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Main project #:

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SALTHOUSE T A PSYCH (404)894-6069

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Title: EFFECTS OF AGE ON SPATIAL ABILITIES AMONG ENGINEERS

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PROJECT ADMINISTRATION DATA

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Administrative comments -
THIS IS YEAR 3 OF A 5 YEAR GRANT.

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

SP 522

Closeout Notice Date 08/28/90

Project No. G-42-642 Center No. 10/24-6-R6328-2A0

Project Director SALTHOUSE T A School/Lab PSYCHOLOGY

Sponsor DHHS/PHS/NIH/NATL INSTITUTES OF HEALTH

Contract/Grant No. 5 R01 AG06858-03 Contract Entity GTRC

Prime Contract No. ______

Title EFFECTS OF AGE ON SPATIAL ABILITIES AMONG ENGINEERS

Effective Completion Date 900531 (Performance) 900831 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	
Final Report of Inventions and/or Subcontracts	Y	
Government Property Inventory & Related Certificate	N	
Classified Material Certificate	N	
Release and Assignment	N	
Other ______	N	

Comments ______

Subproject Under Main Project No. ______

Continues Project No. ______

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Managment	Y
Research Security Services	N
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GTRC	Y
Project File	Y
Other ______	N
______	N

NOTE: Final Patent Questionnaire sent to PDPI.

Final Report

National Institute on Aging Grant AG06858

"Effects of Age on Spatial Abilities Among Engineers"

Timothy A. Salthouse

Previous research has indicated that increased age is associated with lower levels of performance on a variety of measures of cognitive functioning. This negative relation between age and cognitive functioning might imply declining levels of professional competence if abilities relevant to one's occupational competence become impaired with increased age. A general purpose of the research conducted with support from this grant was to explore the potentially interactive effects of age and experience that might allow certain aspects of cognitive functioning to be preserved or even enhanced into late adulthood. The primary focus was on the cognitive ability of spatial visualization because it was assumed to be relevant to the occupational activities of many engineers and architects.

Three major projects were conducted, as well as a number of smaller studies. The initial project consisted of a rather broad assessment of spatial visualization abilities with a battery of paper-and-pencil tests and computer-controlled tasks. College students participated in the first two studies in this project in an attempt to investigate the nature of spatial visualization ability. Results of these studies have recently been published in an article in INTELLIGENCE.

Samples of 10 older architects and 10 unselected older adults were then administered the entire 5-session battery, and their performance compared both with each other, and with the larger sample of young adults. Both groups of older adults performed at lower levels than the young adults on most of the measures, but the architects performed better than the non-architects on many of the measures. Two hypotheses were considered to account for these results. The "differential preservation" interpretation was that the architects performed better than the non-architects because their spatial abilities had been preserved through continuous use, whereas the spatial abilities of non-architects had declined or atrophied from lack of exercise. The "preserved differentiation" view, on the other hand, maintained that the differences between architects and non-architects had existed at least since early adulthood, and that these initial differences were simply preserved across the adult years.

An additional study conducted to attempt to distinguish between the differential preservation and preserved differentation hypotheses consisted of examining age trends on measures of spatial ability among practicing architects. The reasoning was that if continuous use preserves abilities at high levels, then these individuals, who can be presumed to be using spatial abilities on a daily basis, should exhibit little or no age-related decline on relevant measures of spatial ability. However, results from this study revealed that the age relations for several measures of spatial ability were nearly identical for architects and non-architects. The major conclusion from this project, therefore, was that one's level of ability probably influences the choice of the occupation or activities in which one engages (thereby accounting for the superiority of architects over non-architects), but that extensive experience seems to have little effect on the relations between age and performance on certain cognitive measures. A report of this project was recently published in DEVELOPMENTAL PSYCHOLOGY.

The second project focused on the criterion task of interpreting orthographic drawings of three-dimensional objects. Several pilot studies were conducted, including a survey of instructors of engineering graphics courses across the United States. Information obtained from these early studies suggested that the criterion task could be analyzed into three distinct components, corresponding to determining how the object would look from a different perspective, preserving information from one transformation while carrying out another transformation, and assembling the different pieces of information into a three-dimensional representation.

New experimental tasks were devised to assess each hypothesized component, and then computer programs were written so that all tasks could be administered on a microcomputer. This battery of computer-controlled tasks was administered to two groups of research participants. One group consisted of 121 college students who performed six paper-and-pencil cognitive tests in addition to the experimental tasks. Of primary interest in the analyses of the data from this group was the feasibility of the tasks, and the reliability and pattern of intercorrelations of the measures. All of the tasks were found to yield measures with moderate reliability, and the measures loaded on established cognitive factors of spatial visualization and inductive reasoning but not on a perceptual speed factor.

The second, and primary, group in the project consisted of 132 adults with a wide range of age and experience. Many of these individuals were recruited from a pool of engineering alumni of Georgia Institute of Technology. Statistically significant age-related declines were found in either the time or accuracy of the decisions in each task. Of greatest importance, however, were the analyses examining the mediating or moderating effects of self-reported experience on the age relations with the spatial ability measures. In none of these analyses was there any evidence that the age trends were either mediated or moderated by the amount of experience the individuals reported with relevant activities. Additional analyses are still in progress, and a manuscript summarizing the results of this project is currently in preparation.

The third project conducted during the period of the research grant involved an alternative approach to the investigation of the interrelations among age, experience, and spatial visualization ability. One motivation for this new approach was the difficulty experienced in the other projects in attempting to recruit participants from specific occupational groups. To illustrate, letters were sent to 1,100 members of the AIA professional organization of architects in the Atlanta area for the first project, and letters were sent to approximately 1,800 Georgia Tech alumni with Mechanical Engineering degrees for the second project, and yet each appeal only resulted in about 50 volunteers from the target groups.

The strategy employed in this project was to recruit a relatively large (n=383) sample of participants from the general population via newspaper advertisements, and to ask questions about each individual's experience with selected activities presumed to require spatial abilities (e.g., imagining different arrangements of furniture or other objects, producing or interpreting technical drawings of three-dimensional objects). Responses to these questions were then used as the basis for categorizing the research participants according to the amount of experience they had received with activities hypothesized to require spatial abilities. Each participant's spatial visualization ability was assessed by means of paper-and-pencil tests (i.e., Surface Development and Paper Folding).

The major results from this project were that people reporting more experience with spatial activities performed at higher levels on the spatial tests than people reporting less experience, but that the pattern of age-related declines was nearly identical regardless of amount of experience. These findings were interpreted as being consistent with the preserved differentiation hypothesis in that one's level of ability in young adulthood might have influenced the choice of activities in which one participated throughout the adult years, but that experience with those activities seems to have relatively little effect on the direction or the magnitude of the age-related effects on measures of relevant abilities. A report of this project is currently in press in DEVELOPMENTAL PSYCHOLOGY.

General conclusions from these three projects are that there appears to be relatively little effect of experience as either a mediator, or a moderator, of the negative relations between age and efficiency of basic cognitive processes. These findings are of considerable theoretical importance because they suggest that disuse interpretations based on experiential factors may be inadequate to account for adult age differences in certain measures of cognitive functioning.

The practical importance of the research is still not known, however, because all of the research has concentrated on simple measures of cognitive functioning that are unlikely to be affected by increased knowledge associated with cumulative experience. Substantial contributions of experience could occur with more complex aspects of cognition, however, and consequently it cannot be concluded on the basis of the research reported above that older, and more experienced, individuals are any less competent in their daily or occupational lives than young individuals. Research addressing the interrelations of age, experience, and knowledge on complex cognitive tasks is needed before specific practical implications of this and earlier research can be identified.

Publications

Salthouse, T.A., Babcock, R.L., Mitchell, D.R.D., Palmon, R. & Skovronek, E. (in press) Sources of individual differences in spatial visualization ability. Intelligence, 14, 187-230.

Salthouse, T.A., Babcock, R.L., Skovronek, E., Mitchell, D.R.D., & Palmon, R. (1990) Age and experience effects in spatial visualization. Developmental Psychology, 26, 128-136.

Salthouse, T.A. & Mitchell, D.R.D. (in press) Effects of age and naturally occurring experience on spatial visualization performance. Developmental Psychology.

Salthouse, T.A. (in press) Influence of experience on age differences in cognitive functioning. Human Factors.

INTELLIGENCE **14**, 187–230 (1990)

Sources of Individual Differences in Spatial Visualization Ability

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Two experiments are reported in which different batteries of specially designed spatial tasks were administered to male college students. The subjects were selected to be either high or relatively low in spatial visualization ability as assessed by performance on four paper-and-pencil tests (Paper Folding, Surface Development, Form Board, and Cube Comparisons). Three hypotheses proposed to account for individual differences in spatial visualization ability were investigated. These hypotheses attribute differences in spatial visualization ability to variations in: (a) representational quality, (b) transformational efficiency, and (c) preservation of representations during transformations. The failure to find differences related to spatial visualization ability in the accuracy of recognition memory decisions and in the speed of transformations is inconsistent with the first two hypotheses. The evidence was somewhat mixed with respect to the preservation-under-transformation hypothesis, but it does appear that spatial visualization differences are most pronounced when some information must be preserved while the same or other information is being processed.

Spatial visualization is one of several correlated spatial abilities concerned with the encoding, transformation, and recognition of spatial information. Michael, Zimmerman, and Guilford (1950) suggested that spatial visualization ability is required:

> In the solution of problems in which the individual finds it necessary mentally to move, rotate, turn, twist, or invert one or more objects. Following the performance of the presented manipulation the individual is required to recognize the new position, location, or changed appearance of the object or objects (pp. 190–191).

Spatial visualization is similar to, but distinct, in factor analytic studies (e.g., Michael et al., 1950; Michael, Zimmerman, & Guilford, 1951), from the abili-

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ties of spatial relations and inductive reasoning, and Zimmerman (1954) has proposed that spatial visualization ability is intermediate along a difficulty or complexity continuum between spatial relations and reasoning. The primary distinction between tasks assessing spatial relations and those assessing spatial visualization is that the former typically require identity judgments about relatively simple stimuli after a mental rotation of one of the stimuli, whereas the latter involve the mental manipulation of entire spatial configurations, often by changing the relation of elements to one another. Other bases for distinguishing between these two types of spatial abilities are that visualization items involve more stimulus elements or require a greater number of processing operations, and frequently take more time to answer, than spatial relations items (e.g., Barratt, 1953; Just & Carpenter, 1985; Lohman, 1979, 1988; Lohman & Kyllonen, 1983; Lohman, Pellegrino, Alderton, & Regian, 1987; Michael et al., 1950; Michael, Guilford, Fruchter, & Zimmerman, 1957; Mumaw & Pellegrino, 1984; Pellegrino, Alderton, & Shute, 1984; Pellegrino & Kail, 1982; Pellegrino, Mumaw, & Shute, 1985).

The most common tests of spatial visualization are the Paper Folding, Surface Development, and Form Board Tests. These three tests were identified by Ekstrom, French, Harman, and Dermen (1976) as the principal markers of the Spatial Visualization factor, and either together or in isolation have been included in several test batteries used to assess spatial visualization (e.g., Kyllonen, Lohman, & Woltz, 1984; Lansman, 1981; Lansman, Donaldson, Hunt, & Yantis, 1982; Michael et al., 1950; Michael et al., 1951).

In the Paper Folding Test the examinee is instructed to imagine that a piece of paper has been folded in the manner illustrated, and a hole punched in the position indicated by a circle. The task is to decide which of five figures corresponds to the locations of the punched holes in the unfolded paper. The Surface Development Test requires the examinee to imagine how a piece of paper could be folded to form a three-dimensional object, and then to determine the correspondence between numbers in the flat surface and letters in the assembled object. The task in the Form Board Test is to decide which of five shaded pieces will combine to produce a complete polygon.

Another test sometimes considered to assess spatial visualization ability is the Cube Comparisons Test. This test requires the examinee to decide whether two isometric drawings of cubes could represent the same cube. The status of the Cube Comparisons Test as a measure of spatial visualization is somewhat controversial because it is occasionally (e.g., Ekstrom et al., 1976) classified together with mental rotation tests of spatial relations, rather than with other tests of spatial visualization. It has been suggested (e.g., French, 1965; Michael et al., 1950) that the particular spatial abilities required by the Cube Comparisons Test depend on the strategy used by the subject in performing the task. In support of this suggestion is the finding by French (1965) that the loading of Cube Comparisons performance on the spatial visualization factor was high when subjects reported that the cubes were compared by rotating one or both of the cubes, but that it was low when subjects reported that their decisions were based on an analysis of the relations among letters in the two cubes. Regardless of the reasons for the inconsistency in factor assignment, however, several investigators have reported that scores on the Cube Comparisons Test correlate about as highly with scores on tests of spatial visualization as the scores on those tests correlate with themselves (e.g., Borich & Bauman, 1972; Just & Carpenter, 1985; Karlins, Schuerhoff, & Kaplan, 1969; Lansman et al., 1982; Michael et al., 1950; Michael et al., 1951). There is, thus, some justification for assuming that performance on the Cube Comparisons Test is determined by spatial visualization abilities.

In the interest of obtaining as broad an assessment of the construct of spatial visualization as possible, spatial visualization ability was measured in the present studies in terms of an individual's performance on the four tests just described. The primary question addressed in this article is what is responsible for the individual differences in spatial visualization ability? That is, what processing factors serve to differentiate people who vary in their performance on these tests of spatial visualization?

Although sharing some similarities with the componential analysis research strategy (e.g., Pellegrino & Lyon, 1979; Sternberg, 1977), the analytical approach employed in the current studies does not involve the construction, or attempted verification, of detailed processing models for specific tasks. Instead the focus is on the identification of commonalities across several tests assessing the same construct, in this case spatial visualization, with subsequent investigation of potential individual differences in these hypothesized components based on the examination of multiple dependent measures derived from a variety of separate experimental procedures. To the extent that this convergent analysis of commonalities approach is successful, it should allow inferences of greater generality than those based on attempts at modeling performance in a single test or experimental procedure.

Detailed examination of the four classification tests described above suggests that they have at least two aspects in common—each seems to require the execution of a series of mental transformations, and in each, intermediate products must be stored temporarily during the processing of other information. With respect to the first characteristic, in all of the tests, sequences of transformations appear necessary to bring different parts of the figure into congruence so that a decision can be reached. That is, the square paper must be folded, punched, and then unfolded in the Paper Folding Test, the flat surface must be folded and the folded pieces assembled in the Surface Development Test, the various form pieces must be rotated, repositioned, and integrated in the Form Board Test, and one or both cubes must be rotated such that corresponding symbols have identical orientations in the Cube Comparisons Test.

Considerable mental bookkeeping also seems to be involved in each test in that the products of early transformations must be maintained during the execution of later transformations. That is, in the Paper Folding Test the positions of the punched holes must be remembered during each new unfolding operation. The Surface Development Test requires the preservation of earlier assemblies of the folded surface while other portions of the surface are folded into position. In the Form Board Test the orientation of pieces positioned early must be remembered while subsequent pieces are rotated and repositioned into the synthesized composite, and the identity and orientation of symbols in the various cube faces have to be remembered while other faces are rotated in the Cube Comparisons Test.

The preceding task analysis suggests that individual differences in spatial visualization ability might be attributable to variations in transformation efficiency, and/or to variations in the ability to preserve spatial information during transformations. To this list can be added another somewhat more general factor which might contribute to individual differences in spatial visualization ability—quality of the encoded representation. These three hypotheses will now be elaborated, and the literature relevant to each briefly reviewed.

The representational-quality hypothesis attributes differences in spatial visualization ability to variations in the effectiveness of generating accurate and complete internal representations of spatial information (e.g., Cooper & Mumaw, 1985; Lohman, 1979; Mumaw & Pellegrino, 1984; Poltrock & Brown, 1984). The basic assumption in this perspective is that people who are high in spatial visualization ability either encode spatial information more precisely, or have a larger storage capacity for representing spatial information, than people who are low in spatial visualization ability. One version of this hypothesis was recently articulated by Lohman et al. (1987) who proposed that ". . . spatial ability may not consist so much in the ability to transform an image as in the ability to create the type of abstract, relation-preserving structure on which . . . transformations may be most easily and successfully performed (p. 274)." In another source, Lohman (1988) elaborated the hypothesis by suggesting that ". . . spatial ability is in part a facility in creating structurally rich mental representations that can be stored, retrieved, and matched as units (p. 214)."

The transformation-efficiency hypothesis of individual differences in spatial visualization focuses on variations in the efficiency of executing spatial transformations. That is, proficiency in spatial visualization is postulated to be at least partially determined by the speed with which the individual can carry out mental manipulations such as repositioning, folding, rotating, deleting, or integrating. Reports of positive correlations between spatial visualization ability and the speed of mental rotation in a variety of different tasks (e.g., Just & Carpenter, 1985; Lansman, 1981; Lansman et al., 1982; Lohman, 1988) provide some of the strongest evidence for this hypothesis. Also consistent with a relationship between spatial visualization ability and transformation efficiency is the finding by Mumaw and Pellegrino (1984) that scores on a form board test were correlated positively with the rate of locating and integrating form pieces.

Differences in the ability to preserve an accurate and complete internal representation during the transformation process are presumed to be a major determinant of variations in spatial visualization ability according to the preservation-under-transformation hypothesis. Proponents of this view have suggested that people who are high in spatial visualization ability are superior to those lower in this ability in:

1. keeping track of the representation during its transformations (Carpenter & Just, 1986; Just & Carpenter, 1985);
2. maintaining a representation after it has been rotated (Poltrock & Brown, 1984);
3. remembering the changes in the representation as the transformations are performed (Lohman, 1979);
4. comparing the representation after transformation (Mumaw & Pellegrino, 1984);
5. retaining a representation of a first stimulus while viewing a second stimulus (Lohman & Kyllonen, 1983); or
6. maintaining more detail and preserving more information during and following mental transformations (Cooper & Mumaw, 1985).

This perspective is obviously popular, but surprisingly little directly relevant evidence is available. However, findings that decision accuracy often declines as the angle of rotation increases in the mental rotation paradigm (e.g., Lansman, 1981; Lohman, 1986; Poltrock & Brown, 1984; Tapley & Bryden, 1977) can be interpreted as supporting the idea that internal representations can be degraded during the process of transformation.

Although these three hypotheses have certain similarities, and the underlying processes may frequently operate in combination, the hypothesized mechanisms are assumed to be at least conceptually distinct. In other words, it is at least conceivable that differences in the quality of an internal representation could exist independent of the efficiency with which that representation can be transformed, and the likelihood that the representation is intact after execution of the transformation might be independent of both the quality of the initial representation, and the speed with which it is transformed.

The research described in this article was designed to investigate these three hypotheses concerning the sources of individual differences in spatial visualization ability. In the first study the previously described set of paper-and-pencil tests was used to classify individuals with respect to spatial visualization ability. A battery of experimental tasks was then administered to investigate predictions derived from the various hypotheses concerning the sources of individual differences in spatial visualization ability. A new battery of experimental tasks was developed and administered to another sample of subjects in Study 2 to examine additional implications of these hypotheses.

STUDY 1[1]

This study investigated the three hypotheses proposed to account for individual differences in spatial visualization ability by manipulating an experimental variable assumed to be related to the number of spatial transformations required to perform the task. Of particular interest are interactions of spatial visualization ability and the number of hypothesized transformations, because the various hypotheses lead to different expectations concerning the pattern of results with the variables of decision time and decision accuracy. For example, only the transformation-efficiency hypothesis implies the existence of an interaction with the time variable. That is, if spatial visualization differences are at least partially determined by variations in the speed or efficiency with which individual transformations can be executed, then the magnitude of the spatial ability differences in decision time should increase as the number of required transformations increases. The preservation-under-transformation hypothesis predicts a spatial visualization ability × number-of-transformations interaction with the variable of decision accuracy. That is, increasing the number of transformations will increase the number of opportunities for the information to be lost on the part of low-spatial subjects, and therefore the decrease in decision accuracy with additional transformations should be greater for subjects of low levels of spatial visualization ability. Because some type of internal representation is presumably required regardless of the number of transformations, the simplest version of the representational-quality hypothesis predicts a main effect of spatial visualization ability on decision accuracy, (and possibly on decision time if lower-quality representations require more time for subsequent processing), but no interaction of spatial ability and number of transformations with either dependent variable. To summarize, the three hypotheses should be distinguishable because only main effects of spatial visualization ability are predicted from the representational quality hypothesis, while the other two hypotheses lead to predictions of significant ability × number-of-transformations interactions either with the variable of decision time (transformation-efficiency hypothesis), or with the variable of decision accuracy (preservation-under-transformation hypothesis).

Four of the experimental tasks resembled the criterion paper-and-pencil tests, but were implemented on a computer to allow dynamic or interactive displays and precise timing. The experimental task designed to resemble the Paper Folding Test consisted of displays of a rectangle undergoing successive folds, followed by a portrayal of a hole being punched through the folded surface. This was then followed by the target display consisting of a pattern of holes in the complete (unfolded) rectangle, with the subject instructed to determine whether that pattern of holes could have resulted from the prior sequence of folds and

[1]Because most of the statistical comparisons are based on relatively small sample sizes, an alpha level of .05 was used in evaluating statistical significance. However, it should be noted that only a few of the significant comparisons would not have been significant with a criterion of .01, and thus the overall conclusions are not dependent upon the particular significance level adopted.

punch location. Because folding seemed to be the major spatial transformation required in this task, the manipulated experimental variable was the number of folds presented prior to the simulated punching of the hole.

The task designed to resemble the Surface Development Test was an adaptation of a cube folding task developed by Shepard and Feng (1972). The displays in this task consisted of six connected squares, with one of the squares shaded to represent the base, and two of the squares containing outward-pointing arrows. The task for the subject was to mentally fold the squares into a cube, and then to determine whether the tips of the two arrows would be touching in the assembled cube. Following Shepard and Feng (1972), the primary manipulation in this task was the number of folds required to assemble the cube to a stage where the squares containing the arrows were at right angles to one another.

The Cube Comparisons Test was examined experimentally with simultaneous and successive versions of the task. The simultaneous version consisted of the same types of complete displays of the two cube configurations as in the paper-and-pencil test, but discrete presentation of the problems allowed determination of the time and accuracy of each individual item. The successive version of the task involved a display of blank faces on both to-be-compared cubes, with the subject instructed to sequentially examine the contents of as many of the faces considered necessary to reach a decision. Monitoring of the frequency and pattern of face examinations was expected to be informative about the particular strategies used in this task, and about the influence of memory limitations on task performance. The primary experimental manipulation within each version of the task was the angular discrepancy in orientation between the two cubes.

A spatial integration or synthesis task (Salthouse, 1987a; Salthouse & Mitchell, 1989) was used as the experimental analog of the Form Board Test. This task required subjects to integrate the line segments presented in successive visual displays into a unitary composite, and then to decide whether their synthesized composite matched a comparison stimulus. Because the relevant transformation seems to be spatial integration, the primary variable manipulated in this task as the number of separate frames containing segments that must be integrated to form the composite stimulus. An additional manipulation, designed specifically to investigate the preservation-under-transformation hypothesis, involved testing subjects for their memory of earlier-presented information in the context of the integration task.

Two additional tasks included in the study were the WAIS-R Block Design Test (Wechsler, 1981), and a computer-implemented version of that task developed by Salthouse (1987b). Although the WAIS-R Block Design Test was not used as one of the criterion measures of spatial visualization, primarily because it required individual rather than group administration, it also seems to require abilities of spatial visualization. The computer-implemented version of this task has been analyzed into components relating to the speed of encoding and comparing patterns, the speed of manipulating representations of three-dimensional objects, and the subject's degree of concentration, breadth of attention, and quality or completeness of the internal representation of the three-dimensional block (Salthouse, 1987b).

The final task administered in the study was designed to measure spatial working-memory capacity. A common element in two of the three hypotheses (representational-quality, and preservation-under-transformation) is reliance on some type of spatial memory, and, consequently, subjects high in spatial visualization ability might be expected to perform better in tests of spatial memory than subjects low in spatial visualization ability. Subjects in this task were required to remember the locations of discrete line segments, while also simultaneously drawing lines between specified positions.

Method

Subjects. A total of 50 male undergraduates at Georgia Institute of Technology, mean age 19.9, range 17 to 30 years, participated in the study. Compensation for the five 1.5-hour sessions consisted either of $40, credit for experimental participation in an introductory psychology course, or a combination of money and credit.

Procedure. All subjects received the tasks in the same sequence across five sessions completed with a 2-week period. The first session was devoted to the four paper-and-pencil tests and the WAIS-R Block Design Test. Session 2 involved the spatial working-memory task and the paper folding task, Session 3 the cube folding and block design tasks, Session 4 the two versions of the cube comparisons task, and Session 5 the spatial integration task. All but the standardized tests of Session 1 were administered on a computer.

The four criterion tests were from the Ekstrom et al. (1976) Kit of Cognitive Reference Tests. They were initially administered in the following order: Paper Folding, Surface Development, Cube Comparisons, and Form Board. After a short break, the WAIS-R Block Design Test was administered followed by the second part of each of the four tests in the reverse order of their original presentation. Time limits, and the total number of items in each part, of the tests were: Paper Folding—3 min, 10 items; Surface Development—6 min, 30 items; Cube Comparisons—3 min, 21 items; and Form Board—8 min, 24 items. The criterion tests were scored in terms of the number of items completed correctly in the allotted time. The WAIS-R Block Design Test was administered and scored according to the published instructions (Wechsler, 1981).

Spatial Working Memory

The spatial working-memory task consisted of successive displays of a square containing a line and two Xs. All lines and Xs were drawn within an invisible 4 × 4 matrix, with the lines connecting adjacent points in the matrix, and the Xs superimposed on points adjacent to one another in the matrix. Subjects were instructed to try to remember the location of the displayed line, while simultaneously using a mouse interfaced to the computer to draw a line connecting the two Xs. After a variable number of displays of this type, the word RECALL was presented along with a 4 × 4 matrix of small squares. This was the signal for the subject to reproduce the positions of the target lines by using the mouse to connect the appropriate squares in the matrix. The number of displays presented prior to the recall instruction and, consequently, the number of line segments to be remembered, varied according to a double random-staircase psychophysical procedure with the two sequences beginning at 1 and 4 displays. (See Salthouse, Mitchell, Skovronek, & Babcock, 1989, for further details about the procedure.) An estimate of the subject's spatial working-memory capacity was obtained by determining the longest sequence of displays correctly reproduced while also accurately drawing the lines during stimulus presentation.

Paper Folding

The paper folding task consisted of a repeatable set of three practice trials followed by six blocks of 40 trials each. The 240 experimental trials were composed of 24 trials with one fold, 48 trials with two folds, 72 trials with three folds, and 96 trials with four folds. (See Fig. 2 in Salthouse et al., 1989, for an illustration of the displays in this task.) One-half of the trials within each number-of-folds category were SAME, in that the pattern of holes matched the pattern that would have resulted from the displayed sequence of folds and punch location, and one-half were DIFFERENT in that the patterns did not match. Subjects were allowed to view the result of each fold or punch as long as desired, but were encouraged to respond as rapidly and accurately as possible to the target pattern. Pressing any key on the computer keyboard caused the next fold or punch to be displayed, and responses consisted of keypresses of the "/" key for SAME and the "Z" key for DIFFERENT. Dependent variables consisted of the inspection or study times for each successive fold, the accuracy of the decision, and the median time to make correct decisions for SAME trials.

Cube Folding

The cube folding task consisted of a repeatable set of 11 practice trials followed by six blocks of 48 trials each. Each of one, two, three, or four required folds was represented by 72 trials, with one-half SAME (i.e., patterns that would result in touching arrows), and one-half DIFFERENT (i.e., patterns that would result in noncontacting arrows). The entire stimulus configuration for a trial in this task (see Fig. 1 in Shepard & Feng, 1972, for an illustration) was displayed simultaneously, and subjects were requested to respond as rapidly and accurately as possible. As in the paper-folding task, SAME decisions were communicated by pressing the "/" key, and DIFFERENT decisions by pressing the "Z" key. Dependent variables for each number-of-folds condition were the accuracy of the decisions and the median time for correct SAME decisions.

Block Design

The block design task was identical to that described in Experiment 1 of Salthouse (1987b). It consisted of the display of an isometric representation of a three-dimensional cube, a blank response matrix, and a stimulus matrix of 9 cells, with each cell containing one of six different patterns. The task for the subject was to reproduce the stimulus matrix by using the arrow keys on the keyboard of the computer to manipulate the cube such that its front face successively matched the pattern in each cell of the stimulus matrix. Patterns from the front face of the cube were transferred to the response matrix by typing the number corresponding to the appropriate cell in the matrix. Each trial contained a different stimulus matrix, and subjects performed two practice trials followed by two blocks of 20 trials each. Dependent variables consisted of the median time required for each type of cube manipulation or pattern transfer, and the percentage of opportunities in which the most efficient sequence of manipulations was carried out to produce the target pattern on the front face of the cube.

Cube Comparisons

The computer-implemented cube comparisons task involved the subject using a hand-held mouse interfaced to the computer. Two versions of the task were presented, a simultaneous version in which all faces of both cubes were continuously visible, and a successive version in which only one face on either cube could be viewed at any given time. In both versions of the task the right button of the mouse was used to indicate that the displayed cube configurations could represent the same cube (SAME), and the left button was used to indicate that they could not represent the same cube (DIFFERENT). In the successive version of the task the subject indicated which face on either the left or right cube was to be examined by using the mouse to move a cursor within the boundaries of the desired face, and then clicking either mouse button to reveal the contents of that face. Subjects were instructed to try to be as efficient as possible in the number and duration of faces viewed, but they had complete control of the sequence of faces examined and the duration spent viewing any given face.

Six trial-type categories were distinguished by the magnitude of rotation required to bring the two cubes into correspondence, and the number of common letters in the two configurations (see Just & Carpenter, 1985, for further description and illustration). A total of 24 experimental trials were created for each category. DIFFERENT trials within each category were created by altering the identity or orientation of one of the letters from a matching configuration. Two-thirds of the trials in each trial type category were SAME or consistent cubes, and one-third were DIFFERENT or nonmatching cubes. An equal number of the six trial types were presented, with 36 trials in a single block in the simultaneous version, and three blocks of 36 trials each in the successive version. Both versions were preceded by a practice block of 4 trials. Dependent variables consisted of the accuracy of the decisions, the median time to make correct decisions for SAME trials, and the number and sequential pattern of cube faces examined in the successive version of the task.

Spatial Integration

The spatial integration task was composed of two phases preceded by a common set of 5 repeatable practice trials. In both phases the stimuli consisted of line segments connecting locations in an invisible 4 × 4 matrix. (See Salthouse, 1987a, for an illustration.) One-half of the trials were SAME trials in that the pattern resulting from the composite of the successively presented line segments matched a comparison stimulus, and one-half were DIFFERENT because two of the line segments in the comparison stimulus were altered relative to those in the composite pattern. In Phase I there were two blocks of 32 trials, with 16 trials each containing one, two, three or four frames. One of the trial blocks was presented at the beginning of the experimental session, and the other at the end of the session after the trials of Phase II. The composite stimulus in Phase I always consisted of 12 segments, and thus the number of segments in each frame was either 12 (for one-frame trials), 6 (for two-frame trials), 4 (for three-frame trials), or 3 (for four-frame trials).

Subjects were instructed to attempt to integrate the segments from the successive frames into a single composite pattern, and then to decide whether it matched the comparison stimulus. The duration spent inspecting or studying each successive frame was under the control of the subject, and the comparison stimulus followed the disappearance of the last frame by 1 s. Pressing any key on the computer keyboard caused the next frame to be displayed, and decisions were communicated by pressing the "/" key for SAME, and the "Z" key for DIFFERENT. Decisions regarding the identity of the synthesized composite and comparison patterns were to be made as rapidly and accurately as possible.

Phase II of this task, consisting of four blocks of 54 trials each, always involved the presentation of three frames each containing 3 segments. On 72 of the trials the comparison stimulus contained 9 segments, and the subject was to decide whether it matched the synthesized composite. However, in the remaining 144 trials the comparison stimulus consisted of only 3 segments, and the task was to decide whether they were identical to the segments presented in one of the earlier frames. The matching segments for SAME trials originated an equal number of times from the first, second, and third frames. Dependent variables in both phases of the spatial integration task were the accuracy of the decisions, the median time for correct SAME decisions, and the study time for each successively presented frame.

RESULTS

Summary statistics for the average scores across the two parts of each of the paper-and-pencil tests, including means, standard deviations, estimated reliabilities and intercorrelations, are displayed in Table 1. As expected, the reliabilities and intercorrelations of the scores of the four criterion tests were all moderately high, thereby justifying combination of the scores to form a composite index of spatial visualization ability.

The spatial visualization index (SVI) was simply the sum of the individual's z-scores across the Paper Folding, Surface Development, Form Board, and Cube Comparisons tests. Most of the analyses that follow were based on contrasts between the 12 individuals with the highest SVI and the 12 individuals with the lowest SVI in the sample of 50 subjects. However, correlations between SVI and performance in the experimental tasks (reported in Table 3) indicate that for the most part the same patterns were also apparent in analyses of the results from the entire sample of subjects. The range of SVI values for the subjects classified as high in spatial visualization was 2.73 to 5.97 with a mean of 3.68, while the range for the subjects classified as low in spatial visualization was -1.75 to -8.65 with a mean of -4.54. Although the subjects from the extremes of the distribution were classified as high or low in spatial visualization ability, it is important to emphasize that this distinction is relative rather than absolute. That is, because all research participants were undergraduates at a relatively select technically oriented university, it can be expected that their average level of spatial ability was probably higher than that of the general population.

In order to examine the relations between specific combinations of psychometric and experimental measures, correlations were also computed between the psychometric scores and average accuracy and median decision time in each experimental task. These correlations are displayed in Table 2. Notice that although there is some variation in the magnitude of individual correlations, it does not appear to be the case that the correlations are substantial only with particular combinations of psychometric and experimental measures. Instead, the overall pattern seems consistent with the view that a common spatial visualization ability

TABLE 1
Correlations among Psychometric Measures, Study 1 ($N = 50$)

	Paper Folding (PF)	Surface Development (SD)	Form Board (FB)	Cube Comparisons (CC)	Block Design (BD)
PF	(.77)	.65	.55	.38	.51
SD		(.94)	.55	.54	.52
FB			(.73)	.56	.53
CC				(.78)	.45
BD					×
M	7.59	25.44	13.53	14.00	41.40
SD	1.53	4.91	3.74	3.74	6.14

Note. Values in parentheses are estimated reliabilities derived by using the Spearman-Brown formula to boost the correlation between the two parts to predict the reliability of the average score. All remaining correlations are between the averages of the two parts of each test.

was reflected in the psychometric tests and at least the accuracy measures of most of the experimental tasks.

Results from the analyses of variance with the extreme groups, and the correlation coefficients from the entire sample, are summarized in Table 3. The second, third, and fourth columns in this table contain the F-ratios from the analyses of variance for, respectively, the main effect of Spatial Visualization Ability, the main effect of the Experimental Manipulation, and the interaction of Spatial Visualization Ability × Experimental Manipulation. Two exceptions to this arrangement occur with the analyses of the study time measures in the paper folding and spatial integration tasks. With these measures, the manipulation factor was replaced with two different factors—the sequential position of the display being studied, and whether the eventual response in the trial was correct or incorrect.

Examination of Table 3 reveals three important findings. The first is that the experimental manipulations had significant effects on both decision accuracy and decision time in each task. The results are therefore consistent with the assumption that the difficulty of each task was increased because the manipulations increased the number of hypothesized transformations required to perform the

TABLE 2
Correlations Between Psychometric and Experimental Measures, Study 1 (N = 50)

	Psychometric Measures				
	Paper Folding	**Surface Development**	**Form Board**	**Cube Comparisons**	**Block Design**
Experimental Measures					
Paper Folding					
% Correct	.52*	.60*	.37*	.21	.42*
Decision Time	.01	.08	−.05	−.27	.10
Cube Folding					
% Corect	.52*	.61*	.28	.27	.48*
Decision Time	.14	.28*	−.18	−.04	.13
Spatial Integration					
% Correct	.45*	.54*	.46*	.42*	.43*
Decision Time	.10	.30*	.15	.16	.16
Cube Comparisons (Simultaneous)					
% Correct	.48*	.61*	.42*	.26	.34*
Decision Time	.06	−.03	−.11	−.39*	−.02
Cube Comparisons (Successive)					
% Correct	.28	.55*	.16	.10	.30*
Decision Time	−.09	.05	−.06	−.22	−.04
Block Design					
# Manipulations	−.30*	−.14	−.31*	−.15	−.22
Total Time	−.27	−.24	−.28	−.41*	−.40*
Spatial Working Memory	.37*	.32*	.21	.36*	.40*

*$p < .05$

TABLE 3
Summary of Analysis-of-Variance Results and Spatial Visualization Index (SVI) Correlations in Study 1

	Spatial Visualization Ability	Experimental Manipulation	Spatial Visualization Ability × Experimental Manipulation	Correlation with SVI
Paper Folding		**(# Folds)**		
% CORRECT (Between MSe = 145.65, within MSe = 25.69)				
F	22.06*	61.21*	0.30	.52*
DECISION TIME (Between MSe = 3,932, within MSe = 308)				
F	0.09	23.25*	1.55	−.07
STUDY TIME (Between MSe = 118, within [Fold] MSe = 19, within [Acc.] MSe = 7)				
F	0.00	Fold 1.78	0.78	−.06
F		Acc. 1.07	0.06	
Cube Folding		**(# Folds)**		
% CORRECT (Between MSe = 126.1, within MSe = 36.2)				
F	14.71*	78.28*	7.38*	.52*
DECISION TIME (Between MSe = 2,326, within MSe = 1,025)				
F	0.15	52.37*	0.50	.06
Cube Comparisons–Stimultaneous		**(Orientation Discrepancy)**		
% CORRECT (Between MSe = 458.7, within MSe= 203.6)				
F	7.78*	4.45*	0.90	.55*
DECISION TIME (Between MSe = 184,126, within MSe = 9,863)				
F	0.58	22.70*	0.33	−.14
Cube Comparisons–Successive		**(Orientation Discrepancy)**		
% CORRECT (Between MSe = 761.9, within MSe = 72.4)				
F	3.20	6.04*	2.34	.33*
DECISION TIME (Between MSe = 184,126, within MSe = 9,863)				
F	0.12	15.22*	0.95	−.10
N OF CUBE FACES EXAMINED (Between MSe = 93.0, within MSe = 2.5)				
F	0.07	11.64*	0.56	−.04
Spatial Integration		**(# Frames)**		
% CORRECT (Between MSe = 284.1, within MSe = 122.4)				
F	13.37*	18.47*	0.91	.58*
DECISION TIME (Between MSe = 1,733, within MSe = 256)				
F	1.02	14.23*	0.84	.22
STUDY TIME (Between MSe = 671, within [Frame] MSE = 59, Within [Acc.] MSe = 177)				
F	2.01	Frame 4.54*	0.42	.22
F		Acc. 1.46	0.85	
d' BY FRAME (Between MSe = 2.0, within MSe = 0.1)				
F	11.41*	21.21*	1.30	.56*

*$p < .05$

task. The second interesting finding is that the differences between high- and low-spatial subjects were evident only in the measures of decision accuracy, and not in the measures of correct decision time. An apparent implication of this pattern is that differences in spatial visualization ability are not associated with variations in the efficiency of executing transformations, or in the duration of processes associated with encoding or decision. That is, high-spatial subjects appear to have a higher probability of correctly executing the relevant processes than low-spatial subjects, but given that the execution was correct (i.e., the eventual decision was accurate), the total times for the two groups were equivalent. And finally, Table 3 indicates that only one of the Ability × Manipulation interactions was significant, thus suggesting that the manipulations generally had equivalent effects in the groups selected from the extremes of the continuum of spatial visualization ability. The following paragraphs elaborate these findings in the context of the specific tasks.

Paper Folding

Accuracy in the paper folding task as a function of the number of folds displayed prior to the punch is illustrated in Figure 1. Notice that the percentage of correct decisions decreased by approximately 6.4% with each additional fold, but that a nearly uniform difference of about 12% separated the high-spatial and low-spatial

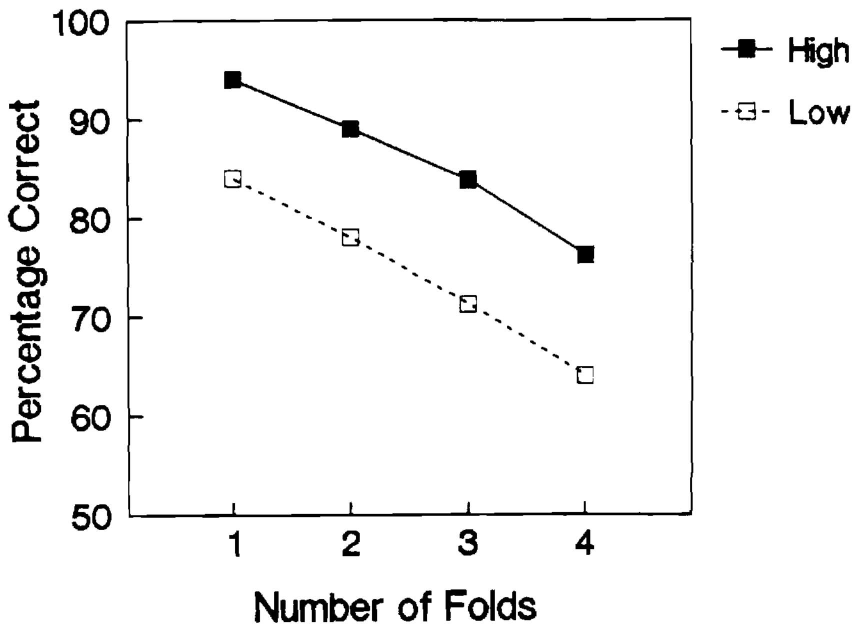


FIG. 1. Mean percentage correct for high- and low-spatial subjects as a function of the number of folds displayed prior to the hole punch in the paper-folding task, Study 1.

groups. The discovery that the two groups had roughly equivalent effects of number of folds suggests that spatial visualization ability is apparently not associated with differences in the ability to execute the folding transformations. However, the constant accuracy difference indicates that the low-spatial subjects are deficient relative to high-spatial subjects in one or more processes unrelated to the folding transformation.

An additional analysis was carried out contrasting performance on trials in which only a single fold was relevant to the decision, and performance on trials in which all of the presented folds were relevant to the decision. One-relevant trials are those in which the decision can be based on the information from a single fold, along with information about the location of the punch, because if there are additional folds they do not alter the number or position of the holes that would result in the unfolded paper. An example might be when a corner of the paper is folded in, and the hole is punched in the folded section. As long as no other folds change the location of the folded section, either before or after the critical fold, then the information from the single relevant fold is sufficient for the decision. In contrast, all-relevant trials are those in which all of the presented folds need to be considered in reaching the decision about the pattern of holes in the unfolded paper.

Comparison of performance of one-relevant and all-relevant trials can be useful in distinguishing between a failure to preserve relevant information, and an inability to integrate the information across multiple folds, as determinants of poor performance in the paper folding task. That is, because no information integration is required when only a single fold is relevant to the decision, any decline in accuracy with one-relevant trials when additional folds are presented can be attributed to problems associated with the storage or retrieval of the relevant information. On the other hand, when all of the folds are relevant to the decision not only must all of the information be available in memory, but it must also be successfully integrated across the multiple folds. Because the changes in performance across varying numbers of presented folds in all-relevant trials are dependent on both information availability and information integration, whereas those in one-relevant trials are dependent only on information availability, the difference between the two provides an estimate of the contribution of information integration processes.

Figure 2 illustrates paper-folding accuracy as a function of the number of presented folds for one-relevant and all-relevant trials for the high-spatial and low-spatial subjects. Notice that in both groups there is little decline in accuracy of one-relevant trials until four folds were presented. This suggests that the drop in accuracy with two and three relevant folds is largely attributable to difficulties in integrating the available information across multiple folds. However, when four folds are presented accuracy is lower for both one-relevant and all-relevant trials, indicating that performance in these trials is affected by the loss of available information as well as by difficulties of integrating what is available.

An analysis of variance with spatial ability (high, low), number-of-presented-folds (2, 3, or 4), and number-of-relevant-folds (1 or all) was conducted on the

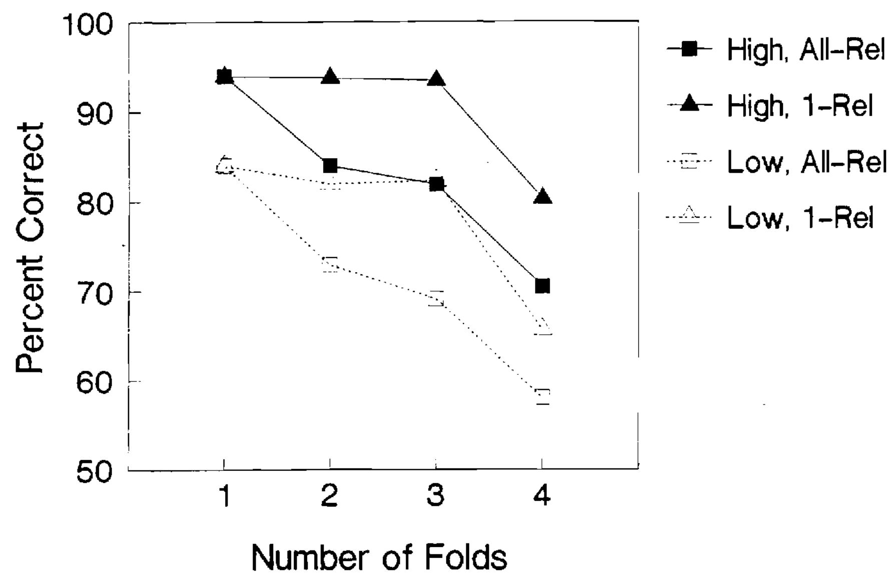


FIG. 2. Mean percentage correct for high- and low-spatial subjects as a function of number of folds for trials in which all folds were relevant to the decision, and for trials with only one relevant fold, Study 1.

data summarized in Figure 2. Data from the one-fold trials were excluded from this analysis because the number-of-relevant-folds factor is not meaningful when the same data are used to represent both levels of the factor. All three main effects in this analysis were significant ($p < 0.5$); Spatial Ability, $F(1,22) = 20.97$, MSe = 262.55; Number-of-Presented-Folds, $F(2,44) = 44.22$, MSe = 69.83; and Number-of-Relevant-Folds, $F(1,22) = 35.69$, MSe = 104.70. Of particular interest, however, was that none of the interactions was significant (i.e., all Fs < 1.0).

The failure to find a significant interaction of Number-of-Presented-Folds × Number-of-Relevant-Folds suggests that the decline in accuracy associated with the requirement of integrating information was constant regardless of the amount of information to be integrated. This is a rather surprising result because it might have been expected that the consequences of attempting to integrate would be greater when there was more information to be integrated. Instead it appears that the important factor influencing eventual decision accuracy is whether any integration of information is required, and not the amount of information involved in the integration.

The absence of significant interactions with the spatial visualization ability factor suggests that the two groups did not differ in the relative influence of information availability and information integration on the changes in accuracy associated with the presentation of additional folds. Stated somewhat differently, except for the lower overall accuracy of the low-spatial subjects, the two groups were indistinguishable with respect to the contributions of the factors of availability and integration to paper folding performance. The results of this analysis therefore reinforce the earlier conclusion that the factors responsible for individual differences in spatial visualization appear to be independent of the processes responsible for further decreases in accuracy as more paper folding transformations are required.

The time spent inspecting the outcome of each successive fold in the four-fold trials was also analyzed to investigate possible ability-related differences in the manner in which subjects performed the task. For example, if low-ability subjects had shorter inspection times than high-ability subjects, then at least some of the performance differences might have been attributable to insufficient processing of the information on the part of subjects classified as low in spatial visualization ability. Furthermore, because the profile of inspection durations across successive folds can be interpreted as a reflection of how the individual allocates his processing time or effort to different phases of the trial, comparisons of high- and low-ability subjects in the sequence of study times might be informative about possible differences in processing strategies. However, the results summarized in Table 3 reveal that neither the main effect of spatial visualization ability, nor any of the interactions of spatial visualization ability with response accuracy or with fold position, were significant. The study time data therefore provide no evidence that individual differences in spatial visualization ability are attributable to differences in the strategy used to perform the paper folding task.

Cube Folding[2]

Average percentage correct in the cube folding task is displayed in Figure 3 as a function of the number of folds required to determine whether the arrows were facing one another. In keeping with the Shepard and Feng (1972) analysis, trials with arrows on adjacent squares in the flat (unassembled) drawing were considered to represent one fold. The results in Figure 3 indicate that the two groups were nearly perfect, and did not differ, when the decisions could be made without any mental manipulation of the stimulus display, but that accuracy decreased, and more so for low-spatial subjects than for high-spatial subjects, when two or

[2]Shepard and Feng (1972) reported that the number of squares carried along during the folds was a better predictor of decision time than the number of folds, presumably because this variable reflects both the number of transformations to be performed and the memory load associated with those transformations. The variables of number-of-folds and number-of-carried-squares tend to be correlated with one another, however, and thus in the present analyses the independent effects of these variables were assessed by simultaneous multiple regression analyses of the data from each subject. The means, across all 50 subjects, of the regression weights for predicting decision time were 1318 ms per fold and 134 ms per carried square, with a mean R^2 of .36. Mean regression weights for prediction of decision accuracy were −6.6%/fold and −0.4%/carried square, with a mean R^2 of .09. The number of folds was a significant predictor of decision time for 49 of the 50 subjects, and a significant predictor of decision accuracy for 40 subjects. In contrast, the number of carried squares was a significant predictor of decision time for only 26 of the subjects, and of decision accuracy for only 2 subjects. It is apparent from these analyses that the number-of-folds variable had the greatest predictive power, and consequently this variable, rather than the number-of-carried-squares, was used in the present analyses of cube-folding performance.

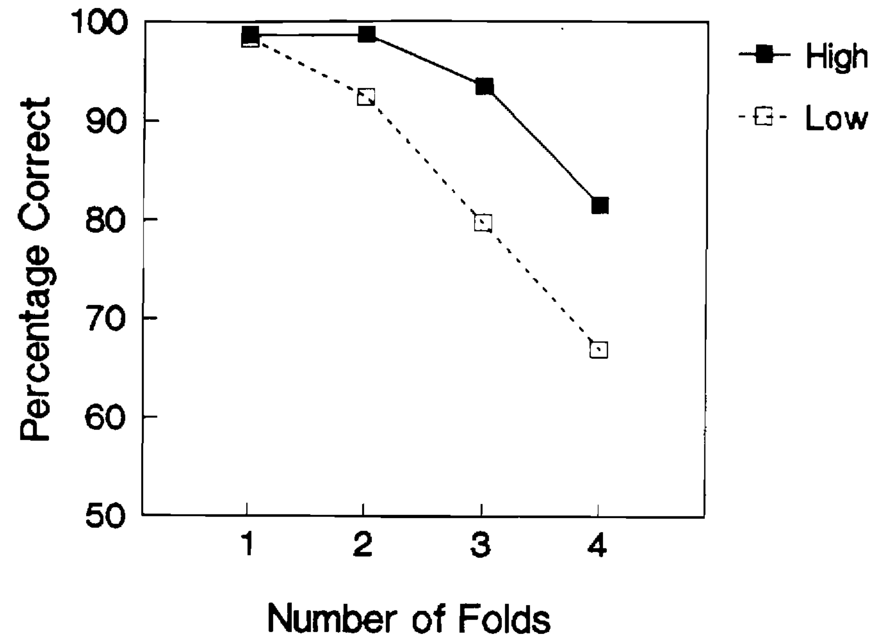


FIG. 3. Mean percentage correct for high- and low-spatial subjects as a function of the number of folds required to assemble the cube in the cube-folding task, Study 1.

more folds were required. The ceiling effect, evident in the 1-fold trials for both groups and also in the 2-fold trials for the high-spatial group, is probably responsible for the spatial ability × manipulation interaction evident in Table 3. Consistent with this interpretation was the discovery that the interaction was not significant ($F[1,22] = 0.07$) when only the data from the 3-fold and 4-fold trials were examined.

Block Design

Measures of performance in the experimental block design task are summarized in Table 4. Total time is simply the average time required to match the nine cells of the stimulus matrix by manipulating the cube and producing the desired patterns in the target matrix. A task analysis conducted by Salthouse (1987b) suggested that the time required to place a cube pattern in the target matrix when the front face matched the target cell without any cube manipulations could be interpreted as the duration needed to encode and compare the patterns. The time to manipulate the cube down or to the left when the target pattern was on the top or right face was interpreted as the time to select an appropriate manipulation. Table 4 reveals that although the extreme-group comparisons were not significant for the process durations, there were significant negative correlations between SVI and each of the temporal measures in the complete sample of 50 subjects.

The number-of-manipulations variable in Table 4 represents the average number of cube manipulations required in each trial to reproduce the patterns

TABLE 4
***Ms*, *t*-test Values, and SVI Correlations from Block Design Comparisons in Study 1**

Measure	High	Low	t(22)	r(SVI)
Total Time	45.41	57.67	2.22*	−.37*
Encode/Compare	1.80	2.03	1.33	−.34*
Manipulate	1.72	1.95	1.27	−.32*
Average Number of Manipulations	19.46	24.30	2.46*	−.28
Concentration	97.2	96.4	0.60	.28
Breadth of Attention	95.7	91.0	2.05	.36*
Quality of Representation	47.1	32.5	1.97	.37*

Note. Entries in the second and third columns are in units of seconds for the first three rows, and in percentages for the bottom three rows.
*$p < .05$

from the stimulus matrix in the response matrix. The remaining variables reflect the efficiency of the manipulations across different types of situations. Specifically, they represent the percentage of occasions in which the most efficient sequence of cube manipulations was selected when the target pattern was visible on the front face of the cube, when it was visible on the top or right face of the cube, and when it was not visible but "present" on the hidden bottom or left face of the cube. Efficiency in these situations can be interpreted as reflecting, respectively, concentration or carefulness of cube monitoring, breadth of attention to adjacent as well as central information sources, and quality of the internal representation of the three-dimensional cube. Table 4 indicates that the high-spatial subjects were somewhat more efficient than the low-spatial subjects in each measure, with the differences achieving the .05 level of significance for the extreme-group contrast on the number-of-manipulations measure, and on the breadth-of-attention and quality-of-representation measures for the correlations in the entire sample.

Cube Comparisons

Mean levels of decision accuracy in the simultaneous and successive versions of the cube comparisons task are displayed in Figures 4A (Simultaneous) and 4B (Successive). The correlation between average accuracy in the two versions of the task was .62 ($p < .05$), suggesting that there were many common processes across the two versions despite the differences in presentation format. In both versions of the task the group differences appear slight to nonexistent for trial type 1, in which the two cubes have identical orientations, and are moderate to

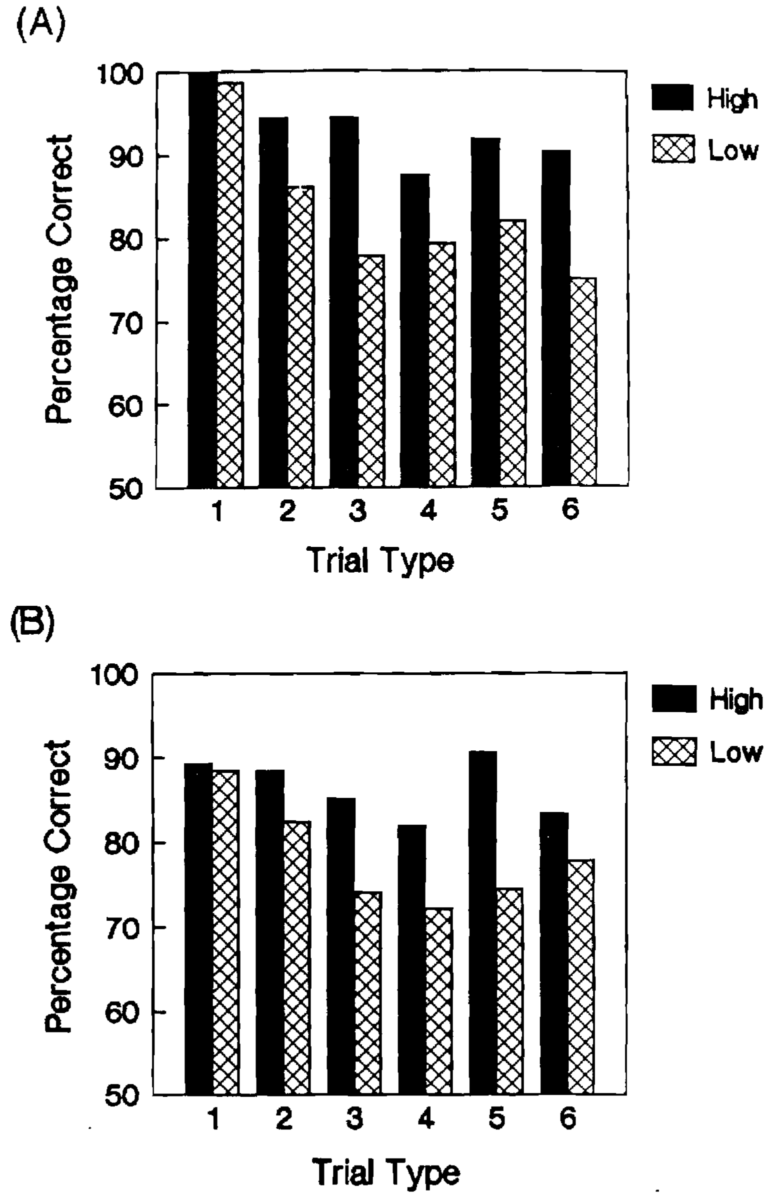


FIG. 4. (A) Mean percentage correct in the simultaneous version of the cube comparisons task for high- and low-spatial subjects as a function of the trial types varying in degree of orientational discrepancy between the two cube configurations and number of corresponding letters. (B) Mean percentage correct in the successive version of the cube comparisons task for high- and low-spatial subjects as a function of the trial types. The number of 90-degree rotations required to transform the cubes into congruent orientations and the number of letters common to the two configurations for each trial type were: 1 = 0,3; 2 = 1,2; 3 = 2,1; 4 = 2,3; 5 = 2,1; 6 = 3,2.

large when the cubes differ in orientation by 90 degrees or more. The interactions of spatial visualization ability × trial type, however, were not statistically significant in either version of the task.

Just and Carpenter (1985; Carpenter & Just, 1986) have suggested recently that many of the differences between high- and low-spatial subjects in the cube comparisons task can be explained by assuming that high-spatial subjects are faster at rotating cubes than low-spatial subjects, and that they frequently rotate along shorter task-defined axes. These assumptions can be examined in the present data by analyzing the slope of the functions relating decision time (for correct SAME trials) to type of trial in the simultaneous version of the task. As Just and Carpenter (1985) pointed out, the slope across the first three trial types provides an estimate of the individual's rate of rotation for standard axes. These slopes averaged 1726 ms/90° for high-spatial subjects and 2177 msec/90° for low-spatial subjects, values which did not differ significantly ($t[22] = 0.94$). The correlation of these slope values with SVI in the entire sample was also not significant ($r = -.09$). One should be cautious in concluding that the two groups do not differ, however, because the data in Figure 4A indicate that the low-spatial subjects had greater reductions in accuracy across the first three trial types than the high-spatial subjects. It is therefore possible that the ability differences in the slope measure might have been significant had the two groups maintained equivalent levels of accuracy.

An expectation from the assumption that high-spatial subjects frequently rotate the cubes along shorter, task-defined, trajectories is that better predictions of decision times should result from regression equations when the angular discrepancies between cubes correspond to the nonstandard trajectories, compared to when the discrepancies correspond to the standard trajectories. According to the analyses of Just and Carpenter (1985), nonstandard trajectories are possible in trial types 4 and 5 (reducing them from 180° to 120°) and in trial type 6 (reducing it from 270° to 180°). Contrary to the prediction, the regression equations for mean correct SAME decision times in the simultaneous cube comparisons task when using the angular deviations corresponding to these nonstandard trajectories actually accounted for a smaller percentage of variance than those based on the standard trajectories. For the high-spatial subjects the mean percentage of variance accounted for was 74% for the nonstandard trajectories, compared to 92% for the standard trajectories. Corresponding values for the low-spatial subjects were 88% for the orientation discrepancies associated with nonstandard trajectories, and 98% for those associated with standard trajectories.

Neither of the slope analyses therefore provide convincing evidence in support of the Just and Carpenter (1985; Carpenter & Just, 1986) suggestions that spatial visualization ability is related to the speed or type of cube rotations. The lack of Spatial Visualization Ability × Trial Type interactions in the accuracy measure are also inconsistent with another of their suggestions that people varying in spatial visualization ability are differentially sensitive to processes specific to particular types of trials, such as the disappearance of a cube face during the rotational trajectory.

A Spatial Visualization Ability × Trial Type analysis of variance was also conducted on the variable of mean number of cube faces examined in the successive version of the cube comparisons task. As indicated in Table 3, neither the difference between high- and low-spatial subjects, nor the interaction of spatial visualization ability and trial type, were significant. Additional analyses revealed that the two groups did not differ in the mean number of repetitions of the same cube face during a trial (i.e., high-spatial = 5.03, low-spatial = 4.96, $t[22] = .05$), nor was the correlation of this variable with SVI significant (i.e., $r = -.07$). There were also no spatial visualization ability differences in the average number of faces intervening between repetitions of the same cube face as the high-spatial subjects averaged 3.75 intervening faces and the low-spatial subjects 3.62 ($t[22] = -.61$), with the SVI correlation equal to 0.0. These results suggest that spatial visualization ability is apparently not associated with differences in memory for relevant information because there were no differences in the number of times the same cube face was examined, or in the number of other faces intervening between reexaminations of the same cube face.

The sequence of cube face inspections was also analyzed in an attempt to identify the strategies used to perform the task. Specifically, trials in which subjects examined all three faces of one cube followed by at least two different faces of the other cube were assumed to be solved by a holistic strategy in which the subject attempts to form a complete representation of one cube before comparing it with the other cube. Although there was a tendency for high-spatial subjects to rely more frequently on this holistic strategy, the percentage of an individual's trials identified as consistent with the holistic strategy was not significantly correlated with SVI ($r = .21$), and the two ability groups did not differ significantly on this variable (i.e., high = 68.4%, low = 44.6%, $t[22] = 1.83$, $p > .10$).

Spatial Integration

Mean accuracy in Phase I of the spatial integration task as a function of the number of frames containing to-be-integrated information is displayed in Figure 5. Notice that the high-spatial subjects performed at higher levels of accuracy than the low-spatial subjects, and that both groups had a similar decline in accuracy when one or more integration operations were required to form the composite figure.

Analysis of study times in the four-frame trials revealed that all subjects decreased their inspection durations across successive frames, but that the two groups did not differ in the mean duration of their inspections, nor in the pattern of inspection durations across frames. These results suggest that, as with the paper-folding task, subjects varying in spatial visualization ability do not differ markedly in the overall strategies used to perform the task.

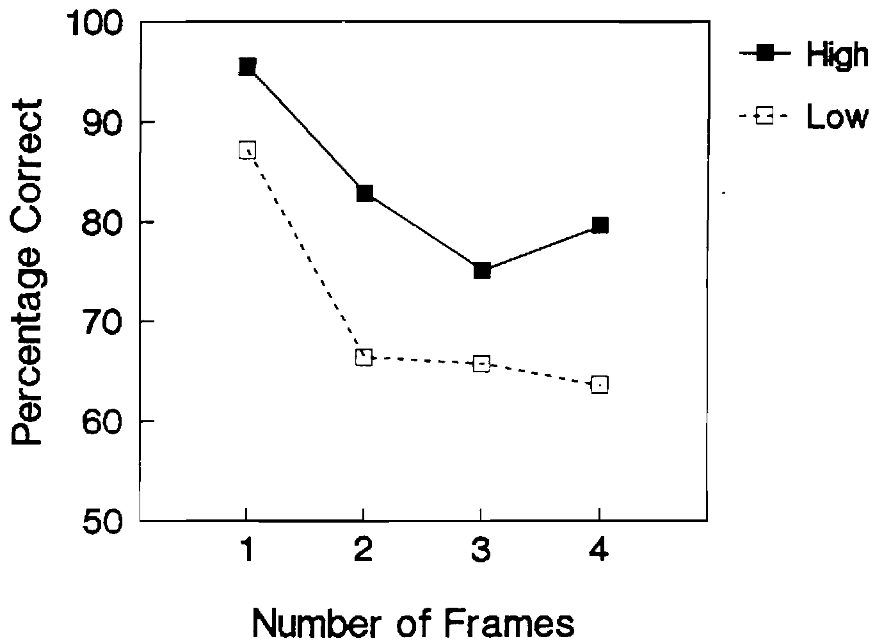


FIG. 5. Mean percentage correct for high- and low-spatial subjects as a function of number of frames to be integrated to form a composite pattern in Phase I of the spatial integration task, Study 1.

Accuracy of recognition decisions for the 3-segment comparison stimuli in Phase II of the spatial integration task was examined with the d' measure of decision sensitivity by considering the percentages of correct judgments for SAME trials in each frame position as the estimates of the respective hit rates, and the percentage of incorrect judgments for DIFFERENT trials as an estimate of the common false alarm rate. The resulting d' values for each frame position are displayed in Figure 6.

It is apparent in Figure 6 that although both high- and low-spatial groups exhibit a recency effect, such that recognition accuracy is higher for segments in the most recently presented frame, the difference between the two groups is nearly uniform across successive frame positions. This is supported by the absence of an interaction of Spatial Visualization Ability × Frame Position in the analysis of variance (see Table 3). The presence of a difference in the most recent frame, together with the absence of an interaction indicating greater differences in earlier frames, suggests that the low-spatial subjects may differ from the high-spatial subjects in the amount or quality of stimulus information encoded, but apparently not in the ability to maintain that information with the presentation of additional information.

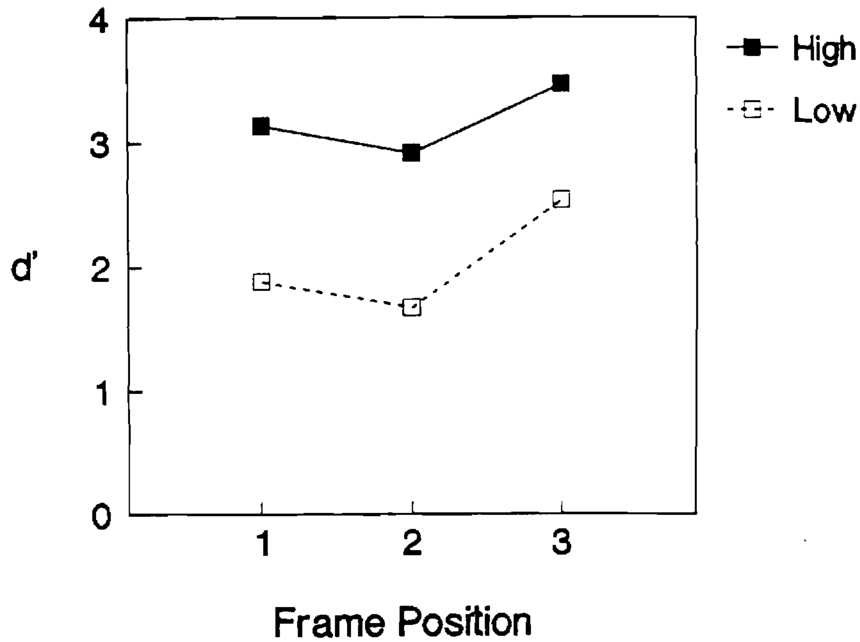


FIG. 6. Mean percentage correct for high- and low-spatial subjects as a function of frame position of target segments in Phase II of the spatial integration task, Study 1.

Spatial Working Memory

Mean values of the spatial working-memory measure for the two groups (with missing data from one subject) were 4.42 (SD = 1.24) for high-spatial subjects and 3.50 (SD = 1.10) for low-spatial subjects, $t(21) = 1.87, p > .05$. Although this difference was not significant, the correlation between the spatial working-memory measure and the composite SVI was significant ($r = .39, p < .05$) in the entire sample of 50 subjects.

STUDY 2

The best-supported hypothesis from Study 1 seems to be that in which individual differences in spatial visualization ability are attributed to differences in the quality (i.e., completeness and accuracy) of the internal representation, independent of the number of required transformations. A primary goal of the current study was to investigate this hypothesis more directly by comparing several characteristics of the memory representations of high- and low-spatial subjects. A second purpose of the present study was to investigate differences associated with spatial visualization ability in tasks requiring different types of spatial transformations, and to examine the role of memory in these tasks by including a special version of each task designed to minimize demands on memory. A final goal was to extend the investigation of the relation between spatial visualization ability and spatial working-memory capacity by repeating the spatial working-memory task used in the previous study, while also adding a new task in which the requirement of concurrent processing were reduced.

The study differed in three ways, besides the inclusion of new tasks, from Study 1. First, a larger number (n = 92) of people were tested on the paper-and-pencil criterion tests, with 12 high-ability and 12 low-ability subjects then selected from the extreme quartiles of the distribution of summed z-scores for more extensive computer-controlled testing. Second, the same types of stimuli (connected line segments) and decisions (SAME or DIFFERENT with respect to identity) were used in most of the tasks, rather than having the tasks vary in type of stimuli, type of decision, and type of transformation. And finally, the instructions in all tasks of the present study emphasized accuracy more than speed, rather than emphasizing them equally as in the previous study.

Four memory tasks were designed to investigate: (a) the efficiency of encoding spatial information by varying the duration of the initial stimulus exposure; (b) the stability of the internal representation by varying the retention interval between the initial presentation and the subsequent recognition test; (c) the precision of the representation by varying the magnitude of the difference between the original stimulus and the comparison stimulus in DIFFERENT trials; and (d) the capacity of the representation by varying the total number of segments in the stimulus figure.

Three transformation tasks were also presented, each in two versions. All tasks involved the initial presentation of a stimulus pattern composed of connected line segments, followed by the requirement either to integrate, delete, or rotate segments before making the recognition decision. In a second version of these tasks, one-half of the trials contained a faint copy of the segments from the first frame during the presentation of the second frame containing the transformation instructions. It was assumed that the presence of information from the first frame would minimize dependence on spatial memory, and thus might reduce or eliminate any performance differences attributable to an inability to preserve earlier-presented information during the transformation process.

The spatial working-memory task from the previous study was administered, as well as a modified version of the task without the requirement that irrelevant lines be created while attempting to remember the target lines. This new task was expected to lead to smaller differences between high- and low-spatial subjects if a major factor contributing to those differences is the ability to preserve early information during the processing of other information because the amount of other processing is substantially reduced relative to that required in the original task.

Method

Subjects. A total of 92 male undergraduates at Georgia Institute of Technology (ages 18 to 24) were administered the criterion battery of paper-and-pencil tests (i.e., Paper Folding, Surface Development, Form Board, and Cube Comparisons) in several group testing sessions. Based on the scores of these tests (see Table 5), 12 subjects each from the top and bottom quartiles of the distribution of summed z-scores composing the SVI were recruited to participate in the study. The range of SVI in the high-spatial subjects was 2.96 to 6.09, with a mean of 4.18, and that in the low-spatial subjects was −2.52 to −6.69 with a mean of −4.67. Because the mean scores on the criterion tests were very similar to those from Study 1, as evident in a comparison of Tables 1 and 5, the subjects would have been classified in the same way had they been in Study 1. That is, use of Study 1 norms resulted in a SVI range of 2.60 to 5.70 with a mean of 3.67 for the present high-spatial subjects, and a range of −3.16 to −7.18 with a mean of −5.65 for the present low-spatial subjects.

Compensation for the five 1.5-hour individual sessions consisted either of $40, credit for experimental participation in an introductory psychology course, or a combination of money and credit.

Procedure. Subjects began the experimental sessions from 1 to 8 weeks after the initial screening session. Most subjects completed the five experimental sessions within a 2-week period. Session 1 consisted of the two versions of the spatial working-memory task, session 2 involved the memory encoding-efficiency and memory stability tasks, session 3 the memory precision and memory capacity tasks, session 4 the integration, deletion, and rotation tasks, and session

TABLE 5
Study 2 Correlation Matrix for Initial Sample, N = 92

	Paper Folding (PF)	Surface Development (SD)	Form Board (FB)	Cube Comparisons (CC)
PF	(.85)	.63	.66	.39
SD		(.88)	.60	.52
FB			(.73)	.45
CC				(.72)
M	7.44	23.60	12.83	13.95
SD	1.51	6.36	4.10	3.19

Note. Values in parentheses are estimated reliabilities derived by using the Spearman-Brown formula to boost the correlation between the two parts to predict the reliability of the average score. All remaining correlations are between the averages of the two parts for each test.

5 the three transformation tasks in the versions with the added display of the information from the first frame during the second frame.

Table 6 summarizes major procedural details of the experimental tasks, including the variables manipulated across and within tasks. Each task began with a repeatable block of practice trials illustrating all levels of the experimental manipulation, followed by two blocks of 50 trials each. One-half of the trials were SAME or matching trials, and one-half were DIFFERENT or mismatching. Successive frames in the transformation tasks could be viewed by pressing any key on the keyboard, and decisions in all tasks were communicated by pressing the "/" key for SAME, and the "Z" key for DIFFERENT.

The sequence of events within a trial was identical for the four memory tasks. It consisted of the initial exposure of the stimulus segments for the specified encoding duration, a blank screen for the designated retention interval, and then the display of the recognition stimulus until the subject made his response. Trials in the integration and deletion tasks consisted of the initial exposure of a pattern of 3, 6, 9, or 12 line segments in the integration task, and 15, 12, 9, or 6

TABLE 6
Design of Tasks in Study 2

Task	Encoding Time (S)	Transformation	Retention Interval (S)	*N* of Different Segments	*N* of Segments in Comparison
Encode	.25–2*	None	6	2	12
Stable	2	None	3–12*	2	12
Precise	2	None	6	1–4*	12
Capacity	2	None	6	2	6–15*
Integrate	Subject Controlled	Integrate* (1 to 4 frames)	2	2	9
Integrate/Copy	Subject Controlled	Integrate/Copy* (2 frames, with or without copy)	1	2	6
Delete	Subject Controlled	Delete* (1 to 4 frames)	2	2	6
Delete/Copy	Subject Controlled	Delete/Copy* (2 frames, with or without copy)	1	2	6
Rotate	Subject Controlled	Rotate* (0°, 90°, 180°)	2	2	6
Rotate/Copy	Subject Controlled	Rotate/Copy* (90°, with or without copy)	1	2	6

*Indicates factor manipulated in task.

segments in the deletion task. This was followed by 0 to 3 frames, each containing 3 connected line segments, and then by the comparison stimulus of 9 segments for the integration task, or 6 segments for the deletion task. Trials in the rotation task consisted of an initial display of a 6-segment stimulus, a display of the type of rotation to be performed, and a display of the 6-segment comparison stimulus rotated to the designated orientation. Trials in the copy versions of the transformation tasks always consisted of three frames containing, in succession, the original pattern, the segments to be added or deleted or the indication of the type of rotation (clockwise or counterclockwise 90°) to be performed, and the comparison stimulus. On a randomly selected one-half of the trials, the line segments from the first frame were displayed as dotted lines during the second frame to provide a faint copy of the previous information.

The frames between the initial stimulus and the comparison stimulus in trials in the transformation tasks contained a display to remind, or inform, the subject of the type of transformation to be performed. In the integration task this consisted of the word "PLUS" below each display of the segments to be added to the initial pattern, and in the deletion task it consisted of the word "MINUS" below each set of segments that were to be subtracted from the original pattern. The information displays in the rotation task consisted of two flags that were either in the same orientation (for 0° rotation), at right angles to one another (for 90° rotation), or rotated 180° (for 180° rotation).

An equal number of trials at each level of the independent variable was presented in a random arrangement in each task. For example, there were 25 trials with a .25-s encoding time, 25 trials with a .50-s encoding time, 25 trials with a 1.0-s encoding time, and 25 trials with a 2.0 s encoding time.

Dependent variables were accuracy in terms of percentage of correct decisions, median decision time for correct trials, and where appropriate, median study or inspection time per frame. Study time in the first frame of the trials in the rotation task was termed encoding time to distinguish it from the study time in the second frame when subjects were viewing the display with the required rotation, which was termed rotation time. Because there was only one type of SAME trial and four types of DIFFERENT trials in the memory precision task, accuracy in this task was evaluated with the d' measure by using the percentages of correct DIFFERENT decisions as the hit rates for each magnitude of difference, and the percentage of incorrect SAME decisions as an estimate of the common false alarm rate.

The two spatial working-memory tasks were identical to that of the previous study except that the new version did not require the subject to connect Xs in the display during the presentation of the to-be-remembered lines. The Xs were still visible in the frames containing the target lines, but subjects were informed that they should be ignored and to concentrate on remembering the positions of the target lines.

TABLE 7
Summary of F-Ratios from Study 2

	Spatial Visualization Ability	Experimental Manipulation	Spatial Visualization Ability × Experimental Manipulation
Encoding		**(Encoding Time)**	
% Correct (Between MSe = 263.5, within MSe = 45.3)			
F	1.98	1.54	0.95
Decision Time (Between MSe = 582, within MSe = 26)			
F	3.01	4.43*	1.12
Stability		**(Retention Interval)**	
% Correct (Between MSe = 329.7, within MSe = 42.9)			
F	0.04	15.10*	0.70
Decision Time (Between MSe = 925, within MSe = 22)			
F	0.93	13.11*	1.03
Precision		**(# of Different Segments)**	
% Correct (Between MSe = 2.54, within MSe = 0.2)			
F	0.00	33.91*	0.55
Decision Time (Between MSe = 916, within MSe = 36)			
F	1.23	25.01*	2.33
Capacity		**(# of Total Segments)**	
% Correct (Between MSe = 177.9, within MSe = 35.0)			
F	0.15	11.20*	0.18
Decision Time (Between MSe = 685, within MSe = 16)			
F	1.43	42.77*	1.40
Integration		**(# of Frames)**	
% Correct (Between MSe = 131.8, within MSe = 80.0)			
F	2.79	26.25*	0.99
Decision Time (Between MSe = 1,809, within MSe = 163)			
F	4.51*	29.77*	1.27
Study Time (Between MSe = 3,155, within [Frame] MSe = 96, within [Acc.] MSe = 102)			
F	3.43	Frame 4.96*	3.21*
F		Acc. 0.17	0.48
Integrate with Copy		**(Copy/NoCopy)**	
% Correct (Between MSe = 76.0, within MSe = 24.0)			
F	0.21	144.50*	2.00
Decision Time (Between MSe = 340, within MSe = 63)			
F	6.44*	64.41*	5.48*
Study Time (Between MSe = 3,068, within [Copy] MSe = 152, within [Frame] = 494, within (Acc.) MSe = 112)			
F	4.49*	Copy 31.37*	4.75*
F		Frame 0.53	0.24
F		Acc. 0.51	1.70

(continued)

TABLE 7 *(Continued)*

	Spatial Visualization Ability	Experimental Manipulation	Spatial Visualization Ability × Experimental Manipulation
Deletion		**(# of Frames)**	
% Correct (Between MSe = 309.9, within MSe = 94.7)			
F	0.52	53.13*	0.47
Decision Time (Between MSe = 1,140, within MSe = 168)			
F	1.67	14.23*	1.67
Study Time (Between MSe = 9,579, within [Frame] MSe = 2,207, within [Acc.] MSe = 54)			
F	3.60	Frame 11.52*	3.17*
F		Acc. 3.10	1.95
Delete with Copy		**(Copy/NoCopy)**	
% Correct (Between MSe = 95.0, within MSe = 58.0)			
F	0.04	68.95*	0.24
Decision Time (Between MSe = 281, within MSe = 11)			
F	1.71	40.15*	1.81
Study Time (Between MSe = 2,537, within [Copy] MSe = 140, within [Frame] MSe = 869, within (Acc.) MSe = 70)			
F	1.79	Copy 37.66*	1.84
F		Frame 0.12	0.09
F		Acc. 5.63*	0.03
Rotation		**(Orientation Discrepancy)**	
% Correct (Between MSe = 145.2, within MSe = 50.9)			
F	0.25	55.30*	0.93
Decision Time (Between MSe = 189, within MSe = 13)			
F	1.05	64.94*	0.13
Encoding Time (Between MSe = 3,938, within MSe = 31)			
F	0.39	5.82*	0.31
Rotation Time (Between MSe = 1,032, within MSe = 187)			
F	0.04	16.75*	0.13
Rotate with Copy		**(Copy/NoCopy)**	
% Correct (Between MSe = 85.7, within MSe = 2.8)			
F	0.01	15.27*	0.19
Decision Time (Between MSe = 101, within MSe = 2)			
F	0.54	1.40	0.17
Encoding Time (Between MSe = 763, within MSe = 3)			
F	0.50	0.24	1.68
Rotation Time (Between MSe = 545, within MSe = 8)			
F	0.22	12.61*	0.56
Spatial Memory		**(Amount of Concurrent Processing)**	
(Between MSe = 3.4, within MSe = 0.5)			
F	6.72*	5.10*	0.32

RESULTS

Results from the Spatial Visualization Ability × Manipulation analyses of variance for the dependent measures in the experimental tasks are summarized in Table 7. Of special interest in this table is that although most of the experimental manipulations were effective in influencing both time and accuracy of the decisions, as evidenced by the significant Manipulation main effects, only a few of the Spatial Visualization Ability differences or Spatial Visualization Ability × Manipulation interactions were significant at $p < .05$.

Mean levels of accuracy in the four tasks designed to investigate characteristics of the memory representations are illustrated in Figure 7. The virtually identical performance of high-spatial and low-spatial subjects in these tasks suggests that variations in spatial visualization ability are not associated with differences in the efficiency of encoding spatial information (Figure 7A), or in the stability (Figure 7B), precision (Figure 7C), or amount (Figure 7D), of the information that is remembered.

High-spatial subjects and low-spatial subjects did not differ significantly in decision accuracy in either the standard or the copy version of the integration task (See Figure 8). At first impression this seems rather puzzling because both tasks are very similar to the spatial integration task of the previous study in which significant ability differences were observed. However, upon closer examination it appears that this discrepancy may simply be attributable to a different manifestation of the spatial visualization ability differences across the two studies, with small differences apparent in both the time and accuracy variables in the present study rather than concentrated as a large difference in only the accuracy variable, as in the previous study. The pattern of group differences in accuracy and time in the two studies is consistent with this interpretation. In Study 1 the accuracy differences was significant (i.e., high = 83.3%, low = 70.7%, $t[22] = 3.66$, $p < .05$), whereas the time difference was not significant and actually in the opposite direction (i.e., high-spatial subjects were slower than low-spatial subjects, high = 1777 ms; low = 1505 ms, $t[22] = 1.01$). On the other hand, the high-spatial subjects in this study were slightly, but not significantly, more accurate (i.e., high = 79.0%, low = 75.1%, $t[22] = 1.67$), but were significantly faster (i.e., high = 1480 ms; low = 2063 ms, $t[22] = 2.12$, $p < .05$) than the low-spatial subjects. Low-spatial subjects were also slower than high-spatial subjects in the Integrate-with-Copy task, with the different more pronounced in the no-copy trials, thereby resulting in an interaction of spatial visualization ability and the copy/no-copy manipulation.

Several of the effects on the study time measures in the two integration tasks were also significant (see Table 7). These were generally attributable to the high-spatial subjects studying the stimuli longer than the low-spatial subjects, with these differences larger on the first compared to later frames, and larger on copy trials than on no-copy trials.

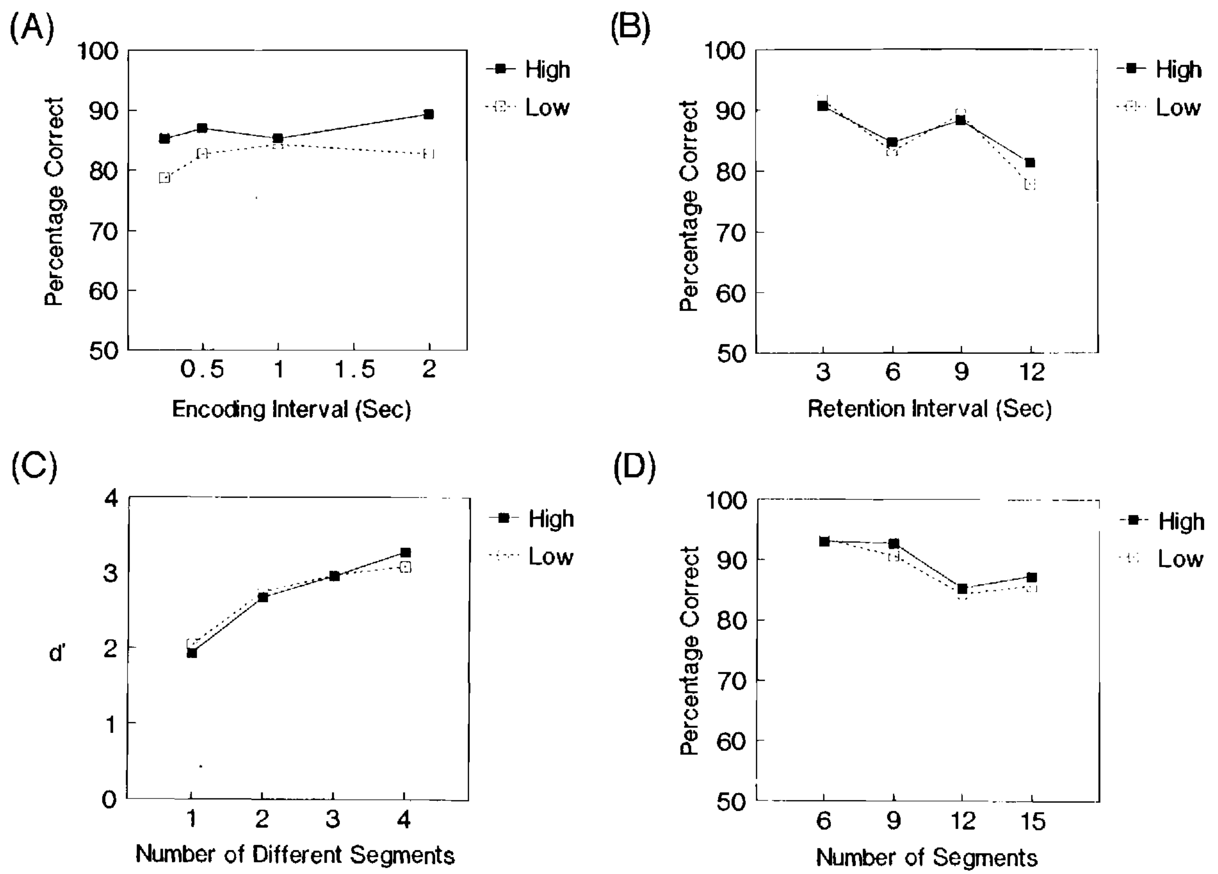


FIG. 7. Accuracy of recognition decisions for high- and low-spatial subjects in Study 2 for: (A) the encoding efficiency task; (B) the memory stability task; (C) the memory precision task; and (D) the memory capacity task.

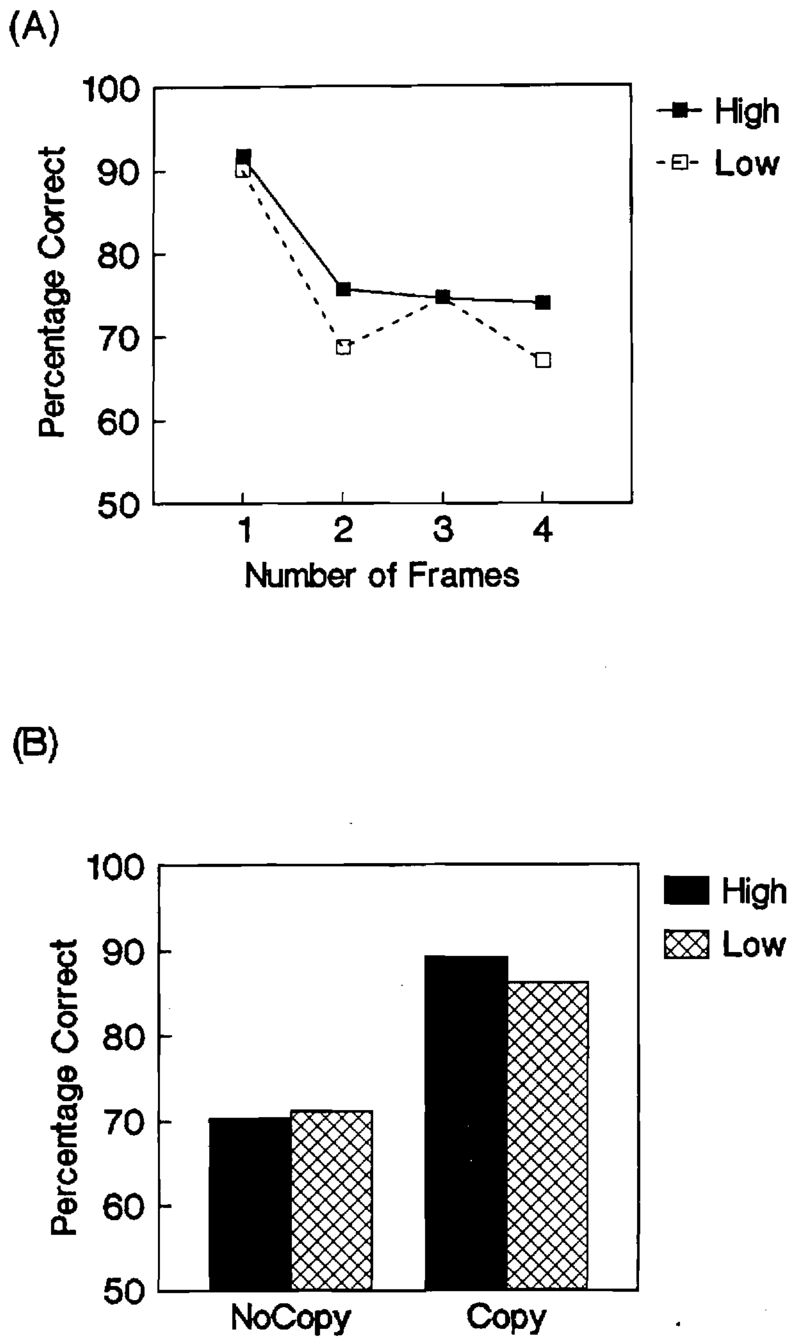


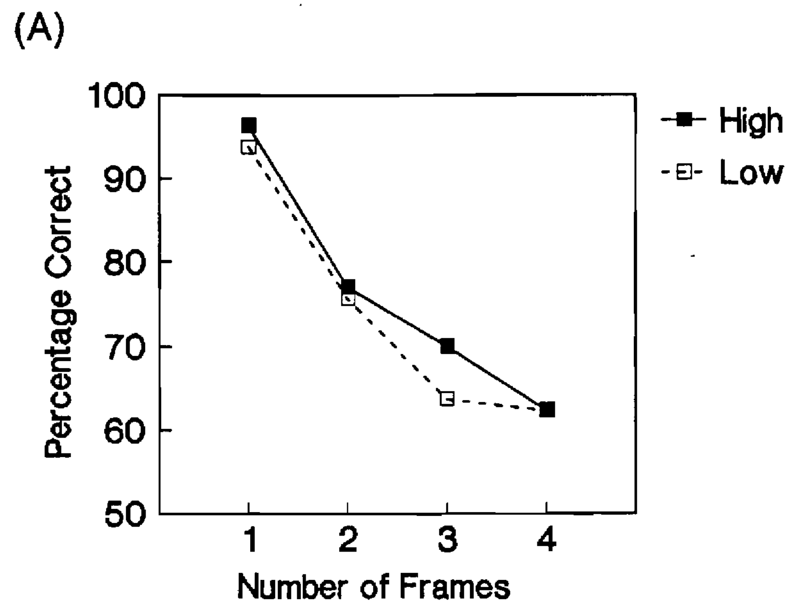
FIG. 8. (A) Mean percentage correct for high- and low-spatial subjects in the spatial integration task of Study 2. (B) Mean percentage correct for high- and low-spatial subjects in the NoCopy and Copy conditions of the spatial integration task in Study 2.

None of the spatial visualization ability differences were significant in either the deletion (see Fig. 9) or the rotation (see Fig. 10) tasks. In both cases accuracy decreased and decision time increased as the number of frames containing to-be-deleted segments (deletion task) or the angular rotation of the stimuli (rotation task) increased, but the two groups did not differ significantly across any levels of these variables. There were also no ability differences in the copy versions of these tasks, nor any differences in sensitivity too the copy manipulation. As with the integration task, high-spatial subjects spent somewhat more time studying the stimuli than the low-spatial subjects, but contrary to the integration task, these differences were larger in the first frame than in later frames.

The spatial visualization ability and manipulation (with or without concurrent processing) factors in the analysis of variance of the spatial working-memory measures were both significant, but their interaction was not. Data from several subjects were unavailable due to computer failure. Mean span estimates were 3.78 (SD = 0.91) for the 9 low-spatial subjects and 5.20 (SD = 1.77) for the 10 high-spatial subjects with available data in the version of the working-memory task with the requirement to connect Xs while remembering line positions, and 4.27 (SD = 0.75) and 5.63 (SD = 1.72) for the 11 and 12 subjects, respectively, in the version without this requirement. The discovery that the spatial ability differences were comparable in magnitude when subjects were not required to connect Xs while remembering the line positions suggests that, at least within the context of these tasks, decreasing the amount of required processing had equivalent effects in both low-spatial and high-spatial subjects. It is important to note, however, that even the version of the task without the requirement to draw irrelevant lines required considerably more concurrent processing than the four recognition memory tasks. That is, because both the input and output phases of this task were successive rather than simultaneous, subjects were always required to retain some information while concurrently encoding or recalling other information. In this respect, therefore, even the version of the task that ostensibly did not require concurrent processing probably did involve a great deal of simultaneous storage and processing.

DISCUSSION

Before attempting to integrate the results of these two studies, two important limitations of the present methodology should be mentioned. These concern the specificity and the generality of the spatial visualization construct employed in the current studies. First, because no tests of other cognitive abilities were administered that might have allowed classification of research participants along different cognitive ability dimensions, it is possible that individuals classified as high or low in spatial visualization ability may also have differed in other abilities such as inductive reasoning or general intellectual level (cf., Lohman, 1988). In this respect, there may be limits on how specific the present results are to spatial



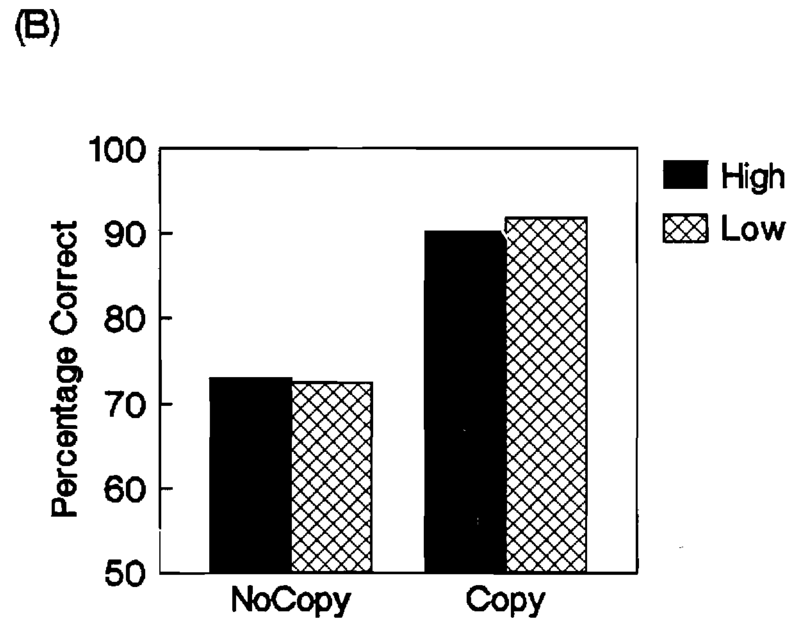


FIG. 9. (A) Mean percentage correct for high- and low-spatial subjects in the spatial deletion task of Study 2. (B) Mean percentage correct for high- and low-spatial subjects in the NoCopy and Copy conditions of the spatial deletion task in Study 2.

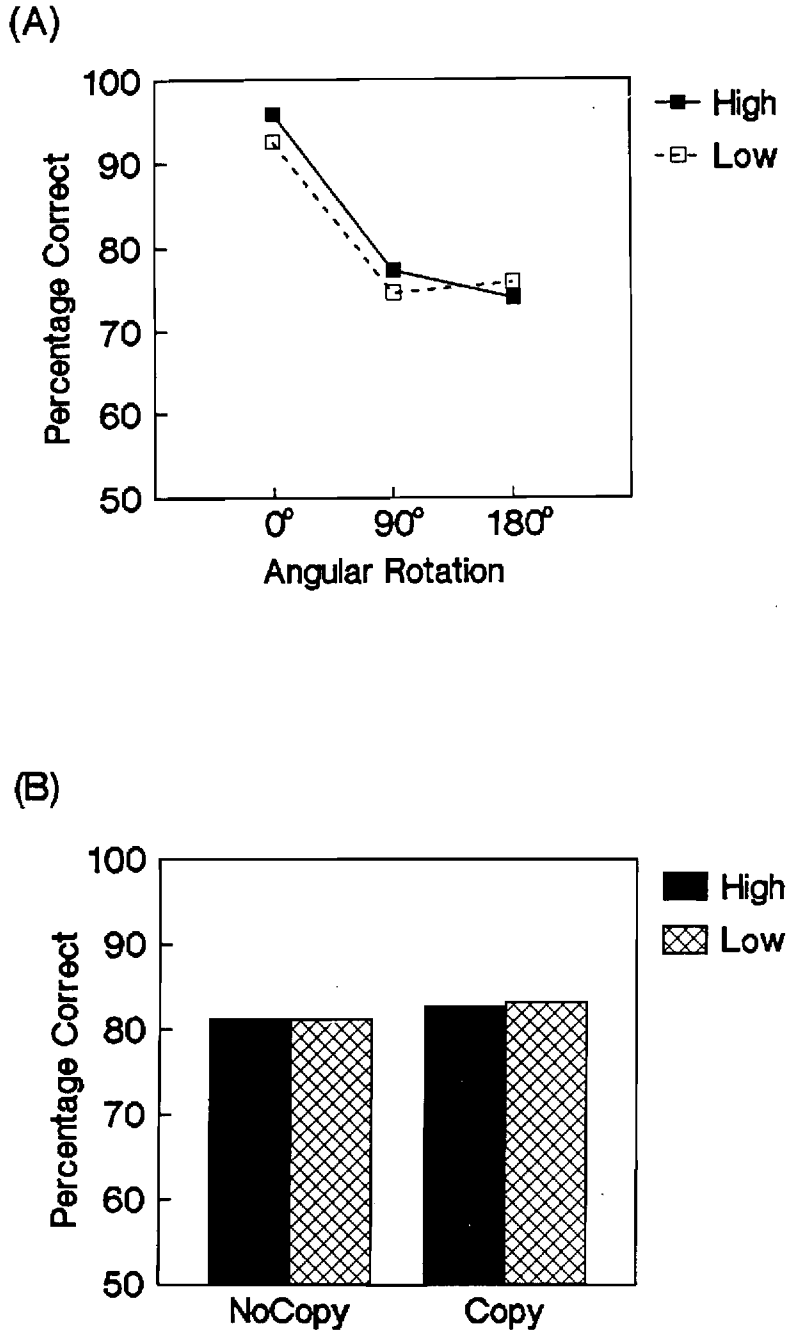


FIG. 10. (A) Mean percentage correct for high- and low-spatial subjects in the spatial rotation task of Study 2. (B) Mean percentage correct for high- and low-spatial subjects in the NoCopy and Copy conditions of the spatial rotation task in Study 2.

visualization ability, per se. The fact that the participants in the current studies were all male students at a technical university may also limit the generality of the findings because the range of spatial visualization ability in these samples is undoubtedly much smaller than that in the general population. Indeed, we suspect that the individuals we are classifying as low in spatial visualization ability would probably be at or above the median level in a broader, and more representative, sample of adults.

Despite these qualifications, substantial individual differences were observed in performance on the four classification tests. The results can therefore be examined with reference to the three hypotheses concerning the sources of individual differences in spatial visualization ability. The major prediction derived from the representational-quality hypothesis was that there should be a main effect of spatial visualization ability on decision accuracy, but no interaction with the number-of-transformations manipulation. This prediction was supported in Study 1 in all but one comparison (cube folding), and reanalysis of the data from that task revealed that the ability × manipulation interaction was not significant when conditions with near-perfect levels of accuracy were eliminated. There were also no significant interactions with the decision accuracy measure in any of the tasks in Study 2. However, questions can be raised about the relevance of the Study 2 results to this hypothesis, or indeed to any of the hypotheses, because there were also no significant spatial visualization ability differences in the accuracy measures in these tasks.

Other findings were inconsistent with the view that individual differences in spatial visualization ability are attributable to differences in the quality of internal representations. For example, the failure in Study 2 to support relatively straightforward implications of the representational-quality hypothesis clearly presents problems for this interpretation. The results of the four memory tasks suggest that, contrary to the predictions, there are little or no differences as a function of spatial visualization ability in the efficiency of encoding spatial information, or in the precision, capacity, or stability of information that is remembered.

Spatial visualization differences were also generally quite small in the transformation tasks of Study 1 on trials in which no transformation was required. Examples of this phenomenon are the equivalent performance of high- and low-spatial subjects in the one-fold trials in the cube folding task, and in trial type 1 (i.e., 0-degrees orientation discrepancy) of both the simultaneous and successive versions of the cube comparisons task. The tendency for the spatial ability differences in the spatial integration task to be smaller for the 1-frame (no integration) trials, than for the trials with two or more frames (see Fig. 5), is also consistent with this pattern.

The evidence relevant to the representational-quality hypothesis is therefore mixed, with the expected absence of ability × manipulation interactions but no spatial ability differences in measures of several presumably important properties of the spatial representation. Only partial support is therefore provided for the view that individual differences in spatial visualization are attributable to differences in the quality (i.e., accuracy and completeness) of information incorporated in the internal representations of spatial information.

The major prediction of the transformation-efficiency hypothesis was that there should be an interaction of spatial visualization ability with the number-of-transformations manipulation on the decision time variable. That is, if the time to execute the relevant transformation is slower among low-spatial subjects, then the absolute time difference between high-spatial and low-spatial subjects should increase as the number of required transformations increase. There was no support for this prediction in any of the tasks in either Study 1 or 2. Furthermore, a direct test of the speed of mental rotation, in the form of comparisons of the slope of correct decision time to orientation discrepancy across the first three trial types in the simultaneous version of the experimental cube comparisons task, failed to provide evidence of a relation between spatial visualization ability and transformation efficiency. In fact, there were no spatial visualization differences in any of the time measures in Study 1 except those in the block design task, which probably reflect the contribution of many processes in addition to transformation efficiency. Two differences were significant in Study 2, but in both cases the presence of time differences was accompanied by the absence of accuracy differences, thereby raising the possibility that the low-spatial subjects might have emphasized accuracy at the expense of speed in these tasks. None of the present results are therefore in agreement with predictions from the hypothesis that individual differences in spatial visualization ability are related to differences in the speed of executing relevant transformations.

The third hypothesis investigated in these studies was the preservation-under-transformation hypothesis in which a major cause of individual differences in spatial visualization is postulated to be the ability to maintain a stable internal representation during the process of transformation. Because it was assumed that each additional transformation increases the likelihood that the representation will be impaired or degraded, this perspective predicts an interaction between spatial visualization ability and the number-of-transformations manipulation on the variable of decision accuracy. As noted earlier, none of the interactions were significant in any of the tasks when measurement ceiling artifacts were eliminated, and, thus, this prediction was not confirmed.

The results of Phase II of the spatial integration task also fail to support the preservation-under-transformation hypothesis. The expectation from this perspective was that the differences in recognition memory between high- and low-spatial subjects would increase with an increase in the number of transformations, in this case integration or synthesis operations, intervening between the presentation and test of the information. However, the data summarized in Figure 6 indicate that the differences were approximately constant across frame positions, and were not significantly larger when there was a greater number of interpolated transformations.

Another analysis relevant to the preservation-under-transformation hypothesis was conducted on the cube face examination data in the successive version of the cube comparisons task. The reasoning was that if low-spatial subjects lose information more rapidly than high-spatial subjects during the execution of spatial transformations, then they should: (a) examine more cube faces; (b) have a greater number of repetitions of the same cube face; and (c) have fewer intervening faces between repetitions of the same face. None of the expected differences was statistically significant, and, consequently, these results are also inconsistent with the preservation-under-transformation hypothesis.

It was also predicted from the preservation-under-transformation hypothesis that low-spatial subjects would derive greater benefits than high-spatial subjects from the presence of a copy of the first-frame information during the second frame in the three transformation tasks of Study 2. However, the unanticipated equivalence of the two groups in performance of the standard versions of these tasks made this particular comparison less meaningful than expected.

In light of the failure to provide convincing support for any of the original hypotheses, it is appropriate to consider what can now be said about the reasons for these individual differences in spatial visualization ability. It is easiest to begin answering this question by first describing what the present results suggest are probably not important sources of those differences.

One factor that does not appear to differentiate among people varying in spatial visualization ability is the speed of executing most information-processing operations. This is somewhat surprising because the classification tests used to characterize an individual's level of spatial visualization ability are highly speeded in the sense that very few subjects are able to complete all of the items in the timed tests. Nevertheless, the decision times of the extreme groups differed in only 2 of the 15 tasks across the two studies for which such measures were available. There were also no spatial visualization ability differences in measures of transformation efficiency in the various tasks, as reflected in the absence of interactions on the variable of decision time between spatial visualization ability and the manipulations designed to affect the number of required transformations. Taken together, these results suggest that individual differences in visualization ability are unrelated to the speed of executing most cognitive operations.

Spatial visualization ability differences also appear to be unrelated to the ability to register, and accurately retain, spatial information. That is, little or no differences were evident in the recognition memory tasks of Study 2 in which various characteristics of memory representations were examined, and in the transformation tasks of Study 1 when no transformations were required.

In contrast to the absence of differences when spatial information only had to be registered, retained, and recognized, performance differences related to spatial visualization ability were frequently found when subjects were required to perform a spatial transformation such as folding, rotation, or integration. Although these findings are consistent with the preservation-under-transformation hypothesis, further results suggest that transformations may neither be necessary, nor sufficient, for the occurrence of performance differences related to spatial visualization ability. For example, no spatial visualization differences were evident in several tasks presumed to require spatial transformations, such as the deletion and rotation tasks of Study 2. Spatial transformations may also not be necessary for the existence of spatial visualization ability differences because effects of spatial ability were found in both the spatial working-memory tasks which do not seem to require spatial transformations.

One interpretation of the pattern of results just described is that a key factor affecting the presence or absence of differences related to spatial visualization ability is whether the task has a substantial concurrent processing component, regardless of whether that processing involves spatial transformations. However, a second interesting feature of the present results is that whereas the performance differences associated with spatial visualization ability seem to emerge when the tasks require concurrent processing, they appear to be relatively insensitive to the amount of processing required. That is, many of the observed differences seem to be of an all-or-none nature in that they are roughly the same magnitude regardless of the number of required transformations, or of the amount of concurrent processing.

This processing-threshold phenomenon is particularly evident in the cube-folding (Fig. 3) and cube comparisons (Fig. 4) tasks in which the groups varying in spatial visualization ability were equivalent when no transformations were required, but they differed by approximately the same amount as more transformations were required. The tendency for the ability differences to remain relatively constant across increases in the number of required transformations is also evident in the data with two or more frames from Phase I of the spatial integration task, illustrated in Figure 5. Although all trials in the paper-folding task required at least one transformation, the parallel functions in Figure 1 relating accuracy to number of folds in high- and low-spatial subjects indicates that the group differences remain constant across further increases in the number of hypothesized transformations.

If the preceding characterization of the performance differences associated with spatial visualization ability is accurate, then the challenge in explaining individual differences in spatial visualization ability is to provide an interpretation that simultaneously accounts for four phenomena. These are that people varying in spatial visualization ability: (a) do not differ in the speed of executing relevant cognitive operations; and (b) do not differ in the accuracy of recognition judgments or simple decisions involving spatial information; but (c) do differ when other processing operations, although not necessarily spatial transformation operations, must be performed; with (d) the magnitude of those differences remaining relatively constant once the amount of concurrent processing exceeds some minimum.

Although not a true explanation, one manner in which these phenomena might be conceptualized is in terms of Broadbent's (1971, pp. 376–377) desktop analogy of memory. The advantage of the desktop metaphor of working memory is that it explicitly incorporates the idea that there can be a tradeoff between storage and processing because the more surface area devoted to storage of books, papers, and other materials, the less that is available for actually working or doing various types of processing. Moreover, if the processing is always confined to the same region of the desktop, then there is no reason to expect further impairments in the amount of material that can be retained as more processing is required because the same proportion of the desktop is available for storage once the space has been partitioned into separate regions for storage and processing.

Now consider how the present results concerning individual differences in spatial visualization ability might be interpreted in terms of this desktop analogy of working memory. First, the fact that people varying in spatial visualization ability do not differ in the accuracy of memory or simple decision tasks when no transformations are required could be attributed to equivalent storage capabilities (e.g., surface area of desktop) when the entire surface can be devoted to storage. Second, the findings that spatial visualization ability is not related either to the efficiency or the effectiveness of executing spatial transformations can be interpreted as indicating that there are little or no differences in the speed or quality of the processing carried out in the region of the desktop allocated to processing. And third, the discovery that individual differences related to spatial visualization ability are moderate to pronounced when simultaneous storage and processing of information are required can be viewed as a problem of maintenance of information when storage space is restricted. This interpretation therefore suggests that low-spatial subjects may lose more information during processing than high-spatial subjects because they require more "work-space" than high-spatial subjects to accomplish the same quantity and quality of processing, and, consequently, previously stored information is displaced or obscured when other information is being processed. In other words, high- and low-spatial subjects may be equally proficient in storage or processing when either is carried out separately, but when performed in combination one or both aspects may be impaired in low-spatial subjects because the joint demands exceed the available capacity.

It is unclear whether this interpretation based on the desktop metaphor of working memory is truly distinct from the other interpretations proposed earlier, or is more appropriately considered a special case of either the representational-quality hypothesis or the preservation-under-transformation hypothesis. Regardless of its classification with respect to previous suggestions, however, the possibility that an important source of individual differences in spatial visualization ability is the effectiveness of storage during concurrent information processing seems to warrant further investigation.

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Age and Experience Effects in Spatial Visualization

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Three studies were conducted to investigate effects related to age and experience on measures of spatial visualization ability. All research participants were college-educated men; those in the experienced group were practicing or recently retired architects. The major results of the studies were (a) that increased age was found to be associated with lower levels of performance on several tests of spatial visualization and (b) that this was true both for unselected adults and for adults with extensive spatial visualization experience. These findings seem to suggest that age-related effects in some aspects of cognitive functioning may be independent of experiential influences.

An important hypothesis concerning the effects of adult age on cognitive functioning attributes the poorer performance of older adults to their lack of recent experience with relevant cognitive abilities. Perhaps the clearest statements of this disuse perspective were by early researchers (e.g., Sorenson, 1933, 1938; Thorndike, Bregman, Tilton, & Woodyard, 1928), but some version of the disuse hypothesis is implicit in the writings of many contemporary researchers (e.g., Ratner, Schell, Crimmins, Mittelman, & Baldinelli, 1987; Willis, 1987). As an illustration of the commitment to this perspective, Kirasic and Allen (1985), in a recent review of research on age and spatial ability, stated as an assertion rather than an hypothesis, that

> A substantial difference . . . [exists] between elderly adults' proficiency outside the psychological laboratory and their proficiency in performing tasks bearing an apparent relationship to their lives outside that setting . . . [and that] age-related performance decrements are more likely to appear on novel tasks or those involving unfamiliar stimuli or settings than on familiar tasks or those involving well-known stimuli or settings. (p. 199)

Despite considerable intuitive appeal and apparent widespread implicit acceptance, there is still very little evidence directly relevant to the disuse hypothesis of age-related cognitive decline. The studies in the current article were designed to investigate this hypothesis by examining the effects of age, experience, and the interrelations of age and experience on spatial visualization ability. *Spatial visualization,* as the term is used here, refers to the mental manipulation of spatial information to determine how a given spatial configuration would appear if portions of that configuration were to be rotated, folded, repositioned, or otherwise transformed. This construct has been identified in a number of factor-analytic studies (e.g., see Lohman, 1988, for a review), and has been found to have predictive validity for success in courses in geometry, drafting, and design (e.g., see reviews in Lohman, Pellegrino, Alderton, & Regian, 1987; McGee, 1979; Smith, 1964).

The purpose of Study 1 in the current project was to determine the nature of the age-related effects on spatial visualization ability within a sample of relatively homogeneous adults. The goal in Study 2 was to investigate possible differences in spatial visualization performance between groups of older adults presumed to vary in the amount of occupational experience requiring spatial visualization abilities. Study 3 involved an examination of the age-related trends in measures of spatial visualization among adults postulated to have continuous and extensive occupational experience using spatial visualization abilities.

Both Studies 1 and 2 involved the same psychometric tests and experimental tasks as those recently used in a study with 50 young adults (Salthouse, Babcock, Mitchell, Palmon, & Skovronek, in press). The current studies capitalized on this commonality by expressing all of the results in terms of standard deviation units of the young adults from the earlier study. This rescaling of the performance measures has the advantage of providing an intrinsically meaningful age comparison by indicating the region in the distribution of young adults in which the performance of the average member in each of the samples in Studies 1 and 2 would be located.

Study 1

As noted earlier, the major purpose of Study 1 was to examine what, if any, age-related trends in spatial visualization performance existed among a sample of adults ranging in age from 20 to 70. The sample can be characterized as relatively homogeneous because all of the participants were male alumni of a university with a primarily technically oriented curriculum, although they were currently engaged in a variety of different occupations.

The four tests of spatial visualization administered in this study, and illustrated in Figure 1, were from the Ekstrom, French, Harman, and Dermen (1976) Kit of Cognitive Reference Tests. It can be seen that the Form Board Test consists of a target shape and several smaller forms; examinees are requested to determine which combination of shaded forms can be assembled to fill the target shape. The Paper Folding Test consists of

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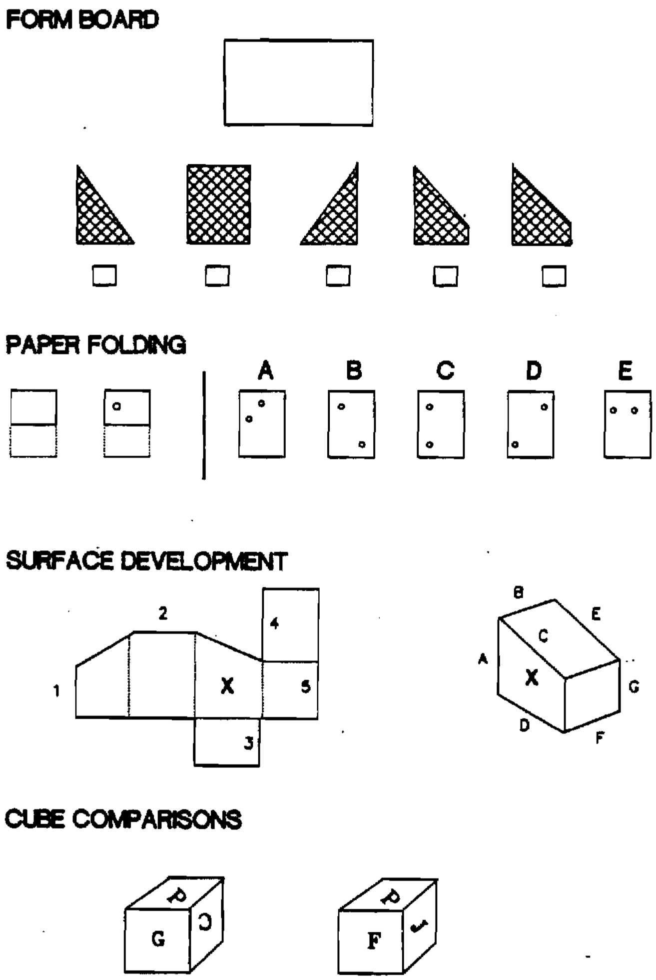

Figure 1. Illustration of types of problems in the four psychometric spatial visualization tests.

a series of illustrations representing a piece of paper undergoing a succession of folds, and then a hole punched through the folded paper. The task for the examinee is to determine which pattern of holes would result from the preceding sequence of folds and punch location. In the Surface Development Test, the examinee is asked to assemble the flat surface on the left into the three-dimensional object on the right, and then to determine the correspondence between letters from the three-dimensional object and numbers from the flat surface. And finally, in the Cube Comparisons Test decisions are to be made concerning whether the two configurations could represent the same cube.

Method

Subjects. Research participants consisted of 50 men between 24 and 67 years of age, with 10 in each decade from 20 to 70 (M = 44.8 years, SD = 13.6). All were alumni of the Georgia Institute of Technology. The mean years of education was 17.0 (age correlation = −.16), and mean health status on a self-rating scale from *excellent* (1) to *poor* (5) was 1.3 (age correlation = .07).

Procedure. Each of the four tests consisted of two separately timed parts, with time limits for each part of 3 min for Paper Folding (10 items), 6 min of Surface Development (30 items), 8 min of Form Board (24 items), and 3 min of Cube Comparisons (21 items). The two parts of each test were administered in immediate succession, with the tests presented in the same sequence (i.e., Paper Folding, Cube Comparisons, Surface Development, and Form Board) for all of the participants.

Results and Discussion

All of the tests were scored in terms of the number of items answered correctly in the allotted time, and scores on the two parts were averaged to provide a single performance measure on each test. Estimates of the reliability of each test, derived by using the Spearman-Brown formula to boost the correlation between the scores on the two parts, ranged from .82 to .89. Correlations among the measures from different tests were all significant ($p < .01$), and ranged from .49 to .71.

The next step in the analysis consisted of converting each participant's score on each test into standard deviation units based on the relevant performance distribution of the sample of 50 young adults (mean age 19.9 years) in Study 1 of Salthouse et al. (in press). These standard deviation scores were then entered into regression analyses, with chronological age as the predictor variable. Results of these analyses, in terms of the linear correlation coefficients and regression lines relating age to performance, are illustrated in Figure 2.

All of the age correlations were negative, and only that with Form Board score was not significant at $p < .01$. In each test, performance was very similar in the decade of the 20s to that of the standardization group of young adults, but it declined about 0.3 SD units per decade through the decade of the 60s. As would be expected from the results of each variable, the same pattern (i.e., an age slope of −.28 SD units per decade, $p < .01$) was evident with a composite measure based on the average of the four standard deviation scores. These results therefore indicate that there appear to be moderately pronounced age-related effects on measures of spatial visualization ability, with adults

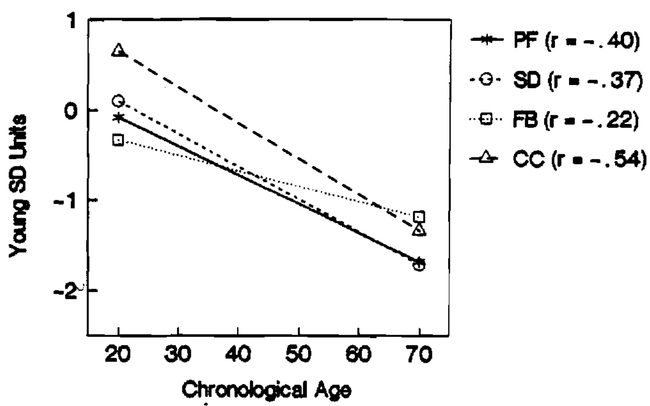

Figure 2. Regression lines indicating the relationship between age and performance for four psychometric tests of spatial visualization in Study 1. (PF = Paper Folding Test; SD = Surface Development Test; FB = Form Board Test; and CC = Cube Comparisons Test. The performance axis in Figure 2 represents the scores scaled in standard deviation units from the relevant performance distribution of 50 young adults in Salthouse, Babcock, Mitchell, Palmon, & Skovronek, in press.)

in their 60s performing between 1.0 and 2.0 *SD* units below the level of adults in their 20s.

Study 2

The goal of Study 2 was to compare two groups of older adults assumed to vary in amount of spatial visualization experience in detailed measures of spatial visualization performance. One of the groups consisted of unselected adults, and the other was composed of currently active or recently retired architects. The contrast between these two groups was considered informative because architects are individuals for whom spatial visualization abilities are presumably in continuous use by virtue of the nature of their occupation. That is, spatial abilities are needed by architects to be able to interpret, and occasionally produce, two-dimensional drawings of three-dimensional structures. It was therefore expected that if continuous and extensive experience can retard or prevent age-related declines that would otherwise occur, then the performance of the architects should be much more similar to that of young adults than to that of their age peers with lesser amounts of relevant experience.

All of the participants were administered a battery of specially designed computer-controlled tasks—in addition to the four paper-and-pencil tests used in Study 1—across five separate testing sessions. The computer-controlled tasks had two advantages over the paper-and-pencil tasks. One was that by presenting each item individually, it was possible to obtain separate measures of both the time and accuracy of the decisions, rather than relying on a single score reflecting an unknown mixture of the two aspects of performance. The second advantage of the computer-controlled tasks was that they allowed systematic manipulation of the number of required spatial transformations (e.g., folds, rotations, and integrations) in each task. This in turn permitted the investigation of possible group differences in the efficiency or effectiveness of transformations by determining whether the accuracy or time differences between the unselected and experienced adults increased as the number of required transformations increased.

Method

Subjects. The unselected and architect groups each consisted of 10 men who were comparable in age (both ranges from 60 to 78, $M = 67.3$ years for unselected, 68.7 years for architects), years of formal education (unselected = 16.3 years, architects = 17.3), and self-reported health status (unselected = 1.5, architects = 1.8).

All of the participants completed a questionnaire designed to assess the amount of experience relevant to spatial visualization ability. The questionnaire began by describing spatial visualization abilities as those used in the production or interpretation of drawings in which three-dimensional objects were represented in two-dimensional form. The first item in the questionnaire requested participants to rate (on a 5-point scale) the importance of spatial visualization abilities in their current, or most recent, job. As expected, all of the architects assigned the highest rating of importance for spatial visualization abilities in their jobs. Only two of the unselected adults assigned a rating greater than 1.0, and the mean importance rating was 1.3 for this group compared with 5.0 for the architects.

The second item in the questionnaire asked respondents whether they had ever had a job in which spatial visualization abilities were important, and if so, to indicate how long they had held that job and how many years had elapsed since they had last worked in that job. All of the architects reported that they had worked in a job requiring spatial visualization abilities, with an average duration of 40.5 years. One of the architects had retired 2 years previously, and consequently the average number of years since last holding a relevant job was 0.2 years. Three of the unselected adults reported that they had once worked in a job requiring spatial visualization abilities. The average duration these individuals worked on that job was 14 years, with an average elapsed time since last holding that position of 26 years.

Finally, respondents were asked to estimate the number of hours per month they spent producing or interpreting drawings of three-dimensional objects in their work and in their hobbies or leisure activities (e.g., in designing or building furniture or scale models). The architects estimated that they devoted an average of 135 hr per month of their work time, and 32.4 hr per month of their leisure time, to the production or interpretation of drawings of three-dimensional objects. In contrast, the three unselected adults with relevant experience estimated that they spent only about 30 hr per month in the production or interpretation of drawings of three-dimensional objects when they were working in a job involving spatial visualization abilities. The average hours per month engaged in leisure activities involving spatial visualization abilities for all 10 of the unselected adults was 0.6.

Procedure. Because the psychometric tests and experimental tasks were identical in content and sequence to those described in Salthouse et al. (in press), only a brief summary of the procedures is provided here. In the first session, participants were administered the four paper-and-pencil tests of spatial visualization used in Study 1, along with the Wechsler Adult Intelligence Scale-Revised (WAIS-R; Wechsler, 1981) Block Design Test. Part 1 of each test was administered in the order: Paper Folding, Surface Development, Cube Comparisons, and Form Board, followed by the Block Design Test, and then Part 2 of each test in the reverse order of original presentation. The computer-controlled tasks were administered in subsequent sessions, with one or two tasks presented in each session.

Five of the computer-controlled tasks loosely resembled the paper-and-pencil spatial visualization tests. The paper-folding task (Session 2) consisted of successive displays of a rectangle being folded from one to four times, followed by a hole being punched through a folded surface. The participant was then asked to decide whether a displayed pattern of holes was consistent with the pattern that would have resulted from the preceding sequence of folds and punch location. A total of 240 separate trials were presented in this task. The cube-folding task (Session 3) involved the presentation of 288 trials, each containing six squares that could be assembled into a cube. Two of the squares contained outward-pointing arrows, and the participant was asked to decide whether the arrows would be facing one another when the squares were assembled into the cube. The spatial-integration task (Session 5) involved displays of one to four frames containing line-segment patterns; the participant was asked to integrate those segments into a unitary composite and to decide whether it matched a comparison pattern. A total of 280 trials were distributed across conditions varying in the number of to-be-integrated frames. Two versions of a cube-comparisons task (Session 4) were presented, one in which all faces of the two cubes were simultaneously visible, and the other in which only one face on either cube could be examined at any given time. In both versions of the task, the configurations had varied orientations relative to one another, and the participant was required to determine whether the two configurations could represent the same cube. The total number of cube comparisons trials across the two versions of the task was 144.

Two other tasks administered in the study were a block design task (Session 3) implemented on a computer (cf. Salthouse, 1987), and a spatial working-memory task (Session 2) involving the retention of line

Table 1
Summary Statistics of Performance Measures From Study 2

	Unselected adults		Architects	
Measure	*M*	*SD*	*M*	*SD*
Psychometric test				
Paper Folding	−2.51	0.71	−1.24	1.05
Surface Development	−2.75	1.38	−1.40	1.39
Form Boards	−2.01	0.94	−0.84	1.29
Cube Comparison	−1.58	0.92	−1.18	0.99
Block Design	−1.89	1.07	−0.83	1.42
Computerized test				
Accuracy				
Paper Folding	−2.65	1.20	−0.75	1.42
Cube Folding	−1.98	1.32	−0.58	1.49
Spatial Integration	−1.24	0.98	−0.51	1.50
Cube Comparison				
Simultaneous	−1.72	1.46	−0.35	1.58
Successive	−1.89	1.72	−0.27	1.49
Time				
Paper Folding	1.38	1.49	3.23	2.29
Cube Folding	2.95	3.53	4.73	5.01
Spatial Integration	1.57	1.60	4.53	5.90
Cube Comparison				
Simultaneous	3.04	2.40	3.28	1.66
Successive	1.75	1.56	3.13	1.48

positions while using a mouse interfaced to the computer to connect points to produce irrelevant lines.

Results

Performance of the two groups in the psychometric tests is summarized in the top portion of Table 1. Notice that, as expected from the results of Study 1, the two groups are generally performing at about 1.0–2.0 *SD* units below the level of young adults. Of potentially greater interest than this age difference, however, is that the architects performed better than did the unselected adults in each of the tests. Analyses on a composite score, based on the average *z* score across the five tests, revealed that the architects ($M = -1.10$, $SD = 1.05$) performed significantly better than the unselected adults ($M = -2.15$, $SD = 0.79$), $t(18) = -2.54$, $p < 05$. Because there were 50 young adults in the standardization sample, statistical significance of the age differences in each group can be evaluated by means of *t* tests contrasting the values of each group against a mean of 0 and a standard deviation of 1. To illustrate, the *t* values for the composite scores were $t(58) = -3.05$, $p < .01$, for the contrast of older architects and young adults, and $t(58) = -7.52$, $p < .01$, for the young adult–unselected older adult contrast.

The initial data analyses in the computer-controlled tasks consisted of analyses of variance (ANOVAS) on the measures of percentage of correct decisions and median time per correct decision with group (unselected vs. architect) and level of experimental manipulation (e.g., number of folds in the paper-folding and cube-folding tasks, number of to-be-integrated frames in the spatial integration task, and number of 90° cube rotations in the cube-comparisons task) as factors. Only one of the Group × Manipulation interactions, that of Group × Number-of-90°-Cube-Rotations in the simultaneous version of the cube-comparisons task with the variable of decision accuracy, was significant, $F(5, 90) = 2.46$, $MS_e = 226.60$, $p < .05$. This interaction originated because the two groups were equivalent when the cube configurations were in the same orientation, but the architects were more accurate than the unselected adults when the configurations differed by more than 90°. Because, with this single exception, the differences between the two groups were approximately constant across levels of the experimental manipulations, in all subsequent analyses the data were collapsed across within-task conditions to yield single measures of time and of accuracy in each task.

Mean levels of accuracy for the two groups in five of the computer-controlled tasks are displayed in the middle rows of Table 1. Notice that although both groups were less accurate than the standardization group of young adults, the architects were more accurate than their unselected age peers in each task. The difference between the two older groups on the composite (average) measure of spatial visualization accuracy was significant (unselected $M = -1.90$, $SD = 1.07$, architects $M = -.49$, $SD = 1.17$), $t(18) = -2.80$, $p < .05$. Only the unselected group performed significantly lower than young adults; unselected, $t(58) = -5.18$, $p < .01$; architects, $t(58) = -1.24$, $p > .05$.

Means of the two groups for the median time to reach correct decisions in these same tasks are displayed in the bottom rows of Table 1. That all of the values are above the average of young adults indicates that both groups of older adults were slower in their decisions than were the young adults. It is interesting, however, that the architects were generally slower in their decisions than the unselected adults. This pattern was evident in the measures from each task, but the group difference was not significant in a *t* test on the composite (average) measure of spatial visualization time (unselected $M = 1.95$, $SD = 1.71$; architects $M = 3.57$, $SD = 2.44$), $t(18) = -1.83$, $p > .10$. Both groups of older adults took significantly more time than young adults to reach their decisions, unselected, $t(58) = 3.08$, $p < .01$; architects, $t(58) = 4.55$, $p < .01$.

Participants in the paper-folding and spatial-integration tasks controlled the time they spent studying the displays preceding the comparison stimulus, and consequently it was possible to analyze the average inspection durations in each of these tasks. The architects studied both sets of displays longer than the unselected adults, but in neither case was the difference statistically significant (i.e., $p > .05$). The study durations in the paper-folding task averaged 1.46 ($SD = 2.13$) young standard deviation units for the unselected adults, and 5.21 ($SD = 6.22$) young standard deviation units for the architects, $t(18) = 1.80$. Study durations in the spatial-integration task averaged 1.60 ($SD = 1.30$) young standard deviation units for the unselected adults, and 2.64 ($SD = 2.69$) for the architects, $t(18) = 1.11$.

The primary variable of interest in the computer-controlled block design task was the average number of block manipulations required to reproduce the stimulus matrix (see Salthouse, 1987, for details). Means of this measure were 1.85 ($SD = 1.46$) young standard deviation units for the unselected adults and 0.76 ($SD = 2.78$) young standard deviation units for the architects, $t(18) = 1.10$, $p > .05$. Efficiency of the block manipulations was also examined as a function of the relation between the target pattern and the initial displayed configuration of the block. A Group (architect vs. unselected) × Relation (which block face matched the target pattern) ANOVA revealed that neither the group main effect nor the Group × Relation interaction was significant ($p > .05$).

No group differences were evident in either the first or the second administration of the spatial-memory task, but in both cases performance was lower than that of the standardization group of young adults. Performance measures from several participants were unavailable because of computer malfunction, but means for the first administration of the 7 unselected adults and the 8 architects with analyzable data were −0.87 (SD = 1.24) and −1.05 (SD = 0.66) standard deviation units, respectively, $t(13) = 0.35$. Values for the 8 unselected adults and 9 architects with analyzable data for the second administration were −1.23 (SD = 0.87) and −0.69 (SD = 0.93), respectively, $t(15) = 1.23$.

Discussion

The results of both Studies 1 and 2 indicate that increased age is associated with lower levels of performance in tests of spatial visualization ability. On the average, across performance measures and subject groups, adults in their 60s appear to perform about 1.0–2.0 *SDs* below the mean level of 20-year-olds. However, the results of Study 2 suggest that these age differences may be less pronounced among individuals whose occupation provides them with extensive amounts of experience using spatial visualization abilities. Although not always statistically significant because of the low statistical power associated with the small sample sizes, the architects were more accurate than the unselected adults in every available comparison of spatial visualization performance.

Examination of the inspection and decision times revealed that the architects generally spent a longer time studying the stimuli and making their decisions than the unselected adults. It is therefore conceivable that the higher levels of accuracy achieved by the architects were a consequence of their devoting more time to all phases of the tasks than the unselected adults. On the other hand, it is also possible that the architects could have been able to perform more accurately than the unselected adults even had the two groups spent the same amount of time in each phase of the tasks. Unfortunately, it appears impossible to distinguish among these alternatives with the available data.

Study 3

Perhaps the most interesting result of Study 2 is the consistent superiority of the architects over the unselected adults in the accuracy of performance in spatial visualization tasks. This finding is subject to two quite different interpretations.

One view, which might be termed *differential preservation*, attributes the group differences to the extensive amount of experience with spatial visualization activities on the part of the architects. That is, according to this perspective, the architects performed better than the unselected adults because their 40 years of experience using spatial visualization abilities in their architectural profession contributed to the maintenance or preservation of abilities that would have declined in the absence of this experience.

The second interpretation of the architect/unselected difference in Study 2, which can be designated the *preserved differentiation* view, postulates that the differences between the two groups in their 60s are merely continuations of differences that existed when the individuals were young adults. In other words, this view suggests that initial differences in spatial visualization ability, which may have originally contributed to the choice of one's profession, were simply preserved as the people grew older.

One means of attempting to distinguish between these two interpretations consists of examining the relation between age and spatial visualization performance in a sample of architects who have been continuously using their spatial visualization abilities. If the differential preservation interpretation is correct, then little or no effects of age should be evident among people for whom age and amount of relevant experience are highly correlated. On the other hand, age-related effects comparable with those observed among unselected adults might be expected from the preserved differentiation interpretation because effects related to age could be independent of the factors contributing to the individual differences in spatial visualization ability evident in young adulthood.

The current study used this research strategy by obtaining three measures of spatial visualization performance from practicing architects whose ages ranged between 21 and 71 years. One of the spatial visualization measures was the score on the paper-and-pencil Surface Development Test, and the other two were derived from slightly modified versions of the computer-controlled paper folding and spatial integration tasks used in Study 2.

Method

Subjects. Research participants consisted of 47 male architects between 21 and 71 years of age (M = 45.0 years, SD = 13.9). The mean years of education was 17.8 (age correlation = .00), and self-assessed health status on the 5-point rating scale described earlier was 1.3 (age correlation = −.18).

Means, and correlations with age, of the responses to the items on the experience questionnaire described in Study 2 were as follows: self-rated importance of spatial visualization abilities in current job, M = 4.9, age correlation = −.34; years in relevant job, M = 20.8, age correlation = .97; hours per month producing or interpreting drawings of three-dimensional objects during work, M = 101.2, age correlation = −.50; and hours per month producing or interpreting drawings of three-dimensional objects in one's hobbies or leisure activities, M = 10.9 hr, age correlation = −.32. All these age-experience correlations were significant at $p < .05$.

Procedure. The three tasks performed by each participant were Part 1 of the Surface Development Test (Ekstrom et al., 1976) and computer-controlled paper-folding and spatial-integration tasks. All of the participants received the tasks in this same order. The paper-folding task consisted of a repeatable set of 4 practice trials, followed by two blocks of 56 trials each. Within each trial block, 8 of the trials had one fold prior to the hole punch, 16 had two folds, and 24 had three folds. An additional 8 trials in each block had no folds and, instead, merely involved recognition judgments about the identity of two patterns of circles. The purpose of these trials was to monitor the participants' attention to the task and their ability to remember configurations representing patterns of punched holes. The time spent inspecting the consequences of each fold was under the control of the participant, as was the time to reach a decision about the comparison stimulus.

The spatial-integration task consisted of a repeatable set of 8 practice trials followed by two blocks of 50 trials each. Across the two blocks, 25 trials each were presented with one, two, three, or four frames prior to the comparison stimulus. The comparison stimulus always contained 12 line segments, and hence the number of segments per frame was 12 for one-frame trials, 6 for two-frame trials, 4 for three-frame trials, and 3 for four-frame trials. As in the paper-folding task, both the time spent inspecting each frame and the time to reach a decision about the comparison stimulus were under the control of the participant.

Results and Discussion

Figure 3 displays performance on the Surface Development Test of individual architects as a function of their age. It is obvious that there is a strong negative relation between age and Surface Development score among the individuals in this sample. The regression equation for these data, represented by the solid line, revealed that there was a decrease of about 3.2 items with each additional 10 years of age. For purposes of comparison, the regression line relating age to score on Part 1 of the Surface Development Test for the 50 unselected adults of Study 1 is also displayed as a dotted line in Figure 3. It can be seen that, if anything, the age relation is less pronounced among the individuals in the sample who presumably have relatively little experience using spatial visualization abilities. The correlation with age in the unselected sample was −.39 compared with the −.69 in the sample of architects ($z = 1.43, p > .05$), and the regression slope was −1.9 items per decade compared with the −3.2 for the sample of architects.

Because the Surface Development Test has time limits that prevent many participants from attempting all items, it is possible that the age-related effects in this test are at least partially attributable to slower perceptual–motor processes rather than to an actual decrease with age in spatial visualization ability. This possibility can be investigated by examining performance

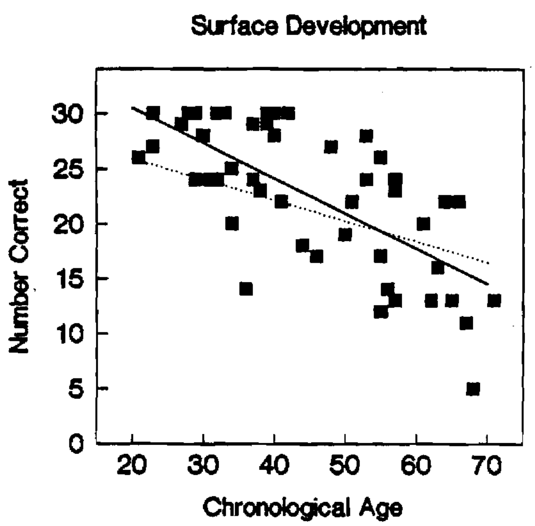

Figure 3. Scatterplot of number of items answered correctly in the Surface Development Test as a function of age in Study 3. (The solid line represents the regression equation for the displayed data, and the dotted line represents the regression equation for the relevant data of the 50 unselected adults of Study 1.

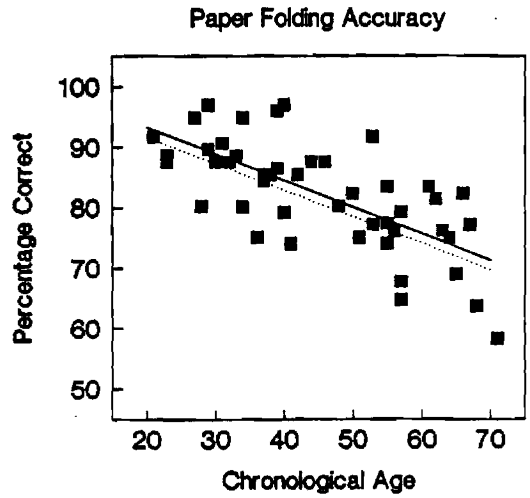

Figure 4. Scatterplot of accuracy in the computer-controlled paper-folding task as a function of age in Study 3. (The solid line represents the regression equation for the displayed data and the dotted line represents the regression equation for the data of 120 adults in a study by Salthouse, Mitchell, Skovronek, & Babcock, 1989.)

in the computer-controlled tasks, in which separate time and accuracy scores were available because the items were individually presented.

Accuracy of the paper-folding decisions averaged across one, two, and three folds is illustrated in Figure 4 as a function of the age of the architects. (Accuracy with zero folds is not included because very few errors were made in this control condition and the correlation with age was −.01.) The solid line represents the regression equation for the data of the architects, and the dotted line indicates the regression equation for comparable trials in the sample of 120 adults tested in Salthouse, Mitchell, Skovronek, and Babcock (1989). These individuals ranged from 20 to 79 years of age, 20 in each decade, and were similar to those in Study 1 in that they were all male graduates of a university with a primarily technically oriented curriculum. Age trends were very similar in the two samples, with a correlation of −.71 ($p < .01$) for the architects and −.52 ($p < .01$) for the unselected adults ($z = 1.06, p > .1$), and identical regression slopes of −4.4% per decade. Both samples also exhibited comparable relations between age and decision time (i.e., age correlations of .61 for architects and .41 for unselected adults) and between age and median inspection time of displays prior to the comparison stimulus (i.e., age correlations of .28 for architects and .37 for unselected adults).

Decision accuracy of individual architects in the spatial-integration task as a function of their age is displayed in Figure 5. The age correlation of −.47 ($p < .01$), and the regression slope of −2.9% per decade, indicate that, as with the other measures of spatial visualization performance, increased age in this sample was associated with generally lower levels of accuracy.

Analyses of median decision time and median time studying each frame containing line segments to be integrated into the composite pattern revealed that neither variable was significantly ($p < .05$) related to age. The age correlations were .15 for the decision time measure and −.09 for the study time measure.

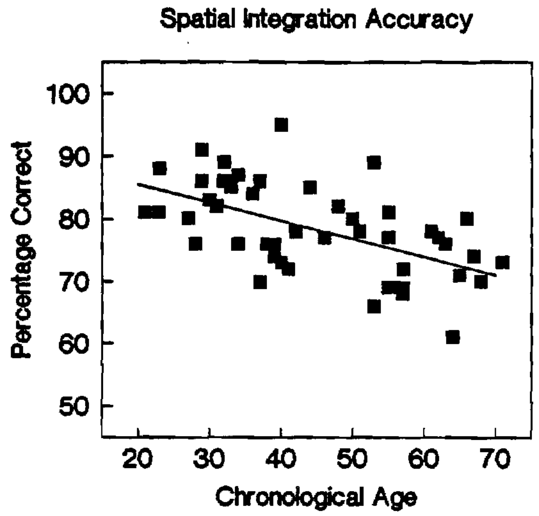

Figure 5. Scatterplot of accuracy in the computer-controlled spatial integration task as a function of age in Study 3. (The solid line represents the regression equation for the displayed data.)

It may be remembered that statistically significant negative age correlations were found with the variables of reported importance of spatial visualization abilities in one's current job and estimated number of hours per month in work or leisure activities using spatial visualization abilities. One possible interpretation of these correlations is that with increased age there is a shift in the pattern of activities within the same occupation, so that as the architects become older they spend less time actually using their spatial visualization abilities and that it is this lack of recent exercise that is responsible for the observed age-related declines in spatial visualization performance.

Although clearly plausible, two points should be considered in evaluating this interpretation. The first is that the correlation of −.34 between age and rated importance of spatial visualization abilities in one's current job is completely attributable to three individuals, because all of the other 44 participants assigned the maximum rating of 5. One of these individuals, age 68 years, assigned a rating of 3, and the other two, ages 53 and 67 years, assigned importance ratings of 4.

The second point is that although the −.50 correlation between age and estimated number of work hours per month using spatial visualization abilities is impressive, note that even the oldest participants reported spending considerable time producing or interpreting drawings of three-dimensional objects. To illustrate, architects from 21 to 45 years of age estimated that they spent about 123 hr per month using spatial visualization abilities in their work, but architects ages 46 to 71 years estimated that their time investment was still about 76 hr per month. Even this latter value represents a substantial amount of relevant experience compared with most members of the general population.

Despite these reservations, it is nevertheless important to examine the possibility that the age trends in the measures of spatial visualization ability observed in the current study might have been attributable to age-related shifts in the pattern of occupational and leisure activities. This was accomplished by examining the effects of age on spatial visualization performance in multiple-regression analyses after first controlling for the variables of rated importance of spatial visualization in one's current job, and the estimated number of work hours and leisure hours using spatial visualization abilities.

The outcome of these analyses was identical for each of the dependent measures. In each case, the age effects remained significant ($p < .01$) after statistical control of the other variables, and the regression coefficients estimating the relation between age and performance were very similar to those obtained when age was the only predictor variable. That is, the age slopes were −3.2 items per decade in both analyses of the score in the Surface Development Test, −4.4% per decade for the initial regression and −5.7% per decade for the adjusted regression of paper-folding accuracy, and −2.9% per decade for the initial regression and −3.5% per decade for the adjusted regression of spatial integration accuracy. The unambiguous conclusion from these analyses, therefore, is that the observed age trends in spatial visualization performance are not explainable in terms of age-related shifts in the type or extent of experience using spatial visualization abilities among practicing architects.

General Discussion

Several studies have previously been reported involving comparisons of adults of different ages from the same occupation, but there have been very few attempts to match tasks to specific occupations in order to investigate age-related effects among highly experienced individuals. For example, although there have been a few studies comparing school teachers in various aspects of memory performance (Fraser, 1958; Klein & Shaffer, 1986; Lachman, Lachman, & Taylor, 1982; Moenster, 1972), or in measures of reasoning (Garfield & Blek, 1952) or creativity (Alpaugh & Birren, 1977), it is not obvious why members of this occupation should be expected to differ from the general population in type or amount of experience using these abilities.

An explicit goal of Studies 2 and 3 in the current project was to investigate age-related effects in spatial visualization ability among members of an occupation in which these abilities are in virtually constant use. The field of architecture was selected as the target occupation, initially because of the intuition that spatial visualization ability was probably important in the daily activities of architects. This intuition was substantiated in the reports of the architects participating in the project because only 3 of the 57 architects in Studies 2 and 3 assigned less than the maximum rating in evaluating the importance of spatial visualization abilities in their job. These individuals also estimated that they devoted an average of over 100 hr per month to the production or interpretation of drawings of three-dimensional objects requiring spatial visualization abilities. This experience is even more impressive when it is realized that it is cumulative in that the number of years working as an architect was almost perfectly correlated (i.e., $r = .97$) with age. Increased age in these individuals was therefore associated with an enormous accumulation of relevant experience.

Of course, it is possible that the measures of spatial visualization ability investigated in the current studies were unrelated to the type of spatial visualization actually used by architects.

Although we cannot completely rule out this possibility, two sets of observations seem to argue against the proposal that different types of spatial visualization were involved in our assessments and in the normal activities of architects. The first set of results are those of Study 2 indicating that the architects were generally more accurate than their unselected age peers on all the available measures of spatial visualization ability. Evidence of this type is usually interpreted as demonstrating the validity of the measures for assessing abilities required in the target occupation, and thus it seems unlikely that the current measures are totally unrelated to the activities performed by practicing architects.

A second set of observations relevant to evaluating the possibility that architects rely on a different type of spatial visualization ability than that assessed in these studies derives from informal questioning of several research participants after they had completed their participation in the project. Without exception, these individuals reported that the psychometric tests and experimental tasks they performed seemed to involve processes similar to those used in producing or interpreting drawings of three-dimensional objects. The assessment procedures were sometimes characterized as rather abstract, but most respondents agreed that processes such as the mental assembly of discrete pieces of spatial information, and imagining transformations of rigid spatial configurations, were frequently required in the activities they performed as architects.

Another factor to consider when interpreting the present results is the possibility that the selection criteria for admission into architectural degree programs might have changed over time, so that greater emphasis was placed on abstract spatial visualization skills for more recent, and hence younger, architects. To the extent that selection criteria have changed in this manner, at least some of the age trends observed in Figures 3, 4, and 5 might be attributed to systematic shifts in sample selection rather than to any intrinsic aging-related processes. The primary difficulty with this interpretation is that it fails to explain why nearly identical age trends were observed among unselected adults for whom potential shifts in criteria used to guide admission into architectural programs were apparently not operative.

If it is accepted that the present sample of architects had considerable experience using relevant spatial visualization abilities, then the results of the current studies seem to imply that increased age is associated with lower levels of spatial visualization ability even among individuals who are using these abilities extensively in their occupation. A similar finding of relatively little influence of experience on the age trends in the efficiency of specific processes was reported by Salthouse (1984) and Salthouse and Saults (1987). Experience in these studies was assessed in terms of various indexes of the time engaged in transcription typing, and the measures of relevant performance consisted of choice reaction-time and visual–manual transcription or substitution rate. Although relative to the young individuals, the older individuals in these studies had considerably more cumulative typing experience, and hence presumably more experience with the components of rapid responding and visual–motor substitution, the age-related trends for the measures of reaction time and substitution rate in these studies were nearly identical to those reported in studies involving unselected samples of adults.

The discovery of sizable age-related effects on performance measures relevant to frequently performed occupational activities among architects in the present study, and among typists in the earlier studies, suggests that the influence of age-related factors on certain aspects of cognitive functioning may be relatively independent of experience. These findings therefore appear inconsistent with interpretations postulating that a major determinant of age-related differences in cognition is a lack of recent exercise or practice with the relevant abilities on the part of older adults. Experience clearly contributes to greater proficiency in many aspects of performance, but the results of these studies seem to suggest that it apparently does not substantially alter the effects associated with increased age on measures of some of those aspects.

It is important to emphasize that even though the present results suggest that older architects are less proficient than their younger colleagues in several measures of spatial visualization ability, it should not be concluded that there is a negative relation between age and professional competence as an architect. It is quite possible that a different level of analysis, or a focus on other architectural activities, would reveal benefits associated with increased experience and age. Architectural competence obviously involves much more than the efficiency of executing certain types of spatial transformations, and none of these other aspects, which might be expected to increase with experience, were evaluated in these studies. For example, amount of relevant knowledge about the interrelations of building materials, building type, and building site almost certainly accumulate with experience, and yet no assessment of this kind of knowledge was attempted in these studies. A reasonable goal for future research is to attempt to identify how specific abilities and various forms of knowledge combine to produce high levels of competence in the architectural (or any other) profession and to determine whether there are changes in this mixture with increased age or experience.

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Effects of Age and Naturally Occurring Experience on Spatial Visualization Performance

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Running Title: Aging and Spatial Experience

Abstract

A questionnaire designed to assess experience with activities presumed to require spatial visualization abilities, and psychometric tests of these abilities, were administered to 383 adults ranging from 20 to 83 years of age. Although research participants varied considerably in the amount of self-reported experience, statistical control of experience resulted in relatively modest attenuations of the relations between age and spatial visualization performance. These findings seem inconsistent with a strong disuse interpretation of cognitive aging phenomena, and suggest that at least some age-related differences in cognitive functioning are independent of the amount of experience with relevant activities.

One of the most popular hypotheses proposed to account for the age-related declines observed with certain measures of cognitive functioning attributes those declines to various forms of disuse or lack of practice. Although seldom articulated as an explicit theory, the following sample of quotations illustrate that this perspective has been implicitly accepted for more than half a century.

> A decrease in test ability among adults is probably caused by the fact that adults, as they grow older, exercise their minds less and less with the materials found in psychological tests (Sorenson, 1933, p. 736).

> The 'losses' are in large measure ... a by-product of disuse ... old age acts selectively and most decidedly on those functions which have suffered for want of practice (Sward, 1945, p. 478-479).

> ...in one's own field where experience has been accumulating over a period of many years, there is little evidence for any decline with the years, at least until extreme old age is reached (Gilbert, 1952, p. 130).

> Those who have spent their lives working with their hands and interpreting perceptual data retain the ability to deal with perceptual and constructional problems ... (Williams, 1960, p. 217-218).

> ...studies of the functions of the organism within his own environment show relatively small age-related differences or changes and in many cases advancing age is correlated with improvement (Fozard & Thomas, 1975, p. 117).

> ...the declines that are observed in abilities which are used frequently appear to begin at a later age and to be less drastic than are the

> declines in abilities which are exercised less frequently (Denney, 1982, p. 824).

> Ability tasks that are commonly used in everyday life tend to be insensitive to age (Birren, Cunningham, & Yamamoto, 1983, p. 552).

> ...when tasks relate more strongly to the ecological niches that the older person inhabits, age-related deficits are less prominent (Charness, 1985, p. 226).

An important category of research relevant to the disuse hypothesis has involved comparisons across people presumed to differ in the nature and extent of their experiences. Research within this category has varied with respect to whether the focus on the individual's experience and cognitive performance has been broad or narrow. Studies with a broad focus have attempted to relate characterizations of the individual's general activity level (e.g., Arbuckle, Gold, & Andres, 1986; DeCarlo, 1974; Schooler, 1984), or his or her self-assessed cognitive demands (e.g., Owens, 1953; Schwartzman, Gold, Andres, Arbuckle, & Chaikelson, 1987), either to a variety of miscellaneous cognitive measures, or to a composite score of general intelligence. Most of these studies have reported rather weak relations between experience and cognitive functioning. For example, the semipartial correlation between a measure of the frequency of 23 activities and a composite measure of intelligence in the Schwartzman, et al. (1987) study was only .13.

Although not without value, studies with a broad focus suffer from two problems associated with the grossness of the categorization of both the experience and the cognition constructs. One problem is that it is difficult to rule out the influence of potentially confounding third variables (such as health status) when the evaluations of neither experience nor of cognition are very specific. A second problem is that the relations between experience and cognition are likely to be quite weak when those constructs are assessed in very general terms. That is, the greatest effects of experience will probably be evident between specific measures of cognition and particular frequently performed activities, rather than between global measures of cognition or general intelligence and gross categorizations of experience.

One means of achieving closer linkages between experience and cognition is to rely on samples comprised of members of particular occupational groups, and to investigate age-related effects on occupationally-relevant measures of cognitive performance. Perhaps the earliest, and almost certainly the largest, of the occupation-specific studies relevant to aging involved a battery of perceptual and cognitive tests administered to 544 aircrew officers (Glanzer & Glaser, 1959; Glanzer, Glaser, & Richlin, 1958). The stated purposes of this project were to "...measure the skills required for performance of aircrew officers ... [and to] ... measure the effects of aging upon skilled performance (Glanzer & Glaser, 1959, p. 89)." Unfortunately, the assessment of age-related effects was not very powerful due to a relatively narrow range of ages, with only 14, or less than 3%, of the research participants over the age of 40. Despite this restricted age range, significant negative correlations between age and performance were reported on 8 of the 14 tests. Furthermore, the largest age effects were evident on a test with the highest face validity as a measure of pilot skill. This was a test titled Instrument Comprehension, in which the examinee is required to integrate information from a compass and an artificial horizon to indicate the current position of an airplane. Not only was the simple age correlation with this measure statistically significant ($r = -.33$), but it was only slightly attenuated (to $r = -.24$) after statistically controlling the presumably relevant variable of total number of hours of flying experience.

A similar finding of significant age-related cognitive differences favoring younger adults within a sample of adults for whom the relevant abilities can be assumed to have been in continuous use was recently reported by Salthouse, Babcock, Skovronek, Mitchell and Palmon (in press). Most of the participants in this project were architects, and the measures of cognitive performance consisted of scores on tests of spatial visualization. The 47 architects in Study 3 of that report ranged from 21 to 71 years of age, with a correlation of .97 between age and number of years using spatial visualization abilities in one's job. Although it seems reasonable to assume that all of these practicing architects had extensive, and nearly continuous, use of spatial visualization abilities, highly significant age-related declines (i.e., age correlations of -.69, -.71, and -.47) were observed in three measures of spatial visualization performance.

The results of the two occupation-specific projects just described are therefore consistent in providing rather discouraging evidence for the disuse perspective of cognitive aging. Objections can be raised against each of these studies, however, and consequently it is desirable to replicate the major results before reaching a definitive conclusion regarding the disuse interpretation. Unfortunately, the strategy of examining age trends in samples comprised of members of a particular profession or occupation is hampered by the difficulty of recruiting appropriate research participants. To illustrate, in our recent study of architects, over 1100 letters were mailed to nearly all of the members of the American Institutes of Architects professional organization residing in a large metropolitan area, and approximately 400 of these individuals were later telephoned to make additional appeals for participation. Ultimately, however, only about 60 individuals were successfully recruited to participate in the two relevant studies. Furthermore, it was impossible to determine whether the architects who participated in the project were representative of the larger population of architects.

A different research strategy was employed in the current project by recruiting participants from the general population, and then administering a questionnaire to evaluate the extent of each individual's experience with different activities presumed to require spatial visualization ability. Three types of information were requested in the questionnaire in order to assess recent experience, cumulative experience, and subjective ability. The two categories of experience were distinguished to allow investigation of age relationships with both the current frequency, and the accumulated frequency, of activities presumed to be relevant to spatial visualization. Information about both kinds of experience is desirable because while proponents of the disuse perspective generally argue that increased age is associated with lesser amounts of recent experience with relevant activities, the cumulative experience of an individual may actually be greater with increased age. Ratings of subjective ability were included because people who spend considerable time performing a given activity might be assumed to have higher perceptions of their level of ability in that activity than people who devote relatively little time to the activity. In this respect the subjective ability ratings may prove useful in evaluating the validity of the experience information.

In addition to the experience questionnaire, six cognitive tests were also administered to all research participants; two designed to assess spatial visualization ability, two designed to assess the closely related cognitive ability of inductive reasoning, and two designed to assess the presumably unrelated cognitive ability of perceptual speed. The purpose of the tests of inductive reasoning and perceptual speed was to provide a further check on the validity of the information obtained from the experience questionnaire. That is, if responses to the experience questionnaire are accurate indications of the amount of experience each individual has had with explicitly spatial activities, then a gradation in the magnitude of the correlations between the questionnaire responses and the measures of cognitive performance would be expected, with the highest correlations for the spatial visualization measures, lower correlations with the inductive reasoning measures, and the lowest correlations with the perceptual speed measures.

The primary questions investigated in the project were whether experience with activities requiring spatial visualization ability either mediates, or moderates, age-related differences in measures of spatial visualization performance. The mediation position would be supported if there is little or no effect associated with age after statistically controlling the influence of variables reflecting amount of relevant experience. A somewhat weaker hypothesis is that differential experience does not mediate the effects related to age, but instead moderates those effects such that the age-related influences are smallest among individuals with the greatest amount of experience. The specific prediction from the moderation perspective, therefore, is that the age and experience variables will have interactive effects on measures of spatial visualization performance.

Method

Subjects A total of 383 adults between 20 and 83 years of age contributed valid data to the project. The data from five additional individuals were considered invalid and were discarded prior to analyses because the participants had difficulty understanding the test materials, or because they arrived at the testing session in an obviously inebriated state. All participants were recruited from newspaper advertisements and were tested in small groups. Participants consisted of 186 males and 197 females, with from 20 to 47 individuals in each decade-sex grouping from the 20s to 70+. Each individual was paid $10 for his or her participation in the 90-minute session.

Procedure The testing session began with the research participants completing a questionnaire intended to assess the amount of recent and cumulative experience the individual had with activities presumed to require spatial visualization abilities, and to obtain a self-appraisal of his or her level of ability in each activity. For each of 10 activities (listed in Table 2), the individual was asked to: (a) rate his or her ability on a 5-point scale ranging from "much below average" to "much above average"; (b) estimate the average number of hours per month devoted to that activity over the last six months; and (c) estimate the number of years in which an average of at least 15 hours per month had been devoted to that activity.

The remainder of the test session was devoted to the performance of six cognitive tests. The tests, in the order in which they were presented, were the Number Comparison Test, the Paper Folding Test, the Letter Sets Test, the Abstraction Test, the Surface Development Test, and the Finding A's Test. All but the Abstraction Test were from the Kit of Factor-Referenced Cognitive Tests (Ekstrom, French, Harman, & Dermen, 1976). The Abstraction Test was from the Shipley Institute of Living Scale (Shipley, 1986).

The Paper Folding and Surface Development Tests were intended to assess spatial visualization ability. The task in the Paper Folding Test is to determine which pattern of holes would result if a piece of paper were folded in the manner illustrated and a hole punched in the specified location. Three minutes are allowed for the individual to complete as many of the 10 five-alternative multiple choice items as possible. Items in the Surface Development Test consist of an unfolded and an assembled drawing of a three-dimensional object, with the examinee required to determine the correspondence between edges in the two drawings. Six minutes are allowed to complete as many of the 30 items as possible.

The Letter Sets and Abstraction Tests were designed to assess inductive reasoning ability. The task in the Letter Sets Test is to determine which of five sets of letters is different in some way from the remaining sets of letters. Seven minutes are allowed for the examinee to perform the 15 problems in the test. The Abstraction Test is a series completion test containing sequences of numbers, letters, or words that are to be continued by supplying the item that most naturally continues the sequence. Five minutes are provided for the solution of the 20 items on the test.

The Number Comparison and Finding A's Tests were designed to assess perceptual speed. The task in the Number Comparison Test is to decide as rapidly as possible whether two numbers are the same or different. A time limit of 90 seconds is provided for examinees to complete as many of the 48 items as possible. The task in the Finding A's Test is to locate all the words containing the letter "a" in five columns of 41 words each. Two minutes are allowed for the examinee to detect as many of the 100 targets as possible.

Results

Cognitive Performance Measures

For most of the analyses, performance in each test was summarized by the number of items answered correctly minus the number of items answered incorrectly. This scoring method has the dual advantages of providing a correction for guessing, while also increasing the range of possible scores. The correlation matrix illustrating the relations among these cognitive performance measures and the variables of age, sex, education, and self-reported health status is displayed in Table 1.

Place Table 1 about here

Because the cognitive tests were selected a priori to represent three distinct abilities, and because the largest correlation with each measure was generally with the other measure hypothesized to represent the same ability (Table 1), composite ability scores were created by averaging the z-scores from the two relevant measures. That is, a spatial visualization composite was created by averaging the individual's z-scores from the Paper Folding and Surface Development Tests, an inductive reasoning composite was created by averaging z-scores from the Letter Sets and Abstraction Tests, and a perceptual speed composite was created by averaging z-scores from the the Number Comparison and Finding A's Tests. Correlations of these composite measures with chronological age were -.37 for spatial visualization, -.27 for inductive reasoning, and -.28 for perceptual speed (all significant at $p < .01$).

Although conceptually distinct, the composite measures were not independent as the intercorrelations were .69 between spatial visualization and inductive reasoning, .33 between spatial visualization and perceptual speed, and .51 between inductive reasoning and perceptual speed.

Questionnaire Responses

Means and standard deviations of the responses to the individual questionnaire items are presented in Table 2. Responses were missing on one or more items in 40 of the questionnaires, and hence all subsequent analyses are based on data from the 343 individuals with complete records. In all cases higher numbers reflect greater quantities, with the values in the recent experience column representing hours per month over the last six months and those in the cumulative experience column representing years with an average of at least 15 hours per month. Most of the distributions of recent experience responses were positively skewed. To illustrate, all of the medians (50th percentile values) were 3 or less whereas the values at the 95th percentile for items 1 through 10 were, respectively, 37.5, 30, 30, 20, 20, 20, 40, 5, 10, and 4 hours per month. For all but the last three activities, therefore, a considerable amount of recent experience was reported by at least some of the research participants.

Place Table 2 about here

In order to reduce the number of questionnaire variables for subsequent analyses, a principal components analysis was conducted on the data from all 30 items in the questionnaire. (Very similar results were obtained with oblique-rotation factor-analysis procedures, and hence the structural configuration of scores is not specific to this particular method of analysis.) Loadings of the items in excess of .3 on the eight components with eigenvalues greater than one, after orthogonal rotation, are displayed in Table 3. Correlations between the component scores and the age, sex, spatial visualization, inductive reasoning, and perceptual speed variables are displayed in Table 4. None of the correlations between the component scores and the education or self-reported health variables was significant (i.e., $p > .05$), and thus they are not reported in Table 4.

Place Tables 3 and 4 about here

The first three components can be interpreted as representing relatively broad or non-specific cumulative experience, subjective ability, and recent experience components because all of the loadings for each component derive from the same type of response items. That is, the first component is based exclusively on responses to the cumulative experience questions, the second component on responses to the self-rated ability questions, and the third component on responses to the recent experience questions.

As might be expected, Table 4 indicates that scores on the cumulative experience component increase with age whereas those on the recent experience component decrease with age. Scores on the subjective ability component are negatively correlated with age, but positively correlated with both spatial visualization performance and inductive reasoning performance. These latter results suggest that the overall self-appraisals of ability have some validity in that people with higher self ratings perform better than people with lower self ratings on tests of spatial visualization, and to a lesser extent, also on tests of the closely-related inductive reasoning ability.

In contrast to the first three components, the pattern of loadings for the remaining components are more specific to the particular activity being described rather than to the type of response information requested. These components can therefore be inferred to represent experience with specific spatial activities. Based on the loading patterns, the components have been labeled Perspective, Clothes, Puzzles 1, Puzzles 2, and Directions, respectively. Examination of Table 4 reveals that, among the specific components, only Component 4 (Perspective) and Component 8 (Directions) have significant correlations with the composite measure of spatial visualization performance.

One means of examining the validity of the experience assessments is to compare the responses of members of occupations assumed to require spatial visualization abilities with the responses of the entire sample. For this purpose the data from 11 participants who reported their occupations as architects, civil engineers, or interior decorators were grouped together and their scores on each of the components computed. The mean values for the individuals in this subsample were within one standard deviation of the sample mean for all components except component 4, for which their mean component score was 2.29 with a range of 1.04 to 3.78. Component 4 is the perspective component with primary loadings on activities 2, 4, and 7 (see Table 3). Comparisons of the estimated number of hours per month devoted to these activities revealed that the subsample estimates averaged 50.9 hours per month "considering how an object or building would look from a different position" (compared to 7.2 hours for the entire sample), 27.2 hours per month "following instructions for the assembly of furniture, toys, models, etc." (compared to 5.8 hours per month for the entire sample), and 50.7 hours per month "producing or interpreting technical drawings of three-dimensional objects" (compared to 5.7 hours for the entire sample). The finding that the estimates from people expected to have greater experience with certain spatial visualization activities were substantially higher than those from the entire sample enhances the credibility of the experience ratings.

Simultaneous Analysis of Age and Experience

A series of multiple regression analyses were conducted on the spatial visualization, inductive reasoning, and perceptual speed composite variables. The first analysis with each variable was a stepwise regression to determine which of the eight components from the questionnaire data had significant ($p < .01$) effects on the composite measures of cognitive performance. Three components -- 2, 4, and 8 -- were significant with the spatial visualization variable, one -- component 2 -- was significant with the inductive reasoning variable, and none was significant with the perceptual speed variable. The regression analyses were then repeated with only the significant components and age as predictors, and then were repeated again for the spatial visualization and inductive reasoning variables with perceptual speed as an additional predictor. Identical analyses were conducted on composites based on the number of correct or right responses and on the number of incorrect or wrong responses, as well as the primary analysis based on the number of right responses minus the number of wrong responses. Results from these analyses are summarized in Table 5.

Place Table 5 about here

The first point to note about Table 5 is that the absolute value of the variance estimates are larger with the composite based on number of right responses than with that based on the right-wrong scores. This is probably a reflection of the lower reliability of difference scores because all of the age correlations with number right scores were negative and all of those with the number wrong scores were positive. (Note that this is inconsistent with what one would expect if there were a greater emphasis on accuracy than on speed with increased age.) A second point concerning the data in Table 5 is that although similar patterns are evident in the right-wrong and right scores, very few systematic effects were evident in the analyses based on number of wrong responses.

It is evident in Table 5 that the age-related effects in both the spatial visualization and inductive reasoning variables were attenuated by statistical control of the questionnaire components and of perceptual speed. The proportion of age-associated variance for the spatial visualization variable was reduced from .139 to .083 after controlling the significant components from the questionnaire, to .085 after controlling perceptual speed, and to .048 after controlling both the questionnaire components and perceptual speed. Expressed in percentages, the age effect was reduced by 40.3% [(.139-.083)/.139] after control of the questionnaire components, by 38.8% [(.139-.085)/.139] after control of perceptual speed, and by 65.5% [(.139-.048)/.139] after control of both. The age effects on the inductive reasoning variable were reduced less by controlling the questionnaire components, and more by controlling perceptual speed. That is, the age effects were reduced 21.6% [(.088-.069)/.088] after control of Component 2, 67.0% [(.088-.029)/.088] after control of perceptual speed, and 77.3% [(.088-.020)/.088] after simultaneous control of both Component 2 and perceptual speed.

As noted earlier, Component 2 reflects the individual's estimates of his or her level of ability across all activities, and because of the method used to identify components, is independent of the amount of cumulative or recent experience with any of the activities. A more appropriate evaluation of the contribution of relevant experience to the age effects on measures of spatial visualization should therefore be restricted to effects associated with Components 4 and 8. The total variance accounted for by age, Component 4, and Component 8 was .176, with .120 of that uniquely associated with age. The reduction of age-associated effects was therefore 13.7%, [(.139-.120)/.139]. After control of perceptual speed the proportion of age-related variance was .085, and this was reduced by 15.3%, to .072, after control of Components 4 and 8. Very similar estimates of the contributions of experience were derived from the measure of number of right responses as the reductions in age-related variance were 13.1% without considering perceptual speed, and 14.1% for the speed-adjusted measures.

Multiple regression analyses were also conducted with age X component cross-product interaction terms entered after age and the eight questionnaire components. None of the interactions was significant (i.e., all $p > .20$) for either the right-wrong or the right scores for the inductive reasoning or perceptual speed variables. None of the interactions reached the .01 significance level with the right-wrong scores for the spatial visualization variable, but the interactions of age with Components 2, 4, and 8 approached significance (i.e., $p < .10$) with one or both of the right-wrong or the right scores. Another analysis was therefore conducted as a further check on the possibility that experience may have moderated age-related effects on spatial visualization. For this purpose individuals were categorized into three groups on the basis of their scores on Components 2 (Subjective Ability), 4 (Perspective), and 8 (Directions). Regression equations relating age to the composite measure of spatial visualization performance were then computed for the individuals in each of these three groups. The resulting regression lines are illustrated in Figures 1 (Component 2), 2 (Component 4), and 3 (Component 8). Confidence intervals around the regression coefficients revealed that only the medium Component 2 and low Component 2 regression equations had significantly ($p < .01$) different slopes.

Place Figures 1, 2, and 3 about here

The important point to note in Figures 1, 2, and 3 is that although the regression lines for the individuals with higher values on the components are elevated relative to those with lower values, reflecting the significant main effects of these components, the slopes of the lines, and particularly those of the extreme groups, are nearly parallel. This suggests that the age effects are similar throughout the range of component values, and implies that it is not the case that the magnitude of the age effects is attenuated among individuals with the greatest amount of experience or self-assessed ability.

Discussion

Before considering the implications of the current results, it is important to note that the relation between age and spatial visualization performance evident in this study is consistent with that found in numerous earlier studies. For example, the correlation of -.37 between age and the composite measure of spatial visualization in the present study is nearly identical to the median of -.39 for 18 correlations between age and spatial ability measures summarized in Table 12.1 of Salthouse (1985). This is noteworthy because the current sample is relatively select, with an average of over 15 years of education and a -.01 correlation between age and amount of education (Table 1).

The age-related effects on both the spatial visualization and inductive reasoning variables were substantially reduced after control of perceptual speed and self-rated ability. The findings with perceptual speed replicate those of earlier studies (e.g., Hertzog, 1989; Salthouse, Kausler & Saults, 1988; Schaie, 1989), and are consistent with suggestions that at least some of the adult age differences in cognitive functioning are attributable to age-related reductions in the rate of processing information.

The effects associated with Component 2 are not easy to evaluate because it is not clear how the self-ratings of ability should be interpreted. In particular, it is difficult to determine the extent to which these ratings reflect personality characteristics such as self-confidence or feelings of self efficacy, as opposed to actual levels of cognitive ability. If the self ratings are merely alternative indicators of general cognitive ability, then they are of limited interest as potential mediators or moderators of age-related differences in cognitive functioning. Unfortunately, it was not possible to distinguish between these interpretations of the self-rating measures in the present study.

The major conclusion implied from the present findings is that many of the age-related effects on spatial visualization observed in this study, and presumably other studies, seem to be relatively independent of the amount of relevant experience the individuals have received. That is, experiential factors appear to be responsible for only about 15% of the total age-related variance observed in measures of spatial visualization. However, acceptance of this conclusion is contingent upon a number of assumptions which can each be challenged. It is therefore useful to consider arguments that can be raised in defense of three critical assumptions.

One assumption of the current approach is that the responses to the questionnaire provide a valid indication of the actual experiences of the individuals. Evaluating the validity of self-report information of this type is always difficult, but there are several reasons to have confidence in the present questionnaire results. First, the distributions of responses to the questionnaire items appear plausible, with average responses near the middle of the range for the subjective ability ratings, and relatively small amounts of reported experience for most activities (see Table 2). Second, the principal components analysis resulted in a coherent pattern of both general components, reflecting responses to each type of scale, and specific components, representing meaningful configurations of self-rated ability, recent experience, and cumulative experience for specific abilities. And third, members of occupations in which one would expect frequent usage of spatial visualization abilities had exceptionally high scores on the component concerned with spatial perspective.

A second assumption implicit in the current approach that could be challenged is that the range of experience was sufficient to reveal the expected influences of differential experience. Although it may be impossible to dispel all reservations about this assumption, it is important to point out that a considerable range of relevant experience was reported across participants in the current study. To illustrate, the individuals in the top third of the distribution of values on Component 4 reported an average of 40 hours per month performing the three constituent activities (i.e., 2, 4, and 7), while those in the bottom third of the distribution reported an average of only 6.5 hours per month with these activities. Despite this substantial difference in the amount of time spent performing what appear to be relevant activities, the data in Figure 2 indicate that the age trends in measures of spatial visualization performance for the two subgroups were nearly identical. It is clearly possible that individuals with more extreme levels of experience might be found and that differential age trends might be evident within that sample, but the range of naturally occurring experience with spatial visualization activities in the current sample does not appear unrepresentative of that expected in the general population.

A third assumption implicit in the approach used in this study is that the activities mentioned in the questionnaire are among the most relevant for spatial visualization abilities. An objection could be raised that the requirements of these activities are not sufficiently similar to what the examinee must do in the Paper Folding and Surface Development tests used in the assessment of spatial visualization ability to expect substantial relations between experience and spatial visualization performance. This is a plausible concern, but we have been unable to identify relatively common activities that appear to have greater relevance to the spatial visualization construct. Moreover, it is interesting to consider the implications for the disuse hypothesis of the difficulty of finding activities relevant to the abilities observed to decrease with increased age: if there are no activities which provide appropriate experience, then neither the concepts of use nor of disuse may be very meaningful with respect to the maintenance or decline of spatial abilities across the lifespan.

Additional objections to the current procedures could undoubtedly be raised, but it is noteworthy that results similar to those found in this study have previously been reported with quite different methodologies. For example, three studies have employed a strategy of examining age trends in molecular, or basic, processes after equating individuals of different ages in the proficiency of a molar target activity. Charness examined unexpected recall of bridge hands among bridge players (Charness, 1979), and of chess configurations among chess players (Charness, 1981), and Salthouse examined measures of perceptual-motor speed among transcription typists (Salthouse, 1984). In each case, significant age-related declines were found in the measures of the molecular processes despite what can be assumed to be moderate to high amounts of relevant experience for most research participants.

Two studies examining the joint effects of age and reading habits on recall of prose material are also pertinent to the disuse perspective if it is assumed that experience with reading is relevant to the task of recalling prose material. In a 1986 study, a questionnaire was administered to assess the number of hours per week reading different types of material and the individual's preferences for various kinds of reading (Rice & Meyer, 1986). Although several of the summary scores derived from a principal components analysis were significantly related to both age and total recall performance, there was no evidence that the age effects varied as a function of the amount of reading experience. A later study by the same investigators (Rice, Meyer, & Miller, 1988) involved the simultaneous examination of prose recall performance and degree of reading activity, as determined from analyses of diaries. Unfortunately, the authors did not report the extent to which the age-related effects in recall were attenuated by controlling for amount of reading experience, but they did indicate that the effects of age and educational level were much greater than those associated with reading habits.

In summary, the findings of the present study, in conjunction with the results of the studies just reviewed and the occupation-specific studies described earlier, appear inconsistent with the disuse perspective. Not only are the age-related effects generally similar across different levels of presumably relevant experience (this study and probably the studies by Rice and Meyer, 1986; and Rice, et al., 1988), but they appear to be substantial even among samples selected to be equivalent with respect to occupation (e.g., Glanzer & Glaser, 1959; Glanzer, Glaser, & Richlin, 1958; Salthouse, et al., in press), or to level of molar ability (e.g., Charness, 1979; 1981; Salthouse, 1984). The seemingly inescapable conclusion from this body of evidence is that many of the age-related effects on measures of relatively basic abilities are largely independent of the amount of relevant experience.

We hasten to point out, however, that this conclusion does not imply that there are no positive benefits of experience, or that increased age in adulthood is inevitably associated with declining levels of competence. More extensive experience frequently results in greater knowledge (both declarative and procedural), better discrimination between relevant and irrelevant information, more successful execution of complex activities, and perhaps more effective monitoring and deployment of basic abilities. What remains to be resolved is the dynamic relationship between the efficiency of basic abilities and the operation of these higher-order processes, and whether, and if so how, this relationship changes with age.

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Author Identification Notes

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Table 1
Correlation matrix for performance measures and demographic variables (n=383)

	Age	Sex	Educ	Hlth	PF	SD	Ab	LS	FA	NC
Age	X	.13	-.01	.10	-.38*	-.30*	-.25*	-.26*	-.17*	-.30*
Sex		X	-.05	.06	-.14*	-.22*	-.07	.01	.13	.17*
Educ			X	-.01	.26*	.23*	.30*	.27*	.14*	.13
Hlth				X	-.02	-.06	.00	-.05	.00	-.08
PF					X	.67*	.60*	.59*	.21*	.29*
SD						X	.58*	.54*	.24*	.30*
Ab							X	.69*	.33*	.36*
LS								X	.44*	.47*
FA									X	.46*
NC										X
Mean	46.0	.51	15.1	2.0	1.69	7.23	11.10	7.52	27.33	22.20
Stand. Dev.	16.8	.50	2.5	1.1	4.30	11.4	5.37	4.79	10.33	6.16

Age: Chronological age in years
Sex: Males=0, Females=1
Educ: Years of Formal Education
Hlth: Self-rating of health, 1=Excellent, 5=Poor
PF: Paper Folding
SD: Surface Development
Ab: Abstraction
LS: Letter Sets
FA: Finding A's
NC: Number Comparison

*$p < .01$

Table 2
Means (and standard deviations) of responses to Spatial Experience Questionnaire (n=343)

	Ability Rating	Recent Experience	Cumulative Experience
1. imagining different arrangements of furniture or other objects	3.5 (0.9)	10.9 (36.6)	5.8(10.2)
2. considering how an object or building would look from a different viewing position	3.3 (1.1)	7.2 (21.0)	4.3 (8.4)
3. devising efficient ways of packing or loading a box or car trunk	3.8 (0.9)	6.8 (17.0)	5.0 (8.7)
4. following instructions for the assembly of furniture, toys, models, etc.	3.5 (1.1)	5.8 (17.2)	4.9 (8.6)
5. visualizing travel directions from a verbal description	3.6 (1.0)	5.9 (11.6)	6.2 (9.4)
6. designing or making clothes according to patterns	2.7 (1.3)	3.6 (14.5)	4.0 (10.0)
7. producing or interpreting technical drawings (e.g., blueprints) of three-dimensional objects	3.0 (1.3)	5.7 (18.9)	3.4 (7.7)
8. performing paper-folding activities such as ORIGAMI	2.7 (1.1)	0.8 (2.2)	1.2 (3.7)
9. solving piece-assembly games such as jigsaw puzzles	3.4 (0.9)	1.9 (4.0)	3.5 (7.2)
10. working on spatial-manipulation puzzles like Rubik's Cube	2.5 (0.9)	0.9 (3.4)	1.2 (4.1)

Table 3
Component Loadings from Principal Components Analysis of Questionnaire Responses after Varimax Orthogonal Rotation (n=343)

Item	C1	C2	C3	C4	C5	C6	C7	C8	h^2
Abil1		.67							.58
REx1			.77						.72
CumEx1	.80								.72
Abil2		.65		.37					.60
REx2			.61	.43					.69
CumEx2	.78								.71
Abil3		.52							.52
REx3			.80						.68
CumEx3	.87								.77
Abil4		.51						.52	.64
REx4			.47	.41		.36			.57
CumEx4	.70								.63
Abil5		.31						.56	.44
REx5			.64					.33	.62
CumEx5	.63							.36	.68
Abil6		.42			.65				.66
REx6					.80				.68
CumEx6					.87				.79
Abil7		.57		.59					.75
REx7				.68					.58
CumEx7	.53			.59					.70
Abil8		.75					.36		.73
REx8						.41	.69		.75
CumEx8	.35						.79		.77
Abil9		.64							.54
REx9			.36			.57			.56
CumEx9	.66						.39		.69
Abil10		.71							.57
REx10						.76			.60
CumEx10	.55					.46			.60
Eigenvalue	6.13	3.44	2.64	1.96	1.79	1.32	1.21	1.03	

C1: Non-specific cumulative experience
C2: Non-specific subjective ability
C3: Non-specific recent experience
C4: Perspective
C5: Clothes
C6: Puzzles 1
C7: Puzzles 2
C8: Directions

Table 4
Correlations with Principal Components (n=343)

	Age	Sex	Spatial Visualiz.	Inductive Reason.	Perceptual Speed
C1 (Cumulative Exp.)	.26*	-.06	-.08	-.12	-.09
C2 (Subjective Ability)	-.18*	-.12	.36*	.21*	.10
C3 (Recent Exp.)	-.24*	.01	-.04	-.00	.00
C4 (Perspective)	-.11	-.23*	.17*	.02	-.03
C5 (Clothes)	.20*	.38*	-.11	-.02	-.02
C6 (Puzzles 1)	-.13	-.07	-.07	-.02	.03
C7 (Puzzles 2)	-.02	.05	-.07	-.09	-.02
C8 (Directions)	-.06	-.23*	.17*	.16*	.08

*p < .01

Table 5
Proportion of Variance Accounted for in Hierarchical Regression Analyses (n=343)

	Right-Wrong		Right		Wrong	
	R^2	Cum. R^2	R^2	Cum. R^2	R^2	Cum. R^2
SPATIAL VISUALIZATION						
Age	.139*	.139	.206*	.206	.023	.023
Component 2	.129*	.129	.150*	.150	.051*	.051
Component 4	.028*	.157	.043*	.193	.004	.055
Component 8	.027*	.184	.035*	.228	.007	.062
Age	.083*	.267	.129*	.357	.011	.073
Perceptual Speed	.104*	.104	.085*	.085	.074*	.074
Age	.085*	.189	.149*	.234	.006	.080
Perceptual Speed	.104*	.104	.085*	.085	.074*	.074
Component 2	.107*	.211	.129*	.214	.039*	.113
Component 4	.031*	.242	.046*	.260	.006	.119
Component 8	.020*	.262	.028*	.288	.004	.123
Age	.048*	.310	.093*	.381	.001	.124
REASON						
Age	.088*	.088	.157*	.157	.005	.005
Component 2	.044*	.044	.052*	.052	.016	.016
Age	.069*	.113	.131*	.183	.002	.018
Perceptual Speed	.227*	.227	.263*	.263	.087*	.087
Age	.029*	.256	.069*	.332	.000	.087
Perceptual Speed	.227*	.227	.263*	.263	.087*	.087
Component 2	.027*	.254	.032*	.295	.009	.096
Age	.020*	.274	.056*	.351	.001	.097
SPEED						
Age	.081*	.081	.081*	.081	.006	.006

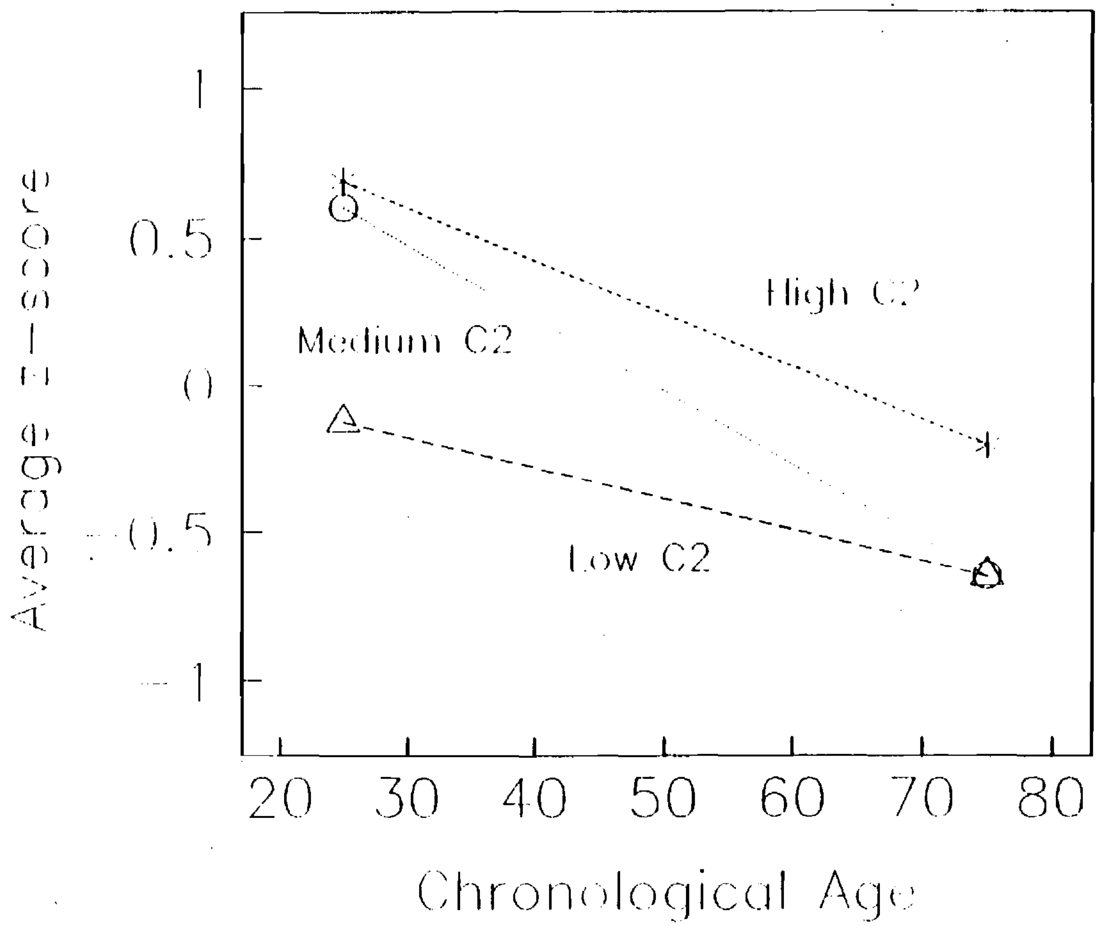
*$p < .01$ (for R^2 only)

Figure Captions

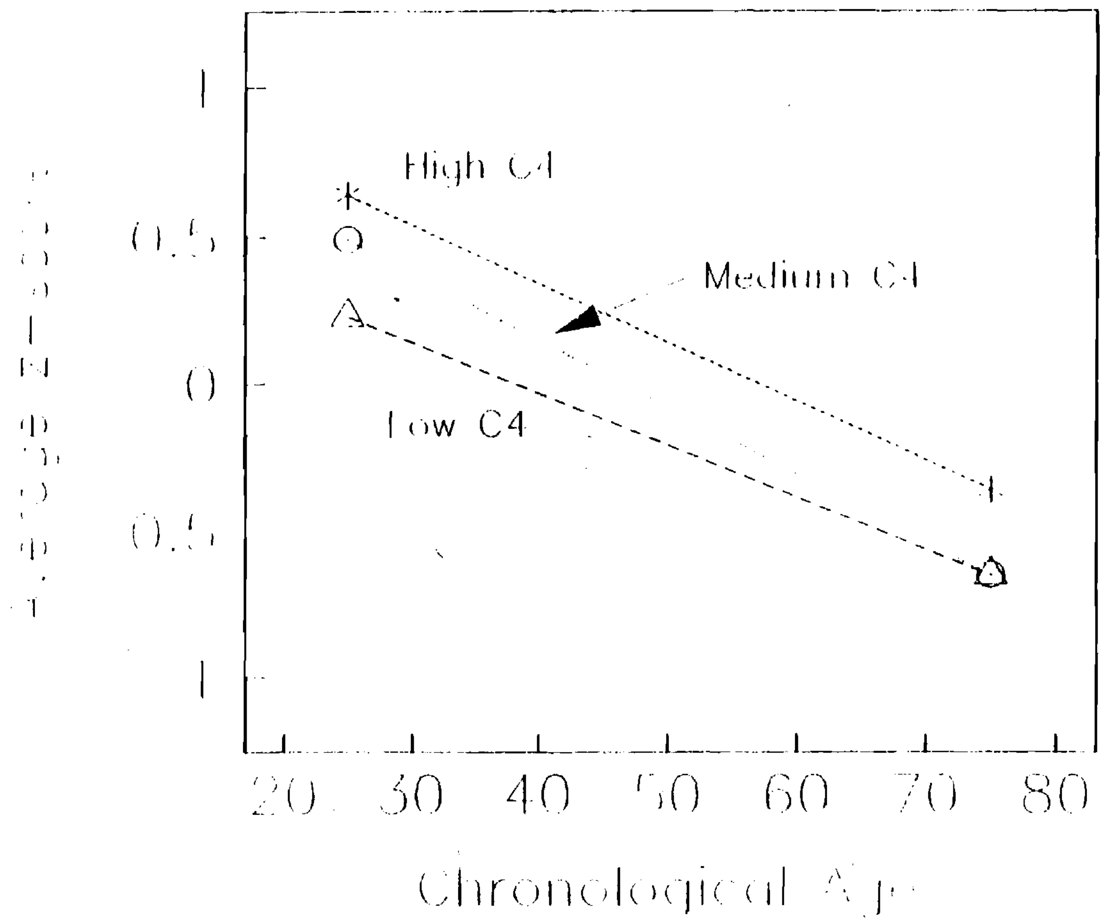
Figure 1 - Regression lines relating composite spatial visualization score to age for individuals in the top, middle, and bottom thirds of the distribution of scores on Component 2 (Subjective Ability).

Figure 2 - Regression lines relating composite spatial visualization score to age for individuals in the top, middle, and bottom thirds of the distribution of scores on Component 4 (Perspective).

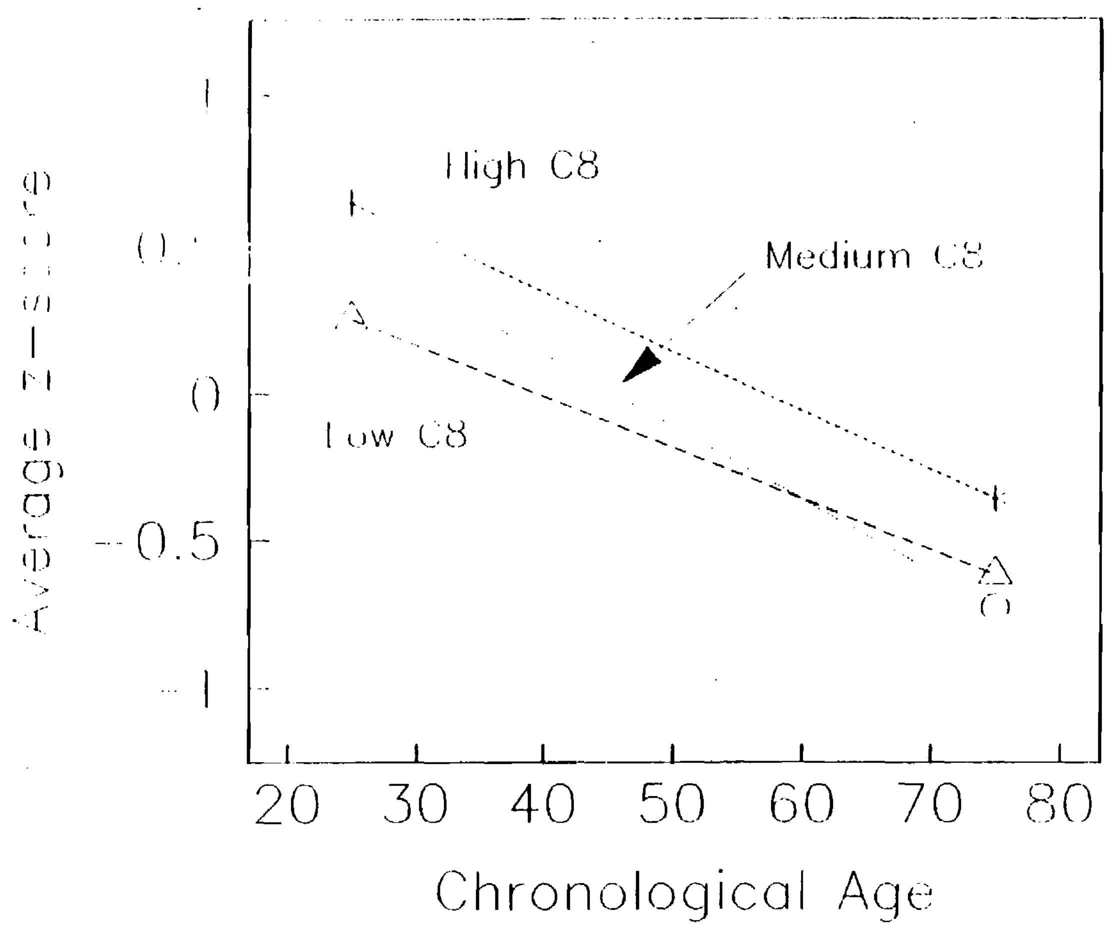
Figure 3 - Regression lines relating composite spatial visualization score to age for individuals in the top, middle, and bottom thirds of the distribution of scores on Component 8 (Directions).



Average Z-score
1
0.5
0
-0.5
-1
High C2
Medium C2
Low C2
20
30
40
50
60
70
80
Chronological Age



High C4
Medium C4
Low C4
1
0.5
0
0.5
1
20
30
40
50
60
70
80
Chronological Age



High C8
Medium C8
Low C8
Average Z-score
1
0
-0.5
-1
20
30
40
50
60
70
80
Chronological Age

Influence of Experience on Age Differences in Cognitive Functioning

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To the extent that adult age differences in measures of cognitive performance have implications for functioning outside the psychological laboratory, the question of the role of experience as a potential moderator of these differences becomes extremely important. Three categories of research relevant to this issue are reviewed, and methodological limitations of each type of research discussed. Although it is frequently asserted that experience minimizes cognitive differences associated with aging, the currently available evidence does not appear consistent with a strong experiential moderation of age-related effects in cognitive performance. However, a combination of few relevant studies and methodological weaknesses of the studies that are available precludes a definitive conclusion at the present time. It is suggested that additional research, with improved methodology, is necessary before strong conclusions can be reached concerning effects of experience on age differences in cognition.

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Key words: aging, cognition, experience, practice

Cross-sectional comparisons of adults of different ages frequently reveal that increased age is associated with lower performance on various measures of cognitive functioning. Among the questions often raised in connection with these findings are the following: Are these age differences confined to measures from novel and abstract tasks, and much reduced or even completely absent in measures from familiar and concrete tasks? Can the age differences be attenuated or eliminated with additional practice or training? And, do the age differences disappear when individuals of all ages have extensive experience with relevant activities? The purpose of the current article is to review the research literature relevant to these questions concerning the influence of experience as a potential mediator, or moderator, of age-related differences in cognition.

In order to provide an appropriate context for interpreting the research relevant to age and experience, a brief summary of previous findings on the relation between age and cognition will first be presented. One of the earliest and least controversial results in the cognitive aging literature is the finding that age-related effects vary as a function of the type of cognition being assessed. Over the years a number of different labels have been used to characterize the major categories of cognition, with the terms crystallized and fluid, or product and process, currently the most popular. The distinction is essentially between measures of cognitive functioning based on the crystallized residue or accumulated products from processing at earlier times, and measures reflecting the efficiency of acquiring, transforming, retaining -- or more generally, processing -- information at the current time.

Results from many studies with a variety of psychometric test batteries have revealed that age-related effects are usually very small, and are sometimes manifested in increases rather than decreases, for crystallized or product measures of cognition such as scores on tests of vocabulary or general information. In contrast, measures reflecting the efficiency of current processing, as required by tests or tasks emphasizing speed or accuracy of associations, transformations, decisions, or responses, are generally found to decrease with age. The magnitudes of the adult age relations on process or fluid measures of cognition are not great up to about age 75 (e.g., Salthouse, 1985b, reported a median age correlation across 54 comparisons of -.36), but the extreme group (i.e., young adults vs. older adults) differences are often larger than those associated with most other individual-difference classifications such as race, sex, or personality type. There is still controversy concerning the age at which the cross-sectional decline in fluid or process aspects of cognition first begins, with some researchers suggesting that it starts in the 20s, and others arguing that declines are not noticeable until the 50s or 60s. One possibility is that with relatively easy tests the predominant age trend is a period of stability followed by a decline beginning at about the decade of the 50s, whereas for very demanding tests the pattern is one of relatively monotonic declines beginning in the late 20s or early 30s.

There are both practical and theoretical reasons why it is important to determine the effects of experience on age differences in measures assumed to reflect the level of an individual's current processing efficiency. The practical significance derives from the assumption that age-related differences in these aspects of cognitive functioning may have detrimental consequences on the effectiveness of older adults in many occupational situations. However, minimal negative impact of older adults in the work place, and in society in general, would be expected if increased experience is found to attenuate, or possibly even eliminate, the age differences in cognitive functioning observed in inexperienced adults.

It should probably be mentioned that some researchers have disputed the assumption that age-related differences in fluid or process aspects of cognition could have negative implications for real-world functioning, even in the absence of experiential influences. For example, Schaie (e.g., 1988a) has argued that the reported age differences are generally too small to have meaningful consequences in most occupational activities. Perlmutter, Adams, Berry, Kaplan, Person, and Verdonik (1987) have even suggested that in certain situations there may be advantages of mild cognitive impairments such as unreliable memory. Although the validity of these speculations remains an open question, it is important to note that the age-related effects typically observed are large enough to lead to estimates (Fozard and Nuttall, 1971) that the average 60-year-old would be unqualified for more than half of the occupations for which predictive validity has been established with the General Aptitude Test Battery. (It should also be acknowledged, however, that most validation samples have been composed primarily of young adults, and thus it is possible that different estimates might be generated if validity information were available at each of several age ranges.)

Research on the possible interactive effects of age and experience on fluid or process aspects of cognitive functioning also has considerable theoretical importance. At least since the time of Thorndike (Thorndike, Bregman, Tilton and Woodyard, 1928), a major class of explanation has attributed age-related declines in cognition to experiential deprivation or disuse. Examination of the relations between age and measures of cognition across different levels of experience can therefore be expected to be informative about one possible cause of the age-related differences frequently observed in measures of cognitive functioning.

The prevailing opinion, both among lay people and researchers in the field, seems to be that experience attenuates age differences in cognition, allowing overall effectiveness to be maintained either by preserving the original levels of basic abilities, or through the development of compensatory skills. This attitude is reflected in the general culture by expressions such as "Use it or lose it," and "He who lives by his wits, dies with his wits." The following quotations, selected haphazardly from relevant articles and books published over a 50-year period, document the pervasiveness of this perspective in the professional literature.

> In general, then, abilities that are used throughout adult experience tend to increase with age, while abilities required by situations that do not come within the scope of adult experience show a definite decline over a range of adult years (Sorenson, 1938, p. 736).

> Abilities which are exercised during our adult years, such as the maintenance of vocabulary, the capacity to understand and use different words, do not decline during our adult years (Brozek, 1951, p. 224).

> ... the declines that are observed in abilities which are used frequently appear to begin at a later age and to be less drastic than are the declines in abilities which are exercised less frequently (Denney, 1982, p. 824).

> ... extended practice appears to reduce age differences in performance considerably ... and when older individuals are highly experienced at the task they are performing, no age differences emerge (Davies and Sparrow, 1985, p. 303).

Although this sample of quotations suggests that there is a clear preference for the view that increased experience reduces the magnitude of age differences in cognitive functioning, the empirical bases for this preference are much less obvious. It is therefore desirable to conduct a thorough examination of the scientific foundation for conclusions about the role of experience on adult age differences in cognition. In the following sections three classes of evidence relevant to the influence of experience on age-related effects on fluid or process aspects of cognition are reviewed. These consist of research concerned with age differences on familiar activities, research investigating the effects of additional practice or training, and research involving select populations such as members of particular occupational groups. Because the amount of data in each category is still quite limited, the discussion will focus as much on the methodological requirements needed to provide convincing evidence in future research as on summarizing the major empirical results from past research.

FAMILIAR ACTIVITIES

One hypothesis concerning age and experience is that the detrimental effects on cognitive functioning associated with increased age are restricted to novel and unfamiliar tasks, and are not evident on frequently performed activities. Several different rationales have been offered to account for this predicted pattern of results, such as the close association between young adulthood and formal schooling during which there is considerable exposure to novel activities, and a presumed decrease with age in the willingness to perform what might be perceived to be meaningless or irrelevant tasks. The fundamental expectation from all versions of the hypothesis, however, is that age-related effects should be much smaller, and perhaps even non-existent, on familiar tasks than on the presumably more abstract and novel tasks typically used in psychometric and laboratory investigations.

Unfortunately, two major problems make it difficult to reach a definitive conclusion concerning the possibility that adult age differences are smaller on familiar tasks than on unfamiliar tasks. (These problems are in addition to the statistical and logical difficulties associated with interpreting interactions [e.g., between age and familiarity], and with attempting to establish the existence of no differences between groups.) One problem is that the concept of familiarity has seldom been operationally defined, or systematically investigated in adults of different ages. Ideally, claims that some tasks are performed more frequently than others should be documented with evidence concerning the relative amounts of time devoted to different activities among representative samples of adults. However, complete activity inventories of this type have apparently not yet been reported for any age group, much less for several different age groups. Furthermore, even if such data were available, they might be of limited value because the most relevant frequencies probably concern the basic components or processes involved in different activities, and not the superficial activities themselves. For example, paired-associate tasks involving randomly selected words undoubtedly have a low frequency of occurrence in everyday life, but the same fundamental association processes may have an extremely high frequency when considered in the context of pairing cuisine or service with restaurants, athletes with sports teams, faces with names, shops with locations, appointments with days and times, etc. Without accurate and detailed information concerning the frequencies with which particular processes or components are used in daily life, therefore, judgments about the relative familiarity of different tasks are necessarily subjective and of questionable validity.

A second problem complicating the issue of whether age-related differences are smaller with familiar tasks than with unfamiliar or novel tasks is that the two types of tasks may vary in dimensions other than familiarity. For example, there is an obvious confounding if 'familiar' tasks consist of measures of the products of prior processing, such as scores on a vocabulary test, whereas 'unfamiliar' tasks involve assessments of the efficiency of current processing, such as the speed and accuracy of substituting symbols for digits or assembling blocks into novel patterns. Familiarity may also be confounded with amount of processing, in that familiar tasks might involve fewer processing operations, or lower levels of task complexity, than unfamiliar tasks. Matching familiar and unfamiliar tasks on dimensions such as the type of cognition being assessed and the amount of required processing will probably not be easy, but only if the tasks are equivalent in these respects could one be confident in attributing differences in observed age trends to the effects of familiarity.

Although documentation of the actual frequencies is lacking, and novel tasks with equivalent processing requirements to familiar tasks have not yet been identifed, age comparisons have been reported for a variety of tasks which can be argued to represent familiar activities. For example, young and old adults have been contrasted in the ability to remember and immediately dial a telephone number (e.g., Crook, Ferris, McCarthy and Rae, 1980; Pollard and Cooper, 1978), to notice and report information from a street sign after driving or walking past it (Manstead and Lee, 1979), to remember a shopping list of grocery items (McCarthy, Ferris, Clark and Crook, 1981), to remember information from a simulated news broadcast (Hill, Crook, Zadek, Sheikh and Yesavage, 1989), to remember the source of factual information (McIntyre and Craik, 1987), and to comprehend and remember information on prescription medicine bottles (Morrell, Park and Poon, 1989). In each of these cases, and in numerous others summarized in Salthouse (1987b), young adults have been found to perform significantly more accurately than older adults.

Several psychometric tests have also been designed to evaluate the abilities required in daily activities. One such instrument is the Watson-Glaser Test of Critical Thinking, which has been described as follows:

> This test consists of 99 items almost all of which are of a realistic or practical nature involving problems, statements, arguments, and interpretation of data similar to those which a person might encounter in his daily life as he works, reads the newspaper, hears speeches, and participates in discussions on various topics (Friend and Zubek, 1958, p. 407).

Apparently only two studies have investigated adult age differences on the Watson-Glaser Test, but both were consistent in finding significant age differences favoring young adults (i.e., Burton and Joel, 1945; Friend and Zubek, 1958).

The most comprehensive study of age-related differences in a psychometric test designed to assess familiar activities was reported by Schaie and Willis (e.g., Schaie, 1988b; Willis and Schaie, 1986a), using the ETS Basic Skills Test. This test was developed to assess real-life competencies, and evaluates the examinees' ability to understand labels on household articles and medicine bottles, to interpret street maps, to obtain information from bus schedules and from telephone directory advertisements, etc. Not only do these items appear to have face validity as measures of functioning in daily situations, but Willis and Schaie (1986a) also obtained estimates of the frequency with which representative activities within each of eight categories were performed. Within a sample of adults between 60 and 88 years of age, activities from five of the categories were reported to be performed an average of weekly, with activities from an additional category performed at least monthly.

Data from 1500 adults on the Basic Skills test, as reported in Schaie (1988b), are illustrated in Figure 1. It can be seen that performance remains relatively stable until about the 50s or 60s, at which time a pronounced decline is evident. These results clearly indicate that young adults achieve higher scores than older adults, but the exact nature of the age relationship in the relevant abilities is still somewhat equivocal. That is, it could be that actual ability to perform these types of tasks remains stable from the 20s through the 50s or 60s, but it is also possible that there are ability declines without concomitant reductions in measured performance because the performance of young and middle-aged adults is constrained by an absolute or functional measurement ceiling. The transformation of the scores from the original units of measurement into T-scores obscures a possible absolute measurement ceiling because it is impossible to determine how far actual performance is from the maximum possible performance. Functional ceilings can also exist because performance can be less than the highest possible score for a variety of reasons such as the presence of a few extremely difficult items, unrealistically short time allowances, etc. If higher levels of performance were restricted by either an absolute or a functional measurement ceiling, therefore, the true relation between age and ability might be a monotonic decline, rather than a period of stability followed by decline. Regardless of the precise nature of the age trends, however, the data in Figure 1 are unambiguous in indicating that, as with the other studies cited above, young adults achieve substantially higher scores than older adults on instruments designed to assess proficiency in familiar or everyday activities.

Place Figure 1 about here

The studies just described are merely a limited, and not necessarily representative, sample of the research on familiar activities, but they are sufficient to indicate that there are convincing exceptions to the suggestion that age-related differences are small to non-existent on familiar tasks or activities. Definitive research (with documented frequencies of relevant processes, and comparable processing requirements across familiar and novel tasks) does not yet exist, but the research surveyed above clearly provides little support for the proposal that age differences are restricted to novel and unfamiliar activities.

PRACTICE AND TRAINING

A second issue relevant to the relations between age and experience concerns the effects of added experience on the magnitude of age differences in measures of cognitive functioning. The primary question in this context is whether age-related differences are invariant across different amounts of experience, or whether they are reduced in magnitude as a function of additional experience.

Considerable research has focused on the modifiability or plasticity of behavior during late adulthood, and consequently the effects of different amounts and types of instructional training on the cognitive functioning of older adults have been extensively investigated (e.g., see Baltes and Lindenberger, 1988, and Willis, 1987, for reviews). However, because the experiential interventions were only administered to a single age group, this research is not directly relevant to the issue of the effects of added experience on age-related differences in cognition. That is, the most important question for the purpose of determining the effects of experience on age differences in performance is relative rather than absolute modifiability, and it is simply impossible to draw conclusions about possible age-related differences in the benefits of experience without comparisons of two or more age groups.

Unfortunately, even the age-comparative practice or training studies that have been reported suffer from a number of limitations. For example, in several studies samples of young and old adults were compared after very small amounts of experience. It is difficult to specify the amount of experience sufficient to be considered realistic, but at a minimum the practice or training should extend across multiple sessions. Second, some studies have reported results from as few as one individual in each age group. Although virtually all available studies have employed small sample sizes (i.e., 20 or fewer individuals per age group), results based on extremely small numbers of adults in each age range provide a very limited basis for generalization. Furthermore, only two studies have apparently attempted to examine the representativeness of the individuals who agree to participate for extended testing (i.e., Kliegl, Smith, and Baltes, 1989; Salthouse and Somberg, 1982). A final problem is that almost all of the available studies have focused on a single dependent variable from one particular task, thereby greatly restricting inferences beyond the measured variable, and precluding distinctions between changes in the proficiency of the same construct as opposed to changes in the nature of the construct being assessed.

Although the preceding characteristics serve to qualify any conclusions, the existing research literature does provide some tentative information about the effects of manipulated experience on age differences in cognitive functioning. Table 1 summarizes the results from all relevant studies that could be located with a total of at least 12 individuals from two or more different age groups, and comparisons extending across a minimum of four separate sessions. These particular characteristics are somewhat arbitrary, but selected to maximize the meaningfulness of the results while not severely reducing the number of qualifying studies. It should be noted that the outcomes in Table 1 should be interpreted cautiously because in some cases the patterns varied across different stages of practice (e.g., Salthouse and Somberg, 1982), and in others there was no distinction between effects attributable to instruction of a technique and practice with that technique (e.g., Kliegl, et al., 1989). Furthermore, in several of the contrasts the entries in the effect column are inferences based on the reported information because there was apparently no direct evaluation of the equivalence of young and old adults at different levels of practice or of the effectiveness of practice, in the two groups. (This lack of quantitative information in many of the studies also precludes the use of more systematic meta-analytic procedures to integrate the results from different studies.)

Place Table 1 about here

The dominant pattern in Table 1 clearly seems to be that practice-related performance improvements are equivalent in magnitude for young and old adults. There are a few cases where older adults appear to have exhibited greater improvements than young adults, primarily during the initial sessions of practice, but it is more frequently the case that young and old adults benefit nearly the same from practice or training. Young adults improved more than older adults in a couple of studies, but it is not yet clear whether this particular outcome is restricted to situations requiring the acquisition of new skills, or is also evident when the research subjects are increasing the proficiency of existing skills.

There are also a number of miscellaneous reports of age-related differences in more naturalistic learning situations. For example, Thorndike, et al. (1928) reported that, across 15 hours of practice, adults with a mean age of 22 improved their speed of writing with the wrong (i.e., non-preferred) hand more than adults with a mean age of 41. These same authors also reported that the benefits of 20 hours of study and instruction in oral comprehension of the artificial language Esperanto were greater in young adults than in middle-aged adults, although the two groups improved comparable amounts in other measures of language acquisition. Several cases of age differences in the efficiency of retraining for bus drivers, electrical technicians, postal workers, oil production workers and telephone operators have been described by Welford (1958, p. 257-258) and Birren (1964, p. 161-168). More recently, Egan and Gomez (1985), Elias, Elias, Robbins, and Gage (1987), and McAlister (1985) have all reported that older adults have greater difficulty learning to operate a text editor or word processor than young adults (but see Hartley, Hartley, and Johnson, 1984, for a possible exception). Studies investigating the acquisition of other computer-related skills have also found older adults to require more time than young adults to achieve comparable levels of proficiency (e.g., Gist, Rosen and Schwoerer, 1988; Zandi and Charness, 1989).

Detailed analyses of the success of Air Traffic Control trainees as a function of age have been reported by Trites, Cobb, and their associates (e.g., Cobb, Lay and Bourdet, 1971; Trites, 1963; Trites and Cobb, 1964a; 1964b). A consistent finding in all of these studies was that older trainees were much less likely than younger trainees to complete the training program and perform successfully as a controller. One illustration of this age relation is evident in the ratio of failures to successes at different ages. According to Trites (1963), the ratio of failures to successes was 1:1 for trainees under the age of 35, but increased to 4.7:1 for trainees age 35 or older, and reached 7.4:1 for trainees age 39 or older.

Although the sample sizes have been small and the range of manipulated experience limited, two findings from research on manipulated experience appear to be fairly consistent. The first is the encouraging result that virtually all of the available research suggests that both young and old adults improve their performance with additional experience. If it is the absolute level of functioning that is important, therefore, then adults of nearly any age may eventually reach acceptable limits of performance. However, the second consistent finding is the complete absence of any evidence that age differences in certain types of cognitive performance are eliminated after all individuals have received comparable amounts of practice or training. At the present time there are not even many convincing demonstrations of age-by-practice interactions in which the size of the age differences in performance was merely reduced with extended experience. A tentative conclusion from the available research on manipulated experience, therefore, is that it seems unlikely that age differences in measures of cognitive functioning can be easily eliminated by the provision of additional experience.

In light of this relatively negative conclusion it is perhaps appropriate to briefly describe a research project which is sometimes cited as indicating that age-related cognitive deficits can be reversed with small to moderate amounts of training. Schaie and Willis (e.g., Schaie and Willis, 1986; Willis and Schaie, 1986b) relied upon longitudinal data to classify older adults as having remained stable or having declined in either spatial or reasoning ability, and then administered one of two training interventions designed to improve performance in either the spatial or reasoning domain. The basic prediction from the hypothesis that the declines were due to experiential deprivation is that the individuals who had declined in a given ability would have greater training-related benefits in that ability than the individuals whose abilities had remained stable. Contrary to the prediction, however, the results of the studies indicated that the training benefits were virtually equivalent for the individuals whose abilities had declined and for those whose abilities had remained stable. (One of four group-by-training interactions was significant at the .05 level, but since it occurred in the context of 60 statistical tests it can probably be dismissed as a chance occurrence.) Because the experientially-mediated improvements were not selective, the results of the Schaie and Willis studies provide no evidence that the training altered the processes or mechanisms actually responsible for the longitudinal decline. Therefore, in the absence of evidence that additional experience is of greater benefit to older adults than to young adults, or to individuals whose abilities had declined relative to those whose abilities had remained stable, it seems premature to claim that experiential interventions can reverse or remediate age-related cognitive declines.

SELECT POPULATIONS

A third manner in which experience could influence the magnitude of age-related effects on cognitive functioning is that age effects might be attenuated when the activities are highly overlearned, and in continuous use. In other words, extensively performed activities might be maintained at high levels of proficiency, even if there are age-related differences in the efficiency of performing the activities when first encountered, or in the ease of acquiring high levels of proficiency. This possibility can be investigated by examining age-related trends among individuals within certain experientially-homogeneous categories, such as members of particular occupations. The reasoning is that if a given set of activities are regularly performed by all members of a particular occupation, and if extensive use prevents or retards age-related decline, then small to non-existent age differences might be expected in measures of the efficiency or effectiveness of those activities. This category of evidence is therefore similar to that involving familiar activities, but the critical variation in experience is postulated to exist across different groups of people for the same activities, rather than across different types of activities for virtually all people.

Perhaps the optimal means of determining whether there are age differences in activities related to one's occupation is simply to examine age trends in appropriate measures of job performance. Although potentially informative, occupational performance studies suffer from a number of weaknesses which limit their value as a means of determining the joint effects of age and experience on cognitive functioning. A major problem concerns the issue of selective attrition. On the one hand, the poorest workers may not continue on a job because employers are unlikely to retain unproductive individuals, but instead would either lay them off or shift them to less demanding positions. On the other hand, some of the best workers may not stay on the job because they are promoted to positions of greater responsibility. It is difficult to determine which of these factors predominates in any given situation, but the strong possibility that the surviving older members in a given occupation may be less representative of their age peers than the younger members in the occupation should make one very cautious in interpreting results based on age comparisons involving measures of job performance.

A second complication of analyses of age differences in occupational performance is that workers of different ages may not have precisely equivalent job requirements. Even within the same job classification, older workers will often have more seniority than their younger counterparts, and seniority may result in more desirable, and possibly less strenuous or demanding, job assignments. To the extent that workers of different ages are not performing under identical conditions, therefore, age comparisons in measures of job performance may not be very meaningful.

Finally, age comparisons of job performance are sometimes of limited usefulness because the analyses are based on coarse evaluations of overall effectiveness in relatively broad occupational categories. It would be much more informative for the purpose of examining interrelations of age and experience on cognitive functioning if the age comparisons were reported on specific dimensions of job performance with known involvements of different types of cognitive abilities. Moreover, it is probably not sufficient merely to restrict comparisons to individuals within what is ostensibly the same job classification. For example, the cognitive demands would probably be quite different for mechanics primarily responsible for diagnosing engine problems compared to mechanics who spend most of their time changing tires. Although measures of overall effectiveness are frequently useful for personnel evaluation in actual work situations, collapsing across cognitively diverse activities in performance evaluations makes it very difficult to identify potentially systematic effects of age and experience on aspects of cognitive functioning.

Various combinations of these three factors may be partially responsible for the generally small and inconsistent relations between age and job performance reported in recent reviews (e.g., Davies and Sparrow, 1985; McEvoy and Cascio, 1989; Rhodes, 1983; Waldman and Avolio, 1986). In keeping with this suggestion, it should be noted that more systematic age relations are sometimes reported within relatively narrow occupational categories reported to have high cognitive demands. Several studies, for example, have reported significant negative correlations between age and rated effectiveness as an air traffic controller (e.g., Trites, 1962; Trites and Cobb, 1964a, 1964b) with almost no attentuation of the age-related effects after controlling for amount of experience (e.g., Cobb, 1968; Matthews and Cobb, 1974).

Comparisons across adults of varying ages from select occupations have also been reported on measures of performance derived from specially designed experimental tasks or psychometric tests. Studies of this type generally provide more analytical information than those based on overall evaluations of job effectiveness, but the performance measures are sometimes of questionable relevance to the occupation. An illustration of the confusion that can result from the lack of objective evidence concerning the relevance of measures to occupational activities is evident in a comparison of two studies in which age trends in the speed of handwriting were examined in samples of adults from different occupational groups. Smith and Greene (1962) reported very slight age effects "...in professional and managerial groups, which use handwriting as a familiar daily task (p. 161)", but LaRiviere and Simonson (1965) claimed that there was a decline in handwriting speed among members of professional and managerial occupations "...whose jobs did not require a great deal of writing (p. 416)." Regardless of the purported difference in outcomes, which should be considered tentative because apparently in neither case were the age trends evaluated statistically, one cannot hope to reach meaningful conclusions about the contributions of experience when there is such little agreement about the frequency of the target activity in different occupations.

Two of the most intriguing studies within the select population category were reported by Murrell and his colleagues. Murrell, Powesland, and Forsaith (1962) reported that there were no performance differences between experienced young and experienced old operators of a drill-press device, but that novice older adults performed at lower levels than novice young adults. A similar finding of no age differences among experienced workers, and age differences favoring young adults among inexperienced individuals, was reported by Murrell and Humphries (1978) with the task of speech shadowing among simultaneous language translators. Although these results are consistent with the interpretation that extensive experience prevents age-related declines that would otherwise occur, they are also consistent with a selective survival interpretation in that the experienced older adults may be a positively biased sample of their age group. It is unfortunate that additional information that might have allowed an assessment of the representativeness of each sample was not provided to allow these possibilities to be distinguished.

Most of the research involving targeted occupational groups has focused on pilots and air traffic controllers because of the importance of these individuals to air transportation safety. Furthermore, because a key requirement in these jobs is effectiveness in high-speed decision making, the majority of the research has focused on various measures of speeded performance. For example, one project measured choice reaction time and digit symbol substitution performance in air traffic controllers and civil air pilots (Birren and Spieth, 1962; Spieth, 1964). Both reports, based on 161 and 560 adults, respectively, revealed that measures of perceptual-motor speed declined with increased age in these samples. Despite a restricted age range, with 83% of the individuals below the age of 50, correlations with age in the Birren and Spieth study were .59 with choice reaction time and .42 with digit symbol substitution performance. Both of these values are comparable in magnitude to those found in unselected samples of adults (cf., Salthouse, 1985a).

Another project involving the measurement of reaction time among airline, military, and test pilots of different ages was conducted by Szafran (1970). Szafran hypothesized that flying required the making of high speed decisions, and the receiving and retaining of information while carrying out routine operations. A choice reaction time task containing three, five, or eight alternatives was therefore administered either alone, or in the presence of a concurrent memory task requiring the report of items presented two positions earlier in the sequence. The primary dependent variables were the slope and intercept of the regression lines relating reaction time to number of alternatives in the single and concurrent conditions, and a measure of the amount of information transmitted in each condition. Interim reports of the project were published, with successively larger samples, in several articles appearing between 1965 and 1968. Results from what was apparently the final report, based on a total of 396 pilots, were described in a 1970 publication (Szafran, 1970). The major findings were that there were no significant correlations between age and measures from the reaction time task when it was performed alone, but when the memory task was performed concurrently with the reaction time task there were significant increases with age in the intercept of the regression equation relating number of stimulus-response alternatives to reaction time ($r = .26$), and in the number of errors in the memory task ($r = .16$), and a significant age-related decrease in the rate of information transmission ($r = -.35$).

Although in his early reports Szafran suggested that these results were inconsistent with the findings from unselected adults, it is not clear whether this conclusion is justified because the individuals in his sample were unrepresentative of the general population in several respects. For example, his sample of pilots was probably healthier, of a higher socio-economic level, and from a more restricted age range (i.e., 79% of the pilots were younger than 50 years of age) than participants in many other studies. Furthermore, because absolute levels of performance, and possibly the relations between age and performance, vary as a function of the particular apparatus and procedures employed, it is risky to make inferences about age trends in unselected adults without actual measurements using the same procedure and apparatus.

Perhaps the most comprehensive age-related project involving aircrew personnel was that of Glanzer and Glaser (e.g., Glanzer and Glaser, 1959; Glanzer, Glaser and Richlin, 1958). These researchers based their selection of job-relevant tests of perceptual and intellectual functions on an earlier study of critical incidents, and on a detailed job analysis of aircrew activities. A total of 544 aircrew personnel, 518 of whom were pilots in the Air National Guard or working for commercial airlines, were ultimately administered a battery of 14 psychometric tests. Significant age-related declines were reported on eight of the tests. Two of the tests with the largest age correlations were the Orientation to New Equipment ($r = -.20$), and Instrument Comprehension ($r = -.33$) tests. The former assessed comprehension and memory of information about new equipment of the type presented in oral briefings, and the latter required the integration of information from a compass and an artificial horizon to determine current position of an airplane. What is particularly striking about these correlations is that while they are small in absolute magnitude, they were still statistically significant when hours of flying experience was partialled out (i.e., -.15 for Orientation to New Equipment, and -.24 for Instrument Comprehension), and the correlations were almost certainly attenuated by a restricted age range. That is, although pilots up to age 50 were tested, the mean age in the sample was only 31.8 years, and 80% of the participants were less than 35 years old.

One of the few studies in the select population category not focusing on aircraft pilots was recently reported by Salthouse, Babcock, Skovronek, Mitchell and Palmon (1990), who measured spatial visualization abilities among practicing architects. The major assumption underlying this project was that architects are continuously involved in the production or interpretation of two-dimensional drawings of three-dimensional objects. It was therefore hypothesized that because they have received frequent experience using their spatial visualization abilities, architects might exhibit much smaller age-related declines in measures of spatial visualization performance than unselected adults. This was not the case, however, as significant age-related decrements were found in three separate measures of spatial visualization performance.

Figure 2 illustrates the regression equations summarizing the relations between age and performance in three samples of adult males on one of the spatial visualization measures -- score on the Surface Development Test, which requires determination of the correspondence between edges on unassembled and assembled drawings of three-dimensional objects. Each sample consisted entirely of male college graduates with mean ages in the mid-40s, but the samples differed with respect to whether the individuals were practicing architects, graduates of a college with a predominantly engineering-oriented curriculum, or unselected adults responding to a newspaper advertisement requesting volunteers for behavioral research projects.

Place Figure 2 about here

Notice that although the regression line for the architects is above that of the engineering school graduates and of the unselected adults, the slopes -- indicating the amount of performance decline with each additional year of age -- are very similar. If anything, the age relation, as indexed by both the slope and the percentage of variance accounted for by the linear equation, appears greater for the architects who presumably have the greatest experience with activities related to the performance measure.

This basic result has been replicated in a subsequent study (Salthouse and Mitchell, in press) in which unselected adults were categorized in terms of naturally occurring experience with activities presumed to require spatial visualization abilities. As in the architect study, the age trends were nearly identical for adults reporting different amounts of experience with the relevant activities.

Research with select populations offers the opportunity for investigating the effects of much more extensive amounts of experience than that generally possible in practice or training studies, but it suffers from the problem that the young and old members of the target groups might not be equally representative of their age peers because of the possibility of selective attrition. Results from several studies seem to suggest that age-related declines may still be evident in measures of occupationally-relevant activities, but the findings should be considered tentative until they are replicated with larger samples, with individuals from a broader range of ages, and with a greater number of performance measures of documented relevance to the occupation.

LIMITATIONS OF EXISTING RESEARCH

In addition to the specific methodological problems discussed in the context of each category of evidence, two broader objections can be raised against most of the research reviewed above. These are that the analyses have generally ignored the contribution of knowledge factors, and that most of the studies have been based on a rather narrow conceptualization of the consequences of experience.

One of the dominant distinguishing characteristics of experts in any given field is their possession of large amounts of structured knowledge. However, knowledge factors have largely been neglected in age-comparative studies focusing on fluid or process aspects of cognition. This is a potentially serious omission because effectiveness in many situations may be dependent more on factors related to one's knowledge than upon the efficiency with which he or she can execute basic processing operations. In fact, Schmidt, Hunter and Outerbridge (1986) have reported that in some situations a sizable proportion of the influence of experience on job performance is mediated through greater job knowledge. Important goals of future research should therefore be to document relations between quantity or quality of knowledge and the variables of age and experience, and to identify the specific manner by which knowledge factors contribute to enhanced performance in particular cognitive activities.

Although seldom explicitly stated, most of the studies designed to investigate interrelations of age and experience seem to have implicitly adopted either a maintenance (i.e., experience preserves abilities that would otherwise decline) or a remediation (i.e., added experience reverses ability declines) interpretation of the role of experience. It is possible, however, that the most pronounced effects of experience are not evident at the level of basic abilities, but instead are operative at more global or molar levels. Consistent with this suggestion are several reports of age invariances in the proficiency of a molar activity despite age-related declines in measures of presumably relevant molecular components. This general pattern has been reported in activities of bridge (Charness, 1979), chess (Charness, 1981; Pfau and Murphy, 1988), and transcription typing (Salthouse, 1984; Salthouse and Saults, 1987). The apparent implication of these findings is that the composition of competence may shift with increased age and experience.

Several mechanisms by which experience might result in the preservation of overall competence despite age-related declines in the efficiency of basic processes have been discussed by Salthouse (e.g., 1984, 1987a, 1987b, 1989a, 1989b). For example, effective functioning might be maintained by: (a) compensation, in which losses in some processes are offset by gains in other processes; (b) accomodation, in which the nature of one's activities is altered to minimize deficit-revealing situations; (c) elimination, in which the impaired processes are gradually reduced in importance as proficiency in the relevant skills develops; and (d) compilation, whereby once the higher-order skills are assembled or compiled they become independent of any subsequent declines in the efficiency of the constituent processes. Unfortunately, very little research with reasonably complex activities has been reported that would allow these speculations to be investigated and discriminated. This is regrettable because it is at least plausible that the greatest effects of experience are not evident in the efficiency of basic processes, but rather at higher-order levels concerned with the optimal combinations of different abilities to maintain or increase competence in relatively complex activities.

CONCLUSION

Because the currently available evidence is equivocal, there is ample opportunity for one's biases and prejudices to influence the nature of the conclusion regarding the possibility that experience attenuates age-related differences in cognition. If the lack of strong evidence for an experientially-mediated reduction of age differences is emphasized, then one could reasonably argue for a negative conclusion. However, if one focused on the methodological and conceptual limitations of previous studies, then it could be justifiably claimed that a positive conclusion might still be forthcoming after the appropriate studies have been conducted.

The most defensible conclusion at the present time is probably that it is premature to reach a conclusion. That is, the existing research is still too equivocal to allow firm decisions about whether age differences on familiar activities are smaller than those on novel activities, whether age differences can be reduced or eliminated with extensive experience, or whether age differences are absent on continuously practiced activities associated with one's occupation. Instead of trying to force a decision from the currently inadequate data, therefore, it is suggested that it will be more productive to use the lessons learned from the earlier studies to guide the design of future studies which might eventually allow more definitive conclusions. Among the features recommended to be included in future research are: (a) use of larger samples to provide a firmer foundation for generalizability; (b) inclusion of multiple indicators of the relevant abilities to allow inferences at the level of interesting theoretical constructs rather than single, potentially task-specific, variables; (c) exploration of the contribution of knowledge factors to different measures of performance; (d) examination of relatively complex activities which permit analyses of the manner in which a given level of proficiency is accomplished; and (e) better documentation of the extent and type of experience to ensure realism and relevance of the experience to the measured abilities.

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Table 1
Studies of practice effects in young and old adults

Measure	# Sessions	# Trials/ Session	Young N/Age	Old N/Age
PERCEPTUAL DISCRIMINATION				
(1)	7	500/600	8/18-28	9/62-72
(2)	5	60+	12/19	12/67
(3)	50	200	8/23	8/69
(4)	50	50	8/23	8/69
MEAN REACTION TIME				
(5)	4	480	15/21	16/63
(6)	10	1000	6/18-27	18/50-58
(7)	4	492	10/20	10/69
(8)	9	288	8/22	8/68
(9)	6	30	6/23	6/70
(10)	6	240	8/19	8/64
(11)	50	100	8/23	8/69
MENTAL ROTATION SLOPE				
(12)	4	480	16/21	16/63
MEMORY/VISUAL SEARCH SLOPE (VARIED MAPPING CONDITIONS)				
(13)	?	(Total # trials = 4200)	7/20	7/70
MEMORY/VISUAL SEARCH SLOPE (CONSISTENT MAPPING CONDITIONS)				
(14)	?	(Total # trials = 4200)	7/20	7/70
(15)	4	492	10/20	10/69
(16)	9	288	8/22	8/68
(17)	50	100	8/23	8/69
CARD SORTING				
(18)	7	30/36	8/17-25	8/62-75
(19)	6	10	8/24	8/75
DIGIT SYMBOL SUBSTITUTION				
(20)	5	20	12/23	12/69
RECOGNITION MEMORY ACCURACY				
(21)	7	3	10/18-26	10/62-75

Table 1 (Continued)

	Effect of Practice	Source
(1)	Y = O	Ball and Sekuler (1986)
(2)	Y = O	Hertzog, et al. (1976)
(3)	Y = O	Salthouse and Somberg (1982)
(4)	Y = O	" " " "
(5)	Y = O	Berg, et al. (1982)
(6)	Y = O	Leonard and Newman (1965)
(7)	Y = O	Madden (1983)
(8)	Y = O	Madden and Nebes (1980)
(9)	Y = O	McDowd (1986)
(10)	Y > O	Plude, et al. (1983)
(11)	Y < O, Y = O	Salthouse and Somberg (1982)
(12)	Y = O	Berg, et al. (1982)
(13)	Y = O	Fisk, et al. (1988)
(14)	Y > O	Fisk, et al. (1988)
(15)	Y = O	Madden (1983)
(16)	Y = O	Madden & Nebes (1980)
(17)	Y < O	Salthouse and Somberg (1982)
(18)	Y = O	Falduto and Baron (1986)
(19)	Y > O, Y = O	Plude and Hoyer (1981)
(20)	Y = O	Beres and Baron (1981)
(21)	Y = O	LeBreck and Baron (1981)

Table 1 (Continued)

MEMORY SPAN				
(22)	5	20+	16/26	16/70
(23)	5	36+	14/25	12/71
(24)	Variable	Variable	4/23	20/72
(25)	20	Variable	18/24	19/72
MENTAL SQUARING				
(26)	6	Variable	16/24	16/67
INTELLECTUAL ABILITIES				
(27)	4	Variable	25/17(?)	25/72

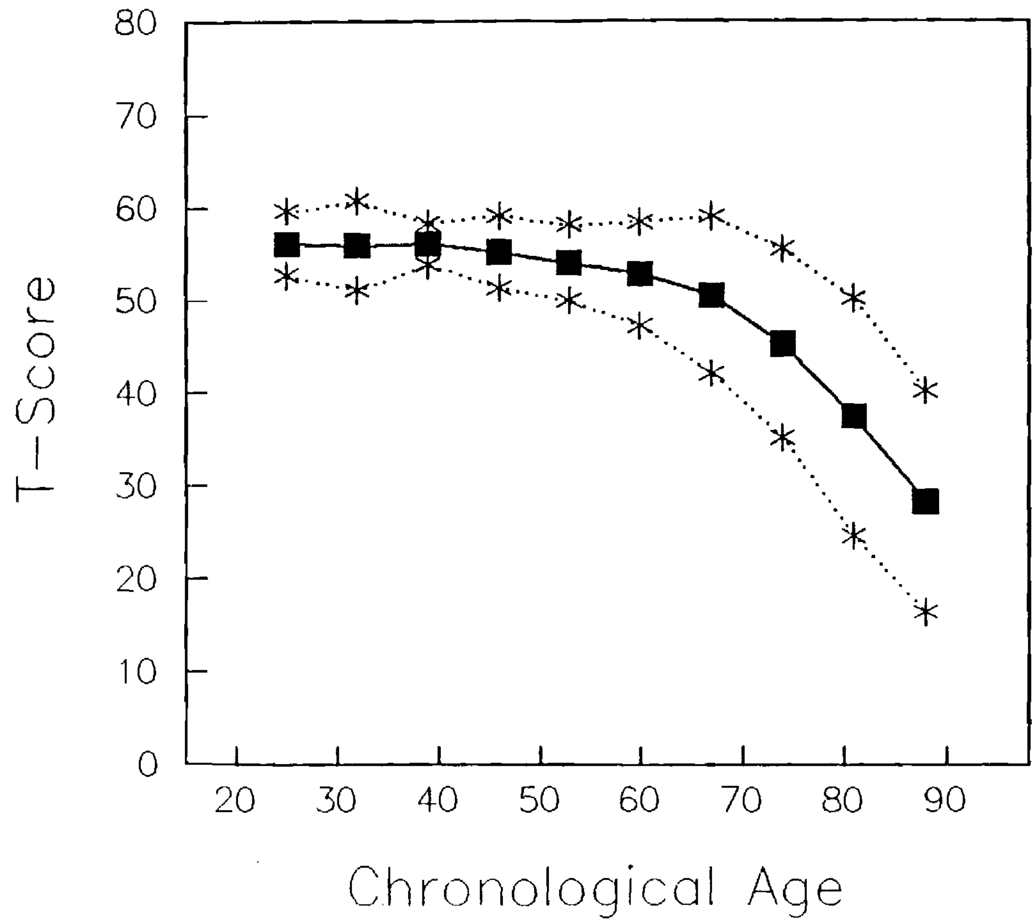
Table 1 (Continued)

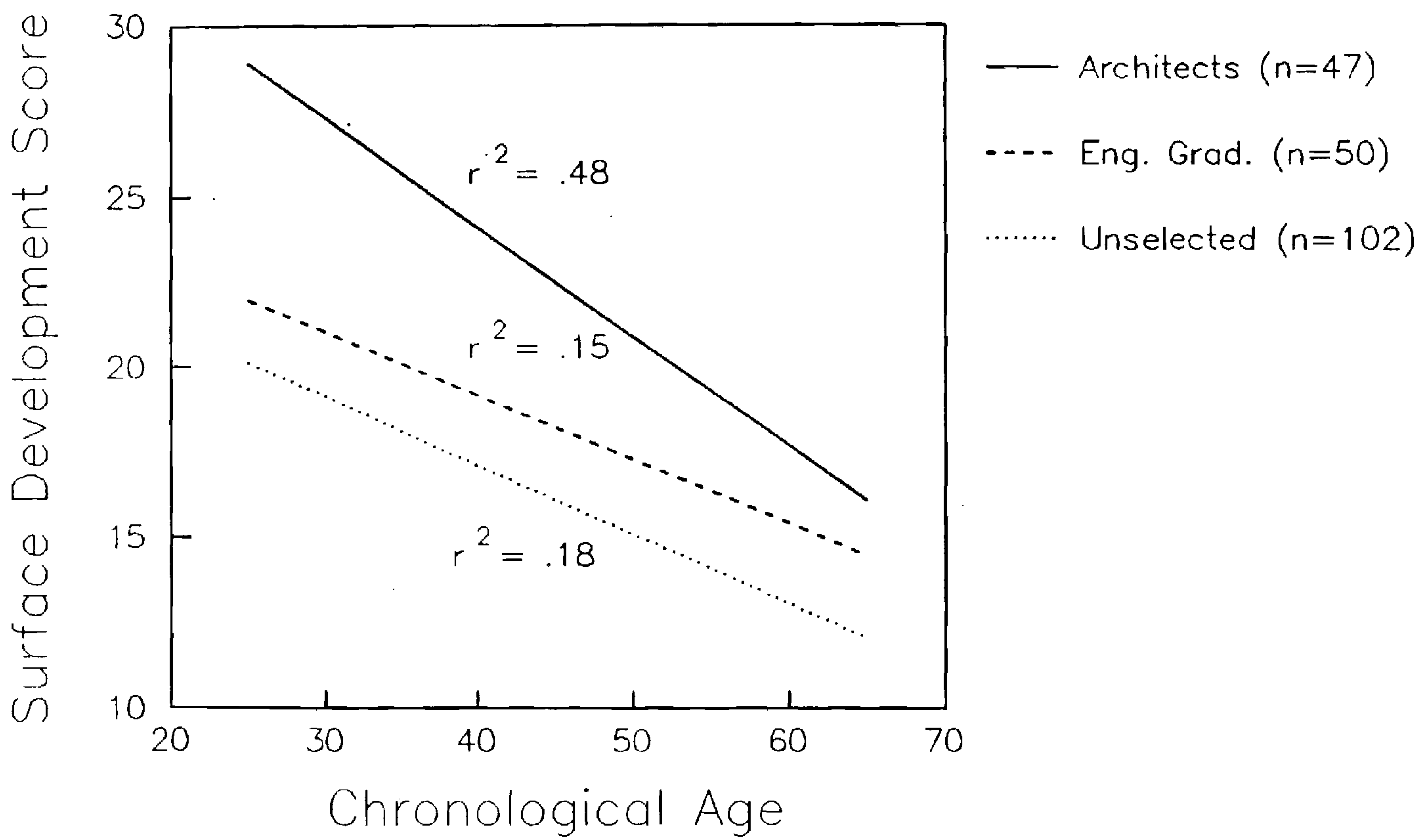
(22)	Y = O, Y > O	Taub (1973)
(23)	Y = O	Taub and Long (1972)
(24)	Y > O	Kliegl, et al. (1989)
(25)	Y > O	" " "
(26)	Y = O	Charness and Campbell (1988)
(27)	Y > O	Kamin (1957)

Figure Captions

Figure 1 - Mean levels of performance on the ETS Basic Skills Test as a function of age. Values are represented in T-score units, with bars representing plus and minus one standard deviation. Data from Schaie (1988b).

Figure 2 - Regression equations relating age to Surface Development performance for three groups of male college graduates. Data from Salthouse, et al. (1990) and Salthouse and Mitchell (in press).


80
70
60
50
40
30
20
10
0
T-Score
20
30
40
50
60
70
80
90
Chronological Age



Surface Development Score
30
25
20
15
10
20
30
40
50
60
70
Chronological Age
$r^2 = .48$
$r^2 = .15$
$r^2 = .18$
Architects (n=47)
Eng. Grad. (n=50)
Unselected (n=102)