SD	1.6	1.8	1.2	1.4
Old				
M	63.8	60.7	61.5	62.8
SD	2.9	3.3	3.7	4.4
Education[a]				
Young				
M	13.6	13.6	13.7	14.4
SD	1.5	1.2	1.0	1.3
Old				
M	16.7	16.7	16.5	16.8
SD	1.8	1.5	1.5	1.6
Health[b]				
Young				
M	1.38	1.50	1.67	1.63
SD	0.6	0.7	1.1	0.7
Old				
M	1.63	1.48	1.79	1.58
SD	0.8	0.7	0.8	0.9
Vision[c]				
Young				
M	1.31	1.35	1.31	1.42
SD	0.4	0.6	0.5	0.7
Old				
M	1.31	1.67	1.46	1.46
SD	0.4	0.9	0.7	0.7
Digit Symbol[d]				
Young				
M	59.7	68.3	65.3	66.7
SD	10.6	8.7	8.9	9.7
Old				
M	47.9	50.6	48.1	50.0
SD	10.6	7.8	9.4	9.9

[a] Years of formal education. [b] Self-rating on scale ranging from *excellent* (1) to *poor* (5). [c] Pixel threshold for discrimination of line position. [d] Number of item correctly completed in 90 s.

The sequence of events within a given trial consisted of a 1.5-s presentation of the line segments within a frame, followed immediately by a brief screen-erasing solid mask, a 0.1-s blank interval between frames, and a 1.0-s blank interval between the last frame and the comparison stimulus, which remained visible until registration of the response. Decisions were communicated by pressing the / key on the computer keyboard for same and by pressing the Z key on the keyboard for different. Participants were allowed as much time as they desired for their decision, and they were informed that the accuracy of the decision was much more important than the speed with which it was communicated.

A post hoc ability factor was created in each experiment by dividing young and old adults into two subgroups on the basis of their performance, relative to the median for their age group, in a condition in which nine-segment stimuli were presented with three segments in each of three frames. This condition was used as the basis for forming the ability groups, primarily because a version of it was common to all four experiments.

Experiment 1

The first experiment had two goals, one primary and one secondary. The primary goal was to attempt to replicate the major findings of Salthouse (1987) within the context of a single experiment. That is, the results described earlier were obtained in two separate series of experiments, and it was considered desirable to determine whether the same pattern would be evident when the number of frames and the total number of stimulus segments were manipulated simultaneously in a single experiment.

The secondary goal of Experiment 1 was to investigate the possibility that older adults might perform at lower levels than young adults in spatial integration tasks because they forget visual–spatial information at a faster rate than do young adults. This hypothesis was tested by presenting some trials in which the to-be-remembered stimuli were displayed in a single frame presented at one of three intervals prior to the occurrence of the comparison stimulus. If age differences in integration or synthesis tasks originate because older adults forget information faster than do young adults, then there should be an Age × Retention Interval interaction such that the decline in recognition accuracy with increased retention interval is greater for older adults than for young adults.

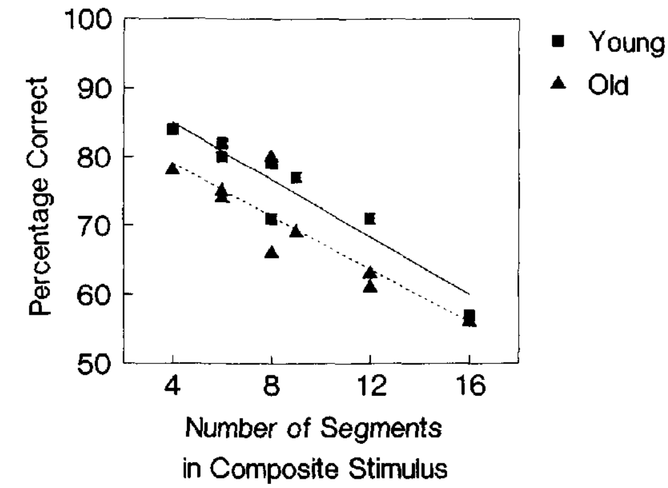


Figure 1. Mean percentage correct for young and old adults as a function of the number of segments in the composite stimulus in Experiment 1. (The solid line is the least squares regression line for the young adult data, and the dashed line is that for the old adult data.)

Method

The basic design consisted of the factorial combination of two, three, or four frames with two, three, or four segments per frame. After an initial series of practice trials, each of the nine combinations of number-of-frames and number-of-segments-per-frame were presented for 4 trials (2 same and 2 different) in each of five blocks of trials. In addition, 12 trials (6 same and 6 different) in each block contained a single-frame presentation of a nine-segment stimulus. This presentation occurred at one of three times (for 4 trials each), with the resulting retention intervals until the presentation of the comparison stimulus corresponding to the temporal intervals between the first frame and the comparison stimulus for trials with four (i.e., 4.2 s), three (i.e., 2.6 s), and two (i.e., 1.0 s) frames.

Results and Discussion

Performance in the experimental trials was represented in terms of the percentage of correct decisions across the relevant trials in each condition. The first analysis conducted on these data was an Age (young, old) × Ability (high, low) × Number-of-Frames (2, 3, or 4) × Number-of-Segments-per-Frame (2, 3, or 4) analysis of variance (ANOVA).

The significant effect of age (young = 74.8%, old = 69.2%), $F(1, 44) = 10.21$, $MS_e = 291.66$, $p < .01$, was expected on the basis of previous research. The significant effect of ability (high = 75.3%, low = 68.1%), $F(1, 44) = 19.03$, $MS_e = 291.66$, $p < .01$, was also not very interesting because it was undoubtedly a consequence of assigning the individuals to high and low groups on the basis of their performance in one of the conditions. Somewhat surprising, however, was the significant Age × Ability interaction, $F(1, 44) = 5.05$, $MS_e = 291.66$, $p < .05$, because Bonferroni *t* tests revealed that the means of the high-ability young and older adults were significantly different (79.8% for young adults and 70.8% for older adults), but that the means for low-ability young and old adults did not differ (68.9% for young adults and 67.3% for older adults).

The main effects of number-of-frames (2 = 76.0%, 3 = 72.2%, 4 = 67.8%), $F(2, 88) = 106.28$, $MS_e = 82.63$, $p < .01$, and number-of-segments-per-frame (2 = 79.4%, 3 = 72.8%, 4 = 63.8%), $F(2, 88) = 29.18$, $MS_e = 84.09$, $p < .01$, were both significant. Of greater interest are the interactions between age and number-of-frames and between age and number-of-segments-per-frame. Both of these effects were inconsistent (i.e., age differences were greatest at intermediate levels of each variable) and rather weak, with the former not achieving the conventional level of significance, $F(2, 88) = 2.69$, $MS_e = 82.63$, $p = .07$, and the latter just achieving that criterion, $F(2, 88) = 3.74$, $MS_e = 84.09$, $p < .05$. None of the other interactions involving the age variable approached significance (all *F*s < 1.0).

Because the number-of-frames and number-of-segments-per-frame variables were manipulated factorially in the current experiment, both were confounded with the total number of segments in the composite stimulus. It is therefore possible that the most important determinant of performance in the task was a variable that was only indirectly related to the experimental manipulations. This possibility was investigated by examining accuracy as a function of the product of the number-of-frames and number-of-segments-per-frame variables, that is, the number of segments in the composite stimulus. Means from each age group at each level of this new variable are displayed in Figure 1, along with the regression lines derived from those means.

In order to evaluate the apparent parallelism of the regression lines in Figure 1, least squares linear regression equations were fit to the data of each participant, and Age × Ability ANOVAS were conducted on the resulting slope parameters. None of the effects in this analysis were statistically significant (all *F* ratios were less than 1.0). The means and standard deviations of the slopes, in units of percentage correct per segment, were −2.07 and 0.71 for young adults, and −1.92 and 1.22 for older adults. The nearly parallel performance declines with increases in the number of segments in the composite stimulus apparent in Figure 1 and, implied by the absence of significant age differences in the slope of the linear regression equations, replicates the pattern reported in Experiment 3 of Salthouse (1987).

Performance in the single-frame trials was examined in an Age × Ability × Retention Interval ANOVA. Only the age (young = 88.4%, old = 83.8%), $F(1, 44) = 6.64$, $MS_e = 119.34$, $p < .05$, and ability, (high = 88.1%, low = 83.7%), $F(1, 44) = 6.00$, $MS_e = 119.34$, $p < .05$, effects were significant. The retention interval effect just failed to achieve significance, (1.0 s = 88.6%, 2.6 s = 85.0%, and 4.2 s = 84.1%), $F(2, 88) = 2.92$, $MS_e = 74.25$, $p = .06$, but the Age × Retention Interval interaction was far from significant ($F < 1.0$). The lack of an interaction between age and retention interval is inconsistent with the hypothesis that older individuals lose line-segment information more rapidly than young individuals when no further processing is required during the retention interval.

Experiment 2

The purpose of Experiment 2 was to examine possible interactive effects between age and both the number of to-be-integrated frames and the total number of segments in the composite figure when neither of the latter variables was confounded with another variable. The experimental design was also modified in an attempt to make the task less confusing to the research participants than that of Experiment 1. In contrast to the previous experiment, in which a large mixture of trial types were presented within each block (i.e., the factorial combination of two, three, or four frames with two, three, or four segments per frame, plus single-frame presentations of nine-segment stimuli with one of three retention intervals), the present experiment involved homogeneous blocks of either one-frame or three-frame presentations. Within a given block of trials, the number of segments in the composite stimulus ranged from 3 to 15, but those segments were always distributed across the same number of frames (i.e., either one or three).

Method

Each participant performed in 400 experimental trials, arranged in eight blocks of 50 trials each, preceded by an instructional sequence of practice trials. A total of 10 trials each (5 same and 5 different) within each block had 3, 6, 9, 12, or 15 line segments in the composite stimulus. The first two and last two blocks in the session involved single-frame presentations of the target stimuli, and the target stimuli were equally distributed across three frames (i.e., either 1, 2, 3, 4, or 5 segments per frame) in Blocks 3–6.

Results and Discussion

Performance was represented as the percentage of correct decisions across the relevant trials in each experimental condition. Means for the young and old adults in each condition are displayed in Figure 2. The major analysis conducted on these data was an Age (young, old) × Ability (high, low) × Number-of-Frames (1 or 3) × Number-of-Segments-in-the-Composite-Stimulus (3, 6, 9, 12, or 15) ANOVA. All main effects were statistically significant in this analysis: age (young = 87.3%, old = 82.7%), $F(1, 44) = 21.07$, $MS_e = 124.47$, $p < .01$; ability (high = 87.1%, low = 83.2%), $F(1, 44) = 14.34$, $MS_e = 124.47$, $p < .01$; number-of-frames (1 = 93.7%, 3 = 76.3%), $F(1, 44) = 455.97$,

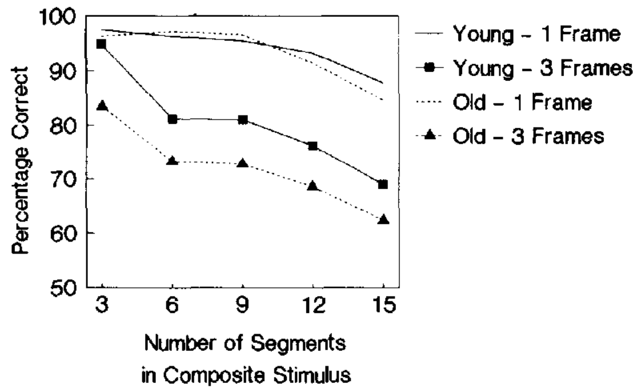


Figure 2. Mean percentage correct for young and old adults as a function of number of frames and number of segments in the composite stimulus in Experiment 2.

$MS_e = 77.01$, $p < .01$; and number-of-segments-in-the-composite-stimulus (3 = 93.0%, 6 = 87.0%, 9 = 86.5%, 12 = 82.4%, and 15 = 75.9%), $F(4, 176) = 136.02$, $MS_e = 27.81$, $p < .01$. Of the interactions involving age, only that between age and number-of-frames was significant, $F(1, 44) = 21.68$, $MS_e = 77.01$, $p < .01$.

Several aspects of these data are particularly noteworthy. The first is that the significant Age × Ability interaction reported in Experiment 1 was not replicated in this sample. A pattern similar to that of the previous experiment was evident as the age difference in average accuracy was 5.8% in the high-ability group (young = 90.0%, old = 84.2%), compared with 3.6% in the low-ability group (young = 85.0%, old = 81.4%), but the interaction failed to reach significance, $F(1, 44) = 1.14$, $MS_e = 124.47$, $p > .25$.

A second noteworthy aspect of the current results is that the interaction of Age × Number-of-Frames was significant (see above), but the interaction of Age × Number-of-Segments-in-the-Composite-Stimulus was not significant ($F < 1.0$). Both of these findings are consistent with earlier results in that the tendency for age differences to increase with an increase in the number of frames that must be integrated was reported in Experiments 1 and 2 of Salthouse (1987), and parallel effects in young and older adults of the number of segments in the composite stimulus were reported in Experiment 3 of Salthouse (1987) and in Experiment 1 of this article. Although the obvious measurement ceiling in the one-frame condition makes it impossible to determine whether the absence of performance differences between young and older adults would remain if the range of variation were not restricted, the results clearly indicate that substantial age differences are evident when the components of the target stimulus are distributed across three discrete frames.

Figure 2 indicates that the effects of increases in the total number of segments in the composite figure were nearly parallel for young and old adults. An Age × Ability ANOVA on the slope parameters from the linear regression equations for each participant in the one-frame and three-frame conditions confirmed this impression. The only significant effect was number-of-frames, $F(1, 44) = 48.30$, $MS_e = 0.42$, $p < .01$, and no effects were significant in separate analyses of the data from one-frame and three-frame conditions (all Fs < 1.90, $p > .15$). Means and standard deviations of the slope values, in units of percentage correct per segment, were as follows: one frame, −0.74 and 0.60 for young adults, and −0.97 and 0.53 for older adults; three frames, −1.89 and 0.63 for young adults, and −1.65 and 0.85 for older adults.

Experiment 3

The results of Experiments 1 and 2, and those of Salthouse (1987), can be summarized as follows. First, there appears to be little or no difference between young and older adults in their sensitivity to the total number of segments in the composite stimulus. This is evident in the nearly parallel functions relating decision accuracy to total number of segments in (a) Experiment 3 of Salthouse (1987), involving a range of 4 to 12 segments across two frames; (b) Experiment 1 of the present project involving a range of 4 to 16 segments across two, three, or four frames; and (c) Experiment 2 of the present project involving a range of 3 to 15 segments in either one or three frames. However, pronounced differences favoring younger adults are evident when the relevant information is presented across multiple frames and some type of synthesis or integration is presumably required to form the composite stimulus. Among the evidence supporting this inference are the main effects of age in all of the analyses involving multiple-frame synthesis tasks and, particularly, the statistically significant interactions of Age × Number-of-Frames in the previous experiment and in Experiments 1 and 2 of Salthouse (1987).

In the terminology introduced earlier, these results suggest that there are small to nonexistent age differences in what has been referred to as *structural capacity*, but rather substantial differences in what has been designated *operational capacity*. Still unresolved, however, are the reasons for the age differences in operational capacity. Because synthesis operations will be unsuccessful if not all of the relevant information is available when an integrated composite is formed, one plausible source of the age differences is an age-related difficulty in remembering spatial information. This interpretation may seem unlikely because the absence of a significant interaction of Age × Retention Interval in Experiment 1 of the current project suggests that the poorer performance of older adults in multiple-frame conditions is apparently not attributable to a faster rate of forgetting the relevant information on the part of older adults compared with young adults. However, it is conceivable that age differences in synthesis tasks originate not because of a faster decay of information in the absence of additional processing, but rather are attributable to a greater loss of early information during the processing of later information. That is, the memory test in Experiment 1 involved a single-frame presentation of nine-segment stimuli with no further activity until the presentation of the comparison stimulus. In the synthesis task, on the other hand, the information from the early frames must be preserved while information from later frames is being processed, and thus it is possible that later processing somehow interferes with retention of information presented earlier.

The present experiment used a procedure designed to investigate this interference interpretation of the age differences hypothesized to exist in operational capacity. The procedure involves the presentation of nine-segment stimuli across three frames of three segments each, and then presenting a mixture of nine-segment and three-segment comparison stimuli. When the comparison stimulus consists of nine segments, the task is identical to the synthesis task used in the previous experiments. However, when the comparison stimulus contains only three segments, the participant is instructed to decide whether that fragment was a part of the composite stimulus. If information from early frames is lost during the processing of information from later frames, then recognition accuracy for material presented in the first and second frames should be poorer than that for material presented in the third frame. Moreover, if a greater susceptibility to this type of interference is responsible for the poorer performance of older adults in multiple-frame synthesis tasks, then this effect should be greater among older adults than among young adults.

Method

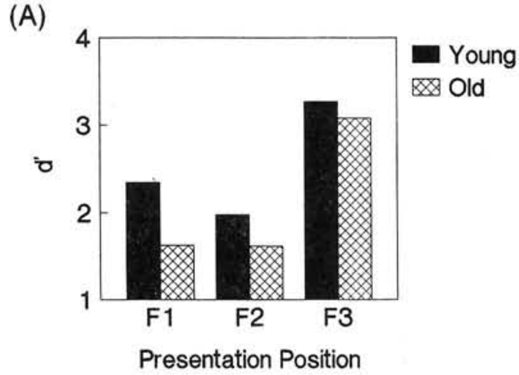
Each participant, after a short set of practice trials, performed in six experimental blocks of 40 trials each. Within each block, 16 trials consisted of a nine-segment comparison (8 same and 8 different) and 24 trials consisted of a three-segment comparison (12 same and 12 different). The line segments in the three-segment comparisons were identical to those presented in either the first, second, or third frame for each of four of the same trials within each block.

Results and Discussion

The initial analysis of the data examined the effects of age and ability on the percentage of correct decisions when nine-segment stimuli were presented in three frames of three segments each. Both main effects were significant: age (young = 73.4%, old = 66.5%), $F(1, 44) = 17.04$, $MS_e = 332.8$, $p < .01$, and ability (high = 77.9%, low = 62.0%), $F(1, 44) = 90.29$, $MS_e = 332.8$, $p < .01$. The Age × Ability interaction was not significant ($F < 1.0$), despite a tendency for age differences to be greater in the high-ability group (young = 82.1%, old = 73.6%) than in the low-ability group (young = 64.7%, old = 59.4%).

Recognition accuracy with three-segment comparison stimuli was analyzed in terms of the d' measure of discriminability by using the percentage of same responses to the 72 different three-segment comparisons as an estimate of the common false-alarm rate, and using the percentage of same responses to the 24 same three-segment comparisons from a given frame as the estimate of the hit rate for that frame. The resulting d' values were then subjected to an Age (young, old) × Ability (high, low) × Frame (first, second, or third) ANOVA. The age effect was not significant (young = 2.05, old = 1.77), $F(1, 44) = 3.57$, $MS_e = 0.81$, $p = .07$, but both the ability (high = 2.33, low = 1.49), $F(1, 44) = 31.38$, $MS_e = 0.81$, $p < .01$, and frame (1 = 1.69, 2 = 1.54, 3 = 2.51), $F(2, 88) = 67.90$, $MS_e = 0.20$, $p < .01$, effects were significant. The Age × Ability interaction was not significant, $F(1, 44) = 2.12$, $MS_e = 0.81$, $p = .15$, although the differences between young and old adults were slightly greater in the high-ability group (young = 2.58, old = 2.08) than in the low-ability group (young = 1.52, old = 1.46).

The significant triple interaction of Age × Ability × Frame,



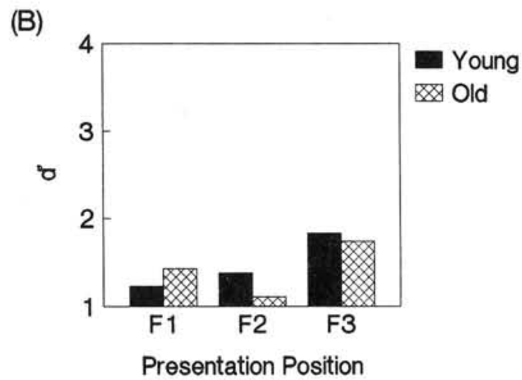


Figure 3. Mean d' in each frame for high-ability (A) and low-ability (B) individuals in Experiment 3.

$F(2, 88) = 4.93$, $MS_e = 0.20$, $p < .01$, is particularly interesting because it indicates that the Age × Frame interaction varies with the ability level of the participants. Figure 3 illustrates that only among the high-ability individuals do the older adults exhibit greater loss of information from early frames than young adults.

Age × Frame ANOVAs within each ability level confirmed the trends apparent in Figure 3. Among the high-ability individuals, the young adults had significantly greater discriminability than the older adults, $F(1, 22) = 6.77$, $MS_e = 0.67$, $p < .05$, but a significant Age × Frame interaction, $F(2, 44) = 3.78$, $MS_e = 0.17$, $p < .05$, indicated that the magnitude of these differences varied with the frame in which the segments were initially presented. Bonferroni t tests on the differences in each frame indicated that the difference at Frame 1 was significant, that at Frame 2 approached significance, but that at Frame 3 was far short of significance.

In contrast to the significant patterns evident in the high-ability individuals, there were no significant effects of either age ($F < 1.0$) or Age × Frame, $F(2, 44) = 1.78$, $MS_e = 0.23$, $p > .18$, in the data from low-ability subjects. None of the Bonferroni t tests on differences at individual frames were close to significant.

The results just described indicate that the predicted pattern was evident only in the better performing members of both age groups. In this subset of the total sample, the age differences in recognition accuracy for three-segment comparison stimuli were greater when the segments were presented in earlier frames than when presented in the latest, or most recent, frame. As noted earlier, this pattern is consistent with the idea that older individuals are more likely to have lost the relevant information by the time the comparison stimulus is presented, and thus memory factors seem to be implicated in at least some of the age differences in synthesis tasks.

Experiment 4

The results relevant to the prediction that older adults compared with young adults experience a greater loss of earlier information during the processing of later information were not definitive in Experiment 3 because the predicted pattern only held for the better performing individuals in each age group. In an attempt to provide more conclusive support for the predictions, the design of the previous experiment was repeated with an increase in the number of trials in the most relevant conditions.

Because at least some of the results from Experiment 3 suggest that working-memory factors might play an important role in synthesis tasks, all of the participants in the current experiment were also administered a task designed to assess the individual's working-memory capacity. To the extent that the synthesis task requires the involvement of some type of working memory, performance in the synthesis task should be correlated with an estimate of working-memory capacity.

Method

After a short set of practice trials, each participant performed in six blocks of 54 trials each. All trials had three frames of three segments each, with 18 trials (12 same and 6 different) containing a nine-segment comparison stimulus, and 36 trials (24 same and 12 different) containing a three-segment comparison stimulus. In each block, 8 of the same trials with three-segment comparison stimuli contained segments identical to those presented in the first frame, 8 had segments identical to those in the second frame, and 8 had segments identical to those presented in the third frame.

The Computational Span task used to assess working-memory capacity was a modification of a task used by Salthouse (1988b) and Salthouse and Prill (1987), and described more fully in Salthouse, Mitchell, Skovronek, and Babcock (in press). The task consists of the presentation of a series of arithmetic problems, with the research participant instructed to answer the problem while simultaneously remembering the second, highlighted, digit from each problem. The number of problems presented on a trial is increased when the previous attempt at recalling the target digits was correct, and is decreased when the previous recall attempt was unsuccessful. Two independent sequences of problems were presented, one starting with nine problems and the other starting with two problems. The individual's span corresponded to the average of the number of problems in the two sequences when they converged to within two problems of one another for six consecutive trials.

Results and Discussion

The initial analysis of the data examined the effects of age and ability on the percentage of correct decisions when nine-segment stimuli were presented in three frames of three seg-

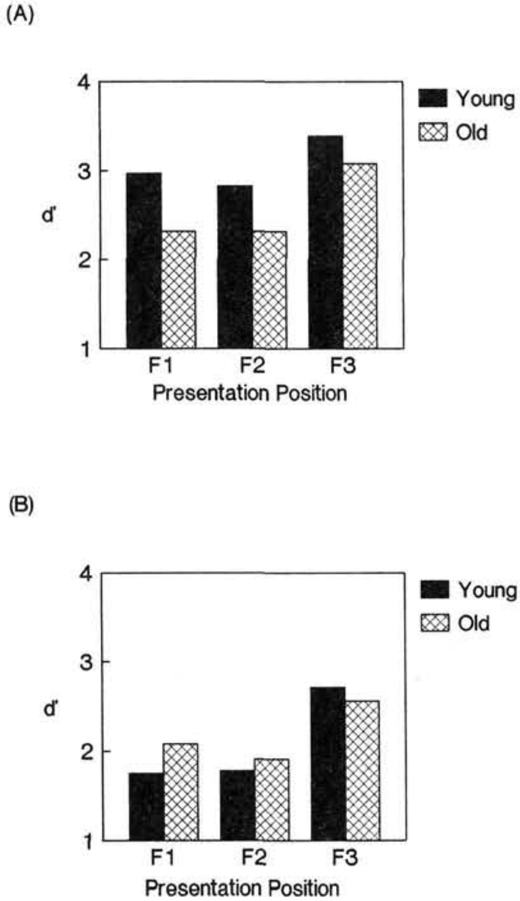


Figure 4. Mean d' in each frame for high-ability (A) and low-ability (B) individuals in Experiment 4.

ments each. The main effects of age (young = 76.9%, old = 71.3%), $F(1, 44) = 16.07$, $MS_e = 234.2$, $p < .01$, and ability (high = 79.0%, low = 67.9%), $F(1, 44) = 62.17$, $MS_e = 234.2$, $p < .01$, were significant, but their interaction was not ($F < 1.0$). The means of young and older adults in the high-ability group were 81.9% and 76.1%, respectively, whereas those in the low-ability group were 71.0% and 64.7%, respectively.

As in Experiment 3, recognition accuracy with the three-segment comparison stimuli was assessed in terms of the d' measure of discriminability by using the percentage of same responses to the 72 different three-segment comparisons as the estimate of the common false-alarm rate, and using the percentage of same responses to the 48 same three-segment comparisons from each frame as the relevant hit rate. An Age (young, old) × Ability (high, low) × Frame (first, second, or third) ANOVA revealed that the age effect was not significant (young = 2.61, old = 2.41), $F(1, 44) = 1.15$, $MS_e = 1.15$, $p > .25$, but that the ability (high = 2.82, low = 2.13), $F(1, 44) = 14.56$, $MS_e = 1.15$, $p < .01$, and frame (1 = 2.32, 2 = 2.25, 3 = 2.97), $F(2, 88) = 89.65$, $MS_e = 0.08$, $p < .01$, effects were significant. The Age × Ability interaction was not significant, $F(1, 44) = 2.73$, $MS_e = 1.15$, $p > .10$, although the slight young adult advantage in the high-ability group (young = 3.06, old = 2.57) was completely absent in the low-ability group (young = 2.08, old = 2.18). The Age × Frame interaction was not significant ($F < 1.0$), but the triple interaction of Age × Ability × Frame was significant, $F(2, 88) = 6.13$, $MS_e = 0.08$, $p < .01$.

The significant Age × Ability × Frame interaction appears similar to that found in Experiment 3, but a more detailed examination reveals that it has a somewhat different composition than that of the previous experiment. Separate Age by Frame ANOVAs on the data from each ability group revealed that the Age × Frame interaction was statistically significant for the low-ability group, $F(2, 38) = 3.60$, $MS_e = 0.09$, $p < .05$, but was not significant for the high-ability group, $F(2, 50) = 2.51$, $MS_e = 0.08$, $p = .09$. Inspection of the means for the high-ability and low-ability individuals in each age group, illustrated in Figure 4, reveals that the interaction in the low-ability group is attributable to a reversal of the age differences across frame positions because the young adults were slightly superior to the older adults in Frame 3, but were slightly inferior in Frames 1 and 2. However, none of the differences at any frame were statistically significant by Bonferroni t tests. Although the Age × Frame interaction with the high-ability individuals failed to achieve an acceptable significance level, Bonferroni t tests revealed that the young adults had significantly greater performance than the older adults in Frames 1 and 2, but not in Frame 3. Note that this is the same pattern of results reported for the high-ability group in Experiment 3.

Mean computational spans averaged 6.33 (SD = 1.44) for young adults and 5.18 (SD = 0.97) for older adults, $t(46) = 3.26$, $p < .01$. Correlations between the computational span measure and d's from each frame are illustrated in Table 2. Notice that all of the correlations are positive and that those for the first frame are significantly greater than zero for both young and old adults. This finding is consistent with the view that poor performance in early frames is attributable to reduced working-memory capacity.

General Discussion

The results of the current experiments replicate and extend the evidence that led to the proposed distinction between structural and operational capacity (Salthouse, 1987). The reliable absence of age differences in sensitivity to the number of segments in the composite stimulus (Experiments 1 and 2) suggests that structural capacity, defined as the number of discrete informational units that can be remembered in the absence of interfering activity, is largely invariant across the range of about 20 to 70 years. However, pronounced age differences are evident

Table 2
Correlations Between Computational Span and d' at Each Frame in Experiment 4

	Frame		
Subjects	1	2	3
Young	.46*	.52*	.39
Older	.45*	.32	.22

* $p < .05$. ** $p < .01$.

when the information must be integrated across successive frames, as indicated by the significant age effects in the percentage correct measure for multiple-frame presentations in all experiments. These latter performance differences can be attributed to age-related differences in operational capacity because it is defined as the ability to preserve the products of earlier processing during the execution of later processing operations.

Attempts to identify the locus of problems in operational capacity were only moderately successful. The failure to find a significant interaction between age and retention interval with one-frame stimuli in Experiment 1 is inconsistent with the hypothesis that spatial information decays at a faster rate for older adults than for young adults. The findings in Experiments 3 and 4 that age differences in the accuracy of recognizing previously presented information were significant when the material was originally presented in the first frame, but not when it was presented in the third frame, suggests that older adults may suffer more interference during the presentation of later information than do young adults. However, this conclusion must be considered quite tentative because these trends were only apparent in the data of the high-ability groups at each age, and we have no explanation for why they were not also present in the low-ability groups.

A linkage between the operational capacity construct inferred in these synthesis tasks and the concept of working memory was established by the discovery in Experiment 4 of positive correlations between recognition accuracy for previously presented stimulus fragments and the Computational Span measure of working memory. The tendency for the correlations to be larger in earlier frames, in which information must be retained during later processing, is also consistent with the idea that successful synthesis performance depends on the size or efficiency of the individual's working memory.

A general conclusion of this research is that the distinction between structural and operational capacity is meaningful and that the former is not related to age in adulthood, whereas the latter decreases across the adult years. These results therefore lead to the prediction that tasks dependent on the formation and maintenance of internal representations will not exhibit age-related differences as the quantity or amount of information in a single representational unit is varied, but that moderate to substantial age differences will be evident when the task requires the maintenance of earlier information in an internal representation during the processing of later information.

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