Emergence and Characterization of Sex Differences in Spatial Ability: A Meta-Analysis

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LINN, MARCIA C., and PETERSEN, ANNE C. *Emergence and Characterization of Sex Differences in Spatial Ability: A Meta-Analysis.* CHILD DEVELOPMENT, 1985, **56**, 1479–1498. Sex differences in spatial ability are widely acknowledged, yet considerable dispute surrounds the magnitude, nature, and age of first occurrence of these differences. This article focuses on 3 questions about sex differences in spatial ability: (*a*) What is the magnitude of sex differences in spatial ability? (*b*) On which aspects of spatial ability are sex differences found? and (*c*) When, in the life span, are sex differences in spatial ability first detected? Implications for clarifying the linkage between sex differences in spatial ability and other differences between males and females are discussed. We use meta-analysis, a method for synthesizing empirical studies, to investigate these questions. Results of the meta-analysis suggest (*a*) that sex differences arise on some types of spatial ability but not others, (*b*) that large sex differences are found only on measures of mental rotation, (*c*) that smaller sex differences are found on measures of spatial perception, and (*d*) that, when sex differences are found, they can be detected across the life span.

Differences between males and females in spatial ability are widely acknowledged, yet considerable dispute surrounds the magnitude, nature, and age of first occurrence of these differences (Harris, 1982; Hyde, 1981; Liben, Patterson, & Newcombe, 1981; Linn & Petersen, in press; Maccoby & Jacklin, 1974; McGee, 1979). To establish the magnitude of sex differences in spatial ability, meta-analysis has proved useful for studies published prior to 1974 (Hyde, 1981).[1] In this article we review studies reported since 1974 using recent refinements of the meta-analysis technique.

It is generally agreed that spatial ability is an important component of intellectual ability, yet its nature remains to be clarified. Activities as disparate as perception of horizontality, mental rotation of objects, and location of simple figures within complex figures have all been referred to as measures of spatial ability. No consensus exists for categorization of measures of spatial ability, although many different schemes have been presented. The only view achieving agreement is that spatial ability involves multiple processes. In this article we draw on recent psychometric studies, information-processing investiga-

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[1] Note that the term "sex" is used to reflect that individuals are assigned to groups on the basis of being males or females. This choice of term does *not* imply that biological differences account for the observed performance of the group. Clearly, different socialization experiences are also associated with membership in the two groups.

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tions, and theories of sex differences. These views, as well as meta-analysis techniques, are used to partition the measures of spatial ability into meaningful categories.

Explanations of sex differences in spatial ability depend, to some extent, on when these differences first occur. The hypothesized emergence of sex differences in spatial ability in early adolescence had led researchers to suggest explanations linked to pubertal change (e.g., Petersen, 1980; Waber, 1976). If, instead, sex differences in spatial ability are found to emerge prior to adolescence, then a biological explanation for the sex differences based on genetic factors (see Wittig & Petersen, 1979) or prenatal hormonal influences (see Reinisch, Gandelman, & Spiegal, 1979) would be preferred.

For example, Waber (1979) has indicated that spatial tests on which males have shown a consistent superiority have several common characteristics: the sex differences do not appear reliably until adolescence, and the mechanisms that mature during that period and permit children to perform the task are sexually differentiated. Maccoby and Jacklin (1974) cited some evidence for emergence of sex differences in adolescence. However, subsequent writers (e.g., Newcombe, Bandura, & Taylor, 1983) identify studies suggesting that male-female differences in spatial ability emerge prior to adolescence. The speculative link of sex differences in spatial ability to the biological changes in adolescence may have been based more on the limited number of convincing studies with preadolescent subjects than on a lack of differences between boys and girls on spatial ability tasks prior to adolescence. In this article we examine the magnitude of sex differences in spatial ability prior to, during, and after adolescence.

Clarification of the character and timing of emergence of sex differences in spatial ability has implications for areas such as science and mathematics education (Linn & Petersen, in press). For example, the possible emergence of sex differences in science and mathematics performance in adolescence has been linked to the emergence of sex differences in spatial ability (Benbow & Stanley, 1980, 1984). This linkage, however, may reflect sex differences in mathematics course experience, which, until recently, often first occurred during adolescence. Recent increases in mathematics course enrollment patterns for females have paralleled delays in the emergence of sex differences in mathematics performance among males and females (e.g., Armstrong, 1979; Chipman, Brush, & Wilson, 1985; Fennema & Sherman, 1978).

Thus we address three questions about sex differences in spatial ability: (*a*) What is the magnitude of sex differences in spatial ability? (*b*) On which aspects of spatial ability are sex differences found? and (*c*) When, in the life span, are sex differences in spatial ability first detected? Implications for clarifying the linkage between sex differences in spatial ability and other differences between males and females are discussed. We use meta-analysis, a method for synthesizing empirical studies, to investigate these questions.

Research on Spatial Ability

Results from meta-analysis depend inexorably on the approach, methodology, and quality of available primary analyses. The research perspectives that motivated those conducting primary analyses of spatial ability provide both the opportunities and the constraints of meta-analysis. Thus we briefly summarize the major research perspectives for investigating spatial ability that influenced our secondary analysis.

Four research perspectives have generated most studies of spatial ability: (*a*) the *differential* perspective, involving comparison of spatial ability for different populations (such as males and females); (*b*) the *psychometric* perspective, involving comparison of correlations between different spatial tasks in order to define "factors" in spatial ability; (*c*) the *cognitive* perspective, involving the identification of the processes used universally to solve a particular spatial ability task, albeit with quantitatively different efficiency; and (*d*) the *strategic* perspective, involving identification of the qualitatively different strategies used to solve a given spatial ability task by different respondents.

These four perspectives illustrate the complexity of this field. Researchers from each of these perspectives consider information at different levels of detail and take qualitatively different approaches. All four influence the planning and interpretation of our meta-analysis. Our meta-analysis, drawing on the differential perspective, focuses on group mean differences. We draw on the psychometric and cognitive perspectives to partition the many studies of spatial ability into homogeneous groups. To interpret variations in performance on the same task we rely on the strategic perspective.

Meta-Analysis

Recent advances in meta-analysis procedures make this a preferred tool for research synthesis (Hedges, 1982a, 1982b). Meta-analysis procedures offer more opportunities for valid inference from empirical studies than "eyeball analysis" or "vote counting" methods do (e.g., Glass, 1976; Hedges & Olkin, 1980; Pillemer & Light, 1980). As mentioned above, the results of a meta-analysis are only as valid as the studies that go into it. Furthermore, the research perspectives in the field influence what researchers study and, therefore, constrain the meta-analysis.

In the meta-analysis we synthesized effect sizes or standardized mean differences between males and females on spatial ability tasks. Using the recently developed methods of Hedges (1982a, 1982b), we computed unbiased estimates of effect size. We computed unbiased effect sizes from ANOVA and *t* test data as well as from means and standard deviations using the methods of Cohen (1977). Unbiased estimates of effect sizes have lower standard deviations than biased estimates and, therefore, are more precise.

Testing for homogeneity is essential to ensure that effect sizes are drawn from a uniform population. When effect sizes are homogeneous, a pooled estimate of effect size provides a summary of the results of a series of studies. However, when effect sizes are not homogeneous, pooled estimates may be misleading. Hedges (1982a) reports a statistical test for homogeneity of effect size within groups and a strategy for fitting a model to effect sizes divided into a priori classes. Hedges's homogeneity test assesses whether studies in the sample can be viewed as replicates of each other. Thus findings that studies are nearly homogeneous imply that they come close to being replications. Since studies entering meta-analysis do differ on many dimensions, near homogeneity may be appropriate (e.g., Class, McGaw, & Smith, 1981). As a wide range of meta-analyses reveal, homogeneity is infrequently achieved (e.g., Hyde & Linn, in press). More experience with these measures is needed to clarify how the statistic behaves when studies are similar but not exact replicates. For further discussion of these issues, see Linn (in press).

Implementing the Hedges (1982a, 1982b) approach in this study, we tested all the spatial ability effect sizes for homogeneity. When an acceptable level of homogeneity was not found, we partitioned the studies into smaller groups following a model derived from the psychometric and cognitive research perspectives. We tested the partitioned studies for homogeneity and basically continued until we located homogeneous or nearly homogeneous groups of studies.

In summary, through meta-analysis we offer a promising method for research synthesis. Advances in methodology, including procedures for computing unbiased estimates of effect size and for testing homogeneity of effects, increase the accuracy of conclusions. Ultimately we expect that meta-analysis techniques will encourage progress from one set of studies to another in ways that vote counting or informal comparisons are not able to accomplish.

Study Selection

In our meta-analysis we included studies of spatial ability published since Maccoby and Jacklin's (1974) review and before June 1982. We searched journals likely to publish studies focused on spatial ability as well as *Psychological Abstracts, Child Development Abstracts*, and the *Index Medicus*. Sources of studies included *Behavioral Genetics, Psychological Bulletin, Journal of Early Adolescence, Developmental Psychology*, and *Child Development*. In addition, papers presented at recent meetings of the American Educational Research Association, the American Psychological Association, and the Society for Research in Child Development were included. Inclusion of unpublished studies as well as studies of topics other than sex differences (where sex differences are reported whether or not significant differences are found) offsets, to some extent, the concern that available studies are biased toward significant effects while other studies remain in the file drawer (Rosenthal, 1979).

Initially we identified over 200 effect sizes; 172 entered our meta-analysis. (The studies and effect sizes are cataloged in Hyde & Linn, in press.) Studies were eliminated because they (*a*) had samples of fewer than 40 volunteers selected haphazardly, (*b*) reported insufficient information to compute effect sizes, or (*c*) had text presentations that did not coincide with the data reported in the tables. (These events were clarified with the author when possible, and several typographical errors were detected.) Furthermore, to avoid dependence among the effect sizes in the data, we randomly selected one effect size from studies that used the same subjects to measure the same category of spatial ability.

Analysis Procedure

The analysis plan involved using a branching procedure governed by a criterion of homogeneity following Hedges (1982a). First, all 172 effect sizes were tested to see whether they could be from a uniform population. As described in detail below, when homogeneity was not achieved, the psychometric and cognitive perspectives were used to identify three categories of spatial ability, and the effect sizes were partitioned into those categories. When homogeneity did not result, effect sizes within a particular category of spatial ability were partitioned according to the age of the respondents and again tested for homogeneity. Partitioning by age reflected both the differential perspective, because different age groups are hypothesized to have different levels of spatial ability, and the cognitive perspective, because tests of spatial ability can tap different processes at different points in development. If homogeneity was still not achieved, we investigated other partitions for the effect sizes.

Categories of Spatial Ability

Spatial ability generally refers to skill in representing, transforming, generating, and recalling symbolic, nonlinguistic information. Given the uncertainty about categories of spatial ability, we first formed broad categories that could be further partitioned if meta-analysis of the effect sizes failed to yield homogeneity. Considerable dispute surrounds the identification of specific spatial abilities and the characterization of the processes used to solve spatial items (e.g., Caplan, MacPherson, & Tobin, in press).

Categorizations of spatial ability, stemming from the psychometric perspective, have frequently used factor analysis (e.g., Lohman, 1979; McGee, 1979). Thurstone and Thurstone (1941) identified space as a prominent aspect of the primary mental abilities. In the 1940s, Air Force researchers partitioned Thurstone's concept of spatial ability into four separate dimensions. The French kit of reference tests (French, Ekstrom, & Price, 1963) identifies three types of spatial ability. Hierarchical models, such as those of Cattell (1971) and Vernon (1965), generally locate spatial ability near the top of the hierarchy and include two or more subabilities in the general category.

Since the psychometric perspective yields categorizations that depend on the tests used for the investigation, this approach will never yield a general answer. In contrast, research from the cognitive perspective, identifying processes used to solve the tasks thought to measure spatial ability, offers some promise for identifying general categories of spatial ability (e.g., Carpenter & Just, 1981; Cooper & Regan, 1982; Guilford, 1969; Shepard & Cooper, 1982). In this research we focus on similarities in the processes that respondents use for individual items, a different level of analysis from the correlational approach used in the psychometric perspective. Informed by these perspectives, the categories we describe are labeled *spatial perception*, *mental rotation*, and *spatial visualization*.

Spatial Perception

In spatial perception tests, subjects are required to determine spatial relationships with respect to the orientation of their own bodies, in spite of distracting information. One example is the Rod and Frame Test (RFT), in which subjects must place a rod vertically while viewing a frame oriented at 22° (Witkin, Dyk, & Faterson, 1962). Another is water level, a task that requires subjects to draw or identify a horizontal line in a tilted bottle (e.g., DeAvila, Havassy, & Pascual-Leone, 1976; Harris, Hanley, & Best, 1978; Inhelder & Piaget, 1958). An example appears in Figure 1.

Cognitive rationale.—What processes characterize spatial perception tasks? Some process analyses of spatial perception tasks suggest that subjects use the gravitational vertical to locate the correct orientation. Corballis and colleagues (Corballis & Roldan, 1975; Corballis, Zbrodoff, & Roldan, 1976) here demonstrated that participants in studies of symmetry detection rotate the stimuli to achieve either visual (consistent with head tilt) or gravitational upright. Respondents may rely on kinesthetic cues for locating the gravitational horizontal or vertical (e.g., Goodenough, Oltman, & Cox, 1984; Linn & Kyllonen, 1981; Sigman, Goodenough, & Flanagan, 1978, 1979). For example, respondents to the RFT report relying on whether the position "feels" upright (Linn & Kyllonen, 1981) and respondents to water level report relying on whether the water "feels" level (Petersen & Gitelson, in press). The other feature of spatial perception tasks is a focus on disembedding or overcoming distracting cues. Respondents can either ignore or correct for the possibly misleading cues from tilted objects

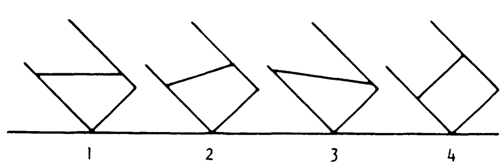

FIG. 1.—A spatial perception item. Respondents are asked to indicate which tilted bottle has a horizontal water line.

in their visual field. Reliance on kinesthetic cues may accompany a decision to ignore the distracting cues in the situation.

Although RFT and water level are certainly not identical in their task demands, they share important features. They both depend on locating the gravitational upright; they both present distracting perceptual information; and they both provide a series of items requiring the same response with slight variation in the distractors.

Psychometric rationale.—Historically, the RFT was introduced by Witkin (1949) to measure what he called Field-Dependence Independence (FDI). Subsequently, high correlations between RFT and the Embedded Figures Test (EFT) were noted, as were similarities in task demands (both included distracting information). Both RFT and EFT became accepted measures of FDI. Recently, however, Witkin and Goodenough (1981) reviewed the work on FDI and concluded that RFT represents FDI better than EFT does and that the two abilities are distinct. Furthermore, they indicated that the role of kinesthetic cues distinguished the RFT from the EFT. In a correlational study, Linn and Kyllonen (1981) supported the distinction between RFT and EFT. Linn and Kyllonen, using both factor analysis and structured equation approaches, showed that measures of spatial orientation could be separated from measures such as EFT, thus providing a psychometric rationale for two distinct categories. Lohman's (1979) identification of an orientation factor in measures of spatial ability corresponds to this distinction. Correlational evidence suggests that RFT and water level are more similar to each other than they are to other measures of spatial ability (Goodenough et al., 1984; Linn & Kyllonen, 1981). Goodenough et al. found that, in a group of spatial tasks, water level had the highest correlation with RFT and that both had their highest loadings on a factor labeled "vestibular."

In summary, the potential advantage of using gravitational kinesthetic processes may differentiate spatial perception tasks from other tasks that require disembedding such as the EFT. The psychometric perspective is consistent with this process analysis, demonstrating that spatial perception tasks are distinct from other tasks requiring disembedding.

Mental Rotation

Shepard and his colleagues (Shepard & Cooper, 1982; Shepard & Metzler, 1971) have studied the ability to rotate a two or three dimensional figure rapidly and accurately. They devised individually administered tasks to measure the speed of response to different amounts of rotation (Cooper & Shepard, 1973; Shepard & Metzler, 1971). Subsequently Vandenberg and Kuse (1978) modified the Shepard-Metzler Mental Rotation Test for group administration (see example in Fig. 2). Other potential measures of this dimension are Flags and Cards from the French kit (French et al., 1963) and Primary Mental Abilities (PMA) space (Thurstone & Thurstone, 1941).

Cognitive rationale.—Shepard and his colleagues (e.g., Shepard & Cooper, 1982) sought to substantiate an analogue process for mental rotation. They hypothesized that during a mental rotation the respondent's internal cognitive processes have a one-to-one correspondence with the external rotation of the object (Shepard & Cooper, 1982). Thus they infer that a Gestalt-like process governs the rotation of objects. Controversy centers on

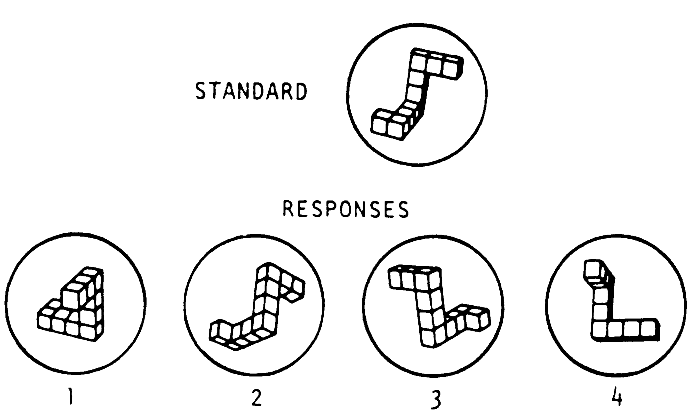

FIG. 2.—A mental rotation item. Respondents are asked to identify the two responses that show the standard in a different orientation.

whether mental rotation is analogous to physical rotation or is subject to analytic processing strategies (e.g., Carpenter & Just, 1978; Just & Carpenter, 1976; Pylsyshyn, 1979, 1981; Shepard & Cooper, 1982).

Evidence for the Gestalt-like process comes from research by Shepard and his coworkers (e.g., Shepard & Cooper, 1982) showing that the reaction time to solution for mental rotation items reflects the number of degrees through which the item must be rotated. Shepard finds that individuals take longer to rotate objects through a larger angle, supporting an analogue process for rotation of the figure. Those attempting to demonstrate that mental rotation is subject to analytic processing have sought to demonstrate effects for stimulus complexity (e.g., Pylsyshyn, 1979, 1981). Taken together, however, the various studies of mental rotation provide a strong case for the availability of Gestalt-like analogue mental rotation processes.

Mental rotation items are used to measure the time required for solution rather than the accuracy of solution (which is extremely high). Conditions of measurement encourage an analogue process. The possibility remains that respondents could use analytic processes to rotate figures when mental rotation is part of a more complex task such as Surface Development (French et al., 1963). When individually administered mental rotation items are translated into a group administered format, different processes may contribute to performance. Thus processes required for mental rotation may vary with the mode of task presentation. Furthermore, since the primary dimension is speed of response, such tasks have not been used successfully with young children because the level of concentration required is often limited in the young.

Some researchers suggest that mental rotation in two dimensions is easier and may reflect a different process than mental rotation in three dimensions (e.g., Rosser, 1980). Shepard and Cooper (1982) question this assertion, finding no effect of dimension when rotation of two- and three-dimensional objects is compared. Another factor differentiating two- and three-dimensional stimuli is complexity. Possibly, when respondents encounter complex stimuli, some find that the strategies they used for simple stimuli are no longer effective. Cooper (1983) suggests that the longer response times for three-dimensional stimuli result from some subjects whose inefficient strategies interfere with success. Thus all subjects may use a process analogous to physical rotation, but some subjects may apply the strategy inefficiently. Such inefficiency would be more apparent for complex stimuli.

Psychometric rationale.—The primary psychometric question is whether mental rotation can be differentiated from other measures of spatial ability. Thurstone's original space factor included mental rotation. French (1951), Fruchter (1954), Smith (1964), and Thurstone and Thurstone (1941) generally concur that two major factors characterize spatial ability: perception and visualization. None of these earlier systems differentiated mental rotation from spatial visualization.

Recently, DeFries et al. (1974) and Wilson and Vandenberg (1978) factor analyzed a group of 15 cognitive tests and found the same factor structure for different ethnic groups, for males and females, and for different age cohorts. In all cases a spatial factor was characterized by the Vandenberg and Kuse (1978) mental rotations test (subsequently called the Vandenberg) and by Cards (French et al., 1963) but also included spatial visualization tasks such as Hidden Patterns, Paper Form Board, and Progressive Matrices. However, the Vandenberg test had a low relationship to the other factors, which were identified as verbal, perceptual speed, and visual memory. In contrast, the spatial visualization tasks were more strongly related to the verbal factor than was the Vandenberg. Thus psychometrically, the Vandenberg test may identify a spatial ability independent of verbal ability and may be differentiated from spatial visualization in this respect.

In summary, results from the process analysis suggest that mental rotation tasks are distinct and involve a Gestalt-like analogue process. Factor analyses using mental rotation tasks have sometimes been used to identify a factor independent from spatial visualization. Our initial categorization of spatial ability separates mental rotation from spatial visualization, but our analysis procedures provide an opportunity to combine the two if effect sizes are similar.

Spatial Visualization

Spatial visualization is the label commonly associated with those spatial ability tasks that involve complicated, multistep manipulations of spatially presented information. These tasks may involve the processes required for spatial perception and mental rotations but are distinguished by the possibility of multiple solution strategies. Spatial visualization tasks include EFT, Hidden Figures, Paper Folding (see Fig. 3), Paper Form

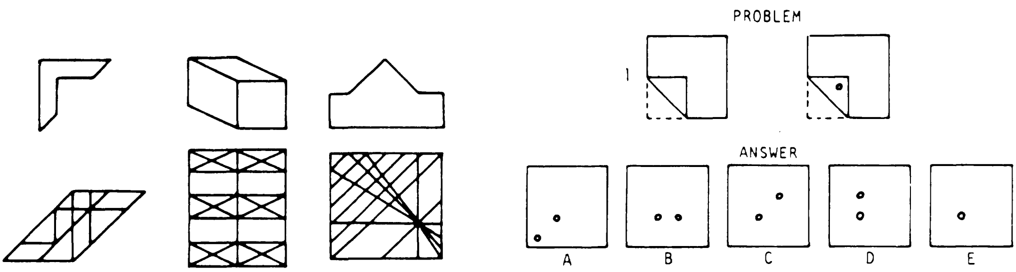

FIG. 3.—Spatial visualization items. Left, Embedded Figures: respondents are asked to find the simple shape shown on the top in the complex shape shown on the bottom. Right, Paper Folding: respondents are asked to indicate how the paper would look when unfolded.

Board, Surface Development, Differential Aptitude Test (spatial relations subtest), Block Design, and Guilford-Zimmerman spatial visualization. As many researchers have noted (Cattell, 1971; Guay & McDaniel, 1977; Shepard & Feng, 1972), an analytic strategy is required to solve these complex tasks. Mental rotation and spatial perception may or may not be elements of that strategy.

Cognitive rationale.—Process analyses of spatial visualization tasks stress that multistep, analytic procedures are required to solve the tasks. Consider Paper Folding (Fig. 3). Subjects must represent the paper and transform their representations by examining pictures that show (*a*) the folding of a piece of paper, (*b*) the punching of a hole through the folded paper, and (*c*) the resulting pattern of holes when the paper is unfolded. As is characteristic of spatial visualization tests, the student is required to work quickly (many fail to finish), rotate figures, and keep track of multistep operations.

Successful performance on spatial visualization tasks involves flexibility in selecting the optimal strategy for each item. As Kyllonen, Woltz, and Lohman (1981) have shown, respondents rapidly adjust their strategies to the unique features of new items. Successful respondents have a repertoire of strategies for these items.

Psychometric rationale.—Correlational studies often, but not always, identify spatial visualization. Guilford (1969) places these tests on a dimension called Cognition of Figural Transformation. Horn and Cattell (1966) identified spatial visualization using factor analysis with oblique rotation. Snow, Kyllonen, and Marshalek (in press) attempted to separate spatial visualization from Horn and Cattell's (1966) construct of general fluid ability, which is defined as the ability to form relationships among symbols, and is measured by tests such as Letter Series (French et al., 1963). They were unable to separate the two constructs in an orthogonal factor analysis, so they defined a construct called general fluid visualization that included both. Thus the distinction between spatial visualization and fluid ability requires further clarification. As discussed above, spatial visualization has sometimes but not always been distinguished from mental rotation but has been distinguished from spatial perception.

In summary, it appears that processes used for spatial visualization are distinct from those used for other spatial abilities. Success on spatial visualization requires analysis of task demands and flexible adaptation of a repertoire of solution procedures. Those conducting psychometric studies suggest that spatial visualization might be distinguished from other spatial abilities but not necessarily from nonspatial tasks such as measures of general fluid ability.

Thus we found three spatial ability categories: (*a*) spatial perception, which can be done efficiently using a gravitational/kinesthetic process; (*b*) mental rotation, which can be done efficiently using a Gestalt-like mental rotation process analogous to physical rotation of the stimuli; and (*c*) spatial visualization, which can be done efficiently using an analytic process. Other categorizations are, of course, possible. Our approach to research synthesis helps us decide whether this categorization is appropriate.

Meta-Analysis Results

As mentioned in the description of our meta-analysis procedure, we first tested to see whether all our effect sizes were homogeneous; they were not. Thus we partitioned the effect sizes using the three spatial ability categories described above.

Spatial Perception

The 62 spatial perception unbiased effect sizes were not homogeneous. Using Hedges's

TABLE 1

EFFECT SIZES (ES) AND HOMOGENEITY FOR SPATIAL ABILITY META-ANALYSIS

Group	ES (*N*)	Weighted Estimator of ES	95% Confidence Interval for ES	Homogeneity Statistic (Critical Value)
Spatial perception:				
All ages	62	.44	.04–.84	110(80)[a]
Under 13	26	.37	−.06–.81	45(38)[a]
13–18	23	.37	−.11–.85	19(34)[b]
Over 18	13	.64	.31–.97	26(21)[a]
Mental rotation:				
All ages	29	.73	.50–.96	247(43)
Vandenberg[c]	18	.94	.77–1.12	28(20)[b]
PMA space[d]	11	.26	.002–.54	18(16)[a]
Spatial visualization				
All ages	81	.13	−.24–.50	98(101)[b]

[a] Close to homogeneity.
[b] Homogeneity achieved with $p < .95$ confidence.
[c] Effect sizes for the Vandenberg version of the Shepard-Metzler figures.
[d] Effect sizes for the PMA-space subtest and other similar tests.

(1982a) methods for fitting categorical models, we partitioned by age of the subjects as shown in Table 1. After partitioning, the within-class homogeneity was reduced (from $\chi^2[62] = 110$ to $\chi^2[61] = 90$) but still high, indicating that heterogeneity remained. The between-class homogeneity was significant ($\chi^2[1] = 20$, $p < .05$), indicating that the observed differences in effect sizes between groups were significant. Partitioning resulted in homogeneity for the 12–18-year-old age range and near homogeneity for the other ages. As discussed above, near homogeneity implies the studies are similar but not exact replicates of each other. The fit was improved by partitioning because the weighted estimator for the over-18 age group exceeded the estimates for younger individuals.

Unbiased effect sizes for sex on spatial perception range between −.27 and 1.00. The weighted estimator is one-third of a standard deviation (favoring males) for those 18 and under and two-thirds of a standard deviation for those over 18 years of age. Only the effect size for those over 18 is significantly different from zero, as indicated by the 95% confidence interval in Table 1.

Why is the effect size for those over 18 years of age larger than for the others? Sex differences in spatial perception may accelerate with age, or they may be larger for one test than for another. We computed separate effect sizes for RFT and water level but found no difference in pattern. Alternatively, this difference could reflect a cohort influence: perhaps older individuals (studied since 1974) have had less access to relevant spatial experiences than younger individuals (e.g., science instruction emphasizing the physical principles involved in water level). A recent study by Liben and Golbeck (1984) suggests that substantial amounts of instruction can reduce or eliminate sex differences on these tasks. Also, the over-18 samples may be drawn from a different population than the other samples (e.g., particular occupation groups). Thus the postadolescent effect size may reflect acceleration in sex differences after 18 years, a cohort effect, or sampling biases that differentiate that group from the other two groups. No clear support for a single hypothesis emerged from review of the 13 studies involved.

When in the life span are sex differences in spatial perception first detected? We consider studies involving young respondents as well as a longitudinal study to answer this question.

First, can this dimension be measured reliably across the life span? Spatial perception can be measured reliably in 4-year-olds (Block & Block, 1982; Foorman, 1979), although the task may measure a different dimension than that assessed in older children. Piaget and Inhelder's (1967) study of water level suggested that younger children view the task as a memory task, whereas older children can reason about the variables.

The youngest respondents to a spatial perception measure entering the meta-analysis were also part of a longitudinal sample. The 4-year-olds in the meta-analysis came from the Block and Block (1982) longitudinal study. These individuals were given the RFT at ages 4, 5, 7, and 11. At age 4, girls outperformed boys. At ages 5 and 7, boys slightly outperformed girls. By 11 years, boys performed significantly better than girls. Between age 7 and 11 the difference between boys' and girls' scores increased threefold. Thus the Block and Block (1982) longitudinal study suggests that sex differences in spatial perception favoring males are first detected around age 7 and accelerate to adult levels by age 11. These differences could account for the slight heterogeneity of effect sizes.

The remaining subjects in the meta-analysis were 8 years of age or older. For those from 8 to 18 years, the analysis reveals homogeneous sex differences in performance on spatial perception favoring males. There is no evidence for a change in the magnitude of sex differences in spatial perception at adolescence. As noted above, the larger effect size for those over 18 years, together with the longitudinal data described suggests the possibility that sex differences in spatial perception may accelerate beyond adolescence.

Maccoby and Jacklin's (1974) review included 21 studies of RFT and no studies of water level (possibly because the few available studies at that time failed to report data by sex). In 16 of their 21 studies, there are significant effects favoring males, including all the youngest groups (age 7 or 8). Thus the conclusions in the studies reviewed by Maccoby and Jacklin (1974) concur with our finding that sex differences in spatial perception exist by age 8 and persist across the life span.

Cognitive and strategic perspective.— The meta-analysis results imply that sex differences in spatial perception can be detected from age 8 onward, although they are only significant, as a group, for those age 18 and older. We turn to the cognitive and strategic research perspectives for some insight into the mechanisms that might govern these differences. Our investigations suggest that knowledge about physical principles, propensity to rely on gravitational/kinesthetic cues, and propensity to combine task features analytically are dimensions that influence spatial perception performance.

A number of researchers (e.g., Liben & Golbeck, 1980; Linn & Delucchi, 1983) have investigated the role of knowledge of physical principles (e.g., that water is horizontal in tilted bottles) in water level performance. They found that the task was easier when knowledge of physical principles was not required for solution but that this knowledge did not interact with sex differences.

In the water level task, instructions that encourage analytic attention to task features also influence performance. Harris et al. (1978) report that sex differences are eliminated when the instructions indicate "the water is in motion" and "the water is at rest." When the instructions indicate that the "water is in motion," males find the task more difficult than they find the standard task. When the instuctions indicate that the "water is at rest," females find the task easier than they find the standard task. However, when the instructions are changed to describe the "container at rest" and the "container in motion," the usual sex differences occur just as they do in the standard version where the illustration suggests that the container is at rest. These results may indicate a sex difference in propensity to rely on cues from the task situation.

Certain visual task features may inhibit reliance on distracting cues. In some studies, but not others, the shape of the container in the water level task influences performance (Thomas & Jamison, 1975, 1981). In another example, reducing the size of the retinal image of the frame in RFT inhibits reliance on the frame (Dichgans, Young, & Brandt, 1972; Sigman et al., 1978, 1979) and fosters performance.

In summary, spatial perception items typically include task features that encourage or discourage analytic solutions to the items. Errors probably reflect inappropriate weighing of these features. In the standard version, reasoners who depend more or primarily on gravitational/kinesthetic cues may well outperform those who use an analytic procedure and rely on visual features.

Mental Rotation

The second category of spatial ability, mental rotation, yielded 29 effect sizes. The effect sizes were not homogeneous, so we partitioned them by age. Homogeneity was not achieved for the separate age groups.

Most of the studies of mental rotation involved either PMA space or the Vandenberg. To investigate whether lack of homogeneity reflected a task effect, we plotted the effect sizes by age and task, as shown in Figure 4. We found larger effects at all ages for the Vandenberg and Kuse (1978) version of the Shepard-Metzler Mental Rotation Test than for the other measures of mental rotation. Thus we partitioned all the effect estimates into two groups: (*a*) Vandenberg and Kuse (1978) and (*b*) PMA space or Coordinated Viewpoints (Guay & McDaniel, 1977) or

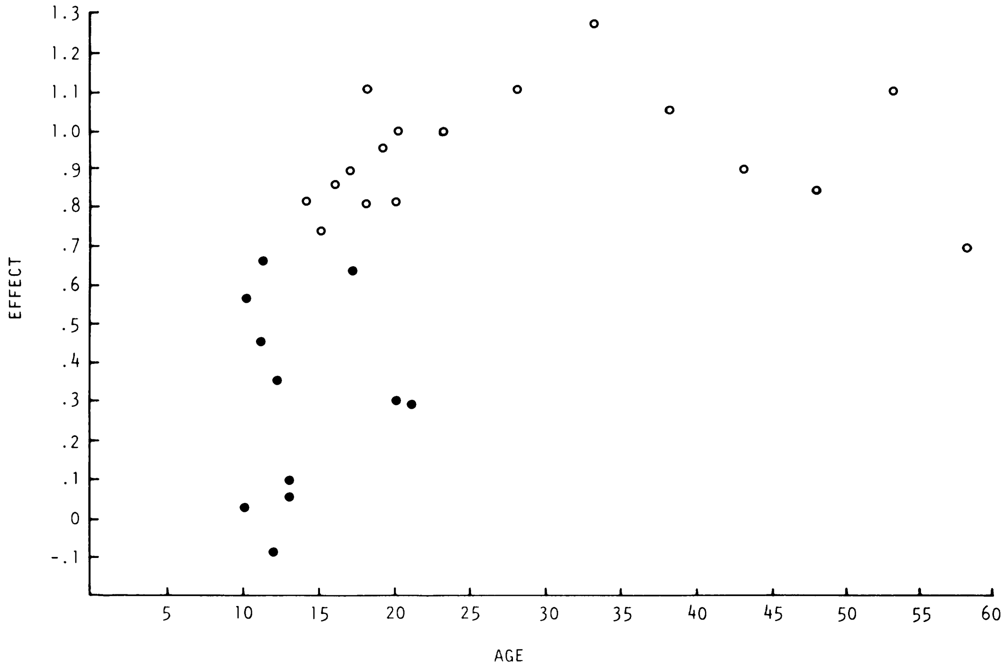

FIG. 4.—Effect sizes for mental rotations tests by age. ○ = Vandenberg (1971). ● = PMA space (Thurstone & Thurstone, 1941), Cards (French et al., 1963), Flags (French et al., 1963).

Cards (French et al., 1963). (Cards and Coordinated Viewpoints were each represented by a single effect estimator.) The resulting partition yielded homogeneity or near homogeneity for each group (Table 1). As discussed above, near homogeneity suggests that the studies are similar but are not perfect replicates of each other. In fact, as can be seen, most effect sizes on the Vandenberg and Kuse (1978) exceeded those on the other tests.

There were no changes in effect size with age over the ages studied. Sex differences are detected as soon as mental rotation could be measured. The two studies with the youngest respondents using PMA space (age 10–11) have means favoring males, but only one is significant. Wilson and Vandenberg (1978) found sex differences on mental rotation from their youngest (age 13) to their oldest (age 60+) subjects. For studies prior to 1974, Maccoby (1966) and Maccoby and Jacklin (1974) report studies of PMA space that detect sex differences at whatever age it is measured.

In summary, the effect sizes for the mental rotation category lacked homogeneity because the tests included have systematically different magnitudes of sex differences. Across ages, we found large homogeneous effects for sex on mental rotation as measured by the Vandenberg test. Similarly, across age we found moderately sized and fairly homogeneous effects for sex on mental rotation as measured by PMA space (Thurstone & Thurstone, 1941). Both types of mental rotation tasks yield consistent sex differences across ages, although the magnitude of the difference depends on the test used, and the Vandenberg and Kuse (1978) task has not been used with those younger than 13.

Cognitive and strategic perspective.—From the process analysis described above we see that mental rotation may often occur as a cognitive process analogous to the physical rotation of an object. Of course, the analogue process can be applied inefficiently, or an analytic process can also be used to rotate figures, but these approaches are less efficient for highly speeded mental rotation tests. As discussed above, the research program of Shepard and his colleagues has verified the existence of an analogue process (Cooper & Regan, 1982; Shepard & Cooper, 1982). Conditions under which the process is applied require investigation.

What differentiates the Vandenberg from PMA space? The Vandenberg items are in three dimensions and are more complex than the two-dimensional PMA-space items (see Figure 2). Research suggests that both the additional complexity and the additional dimension lead to slower reaction times for all subjects (Cooper, 1975; Pylsyshyn, 1979; Shepard & Metzler, 1971). In contrast, in both tests the respondents are required to locate two instances of the rotated stimulus figure and to work quickly. These task characteristics encourage use of an efficient rotation strategy.

Analysis of studies in the cognitive perspective can shed light on this finding. These studies use small numbers of volunteer subjects but assess their performance individually rather than through the use of group-administered paper and pencil tests. Such studies were not entered in the meta-analysis because of nonsystematic subject selection but can help us clarify our results. Comparison of male and female performance on individually administered mental rotation items yields surprisingly consistent results for error rates and for response times for unrotated figures (the intercept from an equation fitted to the responses gives the response time) (Kail, Carter, & Pellegrino, 1979; Metzler & Shepard, 1974; Tapley & Bryden, 1977). Differences are found only in the slopes of the regression lines, which reflect the response times to solution as items are rotated through greater angles.

Essentially, each respondent takes longer to rotate a figure through a larger angle than through a smaller angle, but the rate of increase (or slope of the regression line) differs widely. Females have longer response times than do males. The most comprehensive study (Kail et al., 1979) showed that sex differences in speed of rotation were dramatic (30% of the females were slower than all the males). Besides these group differences, variability in response times for females was greater than for males because of a bimodal distribution of scores for females. Some females performed just like the males; others formed a separate group with longer response times.

If performance on the Vandenberg and the PMA-space measure is based primarily on rate of mental rotation, then the greater magnitude of sex differences on the Vandenberg relative to the PMA space could reflect slower rotation rates for a subgroup of females. Research on rate of eye tracking suggests that females, as a group, track more slowly than males (Kuechenmeister, Linton, Mueller, & White, 1977). Eye tracking, however, has not been linked to mental rotation performance and could be used to investigate this hypothesis. At present, it would be prohibitively expensive to study samples large enough for conclusions to be reached (e.g., Carpenter & Just, 1978).

Another hypothesis to explain the differences between the Vandenberg test and the PMA-space test is based on students selecting inefficient solution strategies. Since all the stimuli are presented simultaneously, subjects could select part-by-part rotation and comparison rather than rotation of a whole integrated figure (e.g., Carpenter & Just, 1978). For the more complex figures in the Vandenberg test, several part-by-part rotations may be necessary to get enough information to choose a response. In contrast, fewer part-by-part rotations may be necessary to get enough information to choose a response for the simpler PMA-space figures. If females, more than males, adopt a part-by-part strategy, then the sex differences should be more apparent on more complex figures.

More generally, a part-by-part strategy could be mediated by an analytic meta-strategy that guides part selection. For the relatively straightforward PMA-space items, such an approach may be as efficient as mental rotation; for the complex Vandenberg items, such an approach may be inefficient. Thus if females adopt an analytic strategy more often than males, then, in situations where the meta-strategy for analytic solution is efficient, few sex differences would be detected. Thus for PMA space, reliance on an analytic meta-strategy may yield small sex differences, whereas for the Vandenberg test, reliance on an analytic meta-strategy may yield large sex differences.

Slower performance on mental rotation may reflect greater caution on the part of females (since few errors are made by either sex) rather than lack of ability to perform quickly. Female caution in testing situations has been documented for tests administered across a wide range of ages such as the National Assessment of Educational Progress (de-Benedictis, Delucchi, Harris, Linn, & Stage, 1982; Wheeler & Harris, 1981). The slower performance of females relative to males on mental rotations may reflect a tendency to double check an answer by rotating twice or by rotating additional parts of the figure (when using a part-by-part strategy) rather than slower rotation of a single figure.

In summary, males tend to outperform females on mental rotation at any age where measurement is possible. Then sex differences may result from differential rate of rotation, differential efficiency in strategy application, differential use of analytic processes, or differential caution.

Spatial Visualization

In the meta-analysis of the 81 effect estimators for spatial visualization we found that effects were small and homogeneous across the life span. Individual studies had effect sizes ranging from −.91 to .71. The average effect size was .13 of a standard deviation unit. The effects were not partitioned since they were homogeneous. A confidence interval for the mean effect included zero, indicating that the average effect size did not differ from zero (see Table 1).

Furthermore, sex differences in spatial visualization do not change across the life span. For most of the studies, no significant differences between males and females were found. Therefore sex differences in spatial visualization are not detected at any point in the life span.

Other research is consistent with this finding. Maccoby and Jacklin (1974) summarized 32 studies of an aspect of spatial visualization: the EFT. In five studies there were significant differences favoring males, and in three there were significant differences favoring females. Thus for the studies reviewed by Maccoby and Jacklin (1974) no consistent sex differences on this aspect of spatial visualization emerged.

One longitudinal study deserves special mention because it illustrates consistency in performance on spatial visualization. Block and Block (1982) administered a version of embedded figures at ages 3, 4, 5, and 11 and found a sex difference at age 4 favoring females but no differences at other ages. This longitudinal study lends further support to the conclusion that spatial visualization is equally difficult for both sexes.

Cognitive and strategic perspective.— Process analyses of performance on spatial visualization items conducted recently show that these items require an analytic procedure. For example, Kyllonen et al. (1981), in a study analyzing performance on paper folding, found that the item characteristics were more likely to determine the strategies used to solve the item than were the characteristics of the individuals responding to the items. Thus individuals tend to select different strategies for different items, rather than performing similarly from item to item. Individuals who do well on spatial visualization items do so because they have an appropriate repertoire of strategies and because they have effective meta-strategies to govern the selection of a strategy for each item.

As we mentioned above, both spatial perception and many of the spatial visualization items require disembedding. In spatial perception the subject may rely on gravitational/kinesthetic cues instead of correcting for distracting cues. In contrast, kinesthetic cues are rarely helpful in spatial visualization disembedding. Thus spatial perception may be uniquely characterized by the possibility of relying on gravitational/kinesthetic cues.

The analogue mental rotation process studied by Shepard and his colleagues could be employed for many spatial visualization items. Recall, however, that males and females differ primarily on speed of mental rotation, not accuracy. The strategy of rotation exists for both groups. Speed of rotation is probably less critical in spatial visualization than in mental rotation because it constitutes much less of the total solution time. Alternatively, consider the hypothesis that speed of rotation reflects caution on the part of females. Caution in the form of double-checking responses may hinder performance on mental rotations but not on the more analytic spatial visualization items.

The repertoire of strategies for spatial visualization items thus probably includes the propensity to rely on gravitational/kinesthetic cues hypothesized to characterize spatial perception performance as well as analogue mental rotation speed hypothesized to characterize mental rotations. These may account for the slight tendency of males to perform better than females on spatial visualization. Tasks requiring reliance on either of these strategies may yield larger sex differences than shown in this meta-analysis. Our investigation does not include sufficient numbers of such tasks to allow a test of this hypothesis, but a larger pool of effect sizes might permit partitioning of the studies by test and provide a more detailed picture of performance. Sex differences in strategy selection might be revealed if the solutions used by males and females for spatial visualization items were studied.

Spatial visualization performance probably reflects the meta-strategy for selecting processes for each item rather than the individual's relative proficiency in using any particular process. Spatial visualization items can be solved using a range of processes besides those associated with spatial perception and mental rotation. Thus the spatial processes that yield sex differences could be among those from which the reasoner flexibly selects to solve spatial visualization items. Reasoners, therefore, could select optimal processes for their own performance and minimize effects of sex differences on total score.

That males and females may differ in the processes they select for solving spatial problems is reflected in correlations between aptitudes and performance for males and females. Kyllonen, Lohman, and Snow (1984) found that for females verbal aptitude correlated with paper folding performance whereas for males spatial aptitude correlated with this task. Similarly, Sternberg and Weil (1980) found that those using a spatial strategy on linear syllogisms showed a relationship between spatial but not verbal aptitude and solution time, whereas those using a verbal strategy showed a relationship between verbal but not spatial aptitude and solution time.

Given the lack of sex differences in spatial visualization and the process analysis reported above, it appears that spatial visualization performance depends on use of meta-strategies. Furthermore, as Lohman (1979) suggests, much of the variance in complex spatial tasks is explained by variation in general ability. These strategies are more characteristic of general ability than of spatial ability. Recall also that Snow et al. (in press) could not separate spatial visualization from fluid ability in factor analysis. Certainly these meta-strategies resemble processes thought to be components of intelligence (e.g., Sternberg, 1982). Spatial visualization performance may depend, in large part, on general abilities that do not exhibit sex differences.

Thus, sex differences in spatial ability may influence which processes reasoners select for spatial visualization items. Flexible selection of the most efficient processes may mean that females select different processes than males for some items. The meta-strategies governing selection appear more similar to general ability than to other spatial ability processes. Further research is needed to establish how or whether sex differences in spatial perception and mental rotations influence spatial visualization performance and how or whether spatial visualization can be distinguished from general ability.

Summary and Discussion

In summary, we identified homogeneous sex differences in two of the three aspects of spatial ability. Spatial perception is easier for males than females. Differences range between one-third of a standard deviation unit for those under 18 to two-thirds of a standard deviation unit for those over 18. Mental rotation is also easier for males than for females; differences range from about one-quarter of a standard deviation unit for PMA space to almost an entire standard deviation unit for the Vandenberg. Spatial visualization, which is characterized by analytic combination of both visual and nonvisual strategies, is about equally difficult for males and females.

Our categorization of spatial ability resulted in nearly homogeneous effect sizes for sex within categories. However, these findings do not imply that this is the only or even the best way to partition spatial ability. For example, the spatial perception effect size for those under 18 is statistically similar to the mental rotation effect size for PMA space. Statistical similarity does not, of course, imply similarity in processes or strategies required to solve the items; such similarity simply raises possibilities.

Originally, we combined diverse measures such as PMA space and the Vandenberg test, both of which seemed to require mental rotation, on the basis of process analysis. Statistical procedures in meta-analysis demonstrated that task features can have large effects on performance even when tasks appear superficially similar. This finding illustrates the advantages of combining ideas from varied research perspectives and the power of recent advances in meta-analysis. This finding also suggests some unanswered questions about spatial ability performance.

Our categories reflect the nature of measures chosen for research study. Measures represented by few studies in recent research receive less emphasis than widely studied measures. For example, two tests are used to establish nearly all the effect sizes for spatial perception. Mental rotation is also primarily assessed by two measures that proved to have effect sizes of different magnitude. In contrast, spatial visualization has a variety of measures, some of which, if sampled more widely, might form a separate category. In particular, spatial visualization tests with many items that could be efficiently solved using a mental rotation strategy might yield small but consistent sex differences.

Magnitude of sex differences in spatial ability.—Sex differences in spatial ability are large only for mental rotation, medium for spatial perception, and small for spatial visualization. Linn and Pulos (1982, 1983) report that approximately 5% of the variance in the water level task is attributable to sex. Hyde (1981) and Plomin and Foch (1982) both report that between 1% and 5% of the variance in performance in the studies of spatial ability reported by Maccoby and Jacklin (1974) can be attributed to sex. In most studies, sex accounts for up to 5% of all the individual differences in performance on spatial tasks, excluding mental rotation.

Our meta-analysis results contradict the assertion that sex differences in spatial ability are first detected in adolescence. For spatial perception, differences are detected in individual studies at about age 8 and, for grouped studies, emerge statistically only at age 18. For mental rotation, sex differences are detected whenever measurement is possible, although some versions of the test are inappropriate for those under 13. For spatial visualization, there are no differences. Thus sex differences in spatial ability are detected prior to adolescence for some categories of spatial ability and not at all for others.

The nature of spatial ability sex differences.—Sex differences in spatial ability appear on tasks for which efficient solution requires rapid manipulation of symbolic information and on tasks that require recognition of the vertical or horizontal. Spatial visualization tasks, where efficient solution depends on effective use of analytic procedures to select strategies for manipulating symbolic information, do not appear to yield sex differences.

Our explanation of the observed sex differences on these tasks centers on selection and efficient application of solution strategies. For both mental rotations and spatial perception, inefficient or inaccurate strategies have been identified. For mental rotations, the less efficient analytic strategy can be used, or an inefficient use of the process analogous to the physical rotation of the object might be employed rather than a process analogous to rotation of the entire physical object. For spatial perception, the less accurate strategy of attempting to correct for distracting information could be used rather than a strategy of reliance on gravitational/kinesthetic cues.

The pattern of sex differences could result from a propensity of females to select and consistently use less efficient or less accurate strategies for these tasks. Cooper (1983) provides evidence for the view that respondents choose from a variety of strategies even for tasks involving mental rotations that seem to encourage use of a single strategy. Cooper (1983) suggests that, for mental rotation, once a respondent has selected a strategy, the same strategy is used for all the items. Since mental rotation items are all very similar to each other, there would be little in the situation to encourage strategy shifting. Linn and Pulos (1983) report similar patterns of consistent strategy use for spatial perception tasks. In constrast, spatial visualization tasks, because of the complexity of their items, may encourage strategy shifting. Further investigation is needed to determine whether tasks that encourage strategy shifting have fewer sex differences than other spatial tasks.

Another explanation centers on acquisition of appropriate strategies for these tasks. If females are less likely to acquire the efficient or accurate strategies, then no amount of skill in strategy selection will help.

Both these explanations for the observed differences could reflect different experiences of males and females relevant to each of these tasks. Inefficient strategy selection for these tasks may reflect a lack of attention to the cues governing strategy selection or lack of opportunity to acquire the strategy. Those conducting training studies have shown that instruction improves performance on spatial perception items for both sexes (Liben & Golbeck, 1980). In addition, the experiences of males and females differ in areas thought relevant to spatial performance (e.g., Newcombe et al., 1983; Petersen & Gitelson, in press). More precise investigations of these questions are needed.

It appears that spatial visualization performance depends, in large part, on metastrategies used to select an approach for each item, so that in this sense spatial visualization resembles general ability. Furthermore, it may be that, as the mental rotation strategy analogous to the physical rotation of the object becomes more central to task performance, sex differences become more pronounced. Further research using tasks that demand more mental rotation skill than those we classified as spatial visualization and less than those classified with PMA space would help to clarify the performance of males and females on spatial ability tasks. Further study of the repertoire of strategies available to reasoners, of the cues used by reasoners to select a particular strategy, and of the efficiency with which reasoners apply strategies would also be illuminating.

Relationship to mathematics and science performance.—The pattern of sex differences in spatial ability and the process analysis hypothesized to account for this pattern do not correspond to the pattern of sex differences found in mathematics and in science performance (e.g., Armstrong, 1979; Malone &

Fleming, 1983; Meehan, 1984; Steinkamp & Maehr, 1983). Processes of speed of mental rotation, most strongly implicated in spatial ability sex differences, do not correspond to processes likely to contribute to mathematics and science performance (see Linn & Petersen, in press, for a more detailed discussion). Correlational studies show a strong relationship between spatial abilities and scientific and mathematical reasoning, probably reflecting the role of general ability in performance in each area. Sex differences in spatial ability do not generally account for sex differences in mathematics and science (e.g., Fennema & Sherman, 1977; Karplus, Pulos, & Stage, 1980; Kreinberg & Stage, 1981; Linn & Pulos, 1982, 1983). Studies that separate each type of spatial ability are needed to clarify these relationships further.

Biological mechanisms for sex differences in spatial ability.—Many hypothesize that sex differences in spatial ability result from hormonal changes at puberty. Since the meta-analysis showed no change in the magnitude of spatial ability sex differences in early adolescence, a pubertal mechanism for sex differences would seem unlikely. Furthermore, although many factors governing the emergence of sex differences in spatial ability at puberty have been proposed, the research evidence is inconsistent (e.g., Carey, Diamond, & Woods, 1980; Newcombe et al., 1983; Petersen, 1983; Waber, 1976, 1977).

For example, Waber originally (1976, 1977) proposed a relationship between spatial ability and the timing of pubertal maturation. She suggested that later maturers would be better spatial visualizers than earlier maturers because of the effects of maturational timing on the development of hemispheric specialization in the brain. This hypothesis, that the brain functioning of later maturers becomes more laterally specialized for spatial ability, would explain sex differences in spatial ability since boys mature 1–2 years later than girls, on the average (e.g., Petersen & Taylor, 1980). The association between maturational timing and spatial ability was supported in some studies (Carey et al., 1980; Newcombe et al., 1983; Petersen & Gitelson, in press) and not supported in several others (Herbst & Petersen, 1979; Petersen, 1976; Roach, 1979; Strauss & Kinsbourne, 1981). Studies supporting the hypothesis generally utilized designs in which extreme maturation groups (earlier and late maturers) were contrasted. The fact that support has been found mainly in such "extreme groups" studies suggests that the effect of maturational timing may be a weak one in the whole population. Waber's subsequent research (Waber, Bauermeister, Cohen, Ferber, & Wolff, 1981) yielded support for the hypothesis only among upper-middle-class students. Furthermore, even when late maturers are found to outperform early maturers on spatial tasks, they usually do not show greater lateralization. Thus the hypothesized proximal cause underlying the association between timing of maturation and spatial ability has not been supported (e.g., Herbst & Petersen, 1979; Newcombe et al., 1983; Waber et al., 1981), and the role for timing of maturation in sex differences is more complex than originally thought. Timing of maturation may be involved with sex differences in spatial ability, but more research with appropriate measures (e.g., mental rotation) is needed at this point.

Genetic factors constitute the other major biological mechanism used to explain sex differences in spatial ability. There is ample evidence that spatial ability, like other cognitive abilities, is highly heritable (e.g., DeFries et al., 1976; Spuhler & Vandenberg, 1980). Some special genetic mechanism, however, is needed to explain sex differences in spatial ability. The primary plausible mechanism is that a spatial gene is carried on the X chromosome (Wittig & Petersen, 1979). Bock and Kolakowski (1973) initially proposed an X-linked recessive major gene for spatial ability.

The evidence for a genetic mechanism for sex differences could be obscured by lumping together studies of diverse forms of spatial ability, only some of which show consistent sex differences. The meta-analysis suggests that mental rotations would be the best task to use to identify a genetic mechanism since it yields the largest sex differences. Indeed, Vandenberg and Kuse (1979) reviewed the evidence for a genetic explanation for sex differences in mental rotations and found that evidence fails to support this explanation.

The total body of research examining the X-linked hypothesis offers contradictory findings. Some researchers have found evidence for X linkage using spatial visualization measures (e.g., Hartlage, 1970; Stafford, 1961), mental rotations (Bock & Kolakowski, 1973), and water level (Thomas & Jamison, 1981). Conversely, other studies fail to support the hypothesis using spatial visualization measures (Corely, DeFries, Kuse, & Vandenberg, 1980) and mental rotations (e.g., McGee, 1978, 1979). Additional studies on all three categories of spatial ability have produced mixed results (Fralley, Eliot, & Dayton, 1978; Goodenough et al., 1977; Loehlin, Sharan, &

Jacoby, 1978; Walker, Krasnoff, & Peaco, 1981; Yen, 1975). Thus no consistent evidence for the X-linked hypothesis has been found.

A biological mechanism for observed sex differences in spatial ability may be expressed through a hormonal mechanism occurring earlier than puberty. Just prior to and after birth, prenatal hormones reach adult levels, with the related sex difference. There is some evidence that brain organization is affected by hormones at this time (Hines & Shipley, 1984; Reinisch et al., 1979). However, no evidence linking this hypothesis to spatial ability has been put forth.

To the extent that any biological factors affect spatial ability they would interact with sex-typed experiences and sex-role expectations to produce the observed patterns of performance (e.g., Newcombe et al., 1983; Tobin-Richards & Petersen, 1981). Males and females have differing experiences across the life span (e.g, Bem & Bem, 1970; Cordua, McGraw, & Drabman, 1979; Haugh, Hoffman, & Cowan, 1980; Papalia & Tennent, 1975). The relationship between these experiences and documented sex differences in spatial ability has not been established but may eventually offer an explanation for sex differences in spatial ability (e.g., those in mental rotations) and for the success of training programs aimed at reducing the differences (Connor, Schackman, & Serbin, 1978; Goodenough et al., 1984; Newcombe et al., 1983; Liben & Golbeck, 1984).

In conclusion, sex differences in spatial ability are now more specifically described. The mechanisms that lead to these differences remain to be established, as do the possible influence of these differences on other behaviors. Individuals probably have an assortment of spatial skills rather than a single ability. Furthermore, several mechanisms may contribute to the observed sex differences. Researchers attempting to characterize the nature and origin of these differences and their potential influence on other behavior need to differentiate the types of spatial ability and the processes respondents use for each item type.

References

Armstrong, J. (1979). *A national assessment of achievement and participation of women in mathematics* (ERIC Document Reproduction Service No. ED 187562). Denver, CO: Education Commission of the States.

Bem, S. L., & Bem, D. J. (1970). Case study of a nonconscious ideology: Training the woman to know her place. In D. J. Bem (Ed.), *Beliefs, attitudes and human affairs* (pp. 89–99). Monterey, CA: Brooks-Cole.

Benbow, C. P., & Stanley, J. C. (1980). Sex differences in mathematical ability: Fact or artifact? *Science*, **210**, 1262–1264.

Benbow, C. P., & Stanley, J. C. (Eds.). (1984). *Academic precocity: Aspects of its development.* Baltimore: Johns Hopkins University Press.

Block, J., & Block, J. (1982). *Cognitive development from childhood and adolescence* (NIMA Research Grant MH16080). Unpublished manuscript.

Bock, R. D., & Kolakowski, D. (1973). Further evidence of sex-linked major-gene influence on human spatial visualizing ability. *American Journal of Human Genetics*, **25**, 1–14.

Caplan, P. J., MacPherson, G. M., & Tobin, P. (in press). Do sex-related differences in spatial abilities exist? *American Psychologist.*

Carey, S. E., Diamond, R., & Woods, B. (1980). Development of face recognition—a maturational component? *Developmental Psychology*, **16**, 257–269.

Carpenter, P. A., & Just, M. A. (1978). Eye fixations during mental rotation. In J. W. Senders, D. F. Fisher, & R. A. Monty (Eds.), *Eye movements and the higher psychological functions* (pp. 128–136). Hillsdale, NJ: Erlbaum.

Carpenter, P. A., & Just, M. A. (1981). *Spatial ability: An information-processing approach to psychometrics.* Unpublished manuscript, Carnegie-Mellon University.

Cattell, R. B. (1971). *Abilities: Their structure, growth, and action.* Boston: Houghton Mifflin.

Chipman, S., Brush, L., & Wilson, D. (1985). *Women and mathematics: Balancing the equation.* New York: Erlbaum.

Cohen, J. (1977). *Statistical power analogies for the behavioral sciences* (2d ed.). New York: Academic Press.

Connor, J. M., Schackman, M., & Serbin, L. A. (1978). Sex-related differences in response to practice on a visual-spatial test and generalization to a related test. *Child Development*, **49**, 24–29.

Cooper, L. A. (1975). Mental rotation of random two-dimensional shapes. *Cognitive Psychology*, **7**, 20–43.

Cooper, L. A. (1983, April). Spatial information processing: The nature of strategic variation. In M. J. Farr (Chair), *Individual differences in spatial ability and information processing.* Symposium conducted at the annual meeting of the American Educational Research Association, Montreal.

Cooper, L. A., & Regan, D. T. (1982). Attention, perception, and intelligence. In R. J. Sternberg (Ed.), *Handbook of human intelligence* (pp.

123–169). New York: Cambridge University Press.

Cooper, L. A., & Shepard, R. N. (1973). The time required to prepare for a rotated stimulus. *Memory and Cognition*, **1**, 246–250.

Corballis, M. C., & Roldan, C. E. (1975). Detection of symmetry as a function of angular orientation: Human perception and performance. *Journal of Experimental Psychology*, **1**, 221–230.

Corballis, M. C., Zbrodoff, J., & Roldan, C. E. (1976). What's up in mental rotation? *Perception and Psychophysics*, **19**, 525–530.

Cordua, G. D., McGraw, K. O., & Drabman, R. S. (1979). Doctor or nurse: Children's perception of sex typed occupations. *Child Development*, **50**, 590–593.

Corely, R. P., DeFries, J. C., Kuse, A. R., & Vandenberg, S. G. (1980). Familial resemblance for the Identical Blocks Test of spatial ability: No evidence for X linkage. *Behavior Genetics*, **10**, 211–215.

DeAvila, E. A., Havassy, B., & Pascual-Leone, J. (1976). *Mexican-American school children: A neo-Piagetian analysis*. Washington, DC: Georgetown University Press.

de-Benedictis, T., Delucchi, K., Harris, A., Linn, M., & Stage, E. (1982, March). Sex differences in science: "I don't know." In M. L. Maehr (Chair), *Sex-related differences in science*. Symposium conducted at the meeting of the American Educational Research Association, New York.

DeFries, J. C., Ashton, G. C., Johnson, R. C., Kuse, A. R., McClearn, G. E., Mi, M. P., Rashad, M. N., Vandenberg, S. G., & Wilson, J. R. (1976). Parent off-spring resemblance for specific cognitive abilities in two ethnic groups. *Nature*, **261**, 131–133.

DeFries, J. C., Vandenberg, S. G., McClearn, G. E., Kuse, A. R., Wilson, J. R., Ashton, G. C., & Johnson, R. C. (1974). Near identity of cognitive structure in two ethnic groups. *Science*, **183**, 338–339.

Dichgans, J., Young, L. R., & Brandt, T. (1972). Moving visual scenes influence the apparent direction of gravity. *Science*, **178**, 1217–1219.

Fennema, E., & Sherman, J. (1977). Sex-related differences in mathematics achievement, spatial visualization and affective factors. *American Educational Research Journal*, **14**, 51–71.

Fennema, E. H., & Sherman, J. A. (1978). Sex-related differences in mathematics achievement and related factors: A further study. *Journal of Research in Mathematics Education*, **9**, 189–203.

Foorman, B. R. (1979, February). *4 year olds' performance on Piaget's water level task: The contribution of maturaticn and experience*. Paper presented at the Ninth Annual International Interdisciplinary University Affiliated Professionals Conference on Piagetian Theory and Its Implications for the Helping Professions, University of Southern California.

Fralley, J. S., Eliot, J., & Dayton, C. M. (1978). Further study of the X-linked recessive gene hypotheses for inheritance of spatial abilities. *Perceptual and Motor Skills*, **47**, 1023–1029.

French, J. W. (1951). The description of aptitude and achievement tests in terms of rotated factors. *Psychometric Monographs*, **5**.

French, J. W., Ekstrom, R. B., & Price, L. A. (1963). *Manual for kit of reference tests for cognitive factors* (rev. ed.). Princeton, NJ: Educational Testing Service.

Fruchter, B. (1954). Measurement of spatial abilities: History and background. *Educational and Psychological Measurement*, **14**, 387–395.

Glass, G. V. (1976). Primary, secondary, and meta-analysis of research. *Educational Researcher*, **5**, 3–8.

Glass, G., McGaw, B., & Smith, M. L. (1981). *Meta-analysis in social research*. Beverly Hills, CA: Sage.

Goodenough, D. R., Gandini, E., Olkin, I., Pizzamiglio, L., Thayer, D., & Witkin, H. A. (1977). A study of X chromosome linkage with field dependence and spatial visualization. *Behavior Genetics*, **7**, 373–413.

Goodenough, D. R., Oltman, P. K., & Cox, P. W. (1984). *The nature of individual differences in field dependence*. Princeton, NJ: Educational Testing Service.

Guay, R. B., & McDaniel, E. D. (1977). The relationship of mathematical achievement and spatial abilities among elementary school children. *Journal of Research in Mathematics Education*, **8**, 211–215.

Guilford, J. P. (1969). *The nature of human intelligence*. New York: McGraw-Hill.

Harris, L. J. (1982). Sex related variations in spatial skill. In L. S. Liben, A. H. Patterson, & N. Newcombe (Eds.), *Spatial representation and behavior across the life span* (pp. 83–128). New York: Academic Press.

Harris, L. J., Hanley, C., & Best, C. T. (1978). Conservation of horizontality: Sex differences in sixth graders and college students. In M. S. Smart & R. C. Smart (Eds.), *Adolescence: Development and relationships* (pp. 95–107). New York: Macmillan.

Hartlage, L. C. (1970). Sex-linked inheritance of spatial ability. *Perceptual and Motor Skills*, **31**, 610.

Haugh, S. S., Hoffman, C. D., & Cowan, G. (1980). The eye of a very young beholder: Sex typing of infants by young children. *Child Development*, **51**, 598–600.

Hedges, L. V. (1982a). Fitting categorical models to effect sizes from a series of experiments. *Journal of Educational Statistics*, **7**, 119–137.

Hedges, L. V. (1982b). Fitting continuous models to effect size data. *Journal of Educational Statistics*, **7**, 245–270.

Hedges, L. V., & Olkin, I. (1980). Vote counting methods in research synthesis. *Psychological Bulletin*, **88**, 359–369.

Herbst, L., & Petersen, A. C. (1979, November). *Timing of maturation, brain lateralization, and cognitive performance in adolescent females*. Paper presented at the meeting of the Fifth Annual Conference on Research on Women and Education, Cleveland, OH.

Hines, M., & Shipley, C. (1984). Prenatal exposure to diethylstilbestrol (DES) and the development of sexually dimorphic cognitive abilities and cerebral lateralization. *Developmental Psychology*, **20**, 81–94.

Horn, J. L., & Cattell, R. B. (1966). Refinement and test of the theory of fluid and crystallized general intelligences. *Journal of Educational Psychology*, **57**(5), 253–270.

Hyde, J. S. (1981). How large are cognitive gender differences? A meta-analysis using w and d. *American Psychologist*, **36**, 892–901.

Hyde, J. S., & Linn, M. C. (in press). *The psychology of gender: Advances through meta-analysis*. Baltimore: Johns Hopkins University Press.

Inhelder, B., & Piaget, J. (1958). *The growth of logical thinking from childhood to adolescence*. New York: Basic.

Just, M. A., & Carpenter, P. A. (1976). Eye fixations and cognitive processes. *Cognitive Psychology*, **8**, 441–480.

Kail, R., Carter, P., & Pellegrino, J. (1979). The locus of sex differences in spatial ability. *Perception and Psychophysics*, **26**, 182–186.

Karplus, R., Pulos, S., & Stage, E. K. (1980, August). Early adolescents' structure of proportional reasoning. In R. Karplus (Ed.), *Proceedings of the Fourth International Conference for the Psychology of Mathematics Education* (pp. 136–142). Berkeley: University of California.

Kreinberg, N., & Stage, E. K. (1981, April). *The equals teacher education program*. Paper presented at the annual meeting of the American Educational Research Association, Los Angeles.

Kuechenmeister, C. A., Linton, P. H., Mueller, T. V., & White, H. B. (1977). Eye tracking in relation to age, sex, and illness. *Archives of General Psychiatry*, **34**, 578–579.

Kyllonen, P. C., Lohman, D. F., & Snow, R. E. (1984). Effects of aptitudes, strategy training, and task facets on spatial task performance. *Journal of Educational Psychology*, **76**, 130–145.

Kyllonen, P. C., Woltz, D. J., & Lohman, D. F. (1981). Models of strategy and strategy-shifting in spatial visualization performance (Technical Report No. 17). Stanford, CA: Stanford University, School of Education, Aptitude Research Project. (NTIS No. AD-A108003)

Liben, L. S., & Golbeck, S. L. (1980). Sex differences in performance on Piagetian spatial tasks: Differences in competence or performance? *Child Development*, **51**, 594–597.

Liben, L. S., & Golbeck, S. L. (1984). Performance on Piagetian horizontality and verticality tasks: Sex-related differences in knowledge of relevant physical phenomena. *Developmental Psychology*, **20**, 595–606.

Liben, L. S., Patterson, A. H., & Newcombe, N. (Eds.). (1981). *Spatial representation and behavior across the life span: Theory and application*. New York: Academic Press.

Linn, M. C., (in press). Meta-analysis of studies of gender differences: Implications and future directions. In J. Hyde & M. C. Linn (Eds.), *The psychology of gender: Advances through meta-analysis*. Baltimore: Johns Hopkins University Press.

Linn, M. C., & Delucchi, K. (1983). *The water level: Influences of task features on gender differences in performance*. Berkeley: University of California, Berkeley, Lawrence Hall of Science, Adolescent Reasoning Project.

Linn, M. C., & Kyllonen, P. (1981). The field dependency construct: Some, one, or none. *Journal of Educational Psychology*, **73**, 261–273.

Linn, M. C., & Petersen, A. C. (in press). Gender differences in spatial ability: Implications for mathematics and science performance. In J. Hyde & M. C. Linn (Eds.), *The psychology of gender: Advances through meta-analysis*. Baltimore: Johns Hopkins University Press.

Linn, M. C., & Pulos, S. (1982). Aptitude and experience influences on proportional reasoning during adolescence: Focus on male-female differences. *Journal of Research in Mathematics Education*, **14**, 30–46.

Linn, M. C., & Pulos, S. (1983). Male-female differences in predicting displaced volume strategy usage, aptitude relationships, and experience influences. *Journal of Educational Psychology*, **75**, 86–96.

Loehlin, J. C., Sharan, S., & Jacoby, R. (1978). In pursuit of the "spatial gene": A family study. *Behavior Genetics*, **8**, 27–41.

Lohman, D. F. (1979). *Spatial ability: A review and re-analysis of the correlational literature* (Technical Report No. 8). Stanford CA: Stanford University, School of Education, Aptitude Research Project. (NTIS No. AD-A075972)

Maccoby, E. E. (Ed.). (1966). *The development of sex differences*. Stanford, CA: Stanford University Press.

Maccoby, E. E., & Jacklin, C. N. (1974). *The psychology of sex differences*. Stanford, CA: Stanford University Press.

Malone, M. R., & Fleming, M. L. (1983, May). The relationship of student characteristics and student performance in science as viewed by meta-analysis research. *Journal of Research in Science Teaching*, **20**(5), 481–495.

McGee, M. G. (1978). Intrafamilial correlations and heritability estimates for spatial ability in a Minnesota sample. *Behavior Genetics*, **8**, 77–80.

McGee, M. G. (1979). Human spatial abilities: Psychometric studies and environmental, genetic, hormonal, and neurological influences. *Psychological Bulletin*, **86**, 899–918.

Meehan, A. M. (1984). A meta-analysis of sex differences in formal operational thought. *Child Development*, **55**, 1110–1124.

Metzler, J., & Shepard, R. N. (1974). Transformational studies of the internal representation of three-dimensional objects. In R. L. Solso (Ed.), *Theories of cognitive psychology: The Loyola symposium* (pp. 147–202). Potomac, MD: Erlbaum.

Newcombe, N., Bandura, M., & Taylor, D. G. (1983). Sex differences in spatial ability and spatial activities. *Sex Roles*, **9**, 377–386.

Papalia, D. E., & Tennent, S. S. (1975). Vocational aspirations in preschoolers: A manifestation of early sex-role stereo-typing. *Sex Roles*, **1**, 197–199.

Petersen, A. C. (1976). Physical androgyny and cognitive functioning in adolescence. *Developmental Psychology*, **12**, 524–533.

Petersen, A. C. (1980). Biopsychosocial processes in the development of sex-related differences. In J. Parsons (Ed.), *The psychobiology of sex differences and sex roles* (pp. 31–55). Washington, DC: Hemisphere.

Petersen, A. C. (1983). Pubertal change and cognition. In J. Brooks-Gunn & A. C. Petersen (Eds.), *Girls at puberty: Biological and psychosocial perspectives* (pp. 179–198). New York: Plenum.

Petersen, A. C., & Gitelson, I. B. (in press). *Toward understanding sex-related differences in cognitive performance.* New York: Academic Press.

Petersen, A. C., & Taylor, B. C. (1980). The biological approach to adolescence: Biological change and psychological adaptations. In J. Adelson (Ed.), *Handbook of adolescent psychology* (pp. 117–155). New York: Wiley.

Piaget, J., & Inhelder, B. (1967). *The child's conception of space* (pp. 375–418). New York: Norton.

Pillemer, D. B., & Light, R. J. (1980, May). Synthesizing outcomes: How to use research evidence from many studies. *Harvard Educational Review*, **50**(2), 176–195.

Plomin, R., & Foch, T. T. (1982). Sex differences and individual differences. *Child Development*, **52**, 383–385.

Pylsyshyn, Z. W. (1979). The rate of "mental rotation" of images: A test of a holistic analogue hypothesis. *Memory and Cognition*, **7**, 19–28.

Pylsyshyn, Z. W. (1981). The imagery debate: Analogue media versus tactic knowledge. *Psychological Review*, **87**, 16–45.

Reinisch, J. M., Gandelman, R., & Spiegal, F. S. (1979). Prenatal influences on cognitive abilities: Data from experimental animals and human genetic and endocrine syndromes. In M. S. Wittig & A. C. Petersen (Eds.), *Sex-related differences in cognitive functioning: Developmental issues* (pp. 215–239). New York: Academic Press.

Roach, D. H. (1979). The effects of conceptual style preference, related cognitive variables, and sex on achievement in mathematics. *British Journal of Educational Psychology*, **49**, 79–82.

Rosenthal, R. (1979). The "file drawer problem" and tolerance for null results. *Psychological Bulletin*, **86**, 638–641.

Rosser, R. (1980). Acquisition of spatial concepts in relation to age and sex (Final Report on Grant No. NIE-6-79-0091 from the National Institute of Education, Department of Education). Tucson: University of Arizona.

Shepard, R. N., & Cooper, L. A. (1982). *Mental images and their transformations.* Cambridge: Massachusetts Institute of Technology.

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

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science*, **171**, 701–703.

Sigman, E., Goodenough, D. R., & Flanagan, M. (1978). Subjective estimates of body tilt and the rod-and-frame test. *Perceptual and Motor Skills*, **47**, 1051–1056.

Sigman, E., Goodenough, D. R., & Flanagan, M. (1979). Instructions, illusory self-tilt and the rod-and-frame test. *Quarterly Journal of Experimental Psychology*, **31**, 155–165.

Smith, I. (1964). *Spatial Ability.* London: University of London Press.

Snow, R. E., Kyllonen, P. C., & Marshalek, B. (in press). The topography of ability and learning correlations. In R. J. Sternberg (Ed.), *Advances in the psychology of human intelligence* (Vol. 2). Hillsdale, NJ: Erlbaum.

Spuhler, K. P., & Vandenberg, S. G. (1980). Comparison of parent-offspring resemblance in specific cognitive abilities. *Behavior Genetics*, **10**, 413–418.

Stafford, R. E. (1961). Sex differences in spatial visualization as evidence of sex-linked inheritance. *Perceptual and Motor Skills*, **13**, 428.

Steinkamp, M. W., & Maehr, M. L. (1983). Affect, ability, and science achievement: A quantitative synthesis of correlational research. *Review of Educational Research,* **53**(3), 369–396.

Sternberg, R. J. (1982). Reasoning, problem solving, and intelligence. In *Handbook of human intelligence* (pp. 227–351). Cambridge: Cambridge University Press.

Sternberg, R. J., & Weil, E. M. (1980). An aptitude-strategy interaction in linear syllogistic reasoning. *Journal of Educational Psychology,* **72,** 226–234.

Strauss, E., & Kinsbourne, M. (1981). Does age of menarche affect the ultimate level of verbal and spatial skills? *Cortex,* **17,** 323–325.

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.

Thomas, H., & Jamison, W. (1975). On the acquisition of understanding that still water is horizontal. *Merrill-Palmer Quarterly,* **21,** 31–44.

Thomas, H., & Jamison, W. (1981). A test of the X-linked genetic hypothesis for sex differences on Piaget's water-level task. *Developmental Review,* **1,** 274–283.

Thurstone, L. L., & Thurstone, T. G. (1941). Factorial studies of intelligence. *Psychometric Monographs,* **2.**

Tobin-Richards, M. H., & Petersen, A. C. (1981, August). *Spatial and sex-appropriate activities: Spatial visual ability during adolescence.* Paper presented at the meetings of the American Psychological Association, Los Angeles.

Vandenberg, S. G., & Kuse, A. R. (1978). Mental rotations: A group test of three-dimensional spatial visualization. *Perceptual and Motor Skills,* **47,** 599–604.

Vandenberg, S. G., & Kuse, A. R. (1979). Spatial ability: A critical review of the sex-linked major gene hypothesis. In M. A. Wittig & A. C. Petersen (Eds.), *Sex-related differences in cognitive functioning: Developmental issues* (pp. 67–95). New York: Academic Press.

Vernon, P. E. (1965). Ability factors and environmental influences. *American Psychologist,* **20,** 723–733.

Waber, D. P. (1976). Sex differences in cognition: A function of maturation rate? *Science,* **192,** 572–574.

Waber, D. P. (1977). Sex differences in mental abilities, hemispheric lateralization, and rate of physical growth at adolescence. *Developmental Psychology,* **13,** 29–38.

Waber, D. P. (1979). The ontogeny of higher cortical functions: Implications for sex differences in cognition. In M. A. Wittig & A. C. Petersen (Eds.), *Sex-related differences in cognitive functioning: Developmental issues* (pp. 161–186). New York: Academic Press.

Waber, D. P., Bauermeister, M., Cohen, C., Ferber, R., & Wolff, P. H. (1981). Behavioral correlates of physical and neuromotor maturity in adolescence from different environments. *Developmental Psychobiology,* **14**(6), 513–522.

Walker, J. T., Krasnoff, A. G., & Peaco, D. (1981). Visual spatial perception in adolescents and their parents: The X-linked recessive hypothesis. *Behavior Genetics,* **11,** 403–413.

Wheeler, R., & Harris, B. (1981). *Comparison of male and female performance on the AP physics test.* New York: College Entrance Examination Board.

Wilson, J. R., & Vandenberg, S. G. (1978). Sex differences in cognition: Evidence from the Hawaii family study. In T. E. McGill, D. A. Dewsbury, & B. D. Sachs (Eds.), *Sex and behavior: Stages and prospectus* (pp. 317–335). New York: Plenum.

Witkin, H. A. (1949). The nature and importance of individual differences in perception. *Journal of Personality,* **18,** 145–170.

Witkin, H. A., Dyk, R. B., & Faterson, H. F. (1962). *Psychological differentiation.* New York: Wiley.

Witkin, H. A., & Goodenough, D. R. (1981). *Cognitive styles: Essence and origins.* New York: International Universities Press.

Wittig, M. A., & Petersen, A. C. (Eds.). (1979). *Sex-related differences in cognitive functioning: Developmental issues.* New York: Academic Press.

Yen, W. M. (1975). Sex-linked major-gene influences on selected types of spatial performance. *Behavior Genetics,* **5,** 281–298.