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Biological Correlates of High Mathematical Reasoning Ability *

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INTRODUCTION

The Study of Mathematically Precocious Youth (SMPY) has gathered extensive data showing that large sex differences in mathematical reasoning ability which favor males, exist before age 13. In this paper we evaluate some of the major "environmental" hypotheses that have been proposed to account for this difference. We will conclude that these "environmental" hypotheses need to be reformulated in order to account for the findings with our population of intellectually talented youths. While it is possible to adapt these exclusively environmental hypotheses to fit our data, we propose to take an alternative approach, which involves both environmental and biological causes for the observed sex difference.

It has long been obvious that certain sex differences, such as those in height, weight, and onset of puberty are largely determined by endogenous factors. No doubt these differences are also accentuated by the environment. Nevertheless, few deny that biological factors strongly contribute to these obvious sex differences. We now wish to propose that a combination of exogenous and endogenous factors also determines the sex difference in mathematical reasoning ability. In support of this hypothesis we present some new findings on possible biological correlates of extremely high mathematical and verbal abilities.

We recognize that any hypothesis involving biological differences between males and females will prove to be unpopular and controversial (see Tomizuka and Tobias, 1981; Stage and Karplus, 1981; Chipman, 1981; Egelman et al., 1981; Moran, 1981; Luchins and Luchins, 1981; Kelly, 1981; Benbow and Stanley, 1981). The scientific method, however, does not always allow one to take the most socially or politically expedient approach. In our opinion the evidence supporting a possible role for biological factors is sufficiently strong to merit serious consideration. We want to emphasize, however, that we are only proposing an hypothesis, not a proven theory.

The data presented in this chapter were obtained at the Study of Mathematically Precocious Youth (SMPY) and the Center for the Advancement of Academically Talented Youth (CTY). SMPY was founded at Johns Hopkins University in 1971 by Julian C. Stanley with the express purpose of identifying and educationally facilitating intellectually advanced students. In 1979 at Johns Hopkins he also helped create CTY, which carries on the tradition

* We wish to dedicate this chapter to Julian C. Stanley on the occasion of his 65th birthday. We also thank Lola L. Minor and Pamela J. Hines for helpful comments. This work was supported by grants from the Spencer and Donner Foundations.

of talent searches and academic programs for academically talented students. The programs created by Julian Stanley have received well-deserved international recognition. Without his foresight, creative ideas, and dedication, the findings presented in this chapter, many of which he contributed to, could not have been made.

SEX DIFFERENCES IN MATHEMATICAL REASONING ABILITY BEFORE AGE 13

The SMPY talent searches

It is well documented that there are large sex differences in mathematical ability and achievement favoring males (Bieri et al., 1958; Very, 1967; Garai and Scheinfeld, 1968; Glennon and Callahan, 1968; Suydam and Weaver, 1970; Backman, 1972; Wilson, 1972; Fennema, 1974; Keating, 1974; Maccoby and Jacklin, 1974; National Assessment of Educational Progress, 1975; Ernest, 1976; Fox, 1976; Fox et al., 1980). In the United States these differences have been found after puberty when the mathematics curriculum becomes more abstract. Sex differences favoring males, however, are not consistent across all mathematical abilities. Boys excel in tasks requiring mathematical reasoning ability, whereas girls excel in computation (Fennema, 1974). Moreover, no differences were seen in ability to apply knowledge that has already been learned.

Before 1980 the generally accepted explanation for these differences was the differential course-taking hypothesis of Fennema and Sherman (1977). They postulated that males developed more advanced mathematical reasoning abilities because males enrolled in more advanced mathematics courses, especially higher level courses, than females. This hypothesis has often been used to discount as sociological artifacts the sex differences found in mathematical ability (e.g., Wise et al., 1979).

In 1980 Benbow and Stanley presented data collected over an 8-year period by the Study of Mathematically Precocious Youth (SMPY), which could not be accounted for by the differential course-taking hypothesis. They showed that large sex differences in mathematical reasoning ability were observed in pre-adolescent students with essentially identical formal educational experiences.

These findings were based on data obtained from SMPY's mathematics talent searches conducted in 1972, 1973, 1974, 1976, 1978 and 1979 and involved 9927 intellectually gifted junior high-school students, who were between 12 and 14 years of age. Students attending schools in the Middle Atlantic Region of the United States were eligible to participate in an SMPY talent search if they scored in the upper 5% (1972), 2% (1973 and 1974), or 3% (1976, 1978 and 1979) in mathematical ability on the national norms of a standardized achievement test administered in the regular testing program of the students' schools. Thus, both male and female talent-search participants were selected by equal criteria for high mathematical ability before entering. Girls comprised 43% of the participants in these searches.

As part of the talent search, these students took the College Board Scholastic Aptitude Test's mathematics (SAT-M) and verbal (SAT-V) sections. These tests normally measure developed mathematical and verbal reasoning abilities, respectively, and are designed for above-average 12th-graders (Donlon and Angoff, 1971). Most of the students in our study, however, were in the middle of the seventh grade and were less than age 13. Few had received formal opportunities to develop their abilities in algebra and beyond (Benbow and Stanley, 1982a,b). Our rationale was that most of these young students were demonstrably unfamiliar with mathematics from algebra onward, yet were able to score highly. This could presumably occur only by the use of extraordinary mathematical reasoning ability. As an example of this, we have established that a majority of the students in the top 10% of our talent-search students (i.e., the top 0.3% of the general population in ability) did not even know Algebra I completely. Yet they scored far higher than most high-school students exposed to algebra and geometry. Thus, we conclude that the SAT-M must function far more at an analytical reasoning level for our SMPY testees than it does for high-school juniors and seniors who have already studied abstract mathematics for several years. We define this talent as mathematical reasoning ability.

The results from the 6 talent searches are shown in Table I. Most students scored high on both the SAT-M and SAT-V. There were no important sex differences in verbal test scores. This is consistent with the findings for high-school students, who also do not show sex differences favoring girls in this specific ability (ATP, 1981). In contrast, Maccoby and Jacklin (1974) concluded that there is a fairly well-established sex difference in verbal ability favoring girls. It is approximately 0.25 S.D. in magnitude.

A large sex difference in mathematical reasoning ability was, however, observed in every talent search. On the average, the boys scored about 0.5 S.D. better than the girls did. Moreover, there were indications that the greatest disparity between the boys and girls was in the upper ranges of mathematical reasoning ability. For example, in SAT-M scores of over 500 (average score of college-bound 12th-grade males) boys outnumbered girls more than 2 to 1 (1817 boys versus 675 girls in all 6 talent searches). It should be noted that the boys' SAT-M scores had a greater variance than the girls. This obviously relates to finding many more high-scoring boys than girls. Why boys tend to be more variable than girls has been addressed by Eysenck and Kamin (1981).

These results were limited by the fact that only selected, mathematically able, highly motivated students were tested. Also, too few cases of extremely high-scoring students were obtained to conclude whether greater differences exist at the high end of the scoring scale of the SAT-M.

Sex differences in mathematical reasoning ability among the most gifted

In 1980 two new talent-search programs were developed. The first was a modification of the original talent-search procedure. As previously, any seventh grader or student of typical seventh-grade age in a higher grade in the Middle Atlantic area of the United States could participate in the 1980, 1981, and 1982 annual talent searches, which were conducted by Johns Hopkins' Center for the Advancement of Academically Talented Youth (CTY). The major change was that not only mathematically able students but also students in the top 3% in verbal or in overall ability were allowed to participate. Thus, we had a more general sample of intellectually talented students. These searches also had equal representation by sex. Despite these modifications, the mean sex difference remained constant at 30 points favoring males among 19 883 boys and 19 937 girls (see Table I and Benbow and Stanley, 1983a). As previously, no important sex differences in mean SAT-V scores nor in the distribution of SAT-V scores were found.

It is not the mean difference in SAT-M scores, however, that should be emphasized. Rather, the ratios of high-scoring boys to girls are of major importance. The ratio of boys to girls scoring ≥ 500 SAT-M (493 was the SAT-M mean of 1982–83 college-bound 12th-grade males) was 2.1 to 1 (based on 5325 cases); at ≥ 600 SAT-M (80th percentile of 12th-

TABLE I
SAT PERFORMANCE BY SEX OF 12–14 YEAR OLDS IN A TALENT SEARCH

Talent-search date	*Grade*	*Number*		*SAT-M scores*• *(mean (S.D.))*		*SAT-V scores (mean (S.D.))*	
		Boys	*Girls*	*Boys*	*Girls*	*Boys*	*Girls*
March 1972	7	90	77	460 (104)	423 (75)		
	8+	133	96	528 (105)	458 (88)		
January 1973	7	135	88	495 (85)	440 (66)	385 (71)	374 (74)
	8+	286	158	551 (85)	511 (63)	431 (89)	442 (83)
January 1974	7	372	222	473 (85)	440 (68)		
	8+	556	369	540 (82)	503 (72)		
December 1976	7	495	356	455 (84)	421 (64)	370 (73)	368 (70)
	8**	12	10	598 (126)	482 (83)	487 (129)	390 (61)
January 1978	7 and 8**	1549	1249	448 (87)	413 (71)	375 (80)	372 (78)
January 1979	7 and 8**	2046	1628	436 (87)	404 (77)	370 (76)	370 (77)
January 1980, 1981, 1982	7 and 8**	19832	19937	416 (87)	386 (74)	367 (77)	365 (76)

	Ratios of high-scoring talent-search boys vs. girls		
	SAT-M ≥ 500	*SAT-M ≥ 600*	*SAT-M ≥ 700*
1972–1979	2.0 : 1	–	–
1980–1982	2.1 : 1	4.1 : 1	12.9 : 1***

• All sex differences on SAT-M were significant by a two-sided t test, mostly at the $P < 0.001$ level.
** The few 8th-graders in this sample had been accelerated by 1 year in their education.
*** This ratio is obtained from the special national talent rearch described on p. 470.

grade males) the ratio was 4.1 to 1 for the 806 students scoring that highly (Benbow and Stanley, 1983a). These ratios were similar to those reported in Benbow and Stanley (1980), but are based on a much larger and more general data base.

Scoring 700 or more on the SAT-M before age 13 is a rare occurrence. We estimate that students who reach this criterion (the 95th percentile of college-bound 12th-grade males) before their 13th birthday comprise the top 1 in 10 000 of their age group. Because of the rarity of such students, a special nationwide talent search was created in November 1980 in order to locate and educationally facilitate such students (Stanley, 1983). As of August 1983, the number of boys identified was 258 and the number of girls, 20; a 12.9 to 1 ratio (Benbow and Stanley, 1983a). This high ratio of boys to girls was found even though the available evidence suggested that essentially equal numbers of boys and girls took the SAT.

In summary, the total number of students tested in the Johns Hopkins regional talent searches and reported so far is 49 747 (9 927 in the initial study plus 39 820 in the later study). Preliminary reports from the 1983 CTY Talent Search based on some 15 000 cases yield essentially identical results. In the 10 Middle Atlantic regional talent searches from 1972 through 1983, therefore, we have tested about 65 000 students. In this large sample it is abundantly clear that *far* more boys than girls (chiefly, 12 year olds) scored high in SAT-M, even though girls were matched with boys by ability, age, grade, and talent-search entry.

Consequences of sex differences in mathematical reasoning

In view of the large sex differences in mathematical reasoning ability observed before age 13, it seemed important to examine the consequences of this difference. Benbow and Stanley (1982a) have carried out a longitudinal study for a subset of the talent-search participants in their 1980 study. These were the students in the 1972, 1973, and 1974 talent searches who as seventh or eighth graders scored at least 370 on SAT-V or 390 on SAT-M. These scores were equivalent to the average scores of a national sample of high-school females. Their development during the 4 or 5 years after participation in the talent search (usually during high

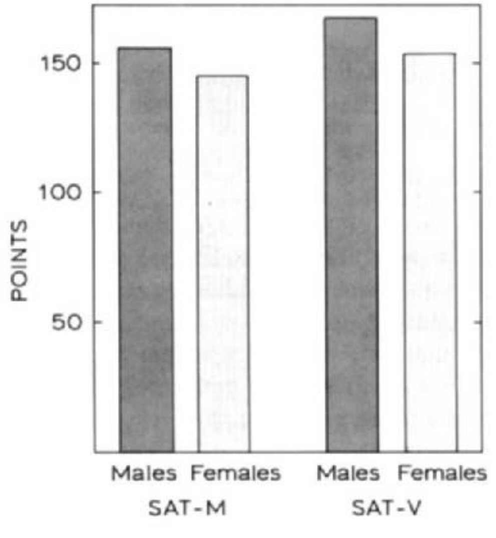

Fig. 1. Improvement on SAT-M and SAT-V during the junior and senior high-school years for SMPY's mathematically talented students by sex.

school) was investigated. It was found that the sex difference in mathematical reasoning ability persisted and was related to subsequent sex differences in mathematics and science achievement (Benbow and Stanley, 1982a, 1983d). Both the verbal and mathematical reasoning abilities of males developed to a more advanced level than those of females during this time. Males improved their scores on SAT-M an average of 10 points more than females (the mean difference went from 40 to 50 points). On the SAT-V, however, the boys also improved their mean score by at least 10 points more than females (see Fig. 1). Moreover, sex differences in achievement during high school favoring males, which were related to and predicted by the initial sex difference on SAT-M, were found in: participation in mathematics and science, performance on the SAT-M 5 years later, and performance on mathematics and science achievement and Advanced Placement Program examinations. The sex difference favoring males in science achievement test scores are shown in Fig. 2. The overall sex difference was slightly greater than 0.5 S.D. in biology and chemistry and approximately 1 S.D. in physics. Although the boys scored better than the girls on standardized tests of mathematics knowledge, it was of interest that SMPY females received better grades in their mathematics courses than SMPY males did (Benbow and Stanley, 1982a).

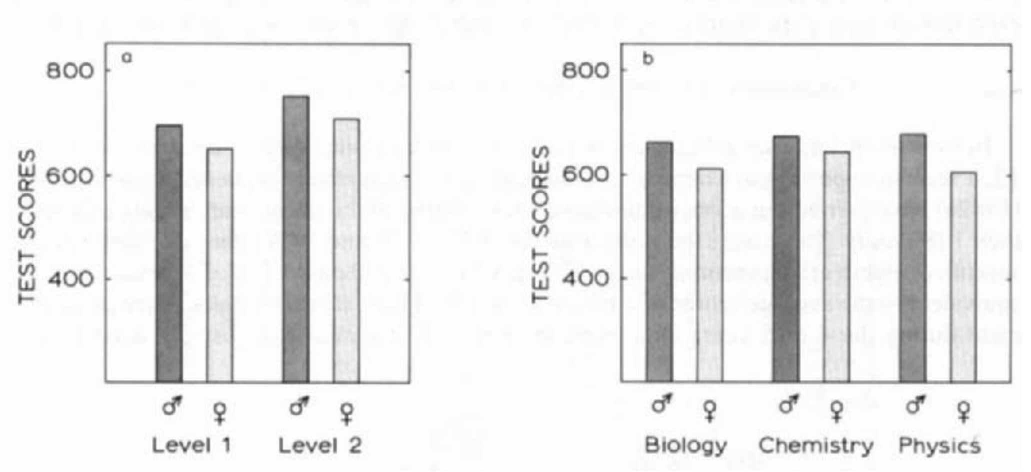

Fig. 2a Fig. 2b

Fig. 2. (a) Sex differences on the College Board mathematics achievement tests taken at the end of high school by SMPY's mathematically talented students. (b) Sex differences on the College Board science achievement tests taken at the end of high school by SMPY's mathematically talented students.

In summary, we have shown that sex differences in mathematical reasoning ability can be found at an early age (before puberty) among intellectually talented students. Moreover, these differences persist over a number of years and are related to subsequent differences in mathematics and science achievement.

SOCIAL AND ENVIRONMENTAL HYPOTHESES

A large number of environmental and sociological hypotheses have been proposed to account for sex differences in mathematical reasoning ability in the general population. In this review, which is not meant to be exhaustive, we consider the major hypotheses, which, for convenience, we have grouped into 4 broad categories: differential course-taking hypothesis, masculine identification hypotheses, social reinforcement hypotheses, and the impact of socializers hypotheses. Each category will be evaluated to determine the extent to which it can account for the sex differences found in the SMPY population. We recognize that it is not possible to do full justice to the complexity of the environmental hypotheses in the limited space available, and apologize in advance for any oversimplification we may have introduced.

Differential course-taking hypothesis

Fennema and Sherman (1977) postulated that sex differences in mathematical reasoning ability are observed in high school because boys take more high-school mathematics courses than girls. It is often called the differential course-taking hypothesis. Because SMPY boys did take slightly more mathematics in high school than SMPY girls, this might appear to be the reason why the boys improved more in their mathematical reasoning ability in high school. The boys, however, also improved more in their verbal reasoning ability, in spite of the fact that girls traditionally take more verbal courses in high school. More importantly, the differential course-taking hypothesis cannot explain why there is a large sex difference on SAT-M before high school. In addition, as we will show, differential course-taking does not even adequately account for the increase in the sex difference in high school. Firstly, the initial sex difference on SAT-M was found in the seventh grade *before* differential course-taking took effect, as is evident from the normal curriculum available to seventh graders and from the students' reports (Benbow and Stanley, 1982b). Secondly, an equal percentage of SMPY girls and boys took mathematics in high school straight up to the 12th grade, when the SATs are normally taken. SMPY boys did take about one semester more of mathematics than did SMPY girls. This difference, however, was due to the larger number of SMPY boys than girls taking calculus: calculus was completed after the SAT-M was taken and calculus items do not appear on the SAT-M. Finally, the best predictor of high school SAT-M score was talent search SAT-M, not the number of semesters of mathematics taken in high school, which accounted for little additional variance (Benbow, 1981). Clearly, the differential course-taking hypothesis does not explain either the ability difference found in this population or the increase in the ability difference during high school. The converse was, however, supported. The students who took calculus in high school had significantly higher initial mathematical and verbal reasoning abilities than students not selecting to take this course (Benbow and Stanley, 1982a).

The masculine identification and social reinforcement hypotheses

The masculine identification hypothesis has been proposed to account for sex differences in mathematical achievement and perhaps also in aptitude (extensively reviewed in Fox et al., 1979). It is based on the postulate that it is necessary for one to identify psychologically with a male in order to have strong interest and ability in mathematics. We have not specifically tested this hypothesis for our population since Fox et al. (1979) in their review of the literature found contradictory results and thus rejected the masculine identification hypothesis.

Fox et al. (1979), however, presented "stronger" evidence to support the social reinforcement hypothesis. In essence, this hypothesis states that sex-related differences in mathematical achievement are, at least in part, the result of differential social conditioning and expectations for boys and girls. "The evidence shows that male prejudice against girls competing in mathematics does exist and the girls believe it exists. The perception of mathematics as a domain restricted to males may create a conflict for mathematically able girls between academic achievement and popularity, leading to reduced course-taking in mathematics" (Fox et al., 1979, p. 324). Furthermore, these investigators concluded that "differences in mathematics course-taking and ability seem to be less a function of biology and identification with a masculine role than of socialization forces (i.e., self-confidence with respect to mathematics, different career interests, and therefore, different perception of the usefulness of mathematics)" (Fox et al., 1979, pp. 324–325).

The socializer hypotheses

Meece et al. (1982) also reviewed the literature describing how socialization might account for the observed sex differences in mathematics. Specifically, they addressed the impact of "socializers" (i.e., individuals who influence the socialization process of children). Their hypothesis states that the "attitudes of teachers, parents, and counselors often reflect cultural stereotypes regarding not only the alleged natural superiority of boys' mathematical abilities but also the different utility of mathematical skills for boys and girls... By embracing these views, socializers could undermine girls' confidence, their motivation to perform well, and their actual learning in mathematics" (p. 327). They postulate that there are 3 main processes by which this takes place: (1) because male and female adults exhibit different attitudes and behaviors toward mathematics, they create differences among minors through their influence as role models; (2) society has different expectations of boys and girls, which are indirectly and directly communicated; and (3) parents and other socializing agents encourage different activities and provide different toys for their children on the basis of sex, which may train different skills and interests. In their comprehensive review of the literature, Meece et al. (1982) found strong support for their hypothesis. The authors also found support for the related hypothesis that student attitudes toward mathematics and math anxiety (both variables favoring boys) were another source of sex differences.

Finally, in a related study of scientists, Benbow and Stanley (1983d) found in their literature review that the typical personality traits associated with scientists are more frequently held by males than females. Females and males in the same field, however, tend to be quite similar. There may be some differences in the way parents treat males and females, and parental evaluation may be more important to females than to males.

The studies on which these environmental and sociological hypotheses are based generally used students of average ability. Undoubtedly, these environmental and sociological factors are important in determining sex differences in mathematics in the average population. Do these hypotheses apply, however, to the students of superior intellectual ability whom we have studied?

SOCIALIZATION HYPOTHESES AND SMPY

The validity of these hypotheses has been evaluated for the high-ability population studied by Benbow and Stanley (1980). No substantial differences were found in attitudes towards mathematics and the sciences (biology, chemistry, and physics) of these high-ability preadolescent boys and girls nor in their backgrounds (Benbow and Stanley, 1982b). Differences are predicted by the socialization hypotheses. Moreover, when these same students were studied 5 years later (after high school), few sex differences in attitudes were found. SMPY boys and girls reported liking mathematics, biology, chemistry, and science at that time. We found no substantial sex differences in their attitudes except perhaps towards physics (Benbow and Stanley, 1982a, 1983d). This was further exemplified by the fact that slightly more girls than boys were planning to major specifically in the mathematical sciences in college. In addition, SMPY females received better grades in their high school mathematics classes than did SMPY males. Moreover, reported attitudes toward mathematics had little relationship with subsequent achievement in mathematics. For example, attitudes toward mathematics at approximately ages 13 and 18 could predict neither the number of semesters of mathematics taken, SAT-M score in high school, nor the high-school mathematics achievement test score (Benbow, 1981; Benbow and Stanley, 1982a).

Relevant in this connection is the finding of Benbow and Stanley (1982a) that high-aptitude girls may participate in mathematics less than high-aptitude boys, not because they like it less, but perhaps because they like verbal areas (especially English) to a greater extent than do boys.

SMPY students do not suffer from "math anxiety". A student with math anxiety would not enter a mathematics competition such as SMPYs. Additionally, the students with whom we deal are all in the top 3% of intellectual ability with a demonstrated aptitude for mathematics and above-average performance in their mathematics classes. Thus, the math anxiety hypothesis is not appropriate for this population.

Fox et al. (1982) have investigated the family backgrounds of SMPY talent-search participants. They found few differences between male and female participants. In particular, few indications of differential training or encouragement of boys and girls were discovered. It is noteworthy that the study of Fox et al. was carried out by researchers who are not part of SMPY and who favor an environmental hypothesis.

It is of particular interest that the sex difference on SAT-M did not increase substantially during the 5 years of high school. The strong well-documented socialization pressures during junior and senior high school have remarkably little effect on sex differences in SAT-M scores. For socialization alone to account for our results, it becomes necessary to hypothesize ad hoc that mainly early socialization experiences significantly influence mathematical reasoning ability as measured by the SAT-M.

We urge caution when generalizing from the results of our limited study of highly able students. For example, it is possible that the variables measured were inadequate indicators of attitudes toward mathematics (i.e., mathematics liking, importance of mathematics for future job, and having rated mathematics as a favorite course in high school) since Fennema and Sherman (1976) have demonstrated that attitude toward mathematics involves several distinct components. Furthermore, the reason for not finding any substantial differences in the socializing experiences of our high-aptitude boys and girls may be because it was not possible to detect subtle social influences that affect a child from birth. Of course, our findings are limited to highly able students. Yet another important variable to be considered is the difference in toys that boys and girls play with. Our precocious boys may have more frequently played with toys that enhance their reasoning abilities than our girls did. Nevertheless, it is not entirely clear how differences in socialization experiences of boys and girls could affect the mathematical reasoning ability of girls so adversely and significantly, yet at the same time have no detectable effect on their reported attitudes toward mathematics, taking of mathematics courses during the pre-SAT years, and mathematics course grades. We are currently examining these hypotheses.

In summary, it appears that the main environmental hypotheses that have been proposed to account for sex differences in mathematical reasoning ability do not explain the results obtained for our high-aptitude group. Although large sex differences in mathematical reasoning ability before age 13 were found, few differences in the relevant socialization of the participants have been discovered. Thus, a reconceptualization of the commonly proposed environmental hypotheses is necessary in order to account for our data.

Rather than attempting to reformulate the environmental hypotheses, we propose to ask if other factors might also contribute to sex differences in mathematical reasoning ability. We do not dispute the fact that environmental influences contribute greatly to mathematical achievement and even to measures of mathematical reasoning ability. Instead, we wish to ask if endogenous factors may also contribute to the large sex difference we have observed.

Mathematical ability and spatial ability

It has been proposed that spatial ability is related to mathematical aptitude (Smith, 1964; Sherman, 1967, 1977; Maccoby and Jacklin, 1974; Harris, 1978; McGee, 1979). Since there is a well-documented sex difference in spatial ability favoring males (see, for example, Maccoby and Jacklin, 1974, for a review), it has been proposed that sex differences in spatial ability can account for the sex difference in mathematical performance (i.e., Sherman, 1967). The results of testing this hypothesis are somewhat mixed, however. Armstrong (1981) did not find that sex differences in mathematics achievement were related to sex differences in spatial ability. Moreover, Becker (1978) found that the three-way interaction of spatial ability, sex, and item performance on the SAT-M was not significant for the seventh-graders in a SMPY mathematics talent search. Her conclusion was that among SMPY students there was no difference in performance from item to item on the SAT-M according to sex and spatial ability. Spatial ability was found, however, to be related to superior performance on the SAT-M as a whole. Becker's results could have been confounded by the spatial ability test used, which had a large verbal component. Thus, the girls may have solved the test using a verbal strategy (McCall, 1955; Sherman, 1974; Benbow, 1978). Alternatively, mathematically precocious girls may require higher spatial ability than mathematically precocious boys in order to perform as well on the SAT-M (Cohn, 1977).

Two studies by Fennema and Sherman (as cited in Sherman, 1977) have, however, found evidence that sex differences in mathematical ability could be attributed in part to sex differences in spatial ability. More recently, Burnett et al. (1979) found that the sex difference on SAT-M was no longer significant after controlling for spatial ability among a college sample. Finally, McGee (1979) concluded that "sex differences in various aspects of perceptual-cognitive functioning (e.g., mathematics and field independence) are a secondary consequence of differences with respect to spatial visualization and spatial orientation abilities" (p. 909).

In view of the results above, the possibility that mathematical reasoning ability and spatial ability are related deserves to be seriously considered. This may also be true for the SMPY population for an additional reason. In a separate study, the most precocious students that SMPY had identified using the SAT-M and SAT-V were tested with a battery of cognitive tests (Benbow et al., 1983b). Two factors accounted for their superior performance: a verbal and a spatial factor. Therefore, spatial ability may be influencing the test performance of mathematically precocious individuals. Moreover, sex differences in spatial ability favoring males were observed in this population (Benbow et al., 1983b).

There might not, however, be a direct link between the two factors (i.e., that spatial ability positively influences mathematical reasoning ability). Instead, these two mental abilities may simply involve similar cognitive processes. For example, both may rely on processes best performed by the right hemisphere of the brain. Thus, the close relationship may indicate that both abilities depend upon similar problem-solving strategies.

The possibility that there is either a connection or a parallel between mathematical reasoning ability and spatial ability is of great interest. A large amount of research has been performed on biological factors that may cause or influence spatial ability. We will review these in the following pages and attempt to relate them to mathematical reasoning ability.

BIOLOGICAL HYPOTHESES FOR SEX DIFFERENCES

Sex-linked gene hypothesis

O'Connor (1943) has proposed that spatial ability is controlled by a recessive sex-linked gene and that this may be the cause of the sex difference in spatial ability favoring males. He, and subsequently several other investigators (Stafford, 1961; Corah, 1965; Hartlage, 1970; Bock and Kolakowski, 1973; Yen, 1975), have reported a pattern of familial correlations that suggest the involvement of a recessive sex-linked gene. Vandenberg and Kuse (1979), however, performed a comprehensive literature review of the topic. They found several contradictory results and therefore did not support O'Connor's theory. They concluded that spatial ability showed a developmental trend, an influence from sex hormones, and might be an autosomal gene with reduced penetrance in women. That spatial ability is under some genetic influence has been clearly demonstrated by several studies (DeFries et al., 1978, 1979; McGee, 1979). This also seems to be the case for the SMPY population (Benbow et al., 1983c).

Laterality studies

Another frequently proposed theory to explain the existence of sex-related differences in spatial ability is that men and women have the left and right hemispheres of the brain lateralized differently. Clinical and experimental data indicate that the left cerebral hemisphere is specialized for language processing and the right cerebral hemisphere is specialized for spatial processing (see Springer and Deutsch, 1981; Bryden, 1982, for comprehensive reviews). Although the evidence that has been presented is not without some methodological problems, it does appear that males have greater right hemisphere specialization than females (see Bryden, 1979; McGee, 1979; McGlone, 1980; Springer and Deutsch, 1981, for reviews) as Levy (1972) proposed. Both Butler (1984) and Kimura and Harshman (1984) have investigated the possibility that males are more lateralized than females. This finding may account for some of the sex differences in spatial ability. Much further research, however, needs to be conducted before any firm conclusions can be drawn.

Hormonal hypotheses

Many researchers have postulated that the different male and female hormones, androgens and estrogens respectively, produce sex-related differences in spatial ability. Petersen (1979) in her review of these studies found little support for the hypothesis that females excel on simple repetitive tasks and males at tasks that require perceptual restructuring because of sex hormones. There is, however, some support for the contention that high body androgenization is associated with low spatial scores among males and with high spatial scores among females (Broverman et al., 1964; Petersen, 1976). Thus, it may be the estrogen–androgen balance rather than the absolute level of androgen that affects spatial ability. This hypothesis states that the estrogen–androgen ratio is optimal and as a result spatial abilities the highest among males low in androgen and among females high in androgen (see Nyborg, 1984).

Sexual maturation is obviously dependent upon sex hormones. Waber (1977) found that late maturing children exhibit better spatial ability than children who mature early. She relates this finding to brain specialization: at the onset of puberty, there is a major reorganization of brain functioning (see Waber, 1979, for a review). Since girls enter puberty earlier than boys, their spatial abilities would tend to be less well developed at that point than in boys. Moreover, males who mature relatively early are perhaps more androgenous than males who mature later (Broverman et al., 1964). Thus, the influence of sex hormones on spatial ability may be through their effect on maturation, which in turn influences the degree to which a person becomes androgenized.

This is also consistent with the findings of Levy (1969) who found that spatial ability depended upon the degree of lateralization of the cerebral hemisphere of the brain. In 1976 she proposed that the degree of lateralization was determined by a gene which is under the influence of the sex hormones. Not entirely consistent with this hypothesis, however, is the fact that degree of lateralization may be established by birth or soon thereafter (Bryden, 1979, for a review). Petersen (1979) has also presented evidence that is difficult to reconcile with this position.

Also to be considered are the possible effects of hormones on the brain during early development. In their review, Reinisch et al. (1979) have concluded that: "(1) prenatal exposure to excess estrogen or to no hormone at all may have a negative influence on the development of spatial-perceptual skills but not on overall measures of intelligence, such as IQ; (2) progesterone exposure may enhance numerical ability; (3) exposure to either exogenously introduced synthetic or naturally occurring progestins may augment school achievement; and (4) the absence or excess of sex chromosomes may have an effect on cognitive abilities and measures of general intelligence in some individuals". Moreover, Geschwind and Behan (1982) postulated that exposure to an increased level of testosterone in a developing fetus has, as one effect, the slowing down of neuronal development of the left hemisphere. As a result, the right hemisphere would become relatively more dominant. Such a connection would perhaps contribute to sex differences in spatial ability. Similarly, Levy and Gur (1980) proposed that high levels of fetal sex hormones (as are found in males) promote the expression of cerebral lateralization and selectively enhance the maturational rate and cognitive capacity of the right hemisphere.

Mathematical reasoning ability: biological correlates

As mentioned above, mathematical reasoning ability appears to be related to spatial ability. Can the various biological explanations for the sex difference in spatial ability apply to mathematical reasoning ability? Little research of this type with mathematical reasoning ability has been done. Only one study has specifically dealt with the way biological factors affect mathematical reasoning ability. Stafford (1972) has shown that there is a genetic component to mathematical reasoning ability, and suggested that the pattern of familial correlations fit the sex-linked recessive gene model fairly well. Since this model was subsequently shown to be invalid for spatial ability, however, it obviously may not apply for mathematical reasoning ability either.

We have chosen to make the assumption, which seems reasonable although by no means proven, that the hypotheses that have been investigated for spatial ability also may apply to mathematical reasoning ability. We have begun to test some of these hypotheses for the abilities to reason mathematically and verbally among the intellectually precocious students identified by SMPY and the Center for the Advancement of Academically Talented Youths (CTY) at Johns Hopkins. Our findings suggest that there are certain specific physiological correlates of extremely high mathematical and verbal reasoning abilities.

PHYSIOLOGICAL CORRELATES OF EXTREME ABILITY

When Julian Stanley and I first published our finding of sex differences in mathematical reasoning ability (Benbow and Stanley, 1980) much controversy was generated over the role of "nature" versus "nurture" in determining high intelligence. This had led us to search for other biological differences, in addition to sex, which correlate with extreme intellectual precocity. Presently, we have found three such correlates: left-handedness, immune disorders, and myopia. Some of our findings relate to possible biological origins for sex differences in cognitive abilities. We again wish to emphasize that this is only our working hypothesis, not a proven theory.

Two organizations at Johns Hopkins, SMPY and CTY, conduct annual national talent searches for pre-adolescents who are *extremely* precocious in their mathematical and verbal reasoning abilities, respectively. The criterion for extreme mathematical precocity is a score of at least 700 on SAT-M prior to age 13. Similarly, the criterion for extreme verbal precocity is a score of 630 or more on SAT-V prior to age 13. Both scores are equivalent to the 95th percentile of above-average 17–18-year-old males. We estimate that selected students comprise the top 1 in 10 000 of their age group. As of August 1983, we had identified 278 mathematically precocious students and 165 verbally precocious students. Our work on physiological correlates of extreme mathematical and verbal precocity is being performed on this sample. The work is still in progress (August 1983), so the frequencies reported here will be slightly different from those in the final report (Benbow, manuscript in preparation).

Handedness and intellectual precocity

Each student was first asked to report his handedness to us and then later to complete the Edinburgh Handedness Inventory of Oldfield (1971). Students were also requested to report whether their natural parents and siblings considered themselves to be left- or right-handed. Ambidexterity was also assessed. Results from the inventory and from the self-report measure were in excellent agreement. Since our comparison studies dealt with self-report data, we will not present the data obtained from the inventory here.

Between 7 and 10% of the general population report that they are left-handed. Approximately twice as many mathematically and verbally precocious Caucasian students than Caucasian students in the general population considered themselves to be strongly left-handed ($P < 0.01$). Many were ambidextrous. When we included such individuals, 19.3% of the mathematically precocious students were either left-handed or ambidextrous and 21.2% of the verbally precocious students (see Table II).

The degree of left-handedness and ambidexterity for the parents and siblings of these students are also shown in Table II. It is clear that the rate is lower among them than among the index cases but still higher than for the general population. Approximately 31% of the

TABLE II

PHYSIOLOGICAL CHARACTERISTICS OF EXTREMELY PRECOCIOUS STUDENTS, THEIR FAMILIES, AND 3 COMPARISON GROUPS

	630 SAT-V students	*700 SAT-M students*	*630 SAT-V and 700 SAT-M students*	*Fathers*	*Mothers*	*Brothers*	*Sisters*	*Low-scoring talent-search students (SAT ≤ 540)*	*Students scoring ≥ 370 SAT-V or ≥ 390 SAT-M*	*Students scoring 2 SAT-M + SAT-V ≥ 1330*
Number	115	218	34	364	364	223	212	191	271	162
Percent left-handed	15.4 (M = 24.0, F = 7.4)*	15.1	13.8	9.9	9.5	13.8	11.5	9.5 (M = 10.8, F = 8.4)	10.7	15.7
Percent ambidextrous	5.8 (M = 0, F = 11.1)*	4.2	0	0.7	0.4	4.2	2.3	2.1 (M = 3.6, F = 0.9)	3.7	1.8
Percent having symptomatic atopic disease	54.2 (M = 62.7, F = 46.4)	56.5	53.8	34.3	36.8	47.1	32.1	35.1 (M = 38, F = 33)	-	-
Mean severity rating of symptomatic atopic disease**	4.5 (M = 4.4, F = 4.5)	4.4	4.2	4.6	4.7	4.6	4.8	4.9 (M = 4.8, F = 4.9)	-	-
Percent myopic	75.5 (M = 71.4, F = 79.6)	52.8	72.0	60.0	53.6	41.2	38.1	19.9 (M = 15.5, F = 23.4)	-	-
Mean age for onset of myopia	8.4 (M = 9.3, F = 7.5)	9.1	9.3	17.1	14.1	10.3	10.1	9.5 (M = 10.1, F = 9.2)	-	-
Percent entering puberty before 12.5 years	31.6 (M = 18.5, F = 43.3)*	18.4	14.3	14.8	42.4	-	-	31.6 (M = 20.2, F = 41.1)*	-	-

* Sex difference between proportions was significant.

** 3, infrequently recurring problem, no longer recurs; 4, mild recurring problem; 5, moderate recurring problem; 6, severe recurring problem.

left-handed or right-handed students had a sibling or parent who was also left-handed. Thus, left-handedness appears to be a familial trait of these precocious students.

In a comparison study handedness responses were obtained from 3 independently selected samples. The first sample, which was least able, was comprised of seventh-grade students scoring least well in the 1983 Hopkins Regional Talent Search conducted by CTY. The combined SAT scores of this group were less than or equal to 540, which means that the students were scoring slightly above chance on the SAT. They must, nevertheless, still be considered gifted since only the top 3% in ability can participate in the Hopkins regional talent searches. Out of a sample of 465 students, 191 returned a questionnaire to us. We could see no logical reason for assuming that the non-respondents would differ from the respondents on the questions, such as handedness. Among such students, 9.5% were left-handed and 2.1% reported that they had equal facility with both hands (see Table II). The second sample consisted of students who had scored as a seventh or eighth grader at least 370 on SAT-V or 390 on SAT-M in 1972 or 1973. They were surveyed when they were approximately 23 years old. Among such students 10.7% reported that they were left-handed and 3.7% that they were ambidextrous (see Table II). The third sample of students were selected from the 1976 talent search and consisted of those seventh-grade students who met the following criterion: 2SAT-M + SAT-V $\geq$ 1330. The top one-third of the talent-search participants met this criterion. In this group, which was the most able of the three comparison samples, 15.7% were left-handed and 1.8% ambidextrous. Since the different ability groups demonstrated a progressively higher degree of left-handedness, it appears that this trait is more frequent among extremely intellectually able students.

Immune disorders and intellectual precocity

The work of Geschwind at Harvard suggested that we should ask whether intellectually precocious students are more likely to suffer from immune disorders than individuals in the general population. Geschwind and Behan (1982) have shown that left-handers in the general population are more likely than right-handers to suffer from immune disorders, learning disabilities, and migraine headaches. Testosterone exposure in utero was proposed to explain this fact. Geschwind and Behan postulated that exposure to increased levels of testosterone as a developing fetus has two effects. "Testosterone slows neuronal development of the left hemisphere, while simultaneously affecting immune development, and thus favoring later immune disorders" (p. 5100). Retarding growth of the left hemisphere would make the right hemisphere relatively stronger and would increase the chance of becoming left-handed. We thus decided to investigate whether mathematically or verbally precocious individuals suffered from immune disorders.

Because there may be a difference between medical definitions of allergies and notions held by the general population, a rather sophisticated allergy and immune disorder questionnaire was mailed to both the students and their parents. This questionnaire was provided by Dr. Franklin Adkinson, who is a specialist in immune disorders at Johns Hopkins University. We found that approximately 56 and 54% of mathematically and verbally precocious students, respectively, suffered from symptomatic atopic disease (allergies of various kinds). By contrast, in the general population of the United States 10% suffer from this affliction (Stites et al., 1982). The percentage of parents and siblings having allergies was significantly lower ($P < 0.01$, see Table II). The severity ratings for the mathematically and verbally precocious, however, did not greatly differ from their parents' and siblings' (see Table II).

As a comparison, the allergy questionnaire was completed by 191 students in the first comparison group described above (i.e., the same age individuals scoring less than 540 on total SAT). Approximately 35% of those individuals reported having symptomatic atopic disease (see Table II). This is much less than for the extremely precocious students ($P < 0.01$), but the severity rating that they gave was slightly higher. It should be emphasized that this control group is also gifted, though less so than our most precocious group. Thus, our data suggest that symptomatic atopic disease may be a physiological correlate of extreme intellectual precocity.

Myopia, blood type and intellectual precocity

Over the past 10 years we have noted that many of our most gifted students wore glasses. These observations coupled with the work of Karlsson (1973, 1975) led us to investigate the possibility that extremely precocious students might tend to be myopic. We found that 53% of the mathematically precocious students were myopic and 75% of the verbally precocious students were myopic (see Table II), while less than 5% were farsighted. For the lowest-in-ability comparison group only 20% were myopic. In the general population approximately 15% of high-school students are myopic (Karlsson, 1975). Clearly, these are substantial differences. The mean age of onset of myopia was 9.1 for the mathematically precocious, 8.4 for the verbally precocious, and 9.5 for the lowest-in-ability comparison group (see Table II). The siblings of the extremely precocious were about 50% less likely to be myopic. Although this is a fascinating finding, we have as yet been unable to think of a plausible mechanism relating myopia to extreme intellectual precocity.

Although it has been reported that blood type related to social class in England (Beardmore and Karimi-Booshehri, 1983), we found no such relationship in our sample. Thus, blood type did *not* relate to intellectual precocity in our study.

BIOLOGICAL CORRELATES OF MATHEMATICAL REASONING ABILITY

In this section we will attempt to relate our findings of biological correlates of extreme mathematical reasoning ability to the sex difference in this trait. The major biologically based hypotheses will be evaluated and we shall propose our own working hypothesis.

Sex differences in left-handedness and symptomatic atopic disease would be interesting. Unfortunately, because such a small number of females had scores that qualified them for the mathematically most precocious group, sex differences could not be investigated among that group. For the students qualifying for the verbally precocious group, there was essentially equal representation by sex. Among such students there were sex differences in the percentage of left-handers and in the percentage with symptomatic atopic disease (see Table II). These differences were significant ($P < 0.05$), however, only for the left-handedness data. For the comparison group, sex differences were also found, which were not large or significant.

How do these findings on immune disorders and left-handedness relate to brain dominance? Familial left-handers (i.e., those who have a close relative, such as a parent or uncle who are left-handed) tend to be more bilateralized in their cognitive functions (McGee, 1979; Springer and Deutsch, 1981; Bryden, 1982). That is, the typical pattern of left-hemisphere dominance for language and right-hemisphere dominance for spatial tasks is not always found. Since our students, who have demonstrably superior skills in mathematical and verbal reasoning as well as in spatial ability (Benbow et al., 1983b), are more likely to be left-handed or come from families with left-handers, we *postulate* that bilateralization is related to their superior abilities. Similar findings have been reported by Burnett et al. (1982) for spatial ability for a college population. If this is the case, however, it is difficult to reconcile with the hypothesis that boys generally score better than girls on spatial tasks because males tend to exhibit greater specialization of their right and left hemispheres or are more lateralized (Levy, 1972). We are currently measuring brain dominance patterns of our verbally and mathematically precocious youths using a computer simulation of a tachistoscope for a verbal and a spatial task in order to resolve this issue.

Since most of our extremely intellectually precocious students did not appear to have entered puberty by the time they took the SAT at approximately age 12.5 (see Table II), our work may be relevant to the hormonal hypotheses proposed by Broverman et al. (1964) and Waber (1977). Because our students have developed superior intellectual abilities and sex differences prior to puberty, it is likely that other factors contribute to the sex differences in our data at age 12.5. We postulate that the onset of puberty may relate to the increase in the sex difference we observe during adolescence. Our data indicate that precocious boys do enter puberty significantly ($P < 0.01$) later than precocious girls (see Table II).

The point we wish to emphasize, however, is that the sex differences we observe were evident before the onset of obvious puberty. It is important to stress that our indicators of entering puberty were not refined, since we could not ask students in the SMPY and CTY programs overly sensitive questions or examine them medically. Our principal indicator for entering puberty was onset of menses for girls and the beginning of voice change for boys. Nevertheless, both the ages of our students and their responses indicate that most had either not entered puberty or had not been in it a very long time. In this context it is of interest that two studies have found sex differences in mathematical reasoning ability even among 7 year olds and among 9 year olds (NAEP, 1975; Dougherty et al., 1980). Clearly, these youths have not entered puberty. Finally, the work of Petersen (1979) is difficult to reconcile with the hypothesis on the effect of timing of puberty.

Of the major biologically based hypotheses to account for differences in intellectual ability, only those dealing with early hormonal exposure are readily reconciled with our data. This does not imply that the other hypotheses are invalid. Each may still be correct for the populations studied, as was also true for the environmental hypotheses discussed earlier. A reformulation of these hypotheses is necessary, however, to account for the data gathered by SMPY and CTY.

We propose the following unifying hypothesis, which is consistent with our results, but needs much further work to validate. Our hypothesis is an extension of the hypothesis proposed by Geschwind and Behan (1982), in which exposure of the developing brain to testosterone is a major factor. It owes certain features to the biopsychosocial hypothesis of Petersen (1981). The environment and the interaction between environment *and* physiological structures are of key significance, however.

Geschwind and Behan (1982) proposed that exposure to increased levels of testosterone in the developing fetus retards neuronal development of the left hemisphere. This implies that the developing individual would have a (relatively) stronger right hemisphere. Because the left hemisphere, which is better at language processing, does not dominate over the right hemisphere, which is specialized for non-verbal problem-solving tasks (e.g., spatial problems), such an individual would have a greater chance at developing his/her spatial or mathematical reasoning abilities through environmental interactions. By contrast, an individual with a dominant left hemisphere would rely more on his left hemisphere and would attempt to solve problems using a verbal approach. Such initial biases are then accentuated by the environment, which shapes the development of cognitive abilities. In our hypothesis, sex differences occur because males are more likely than females to be exposed to increased levels of testosterone. Males are indeed more likely than females to be left-handed or to suffer from immune disorders, which would be consistent with this hypothesis. Moreover, the two consequences of fetal exposure to an increased level of testosterone, as predicted by Geschwind and Behan, were in fact found for mathematically precocious youths. This would be necessary in order to validate our model.

It is not yet clear how extreme verbal precocity fits into this picture. We are not certain what aspects of verbal reasoning ability are tested by the SAT-V, although the ability to form analogies is clearly one. Dimond and Beaumont (1974) used analogical as one adjective to describe the thought processes exhibited by the right hemisphere. Thus, it may be that verbal reasoning as measured by the SAT-V is dependent upon right hemisphere thought processes.

SUMMARY

We conclude that large sex differences in mathematical reasoning ability are found prior to puberty among intellectually advanced students. This difference could predict subsequent sex differences in achievement in mathematics and science. Since few differences were found in the backgrounds and attitudes of the boys and girls tested, it is unlikely that simple environmental hypotheses can entirely explain our data. In addition, some of our findings on physiological correlates of extreme precocity are difficult to reconcile with most of the biologically oriented hypotheses that have been proposed to account for sex differences in cognitive functioning. We have proposed a single unifying hypothesis to account for sex differences observed by us.

Because there are well-documented differences in the environment as well as in the biology of boys and girls, we propose that it is a combination of *both* of these factors that cause the sex difference in mathematical reasoning ability.

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DISCUSSION

G.J. DE VRIES: You demonstrated that precocity in mathematical reasoning ability goes more often with myopia and allergy than the normal group. Should this precocity be seen as a pathological state? To be more exact, does it often go together with, e.g., disturbances in speech?

C.P. BENBOW: Mathematical precocity appears along with some advanced verbal ability. Our mathematically precocious students are also precocious verbally, but to a lesser degree. In terms of achievement in higher level mathematics, verbal ability is very important. It seems that only those of our students who have extreme mathematical *and* verbal precocity do well in very high level mathematics.

E. BRENNER: Did you try to correlate the sex differences in mathematical ability with the choice of hobbies?

C.P. BENBOW: There clearly are differences in the toys that male and female children play with. As of yet nobody has shown that there is a causal link between toys played with and ability. It is also not clear why boys play with certain toys and girls with others. Our retrospective studies of the backgrounds of our students seem to indicate remarkably similar treatment by the parents of their boys and girls. A further study is in progress of the exact toys played with by our students as children.

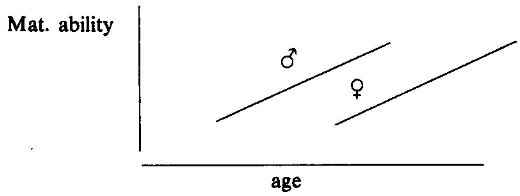
J.M. REINISCH: Does the space-form blindness reported in patients with Turner's syndrome (45XO) relate to the sex-linked recessive gene hypothesis of mathematical ability?

C.P. BENBOW: The sex-linked recessive gene hypothesis for the sex difference in spatial ability is generally not accepted any longer as a viable explanation (see Vandenberg and Kuse, 1979, for a review). Part of the evidence not supporting this hypothesis comes from the Turner syndrome patients. Since this hypothesis is no longer accepted for spatial ability, I doubt that it is viable for mathematical reasoning ability.

A.P. SFIKAKIS: There is a great variation in the hormone profile in girls because of the estrous cycle while this profile is steady in boys. Were there any menstruating girls in the 12-year-old group and did these variations in the 17-year-old girls have any influence when compared to boys?

C.P. BENBOW: We discovered a sex difference in mathematical reasoning ability among 12 year olds. Some of the girls had begun to menstruate by then, but certainly not most. The girls who had begun to menstruate had not done so for very long. Moreover, our boys had a larger variance of their SAT-M scores in our measure for mathematical reasoning ability than had our girls. Therefore, I doubt that the hormone cycle is an important determinant of the sex difference at age 12. Perhaps it relates to the even larger difference at age 17. We do not have any data to address this point.

B. MEYERSON: Could the sex difference between males and females be due to different rates in developing the mathematical ability? What I mean is this:



C.P. BENBOW: Yes, there could be a sex difference in the rates of development of mathematical reasoning ability. Our data indicate, however, that there is a difference in the slopes of the two lines representing developmental growth. The lines for boys and girls are not parallel. The boys appear to be developing their mathematical reasoning ability at a faster rate than the girls.

W.W. BEATTY: In the U.S.A. there has been much recent concern about the quality of education, especially in science and math. Further math and science achievement may be correlated with success in an increasingly technical society. Could you comment on the implications of your work for math and science education, particularly of young women?

C.P. BENBOW: Julian Stanley and I showed that there are many more males than females who can reason extremely well mathematically. This is group data and they are not applicable to any one individual. Thus, they cannot be used to counsel any single person. Our data do, however, tell us that it is likely that many more boys than girls will be successful in their pursuit of degrees or careers in quantitatively oriented sciences.

J.M. REINISCH: Are there any studies of the poorest or least precocious mathematics students? Since males are considered to be more variable in general, might there not be an overrepresentation of males in this group as well?

C.P. BENBOW: It has been established that there are more learning disabled boys than girls. Thus, this would seem likely.

H.H. SWANSON: Is there anything in which girls are better than boys?

C.P. BENBOW: Other studies have shown that girls are better at verbal tasks than males (e.g., Maccoby and Jacklin, 1974). In our sample, however, girls were not better in verbal reasoning ability than the boys.

H.H. SWANSON: Have any similar studies been made in other countries than the U.S.A.?

C.P. BENBOW: Allison Kelly (1978) studied sex differences in mathematical ability in several different countries. Within each country there was a sex difference in mathematics favoring males. Girls of one country, however, were better in some cases than boys of a different country.

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