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# 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

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[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.

abilities 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

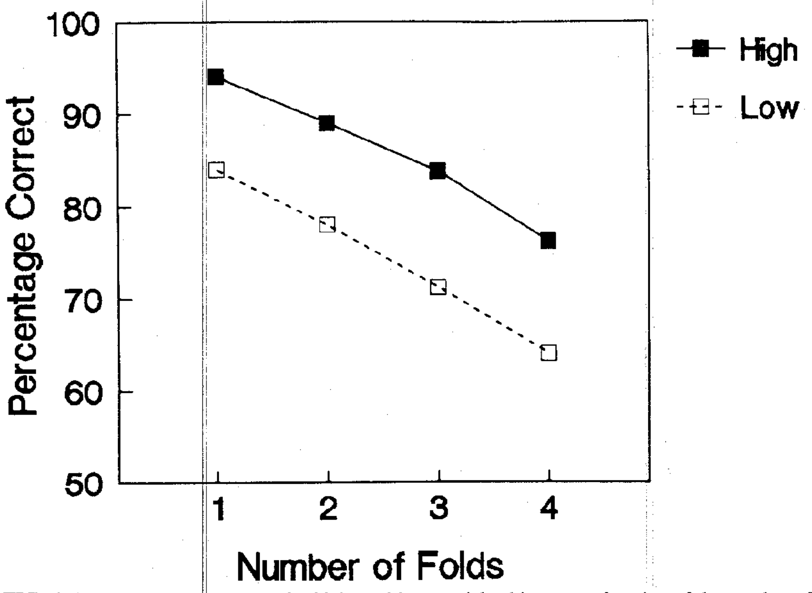

**FIG. 1.** Mean percentage correct for high- and low-spatial subjects as a function of the number of folds displayed prior to the hole punch in the paper-folding task, Study 1.

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

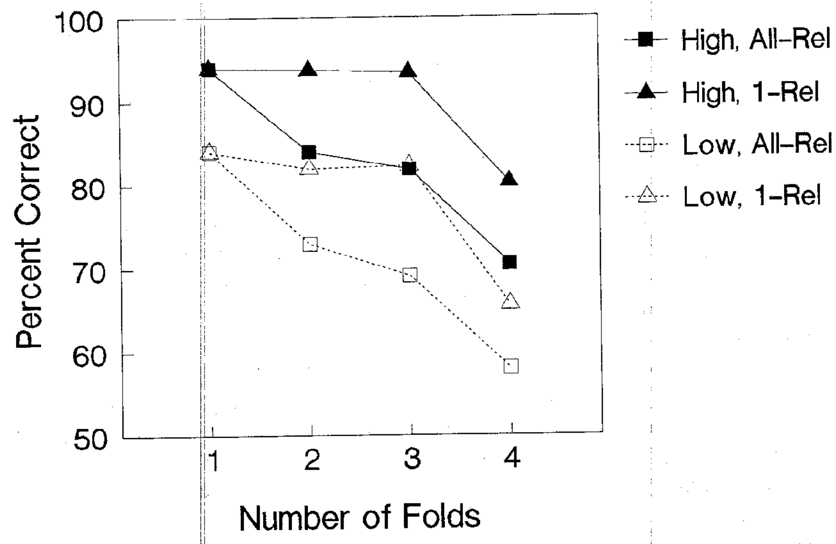

**FIG. 2.** Mean percentage correct for high- and low-spatial subjects as a function of number of folds for trials in which all folds were relevant to the decision, and for trials with only one relevant fold, Study 1.

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.

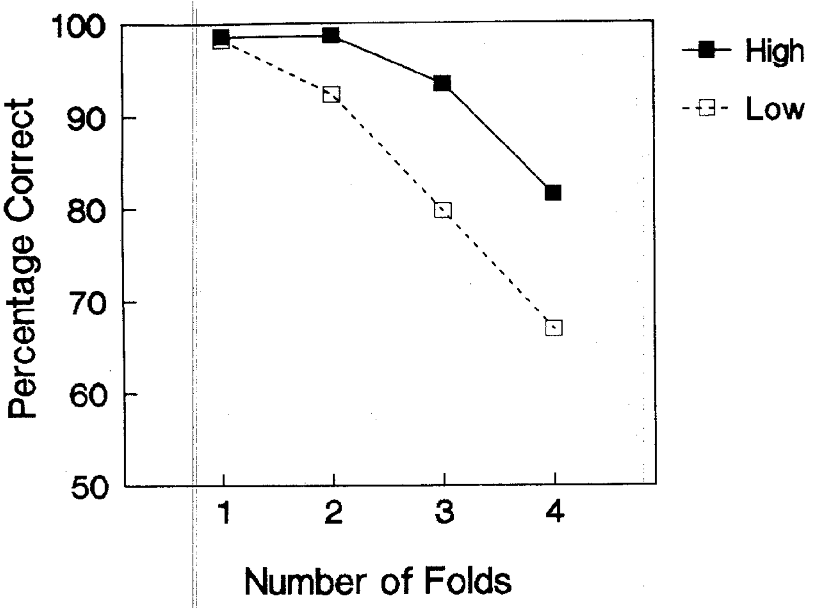

FIG. 3. Mean percentage correct for high- and low-spatial subjects as a function of the number of folds required to assemble the cube in the cube-folding task, Study 1.

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

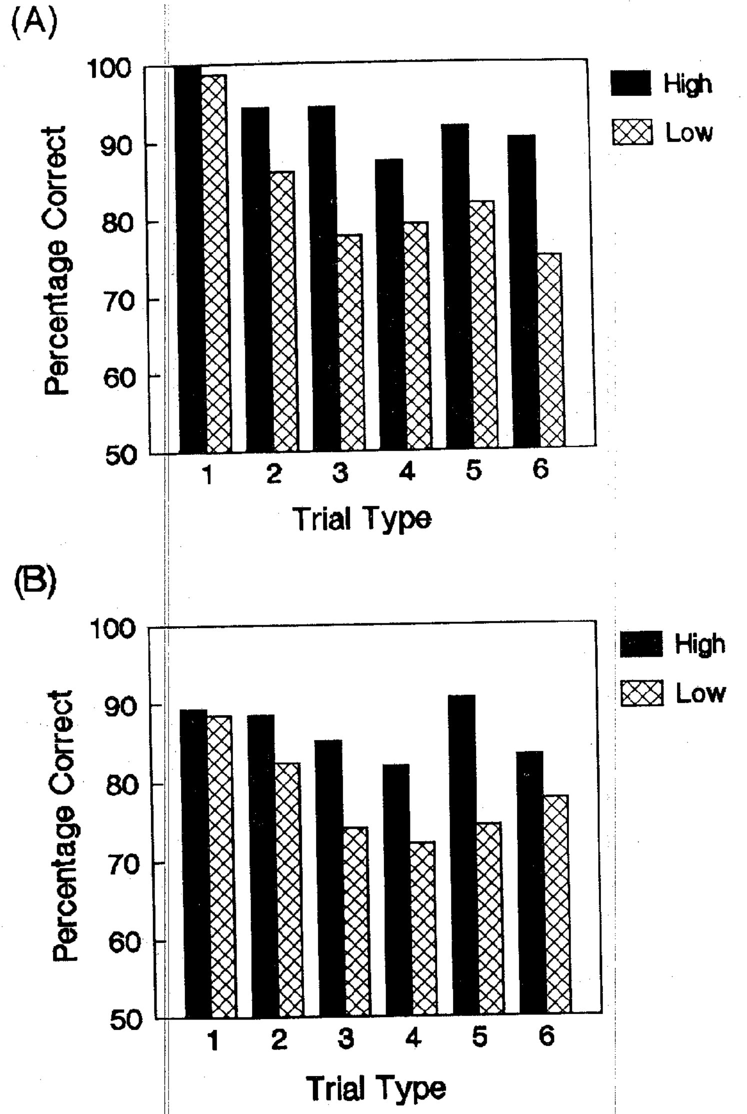

**FIG. 4.** (A) Mean percentage correct in the simultaneous version of the cube comparisons task for high- and low-spatial subjects as a function of the trial types varying in degree of orientational discrepancy between the two cube configurations and number of corresponding letters. (B) Mean percentage 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.

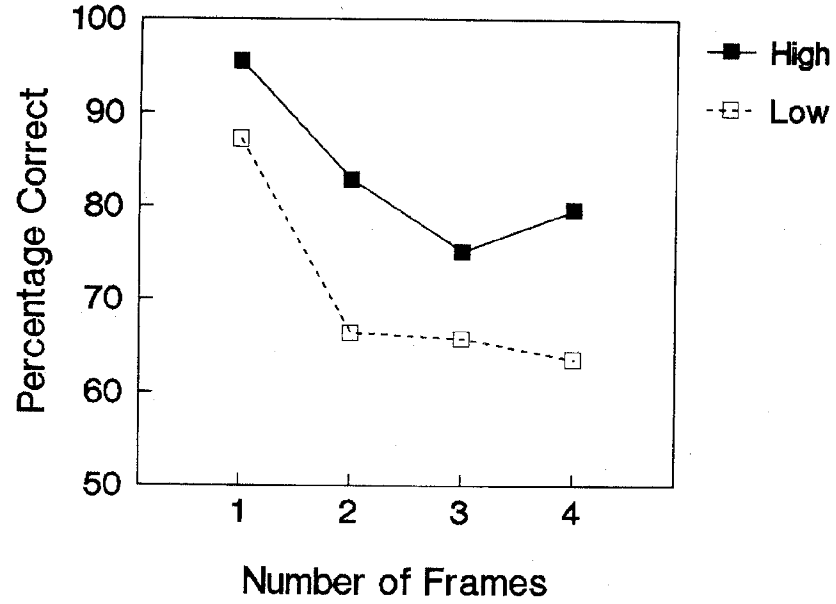

FIG. 5. Mean percentage correct for high- and low-spatial subjects as a function of number of frames to be integrated to form a composite pattern in Phase 1 of the spatial integration task, Study 1.

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.

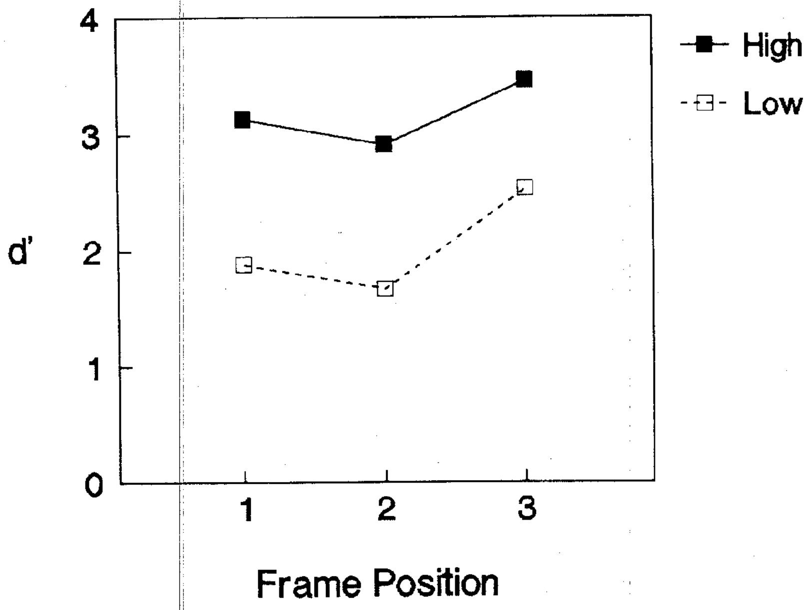

FIG. 6. Mean percentage correct for high- and low-spatial subjects as a function of frame position of target segments in Phase II of the spatial integration task, Study 1.

### 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 MSc = 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.

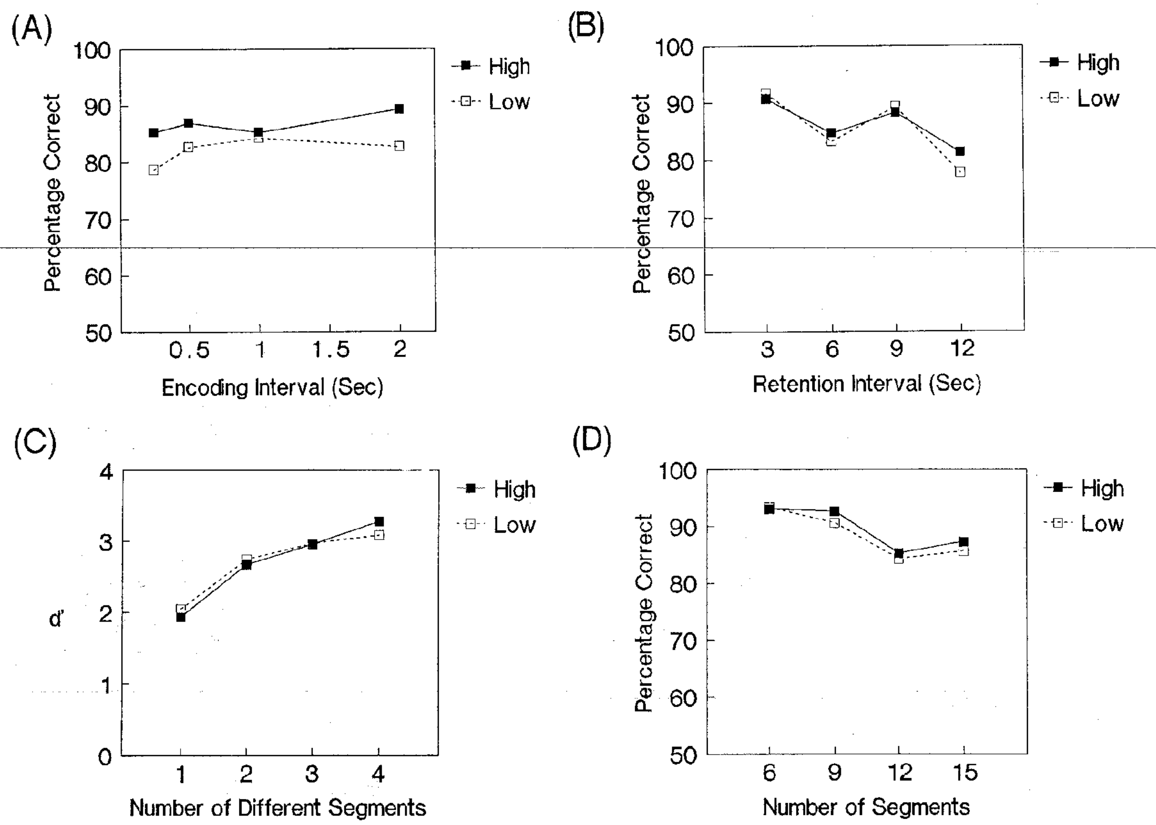

**FIG. 7.** Accuracy of recognition decisions for high- and low-spatial subjects in Study 2 for: (A) the encoding efficiency task; (B) the memory stability task; (C) the memory precision task; and (D) the memory capacity task.

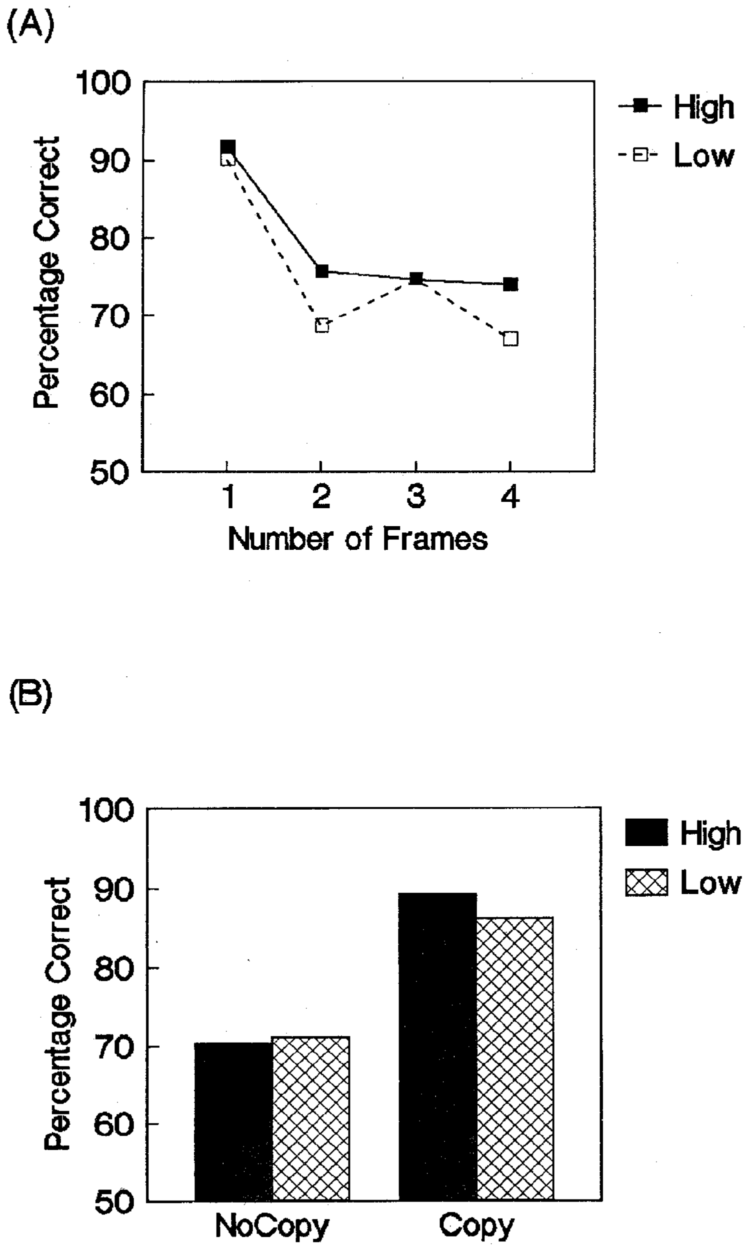

**FIG. 8.** (A) Mean percentage correct for high- and low-spatial subjects in the spatial integration task of Study 2. (B) Mean percentage correct for high- and low-spatial subjects in the NoCopy and Copy conditions of the spatial integration task in Study 2.

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

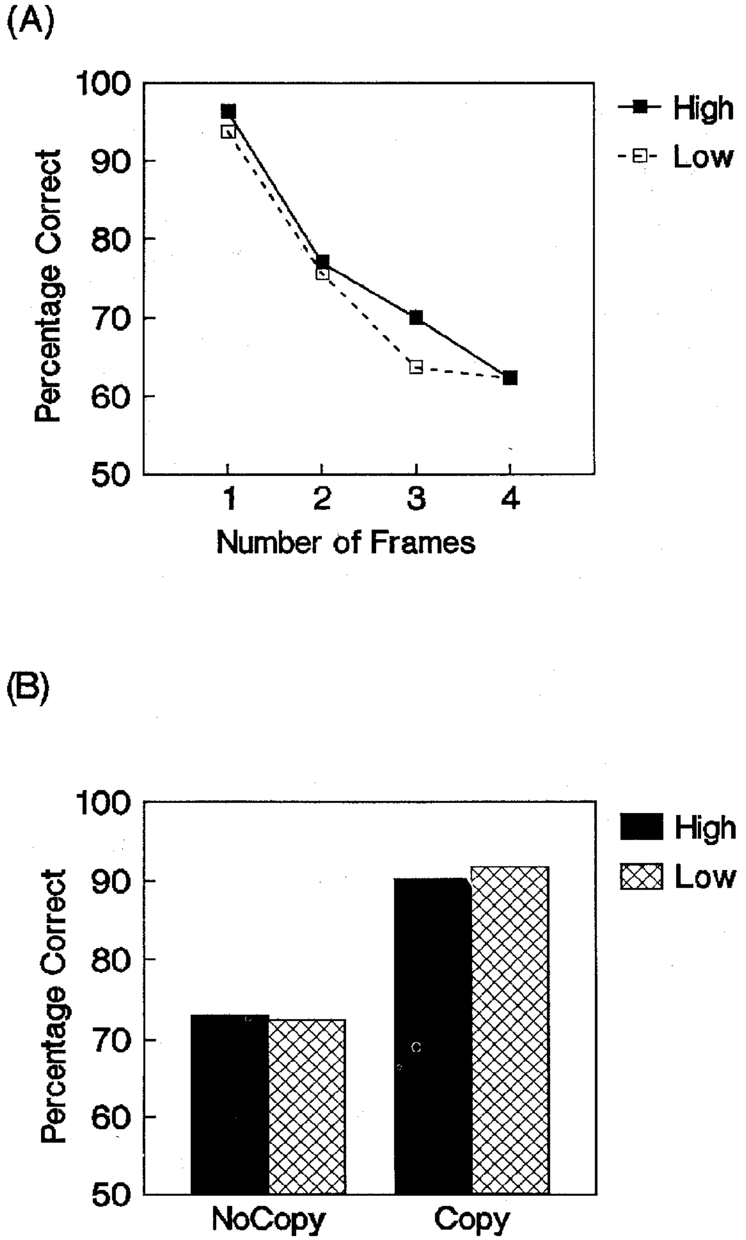

FIG. 9. (A) Mean percentage correct for high- and low-spatial subjects in the spatial deletion task of Study 2. (B) Mean percentage correct for high- and low-spatial subjects in the NoCopy and Copy conditions of the spatial deletion task in Study 2.

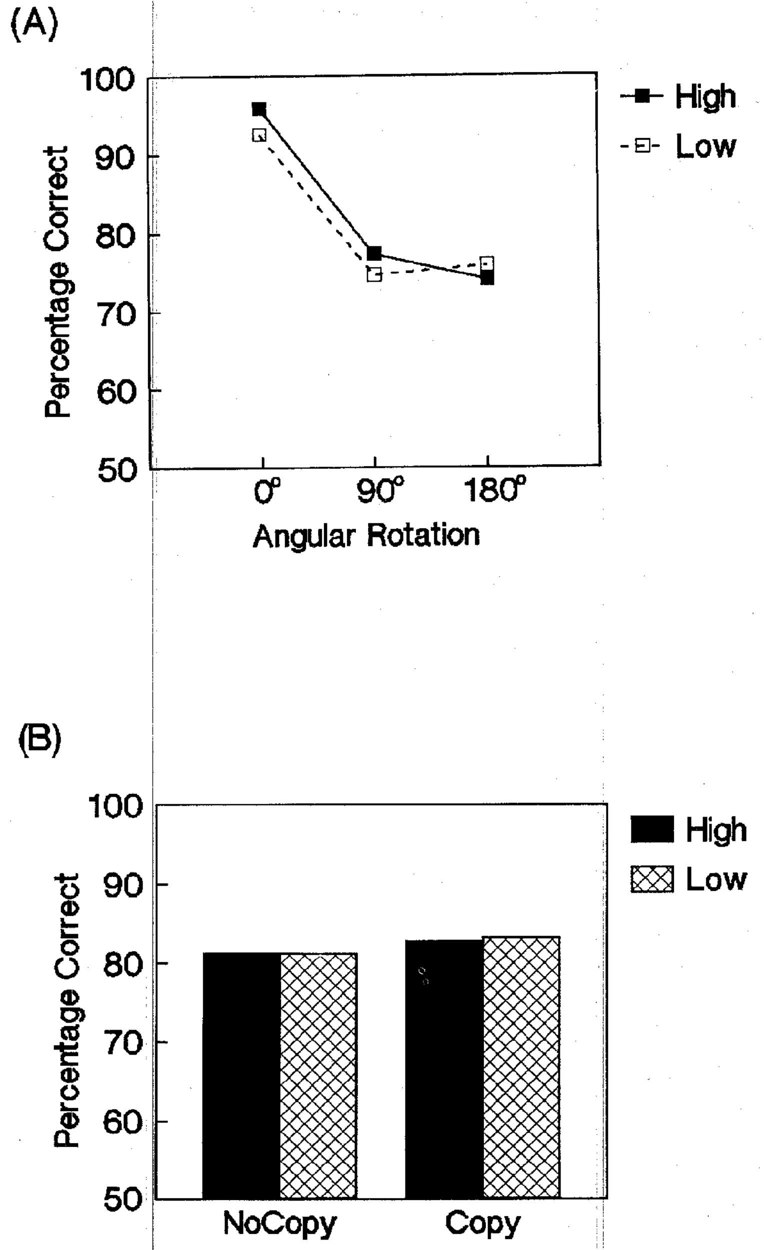

**FIG. 10.** (A) Mean percentage correct for high- and low-spatial subjects in the spatial rotation task of Study 2. (B) Mean percentage correct for high- and low-spatial subjects in the NoCopy and Copy conditions of the spatial rotation task in Study 2.

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 existencc 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.

## REFERENCES

Barratt, E.S. (1953). An analysis of verbal reports of solving spatial problems as an aid in defining spatial factors. *Journal of Psychology, 36,* 17–25.

Borich, G.D., & Bauman, P.M. (1972). Convergent and discriminant validation of the French and Guilford-Zimmerman Spatial Orientation and Spatial Visualization factors. *Educational and Psychological Measurement, 32,* 1029–1032.

Broadbent, D.E. (1971). *Decision and stress.* London: Academic.

Carpenter, P.A., & Just, M.A. (1986). Spatial ability: An information-processing approach to psychometrics. In R.J. Sternberg (Ed.), *Advances in the psychology of human intelligence* (Vol. 3, pp. 221–253). Hillsdale, NJ: Erlbaum.

Cooper, L., & Mumaw, R.J. (1985). Spatial aptitude. In R.F. Dillon (Ed.), *Individual differences in cognition* (Vol. 2, pp. 67–94). Orlando, FL: Academic.

Ekstrom, R.B., French, J.W., Harman, H.H., & Dermen, D. (1976). *Manual for kit of factor-referenced cognitive tests.* Princeton, NJ: Educational Testing Service.

French, J.W. (1965). The relationship of problem-solving styles to the factor composition of tests. *Educational and Psychological Measurement, 25,* 9–28.

Just, M.A., & Carpenter, P.A. (1985). Cognitive coordinate systems: Accounts of mental rotation and individual differences in spatial ability. *Psychological Review, 92,* 137–171.

Karlins, M., Schuerhoff, C., & Kaplan, M. (1969). Some factors related to architectural creativity in graduating architecture students. *Journal of General Psychology, 81,* 203–215.

Kyllonen, P.C., Lohman, D.F., & Woltz, D.J. (1984). Componential modeling of alternative strategies for performing spatial tasks. *Journal of Educational Psychology, 76,* 1325–1345.

Lansman, M. (1981). Ability factors and the speed of information processing. In M. Friedman, J.P. Das, & N. O'Connor (Eds.), *Intelligence and learning* (pp. 441–457). New York: Plenum.

Lansman, M., Donaldson, G., Hunt, E., & Yantis, S. (1982). Ability factors and cognitive processes. *Intelligence, 6,* 347–386.

Lohman, D.F. (1979). *Spatial ability: A review and reanalysis of the correlational literature.* Stanford, CA: Stanford University, School of Education, Aptitude Research Project.

Lohman, D.F. (1986). The effect of speed-accuracy tradeoff on sex differences in mental rotation. *Perception & Psychophysics, 39,* 427–436.

Lohman, D.F. (1988). Spatial abilities as traits, processes, and knowledge. In R.J. Sternberg (Ed.), *Advances in the psychology of human intelligence* (Vol. 4, pp. 181–248). Hillsdale, NJ: Erlbaum.

Lohman, D.F., & Kyllonen, P.C. (1983). Individual differences in solution strategy on spatial tasks. In R.F. Dillon & R.R. Schmeck (Eds.), *Individual differences in cognition* (Vol. 1, pp. 105–135). New York: Academic.

Lohman, D.F., Pellegrino, J.W., Alderton, D.L., & Regian, J.W. (1987). Dimensions and components of individual differences in spatial abilities. In S.H. Irvine & S.E. Newstead (Eds.), *Intelligence and cognition: Contemporary frames of reference* (pp. 253–312). Dordrecht, Netherlands: Martinus Nijhoff.

Michael, W.B., Guilford, J.P., Fruchter, B., & Zimmerman, W.S. (1957). The description of spatial visualization abilities. *Educational and Psychological Measurement, 17,* 185–199.

Michael, W.B., Zimmerman, W.S., & Guilford, J.P. (1950). An investigation of two hypotheses regarding the nature of the spatial relations and visualization factors. *Educational and Psychological Measurement, 10,* 187–213.

Michael, W.B., Zimmerman, W.S., & Guilford, J.P. (1951). An investigation of the nature of spatial relations and visualization factors in two high school samples. *Educational and Psychological Measurement, 11,* 561–577.

Mumaw, R.J., & Pellegrino, J.W. (1984). Individual differences in complex spatial processing. *Journal of Educational Psychology, 76,* 920–939.

Pellegrino, J.W., Alderton, D.L., & Shute, V.J. (1984). Understanding spatial ability. *Educational Psychology, 19,* 239–253.

Pellegrino, J.W., & Kail, R. (1982). Process analyses of spatial aptitude. In R.J. Sternberg (Ed.), *Advances in the psychology of human intelligence* (Vol. 1, pp. 311–365). Hillsdale, NJ: Erlbaum.

Pellegrino, J.W., & Lyon, D.R. (1979). The components of a componential analysis. *Intelligence, 3,* 169–186.

Pellegrino, J.W., Mumaw, R.J., & Shute, V.J. (1985). Analyses of spatial aptitude and expertise. In S.E. Embretson (Ed.), *Test design: Developments in psychology and psychometrics* (pp. 45–76). Orlando, FL: Academic.

Poltrock, S.E., & Brown, P. (1984). Individual differences in visual imagery and spatial ability. *Intelligence, 8,* 93–138.

Salthouse, T.A. (1987a). Adult age differences in integrative spatial ability. *Psychology and Aging, 2,* 254–260.

Salthouse, T.A. (1987b). Sources of age-related individual differences in block design tests. *Intelligence, 11,* 245–262.

Salthouse, T.A., & Mitchell, D.R.D. (1989). Structural and operational capacities in integrative spatial ability. *Psychology and Aging, 4,* 18–25.

Salthouse, T.A., Mitchell, D.R.D., Skovronek, E., & Babcock, R. (1989). Effects of adult age and working memory on reasoning and spatial abilities. *Journal of Experimental Psychology: Learning, Memory and Cognition, 15,* 507–516.

Shepard, R.N., & Feng, C. (1972). A chronometric study of mental paper folding. *Cognitive Psychology, 3,* 228–243.

Sternberg, R.J. (1977). *Intelligence, information processing, and analogical reasoning: The componential analysis of human abilities.* Hillsdale, NJ: Erlbaum.

Tapley, S.M., & Bryden, M.P. (1977). An investigation of sex differences in spatial ability: Mental rotation of three-dimensional objects. *Canadian Journal of Psychology, 31,* 122–130.

Wechsler, D. (1981). *Manual for the Wechsler Adult Intelligence Scale-Revised.* New York: Psychological Corporation.

Zimmerman, W.S. (1954). The influence of item complexity upon the factor composition of a spatial visualization test. *Educational and Psychological Measurement, 14,* 106–119.