ENVIRONMENTAL INPUT TO THE DEVELOPMENT OF SEX-RELATED DIFFERENCES IN SPATIAL AND MATHEMATICAL ABILITY

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ABSTRACT: This article summarizes the empirical support for two conclusions: (1) environmental input is essential for the development of both spatial and mathematical skill; (2) environmental input of the essential sort is more common in the lives of boys than girls. A causal link between these two facts and the existence of sex-related differences in spatial and mathematical ability is less well established, however; the relevant studies have simply not been done. Given this lack of knowledge, but firm support for the first two conclusions, the best course for education is to nurture spatial and mathematical ability more intensively, in both boys and girls.

In 1974, Maccoby and Jacklin published *The Psychology of Sex Differences*, a massive literature review which reached the conclusion that males perform reliably better than females on tests of mathematical and spatial ability. The potential biological and social causes of those differences have been debated ever since, often vociferously and with a focus on an "either/or" approach in which one of these explanations must be primary. Biological differences are generally more prominently featured in the popular media (e.g., *Time*'s cover of January 20, 1992, emblazoned with the teaser "Why are men and women so different? It isn't just upbringing. New

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studies show they are born that way.") On the other hand, however, the possible social causes of sex-related differences have recently been highlighted in the popular press's reporting of the American Association of University Women's (1991) report, *Shortchanging Girls: Shortchanging America*. The AAUW argued that girls receive less favorable treatment in classrooms, compared to boys, and that, somewhere during early adolescence, girls suffer a dramatic loss of self-esteem, especially in mathematics and science.

The purpose of this review is to examine the social and environmental contribution to sex-related differences in spatial and mathematical ability. We show that there is strong evidence that environmental input is essential for the development of high levels of mathematical and spatial ability, in both sexes, and strong evidence that this environmental input is more common in the lives of boys than of girls. However, although a causal link between these facts, in which sex-stereotyped input leads to sex-related ability differences, seems natural to many observers, including the AAUW, the evidential basis for this argument needs to be stronger. Sex-differentiated input may maintain or widen an already-existing biological predisposition, rather than create a difference from nothing. Key empirical studies on this issue remain to be done.

Fine delineation of how biology and environment interact in the development of sex differences in spatial and mathematical ability is, however, not as important to educators as one might think. We argue that, whatever the story on the interaction of biological and social factors in the development of cognitive sex differences turns out to be, the key message for people concerned with effective schooling is that, currently, neither girls nor boys develop their spatial or mathematical ability to the full extent possible. Thus, whatever the cause of sex-related differences, the central social issue is to nurture such abilities more intensively in both girls and boys.

EXPERIENCE HAS CLEAR EFFECTS ON MATHEMATICS AND SPATIAL ABILITY

Performance in mathematics and spatial tasks depends on environmental input. For mathematics, such a conclusion may appear almost self-evident, in that counting and arithmetic notation systems, not to mention calculus and algebra, are invented symbolic tools culturally transmitted in the schools. Nevertheless, a strong commitment by many Americans to a view of mathematical ability as innate sometimes obscures recognition of this fact (Stevenson & Stigler 1992; Geary in press). Spatial competence is less obviously taught in the schools than is mathematics, and the temptation to view it as innate in a very strong sense may be even greater than for mathematics. For instance, people will frequently comment that they have difficulty finding their way or following directions, in a fashion that attributes these facts to native ability and discounts the possibility that they simply haven't worked to develop skills in these areas.

There is clear evidence, however, that, contrary to these popular assumptions, environmental input is crucial for both the mathematical and spatial domains. First, gains in spatial and mathematical ability are tied directly to school experiences, for both boys and girls. Second, training of spatial ability in various types of experimental interventions results in substantial change in spatial ability scores for both sexes.

SCHOOLING EFFECTS

The effects of schooling are difficult to observe in societies where education is universal, and cross-cultural comparisons between schooled and unschooled children are fraught with methodological problems (Rogoff 1981). Recently, however, a number of studies have come out which use two new designs to examine the effects of schooling on the development of cognitive abilities. In one design, the cut-off design, researchers compare the abilities of children who are just barely on either side of official cut-offs for school entry. In another design, researchers compare cognitive growth over periods in which children attend school with growth over periods when school is not in session (i.e., the summer). Investigation using the cut-off design has shown that schooling has large effects on growth of mathematical skill (specifically, addition in first grade) (Bisanz, Morrison, & Dunn 1994). Investigation using the summer vs. school year design has shown that growth in spatial skill is more rapid during the school year than during the summer, for kindergarten and first grade children (Huttenlocher, Levine, & Vevea 1994).

Not all cognitive abilities are affected by schooling, however. For instance, in the Huttenlocher et al. study, memory was found to grow equally over the summer as during periods of formal school attendance. In the Bisanz et al. study, the growth of understanding of conservation of number tasks was age-related rather than school-related. The fact that not all domains are found to be affected by schooling is important, because it shows that effects of schooling are not simply to general improvements in test-taking or attentional skills. Further research will be needed to identify the specific activities in formal schooling which support specific growth patterns.

TRAINING EFFECTS

A number of applied researchers have pursued a variety of means of improving spatial test performance (Baenninger & Newcombe 1989). Several studies were designed to directly test the influence of training on spatial task performance (Blade & Watson 1955; Blatter 1983; Brinkmann 1966; Churchill, Curtis, Coombs, & Harrell 1942; Ciganko 1973; Kyllonen, Lohman, & Snow 1984; Lolla 1973; Lusk & Wright 1981; McGee 1978; Wolfe 1970). An additional group of studies tested practice effects on spatial ability measures (Bergan, McManis, & Melchet 1971; Chance & Goldstein 1971; Connor, Schackman, & Serbin 1978; Lohman 1986; McGee 1978; Sevy 1983; Sherman 1974). In almost every case, exposure to spatial test materials, or training on related materials, raises spatial ability test scores.

Baenninger and Newcombe (1989) conducted meta-analyses of spatial ability training studies. They divided the studies into groups based on the content of the training (specific, general, or indirect), and the duration of training (long, medium, or short). Specific training was defined as training directed at a single spatial measure (e.g., the WISC Block Design, or the Mental Rotations Test). General training was defined as training using a variety of spatial tests, or a variety of items. Indirect training was defined as samples with training that was related to spatial ability, but not focused on a certain test or tests. In terms of duration, Short was defined as single or brief administrations of training taking place over a period of less than three weeks; Medium duration was defined as more than one administration over a period of more than three weeks, but less than a semester; Long duration was defined as at least semester-long or more. Both the "Medium" and "Long" duration groups included some studies of curriculum-based training. An additional group of studies that involved no specific training, but simply repeated administrations of the same test were labeled the "Practice" group. Thus, the included samples ranged from single or multiple pre- and post-test administrations of the same test, to year-long engineering training, with a spatial test battery given at the beginning and the end.

In all cases, the magnitude of the improvement between first and last administration of the spatial test, or the effect size (in this case, reported as r) was at least moderate in size. The effect size for Specific content training was .67, for General content training was .51, and for Indirect content training was .37. In terms of training duration, the effect sizes for Short and Medium duration training were .53 and .61, respectively. An average effect size for the Long duration group could not be calculated because of heterogeneity of effect sizes within the sample of studies. The Practice group showed an average effect size of .51.

All the computable effect sizes were significantly different from zero, and the effect sizes for Indirect, General, and Specific training were all significantly different from each other. The Practice and Medium duration groups were also significantly different from each other. There was, however, no significant differences between the Practice group and the Short duration group, suggesting that repeated administrations of the same test may increase scores as much as brief, specific training. Taken as a whole, these meta-analyses show that training, of a variety of durations and types, increases spatial ability performance. Thus, levels of spatial ability are clearly environmentally malleable.

The value of any training program needs to be judged by its permanence and its generalizability. Training that maximizes specific performances in the short run can be less than optimal for long-term retention and generalizability (Schmidt & Bjork 1992). Baenninger and Newcombe's (1989) meta-analytic results for the General and Indirect Content groups provide evidence that training is generalizable to a variety of *measures* of spatial ability. Whether spatial training would affect classroom performance in math or science, or any other real-life situation, has not been studied. Research with longitudinal samples would be the only way to assess such effects of training; no such samples were found to include in the meta-analysis.

This conclusion that training improves spatial competence seems to apply, however, to one dependent variable other than performance on ability tests, namely, spatial orientation in the natural environment. In this case, "training" may actually be as simple as seemingly trivial instructional variations. For instance, naive subjects who are "rotated" through a windowless building make very large average errors when asked to point at another non-visible building. Simply informing subjects that they will be expected to do the pointing task reduces their error by 60 degrees (Elenteny & Baenninger 1994). Similarly, asking subjects to attend to cardinal directions in processing a map in order to give verbal directions greatly increases subjects' accurate use of direction terms (Ward, Newcombe, & Overton 1986). Studies such as these suggest that existing spatial competence is simply not engaged in many people's daily lives, but can easily be activated.

BOYS AND GIRLS HAVE DIFFERENT EXPERIENCES

In evaluating sex-differentiated experiences, one needs to take into account both formal experience, including classroom learning and other lessons, and informal experiences, including activities and recreation that facilitate spatial and mathematical ability. One needs to look at these formal and informal settings both in terms of the content of what children do, and also in terms of the nature of the social interactions that occur around these experiences.

FORMAL EXPERIENCE

Most of the literature on children's school experiences examines mathematical rather than spatial input, probably because there is typically no formal spatial curriculum. However, because some math and science courses have a large spatial component, any sex-differentiated experience in these domains may affect spatial development as well. The focus of concern in studies of sex differences in mathematics education has been on course taking decisions and on the interactions children have with parents and teachers.

Course Taking Decisions. Boys take more math courses than girls beginning at the time they are able to make choices about which courses they take (e.g., Armstrong 1981; Benbow & Stanley 1982; Fennema & Carpenter 1981; Fennema & Sherman 1977; Pallas & Alexander 1983). This decision seems to depend on perceptions of the usefulness of math for one's future life, as well as to self-assessments of one's abilities and liking for the subject. These perceptions and self-assessments are likely influenced by parents and teachers, as discussed below.

Parents. Parents make attributions about the causes of their children's success, they exert pressure for achievement on their children, they express varying levels of satisfaction with their children's performance, and they model their own sex-role

orientations for their children (Holloway 1986). There is a relation between parental estimates of children's ability and the children's own expectations for their performance and their own self-concepts concerning their math ability (Parsons, Adler, & Kaczala 1982).

Given these facts, it is significant that parents of boys believe that math comes more naturally to their sons, and think that their boys had to exert less effort to do well, compared to parents of girls (Parsons, Adler, & Kaczala 1982). Parents of boys also make more unstable, external attributions about their sons' performance in math; relative to parents of girls, for instance, they are more likely to believe that a specific test grade is high or low because of the teacher, rather than because of the child's ability (Holloway 1986). In contrast, mothers of girls believe that their children's performance in math is more a function of their children's effort and achievement orientation in school than do mothers of boys (Holloway & Hess 1982).

It might be argued that these differences reflect facts about children, not social stereotypes. However, girls themselves, at least at young ages, are more motivated to achieve in math than are boys, even when their level of ability is equal to that of boys; their liking of math is higher than that of boys (Holloway 1986). Yet, the mothers of these same children hold higher aspirations, and exert more pressure for later achievement on their male children than they do their female children (Holloway 1986).

Even when girls like math and excel at it, as in high-ability samples, there are indications that they have sex stereotyped expectations about it. High-ability children tend to view math as a male domain, and their fathers are more likely to engage in math-related activity than are their mothers (Raymond & Benbow 1989; Raymond & Benbow 1986).

Teachers. There are many investigations concerning teachers' differential use of evaluative feedback in the classroom (e.g. Becker 1981; Brophy 1985; Brophy & Good 1970; Dweck, Davidson, Nelson, & Enna 1978; Heller & Parsons 1981). Space precludes an exhaustive review of the literature here. We focus illustratively on the outcome of one investigation that used a large sample of teachers (ten), a large sample of class periods (100), and quantitative and qualitative measures (Becker 1981).

Becker (1981) used an modified version of the Brophy and Good Teacher-Child Dyadic Interaction System (Brophy & Good 1969), appropriate for ninth and tenth grade students, to code student-teacher interaction, along with qualitative analyses of transcripts of classroom dialogue. She studied ninth and tenth grade geometry classes because geometry represents a choice point for students: it is required, but further study in math after geometry is usually not required. Geometry has large spatial and conceptual components as well, so the implications of this study are particularly relevant here.

Becker (1981) found that boys responded to more open questions (where the teacher waits for a student to volunteer a response), more process questions (requiring "higher-order" thought), and made more "call-outs" (responses to questions

before they were called on) than girls. Males also received more sustained interaction than girls, and more teacher-initiated contacts. In terms of encouragement for later participation and success in mathematics, boys had many more positive interchanges with teachers, whereas girls received 90% of the negative interactions.

Particularly poignant were Becker's (1981) reports of lost opportunities to encourage girls in later mathematical pursuits. She cites an interchange in which a female student asks a teacher if she will need to take "Algebra II/Trig." The teacher asks if she wants to go to college, the student says no, and the teacher replies that then she doesn't need to take the course. With no further discussion, a teacher lets a tenth-grade girl foreclose on any future academic interaction with math. Presumably, if such a child later changes her mind and does go to college, she will dread that required college math course.

Becker (1981) reports that teachers made frequent remarks about females' lesser ability and experience with things mathematical, spatial, and mechanical, and that female teachers even engaged in self-deprecating remarks about their own abilities in geometry and other spatially and mechanically oriented tasks, thereby sending the message that girls and women are not expected to have such competencies and experiences. Again, all of these differential expectations are unrelated to the actual ability and performance of girls and boys, because at this age level, girls are performing equal to or better than boys, in math in general (Kimball 1989), and in geometry proof writing, in particular (Senk & Usiskin 1983).

Self-Expectations and Feelings of Competence. Girls and women, relative to boys and men, express reduced feelings of competence and self-efficacy about their abilities in mathematics (Lent, Lopez, & Bieschke 1993). The masculine label on mathematics appears to be responsible for females' reduced feelings of competency, because when presented with a gender-neutral task, females express equally high feelings of competency as males (Hackett & Campbell 1987).

There are also sex differences in attributions for success and failure in mathematics. When success and failure feedback are manipulated, girls are more likely than boys to attribute their successes to unstable factors like effort, whereas boys are likely to attribute their successes to ability. The reverse effect occurs for failures: girls attribute them to ability, boys to unstable factors like effort or task characteristics (Hackett & Campbell 1987; Wolleat, Pedro, Becker, & Fennema 1980). This effect occurs also when girls' and boys' performance levels are controlled (Wolleat et al. 1980). Thus, real success in math does not reduce girls' tendency to disregard natural ability as a cause for their high performance.

Motivational factors appear to interact with students' attributions. Students with "mastery orientations" are more likely to do well in situations where novel concepts or new instructional units are challenging. Since math is a discipline that continually presents new challenges, boys may fare better because they adopt a mastery orientation, rather than a helpless orientation (Licht & Dweck 1984).

It has been argued, however, that the subjective value of a task is more important than attributions for success, or other motivational factors in determining effort (Eccles, Adler, & Meece 1984). When social forces act to reduce the desirability or

value of a specific activity for a certain group, that group will choose not to pursue the activity. Even when girls express confidence in their abilities in math, they may choose to avoid it in favor of another discipline (e.g., English) that has a higher subjective value for them (Eccles et al. 1984; Meece, Parsons, Kaczala, Goff, & Futterman 1982).

These attributional and motivational factors translate into reduced expectations for success in mathematics in girls. It makes sense that girls would choose disciplines seen as not requiring mathematics if they believe their successes in math are the result of effort, not ability, that their future math grades are going to be lower than they actually are (Mura 1987), and that they have little control over their eventual performance.

INFORMAL EXPERIENCE

Mathematical Activity. Boys take more math classes than girls, but outside the classroom they appear to engage in more math and science-related activity as well (Kimball 1989). Hilton and Berglund (1974) found that, when questioned about outside-the-classroom activity, girls consistently reported reading fewer books on science, spending less time reading science magazines, talking less about science and math to friends and parents, and finding math more boring and less interesting than boys find it. Sadly, these differences were minimal in grade seven and quite pronounced in grade 11. At that point, only 6% of the boys, but 18% of the girls, reported finding math boring. The pattern of findings was the same for children in "academic" and "non-academic" curricula.

One might suspect that in highly select samples, high achieving girls would be more similar to boys in the amount of time and attention they devote, of their own accord, to math-related activity. Such is not the case. According to Benbow and Stanley (1982), many more boys than girls in the Study of Mathematically Precocious Youth reported learning some of their math outside of the classroom. Casserly (1980), on interviewing girls in Advanced Placement math and science courses found that they lamented the fact that their parents were unlikely to buy them math and science-related toys, even after considerable pleading, and that they were often forced to appropriate things like Legos, erector sets, and chemistry sets that were originally bought for their brothers.

Spatial Activity. Newcombe, Bandura, and Taylor (1983) developed the Spatial Activities Questionnaire (SAQ) to study adolescents' and adults' self-reports of spatial activity. This questionnaire consists of a list of 81 activities considered relevant to spatial ability by a panel of judges. Forty of those activities turn out to be masculine sex-typed, 21 feminine sex-typed, and the remaining 20 to be neutral. Examples of included items are: soccer, archery, building model airplanes (masculine); figure skating, knitting, gymnastics (feminine); and pingpong, photography, advanced tennis (neutral).

CAUSAL LINKAGES?

To this point, we have shown that environmental input is crucial to mathematical and spatial development, and that boys and girls differ in their mathematical and spatial input. Do sex differences in input cause sex differences in ability, or vice versa? Or, as is most likely, are there complicated interactions between biological and social facts? In this section, we evaluate arguments that the linkage goes, at least to some extent, from experiences to ability, leaving to the next section the task of considering interactions.

Impact of Course-Taking Decisions on Sex Differences in Mathematics. As we have seen, boys take more math courses than girls, beginning at the time they are able to make choices about which courses they take (e.g., Armstrong 1981; Benbow & Stanley 1982; Fennema & Carpenter 1981; Fennema & Sherman 1977; Pallas & Alexander 1983). Pallas and Alexander (1983), analyzing data from the Educational Testing Service's Study of Academic Prediction and Growth (Hilton 1979), found that sex differences of 35 points on the SAT-M favoring boys were reduced to 14 points when the amount of coursework taken was controlled. Furthermore, they found that when girls and boys in this sample started out in ninth grade there were no sex differences, but girls were at a significant disadvantage by twelfth grade. They also found that girls took fewer math courses than boys and that the more advanced the coursework for girls, the less the difference between boys' and girls' twelfth grade scores.

When coursework is "naturally" controlled for by studying male and female samples with equivalent coursework there appears to be essentially no difference between the sexes. For instance, Smith and Walker (1988) found that on the New York State Regents Mathematics Examination, girls slightly outperformed boys in both ninth and eleventh grades, whereas the reverse was true for tenth grade scores. Kimball (1989) concluded that differential course taking accounts for some of the sex-differences in mathematics ability, but that other factors, possibly including differential course taking in the sciences, and other mathematics-related experience outside the classroom, may also account for some of the difference.

Spatial Ability Training. It has often been argued that experiential hypotheses about sex differences predict that spatial test training should raise females' scores more than males' scores, since males came into the training with the benefit of more prior experience than did females. Contrary to this hypothesis, Baenninger and Newcombe (1989) found that while training of all types raised spatial test performance above pre-training levels, females and males improved equally.

We do not think, however, that this finding shows that sex differences in experience are immaterial to sex differences in ability. The key assumption of the original hypothesis actually seems to be flawed. Investigators have assumed that males, because of prior experience, enter any spatial training regime already at or near the asymptotic level. That is, training cannot cause much of an improvement for men

because there isn't much room for an improvement. But this turns out to be false. Men have plenty of room for improvement.

The only way to test sex differences in response to training, on this analysis, is to conduct a training study that trains both females and males to an asymptotic level. It should take more training on average for females to reach their highest level of performance than it does for males, if experience is relevant, but the asymptotic levels for the sexes should be equal (Baenninger & Newcombe 1989). To our knowledge, this crucial study has not been conducted.

Correlations of Informal Spatial Experience and Ability. Baenninger and Newcombe (1989) conducted a meta-analysis on all of the studies they could find that examined the relationships between scores on spatial experience scales and various measures of spatial ability. Spatial experience was assessed by a variety of means, including Newcombe, Bandura and Taylor's (1983) scale, and a shortened version designed by Signorella, Krupa, Jamison, and Lyons (1986). They condensed the 81-item questionnaire to the 30 items (ten within each sex-typed category) for which correlations with spatial ability were highest.

Baenninger and Newcombe (1989) concluded that there was a statistically significant, but small, relation between degree of participation in spatial activities and spatial ability. The association between these two variables was "more significant" for females than males, but this was because of greater statistical power, due to larger numbers of female participants in the included studies. The effect sizes for both sexes were slightly higher when masculine sex-typed activities were considered separately.

Participation in video games and computer programming has also been shown to increase spatial ability scores. Miller, Kelly, and Kelly (1988) found that including Logo programming in the curriculum of fifth and sixth graders significantly improved their PMA spatial subtest performance over controls who had not been exposed to the programming curriculum. Similarly, Dorval and Pépin (1986) showed that eight video game playing sessions improved the performance of college-aged novice video game players on the space relations subtests of the DAT, and Subrahmanyam and Greenfield (1994) found that fifth-graders' spatial skills improved following playing the game *Marble Madness*. This improvement did not differ for the sexes, however, in either study, echoing Baenninger and Newcombe's (1989) finding that spatial ability training did not produce significantly different degrees of improvement for females and males. Law, Pellegrino, and Hunt (1993) also found a relation between reported levels of video game playing and judgments of a target's velocity, but not the distance it had traveled. In this task, males outperformed females, but differential experience with video game playing accounted for more of the variance in velocity judgments than did sex.

Historical Change. In an article with the eye-catching title "Cognitive Gender Differences are Disappearing," Feingold (1988) examined the data from nationwide representative samples of students taking the Differential Aptitude Tests (DAT) between the years 1947 and 1980, and the Preliminary Scholastic Aptitude Test and

the Scholastic Aptitude Test (PSAT/SAT) between 1960 and 1983. Feingold (1988) included data on the verbal portion of the PSAT/SAT and data on all of the DAT subtests, including those on spatial ability. Thus, he was able to look at changes in sex-related differences over a historically long span of time on a variety of measures. Females' average scores were higher than males on DAT Spelling, Language, and Clerical Accuracy, slightly higher on PSAT Verbal, and very slightly higher, or equivalent, on SAT Verbal. Males' average scores were higher on DAT Mechanical Reasoning, and Space Relations, PSAT Math and SAT Math. However, in all cases, but the notable exception of SAT Math scores, the gap between the sexes has been closing consistently since the first administration of the tests (Feingold 1988). Thus, for the most part, on nationally administered standardized tests, "cognitive gender differences are disappearing" (Feingold 1988).

Friedman (1989) presented evidence that reinforces Feingold's (1988) findings. She found that not only is the gap between the sexes closing on a variety of tests, but that when meta-analytic calculations include post-1974 (post-Maccoby & Jacklin) data and include samples with grade school as well as high school children, the mean effect sizes of differences between the sexes are quite small.

For yet another large national sample in Germany, Stumpf and Klieme (1989) report a more dramatic linear drop in differences on the Cubes Perspective Test, which measures spatial visualization ability, from an effect size of .67 in 1978 to an effect size of .40 in 1988. Stumpf and Klieme (1989) argue that, while the 1989 differences are still meaningful, they may be inordinately large because of the large mental rotation component in the Cubes Perspective Test, and the age of the sample, with the modal number of subjects between 18 and 29 years, but with some much older subjects. Perhaps cohort effects, stemming from earlier socialization practices have inflated the 1988 differences.

What about the notable exception, in Feingold's (1988) sample of data, that sex differences in SAT-M scores have slightly increased, with ds at .37 in 1967 and .42 in 1983? This change can be accounted for by the selectivity of the SAT sample, relative to the PSAT sample. As noted above, sex-related differences favoring males are more dramatic at the high end of the distribution (Benbow 1988). Students taking the SAT represent a sample that is closer to the high end of the distribution than the more nationally representative sample of students taking the PSAT. In addition, SAT-M scores may, in fact, reflect sex-related differences in experience, rather than biology, as some have claimed (Benbow 1988), because they could be a reflection of differential course taking in the later high school years.

BIOLOGICAL-SOCIAL INTERACTIONS

Numerous biological hypotheses have been put forth to explain sex-related differences in spatial and mathematics abilities. These include sex differences in cerebral laterality (Benbow 1988; Geschwind & Behan 1982; McGee 1979; McGlone 1980;

Ozer 1987), and its impact on processing strategies (e.g., Newcombe, Dubas, & Baenninger 1989), and the organizing and activating effects of hormones (Collaer & Hines 1995; Hines & Shipley 1984; Newcombe & Baenninger 1989; Resnick, Berenbaum, Gottesman, & Bouchard 1986). A "timing of puberty" hypothesis that incorporates hormonal and cerebral laterality explanations has also been advanced (Waber 1977), but has not received consistent support (Newcombe & Dubas 1987). All of the proposed biological causes have been studied extensively for their own sake, but they are relevant here primarily because it is reasonable to assume that biological factors interact, in not so clear cut ways, with social factors to produce a final outcome. It is likely that any biological foundations for spatial and mathematical abilities are enhanced (or obscured) by social and experiential forces.

The "bent twig" conceptualization of sex-related differences in mathematics and spatial ability embodies this interactive approach (Casey & Brabeck 1990; Sherman 1978). In this approach, biological factors "bend the twig" towards the development of certain kinds of abilities, and experience encourages growth in the "bent" direction. Annett's (1985) genetic handedness theory predicts that the genetic basis for high spatial ability is, in particular, more likely to be present in right-handed females with left-handed relatives (for a thorough discussion of this model, see Annett (1985) and Casey & Brabeck (1990)). Casey and Brabeck (1985) found that for such a subgroup of women, their genetic potential to have high spatial ability was only realized if they had indeed had a large amount of relevant experience with spatial activities. This biosocial hypothesis is important, not only because it is interesting in itself but also because it confirms the potential value of an interactionist approach to sex differences.

INTEGRATING THE EVIDENCE

Two strong conclusions can be drawn from this review. First, mathematics and spatial ability are clearly influenced by experience. For spatial ability, training (even simple practice) results in definite improvements in performance on spatial tests. Exposure to a school curriculum also increases spatial ability scores (but not performance in other areas like memory) and skill at addition (but not understanding of conservation of number).

Second, it is clear that boys and girls are differentially exposed to spatial and mathematics-related training and activity. Boys engage in more spatial and mathematics-related activity than girls, and they take more math courses, beginning at the time when they are able to choose. Perhaps the most profound contrast between boys' and girls' experiences, however, is the differential expectations that their parents and teachers hold for them, and their differential feelings of self-efficacy, and attributions of their own performance in these domains. For girls who are in elementary school or junior high, the attributions and expectations they, their parents, and their teachers hold may translate into "good girls" who are conscien-

tious, neat, obedient, and who answer correctly. Fulfilling these expectations in later years may include the development of a self-concept that includes reduced aspirations for and involvement in math and spatially-oriented courses, activity, and careers.

Showing that sex-differentiated experience leads to sex-differentiated levels of skill in a quantitative fashion is trickier than demonstrating the truth of the first two conclusions. The relation between early participation in spatial activity and later performance on spatial tests is not strong, but it is significant. For mathematical ability, number of courses taken is related to performance on standardized mathematics tests. These facts suggest a causal link between experience and skill, but evaluating self-selection explanations of the associations is not easy.

While it may seem hardly surprising that a student who took advanced algebra, trigonometry, and calculus would perform better, on average, on the SAT-M than a student who took only elementary algebra and geometry, the finding that male students outperform female students on the SAT-M is often presented, at least implicitly, as if biology accounted for the difference. In fact, filtered-down versions of media reports of such differences negatively influence mothers' beliefs about their daughters' math ability and future achievement potential (Eccles & Jacobs 1986).

More research is needed to link hypothesized biological bases for the development of spatial skill to the ability to take advantage of (and the propensity to seek out) environmental experiences engaging and fostering components of spatial skill. We need to identify specific experiences that engage spatial skill, rather than merely speculating on, for instance, the role of aiming sports or puzzles. The finding of school-related effects on spatial development suggests that some particularly crucial kinds of spatial experience may be more common at school than at home. Having identified the sorts of environmental input that foster the growth of spatial ability, we need to determine if the input has equivalent effects on biologically-defined groups, or, as suggested by Casey and Brabeck, differential effects.

Information of the sort we sketched above, when available, may help educators to design finely-tuned mathematical and spatial curricula to foster the growth of spatial and mathematical skill in all of the children they seek to educate. On the basis of current data, however, we believe caution is in order in advocating different curricula for different groups (e.g., mathematics for females). Environmental enrichment seems to, by and large, help everyone. When mathematical and spatial experiences and expectations are gender-blind, there is reason to hope that the educational potential of all children will be better realized.

REFERENCES

American Association of University Women (1991). *Shortchanging girls, shortchanging America: A call to action.* Washington, DC: American Association of University Women.

Annett, M. (1985). *Left, right, hand, and brain: The right shift theory.* Hillsdale, NJ: Erlbaum.

Armstrong, J. M. (1981). "Achievement and participation of women in mathematics: Results of two national surveys." *Journal for Research in Mathematics Education, 12,* 356–372.

Baenninger, M. & N. Newcombe. (1989). "The role of experience in spatial test performance: A meta-analysis." *Sex Roles, 20,* 327–343.

Becker, J. R. (1981). "Differential treatment of males and females in mathematics classes." *Journal for Research in Mathematics Education, 12,* 40–53.

Benbow, C. P. (1988). "Sex differences in mathematical reasoning ability among the intellectually talented: Their characterization, consequences, and possible explanations." *Behavioral and Brain Sciences, 11,* 169–232.

Benbow, C. P. & J. C. Stanley. (1982). "Consequences in high school and college of sex differences in mathematical reasoning ability: Longitudinal perspective." *American Education Research Journal, 19,* 598–622.

Bergan, A., D. L. McManis, & P. A. Melchert. (1971). "Effects of social and token reinforcement of WISC Block Design performance." *Perceptual and Motor Skills, 32,* 871–880.

Bisanz, J., F. J. Morrison, & M. Dunn. (1994). Effects of age and schooling on the acquisition of elementary quantitative skills. Unpublished paper, University of Alberta.

Blade, M. F. & W. S. Watson. (1955). "Increase in spatial visualization test scores during engineering study." *Psychological Monographs, 69* (Whole No. 397).

Blatter, P. (1983). "Training in spatial ability. A test of Sherman's hypothesis." *Perceptual and Motor Skills, 57,* 987–992.

Brinkmann, E. H. (1966). "Programmed instruction as a technique for improving spatial visualization." *Journal of Applied Psychology, 50,* 179–184.

Brophy, J. E. (1985). "Interactions of male and female students with male and female teachers." Pp. 115–142 in *Gender influences in classroom interaction,* edited by L. C. Wilkinson & C. B. Marrett. Orlando, FL: Academic Press.

Brophy, J. E. & T. L. Good. (1969). *Teacher-child dyadic interaction: A manual for coding classroom behavior.* Austin, TX: The Research and Development Center for Teacher Education.

———. (1970). "Teachers' communication of differential expectations of children's classroom performance: Some behavioral data." *Journal of Educational Psychology, 61,* 365–374.

Casey, M. B. & M. M. Brabeck. (1990). "Women who excel on a spatial task: Proposed genetic and environmental factors." *Brain and Cognition, 12,* 73–84.

Casserly, P. L. (1980). "Factors affecting female participation in advanced placement programs in mathematics, chemistry, and physics." Pp. 138–163 in *Women and the mathematical mystique,* edited by L. H. Fox, L. Brody, & D. Tobin. Baltimore, MD: Johns Hopkins University Press.

Chance, J. E. & A. G. Goldstein. (1971). "Internal-external control of reinforcement and embedded figures performance." *Perception and Psychophysics, 9,* 33–34.

Churchill, R. D., J. M. Curtis, C. H. Coombs, & T. W. Harrell. (1942). "Effect of engineer school training on the Surface Development Test." *Educational and Psychological Measurement, 2,* 279–280.

Ciganko, R. A. (1973). The effect of spatial information training and drawing practice upon spatial visualization ability and representational drawings of ninth grade students. Unpublished doctoral dissertation, Illinois State University.

Collaer, M. L. & M. Hines. (1995). "Human behavioral sex differences: Relationships to gonadal hormone levels during early development." *Psychological Bulletin, 118,* 55–107.

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

Dorval, M. & M. Pépin. (1986). "Effect of playing a video game on a measure of spatial visualization." *Perceptual Motor Skills, 62,* 159–162.

Dweck, C. S., W. Davidson, S. Nelson, & B. Enna. (1978). "Sex differences in learned helplessness: II. The contingencies of evaluative feedback in the classroom and III. An experimental analysis." *Developmental Psychology, 14,* 268–276.

Eccles (Parsons), J., T. A. Adler, & J. L. Meece. (1984). "Sex differences in achievement: A test of alternate theories." *Journal of Personality and Social Psychology, 46,* 1, 26–33.

Eccles, J. S. & J. E. Jacobs. (1986). "Social forces shape math attitudes and performance." *Signs, 11,* 367–380.

Elenteny, K. & M. Baenninger. (1995). Pointing to old main: Sex and experience differences in directional sense. Poster presented at the annual meeting of the Eastern Psychological Association, Boston, March.

Feingold, A. (1988). "Cognitive gender differences are disappearing." *American Psychologist, 43,* 95–103.

Fennema, E. & T. P. Carpenter. (1981). "Sex-related differences in mathematics: Results from the national assessment." *Mathematics Teacher, 74,* 554–559.

Fennema, E. & J. Sherman. (1977). "Sex related differences in mathematics achievement, spatial visualization and affective factors." *American Educational Research Journal, 14,* 1, 51–71.

Friedman, L. (1989). "Mathematics and the gender gap: A meta-analysis of recent studies on sex differences in mathematical tasks." *Review of Educational Research, 69,* 185–213.

Geary, D. C. (in press). "Sexual selection and sex differences in mathematical abilities." *Behavioral and Brain Sciences.*

Geschwind, N. & P. Behan. (1982). "Left-handedness: Association with immune disease, migraine, and developmental learning disorder." *Proceedings of the National Academy of Sciences, 79,* 5097–5100.

Hackett, G. & N. K. Campbell. (1987). "Task self-efficacy and task-interest as a function of performance on a gender-neutral task." *Journal of Vocational Behavior, 30,* 203–215.

Heller, K. A. & J. E. Parsons. (1981). "Sex differences in teachers' evaluative feedback and students' expectancies for success in mathematics." *Child Development, 52,* 1015–1019.

Hilton, T. L. (1979). "ETS study of academic prediction and growth." *New Directions for Testing and Measurement, 2,* 27–44.

Hilton, T. L. & G. W. Berglund. (1974). "Sex differences in mathematics achievement: A longitudinal study." *Journal of Educational Research, 67,* 231–237.

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

Holloway, S. D. (1986). "The relationship of mothers' beliefs to children's mathematics achievement: Some effects of sex differences." *Merrill-Palmer Quarterly, 32,* 231–250.

Holloway, S. D. & R. D. Hess. (1982). "Causal explanations for school performance: Contrasts between mothers and children." *Journal of Applied Developmental Psychology, 3,* 319–327.

Huttenlocher, J., S. C. Levine, & J. Vevea. (1994). Unpublished manuscript, Dept. of Psychology, University of Chicago.

Kimball, M. M. (1989). "A new perspective on women's math achievement." *Psychological Bulletin, 105,* 2, 198–214.

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

Law, D. J., J. W. Pellegrino, & E. B. Hunt. (1993). "Comparing the tortoise and the hare: Gender differences and experience in dynamic spatial reasoning tasks." *Psychological Science, 4,* 1, 35–40.

Lent, R. W., F. G. Lopez, & K. J. Bieschke. (1993). "Predicting mathematics related choice and success behaviors: Test of an expanded social cognitive model." *Journal of Vocational Behavior, 42,* 223–236.

Licht, B. G. & C. S. Dweck. (1984). "Determinants of academic achievement: The interaction of children's achievement orientations with skill area." *Developmental Psychology, 20,* 4, 628–636.

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

Lolla, R. L. (1973). The effect of selected instruction in tactual-visual perception on ninth grade male and female's visual imagery, mechanical reasoning and spatial relations abilities. Unpublished doctoral dissertation, Purdue University.

Lusk, E. J. & H. Wright. (1981). "Differences in sex and curricula on learning the group embedded figures tests." *Perceptual and Motor Skills, 53,* 8–10.

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

McGee, M. G. (1978). "Effects of training and practice on sex differences in mental rotation tests score." *Journal of Psychology, 100,* 87–90.

———. (1979). "Human spatial abilities: Psychometric studies and environmental, genetic, hormonal, and neurological influences." *Psychological Bulletin, 86,* 5, 889–918.

McGlone, J. (1980). "Sex differences in human brain asymmetry: A critical survey." *Behavioral and Brain Sciences, 3,* 215–263.

Meece, J. L., J. E. Parsons, C. M. Kaczala, S. B. Goff, & R. Futterman. (1982). "Sex differences in math achievement: Toward a model of academic choice." *Psychological Bulletin, 91,* 2, 324–348.

Miller, R. B., G. N. Kelley, & J. T. Kelly (1988). "Effects of Logo computer programming experience on problem solving and spatial relations ability." *Contemporary Educational Psychology, 13,* 348–357.

Mura, R. (1987). "Sex-related differences in expectations of success in undergraduate mathematics." *Journal for Research in Mathematics Education, 18,* 1, 15–24.

Newcombe, N. & M. Baenninger. (1989). "Biological change and cognitive ability in adolescence." Pp. 168–191 in *Biology of adolescent behavior and development,* edited by G. R. Adams, R. Montemayor, & T. P. Gullota. London: Sage.

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

Newcombe, N. & N. Dubas. (1987). "Individual differences in cognitive ability: Are they related to timing of puberty?" Pp. 249–302 in *Biological-psychosocial interactions in early adolescence,* edited by R. M. Lerner & T. T. Foch. Hillsdale, NJ: Erlbaum.

Newcombe, N., J. S. Dubas, & M. Baenninger. (1989). "Associations of timing of puberty with spatial ability: do they persist into adulthood?" *Child Development, 60,* 246–254.

Ozer, D. (1987). "Personality, intelligence, and spatial visualization: Correlates of mental rotations performance." *Journal of Personality and Social Psychology, 53,* 1, 129–143.

Pallas, A. M. & K. L. Alexander. (1983). "Sex differences in quantitative SAT performance: New evidence on the differential coursework hypothesis." *American Educational Research Journal, 20,* 165–182.

Parsons, J. E., T. F. Adler, & C. M. Kaczala. (1982). "Socialization of achievement attitudes and beliefs: Parental influences." *Child Development, 53,* 322–339.

Raymond, C. L. & C. P. Benbow. (1986). "Gender differences in mathematics: A function of parental support and student sex-typing?" *Developmental Psychology, 22,* 6, 808–819.

———. (1989). "Educational encouragement by parents: Its relationship to precocity and gender." *Gifted Child Quarterly, 33,* 4, 144–151.

Resnick, S. M., S. A. Berenbaum, I. I. Gottesman, & T. J. Bouchard. (1986). "Early hormonal influences on cognitive functioning in congenital adrenal hyperplasia." *Developmental Psychology, 22,* 2, 191–198.

Rogoff, B. (1981). "Schooling and the development of cognitive skills." In *Handbook of cross-cultural psychology* (Vol. 4), edited by H. C. Triandis & A. Heron. Rockleigh, NJ: Allyn & Bacon.

Schmidt, R. A. & R. A. Bjork. (1992). "New conceptualizations of practice: Common principles in three paradigms suggest new concepts for training." *Psychological Science, 3,* 207–217.

Senk, S. & Z. Usiskin. (1983). "Geometry proof writing: A new view of sex differences in mathematics ability." *American Journal of Education, 91,* 187–201.

Sevy, B. A. (1983). Sex-related differences in spatial ability: The differences in spatial ability: The effects of practice. Unpublished doctoral dissertation, University of Minnesota.

Sherman, J. A. (1974). "Field articulation, sex, spatial visualization, dependence, practice, laterality of the brain and birth order." *Perceptual and Motor Skills, 38,* 1223–1235.

———. *Sex-related cognitive differences.* Springfield, IL: Charles C. Thomas.

Signorella, M. L., W. Jamison, & M. H. Krupa. (1989). "Predicting spatial performance from gender stereotyping in activity preferences and self-concept." *Developmental Psychology, 25,* 89–95.

Signorella, M. L., M. H. Krupa, W. Jamison, & N. Lyons. (1986). "A short version of a spatial activities questionnaire." *Sex Roles, 14,* 475–479.

Smith, S. E. & W. J. Walker. (1988). "Sex differences on New York state regents examinations: Support for the differential course-taking hypothesis." *Journal for Research in Mathematics Education, 19,* 81–85.

Stevenson, H. W. & J. W. Stigler. (1992). *The learning gap: Why our schools are failing and what we can learn from Japanese and Chinese education.* New York: Summit Books.

Stumpf, H. & E. Klieme. (1989). "Sex-related differences in spatial ability: More evidence for convergence." *Perceptual and Motor Skills, 69,* 3, 915–921.

Subrahmanyam, K. & P. M. Greenfield. (1994). "Effect of video game practice on spatial skills in girls and boys." *Journal of Applied Developmental Psychology, 15,* 13–32.

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

Ward, S. L., N. Newcombe, & W. F. Overton. (1986). "Turn left at the church, or three miles north: A study of direction giving and sex differences." *Environment and Behavior, 18,* 192–213.

Wolfe, L. R. (1970). The effects of space visualization training on spatial ability and arithmetic achievement of junior high school students. Unpublished doctoral dissertation, State University of New York.

Wolleat, P. L., J. D. Pedro, A. D. Becker, & E. Fennema. (1980). "Sex differences in high school students causal attributions of performance in mathematics." *Journal for Research in Mathematics Education, 11,* 357–366.