Consequences of Gender Differences in Mathematical Reasoning Ability and Some Biological Linkages

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Gender differences in cognitive abilities and achievement are not new. They have been reported for several decades. Yet what is new is that recent reports seem to indicate that these differences are steadily diminishing in normative samples. That is, males and females apparently are converging toward a common mean on a variety of abilities, including mathematics (Feingold, 1988; Hyde et al., 1990; Rosenthal and Rubin, 1982). Hyde et al. (1990), for example, in their meta-analytic review of 100 studies, reported that the average effect size for the gender difference in mathematics was only .14 for studies published in 1974 or later compared to .31 for studies published earlier. Feingold (1988) studied scores on two test batteries over a 30-year period and also concluded that females have been catching up with males. Such findings have led several individuals to conclude that research on gender differences is better referred to as research on sex similarities (Connell, 1987; Riger, 1992). Some investigators have been more flippant, asserting that gender differences in cognitive functioning are decreasing "faster than the gene can travel".

Although such conclusions are encouraging and consonant with the current *Zeitgeist* (Halpern, 1992), they are perhaps misleading. Stanley et al. (1992) have noted that, for at least the past 20 years, some test publishers have attempted to minimize what some would call "gender bias" by discarding, from one revision to the next, items that show the greatest gender disparities. So meta-analytic reviews in this area are difficult to interpret ; and further, not all studies have documented a decline in gender differences (Benbow, 1988; Lubinski and Benbow, 1992). Firm conclusions are still unavailable. What we do know, however, is that gender differences vary as a function of a variety of variables, including age, ability-level of sample surveyed, ethnicity, and the ability itself. For example, Hyde et al. (1990) revealed that girls showed a slight

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superiority in computation in elementary and middle school with no gender differences in problem-solving at those stages. Differences favoring males emerged in high school and in college but only on tests measuring problem-solving or mathematical reasoning ability. Similarly, Aiden (1986,1987) concluded that the largest gender disparities occur for mathematical reasoning ability, and favor males ; Marshall and Smith (1987) have substantiated these claims in a study of third-graders. Third-grade girls surpass boys in computation, while third-grade boys show superiority in solving word problems and on geometry and measurement problems.

Obtaining picture of the magnitude and nature of the many ability parameters on which the genders may differ is complex ; but more definitive conclusions are desperately needed. This need arises from the stubborn and pronounced gender differences in mathematical reasoning ability, plus other key nonverbal abilities such as spatial and mechanical reasoning abilities, which are consistently observed among the most intellectually able students. These are the abilities most critical for educational and career excellence in math/science domains. Further, mathematical reasoning ability is correlated with a number of important personal preferences relevant to making and maintaining a commitment to physical science disciplines. Among the most intellectually able women, there is a tendency for interests in aesthetic and social areas to compete with interests in the physical sciences, while this phenomenon does not appear to operate much in gifted males. Thus, gender differences in personal preferences important for the expression of intellectual talent in nontechnical aesthetic and social domains appear to compound gender differences in mathematical reasoning to exacerbate gender disparities in math/science achievement across a number of disciplines. Although many observers find gender differences in math/science achievement among the gifted perplexing, now that so many educational barriers have been removed for women, our examination of a number of key ability *and* nonability attributes reveals that these disparities are quite understandable.

In this chapter, we will discuss those gender differences in cognitive abilities and preferences that have special significance as determinants of disparate male/female proportions all along the math/science pipeline. We will then frame our review in the context of a theory of vocational adjustment to better understand their psychological implications more fully. Some biological correlates of these gender differences also will be reviewed. Following this, suggestions for future research aimed at underlying biological mechanisms possibly responsible for generating these phenotypic differences at the behavioral level will be offered. But first, because most of our review draws on the research conducted by the Study of Mathematically Precocious Youth (SMPY), it will be useful to describe in some detail this planned 50-year longitudinal study, its goals, and the sample of individuals being tracked over the course of their entire lives.

Study of mathematically precocious youth

SMPY was founded by Julian C. Stanley at Johns Hopkins University in 1971 and predicated on the philosophy of conducting research through service to intellectually talented students. SMPY was interested in first identifying adolescents who possess exceptional intellectual abilites and, then, uncovering the factors that contribute to their optimal educational and vocational development. Special attention has alsways been devoted to math/science disciplines. One intervention, implemented from the start, was to provide these students with better opportunities to develop their already exceptional quantitative skills. Studying at the college level was one form of acceleration offered to these students, which, from the beginning, generated remarkable success (cf. Stanley, 1977; Stanley and Benbow, 1986). To facilitate the uncovering of other beneficial interventions and to answer basic research questions about intellectual giftedness more generally, SMPY established, at Iowa State University in 1986, a 50-year longitudinal study. Through this study, which currently includes about 5,000 talented individuals identified over a 20-year period, SMPY is beginning to bring into focus the factors that contribute to gifted student' educational, intellectual, personal, and vocational development.

Participants in SMPY were identified through a talent search, a concept developed by Stanley (cf. Cohn, 1991; Keating and Stanley, 1972; Stanley et al., 1974). The concept of a talent search has been refined over the last 20 years, but the basic premise remains the same : students in 7th or 8th grade (12 to 13 year-olds), who are already known to have scored in the top 3 % (on national norms) on standardized achievement tests (e.g., the Iowa Test of Basic Skills) administered routinely by american schools, are invited to take the College Board Scholastic Aptitude Test (SAT) at a regular administration[1].The SAT measures mathematical reasoning (SAT-M) and verbal reasoning (SAT-V) ability and is designed for 11th and 12th graders who are planning to attend college. (This form of assessment is known as above-level-testing, inasmuch as the SAT was designed for subjects 4 to 5 years older than SMPY participants, see Stanley, 1990). Nonetheless, the score distributions manifested by these gifted 7th or 8th graders are similar to those observed in random samples of high school students (Benbow, 1988; Keating and Stanley, 1972). It is through this mechanism that the SMPY subject pool for the longitudinal study was formed ; all 5000 subjects, except one group, are drawn from the talent search on the basis of high SAT scores that place them in at least the top 1 % in intellectual ability. (For more detailed reading on this exceptional sample, including case histories of their many remarkable achievements, see Note 1 in Lubinski and Benbow, 1992).

Gender differences in cognitive abilities

In the process of identifying the first group of students to be included in SMPY, the gender difference in mathematical reasoning ability was discovered unexpectedly. It was then reaffirmed in every annual talent search conducted since 1972. To date, annual talent searches organized by Duke, Iowa State, Johns Hopkins, Northwestern, and University of Denver have tested well over 1 million gifted students (approximately equal numbers of males and females) across the United States. Among these students, there are no gender differences in SAT-V scores. The males, however, score almost one-half standard deviation higher than the females on SAT-M and display greater

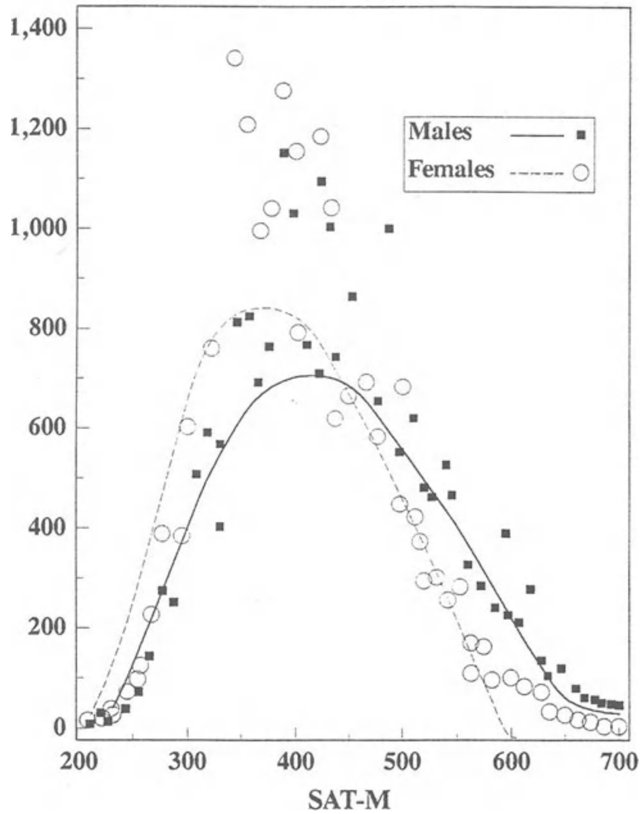

Figure 1 Distribution of SAT-Math scores for participants in the 1980-1982 CTY talent searches by sex (males = 19,833 ; females = 19,937) ; adapted from Benbow (1988).

dispersion of SAT-M scores; a typical score distribution is illustrated in Figure 1

(Benbow, 1988). The resulting proportion of males and females at various cutting scores on the SAT-M is approximately as follows : SAT-M > 500 (average score of college-bound 12th-grade male), 2:1 ; SAT-M > 600, 4:1 ; and SAT-M > 700 (top 1 in 10,000 for 7th-graders), 13:1 (Benbow and Stanley, 1983). These disparate ratios have remained relatively stable over the past 20 years, have now been observed among gifted students in third grade, cross-culturally (but are smaller in Asian populations, see Benbow, 1988), and have profound implications for the math/science pipeline (Benbow, 1992). That is, there are far fewer females than males who qualify for advanced training in disciplines that place a premium on mathematical reasoning (e.g., engineering and the physical sciences).

The picture intensifies when other cognitive abilities are examined, which are salient covariates of SAT-M and contribute to achieving advanced educational credentials in the physical sciences. Mathematically talented students, whether male or female, tend to have highly developed spatial and mechanical reasoning abilities. There are, however, substantial gender differences in those abilities (e.g., Benbow et al., 1983; Benbow and Minor, 1990; Humphreys et al., in press; Lubinski and Benbow, 1992; Lubinski and Humphreys, 1990a). Table I, which is taken from Lubinski and Benbow (1992), exemplifies these differences.

It contains data on abilities (and values) on students tested through SMPY at Iowa State University from 1988-1991. Gender differences in mathematical reasoning ability are consistently observed, paralleling findings described above for the entire nation. Although there are non meaningful differences in SAT-V or Advanced Raven Progressive Matrices scores, there are substantial gender differences in spatial and mechanical reasoning abilities, not unlike those observed 20 years by SMPY. (In 1992 mechanical reasoning was again assessed by SMPY and a gender difference in standard score units of .77 was revealed). These data have further implications for the math/science pipeline because highly developed mechanical and spatial abilities are among the most distinguishing psychological features of physical scientists (Humphreys et al., in press).

Moreover, in select samples as well as in the SMPY sample, gender differences favoring males also are observed on achievement tests in physics, chemistry, computer science, european history and mathematics taken at the end of high school or when in college, and these differences have been stable from at least 1982 to 1991 (Benbow and Minor, 1986; Benbow and Stanley, 1982; Stanley et al., 1992; Stanley, personal communication, 1992). The magnitude of these differences for the select samples studied by Stanley et al. (1992) are illustrated in Figures 2, 3, and 4. It should be noted that the pattern of differences was consistent across many kinds of tests and grade levels and large enough to have a profound effect on admission to (as well as keeping up with the curriculum in) selective universities in the United States.

In sum, gender differences in mathematical reasoning ability among the gifted are accompanied by gender differences in spatial and mechanical reasoning abilities, as well as in subsequent math/science achievement test scores.

YEAR		GENDER	AGE-ADJUSTED N	SAT-M $\bar{X}$	SAT-M SD	SAT-V $\bar{X}$	SAT-V SD	ADVANCED RAVEN'S N	$\bar{X}$	SD	MENTAL ROTATION TEST N	$\bar{X}$	SD	BENNETT MECHANICAL REASONING N	$\bar{X}$	SD	STUDY OF VALUES N	THEORETIC $\bar{X}$	SD	SOCIAL $\bar{X}$	SD	ECONOMIC $\bar{X}$	SD	AESTHETIC $\bar{X}$	SD	POLITICAL $\bar{X}$	SD	RELIGIOUS $\bar{X}$	SD
1991	●	M	68	532	101	426	78	68	25.1	3.9	68	29.9	8.1				68	47.7	7.0	37.1	7.3	41.6	7.2	36.4	8.2	42.9	6.6	34.2	10.4
		F	51	480	87	418	87	51	25.8	4.3	51	25.1	10.2				51	42.0	6.8	43.2	8.1	37.8	6.9	42.6	7.1	39.0	7.2	35.4	10.2
	■	M	107	579	101	413	81	92	25.2	4.2	95	30.0	8.1				77	47.6	6.9	37.1	7.0	41.8	6.9	36.5	8.3	43.1	6.8	33.8	10.1
		F	67	472	85	418	80	58	25.9	4.2	63	24.1	10.0				57	41.7	7.0	43.8	8.3	37.5	7.0	42.8	7.5	38.7	7.0	35.6	10.3
1990	●	M	69	537	100	415	79	69	24.5	6.5	69	29.2	9.1				69	46.6	8.8	38.4	7.8	40.4	8.2	38.4	8.4	42.5	6.9	33.4	11.4
		F	48	487	74	422	76	48	25.3	4.4	48	22.5	9.7				48	40.3	8.0	44.0	8.0	35.8	7.1	42.1	6.4	40.1	6.7	37.5	8.1
	■	M	87	545	96	415	79	82	24.6	6.8	80	29.8	8.8				73	46.6	8.7	38.3	7.6	40.4	8.1	37.8	8.7	42.7	6.8	33.9	11.3
		F	61	487	71	419	80	57	25.1	4.1	56	21.6	9.4				51	40.7	8.0	43.6	8.1	35.3	7.2	42.8	7.1	40.1	6.6	37.1	8.4
1989	●	M	20	585	86	441	98	20	27.3	4.4	20	24.9	9.9	20	40.2	9.4	20	49.3	7.4	35.4	5.9	40.3	9.4	37.3	8.0	45.0	7.8	30.8	11.1
		F	11	505	80	449	96	11	24.7	5.1	11	17.8	4.1	11	35.6	8.0	11	39.0	9.1	42.3	9.1	41.1	9.6	40.6	5.2	40.4	9.3	36.6	12.5
	■	M	43	593	95	446	78	21	27.0	4.4	40	23.8	9.7	42	42.2	10.0	43	50.0	6.8	34.8	7.5	42.2	8.2	37.0	7.7	44.1	8.2	30.9	10.7
		F	34	514	82	455	79	11	24.7	5.1	34	21.8	7.9	32	35.2	9.4	34	41.8	7.4	41.2	8.3	39.6	7.7	43.9	8.2	39.2	7.2	34.3	10.9
1988	●	M	57	562	81	435	59	57	26.6	3.8							57	48.0	8.5	34.4	7.8	44.9	7.6	35.3	8.1	45.2	8.2	32.4	12.8
		F	32	491	65	424	80	32	25.1	5.3							32	42.3	7.5	40.7	8.0	38.2	7.5	43.6	8.4	40.1	6.2	34.9	10.3
	■	M	72	571	85	440	62	66	26.8	3.7				8	39.3	6.5	61	48.3	8.5	34.5	7.6	44.7	7.4	35.0	8.0	44.8	8.3	32.9	12.7
		F	39	500	64	425	76	36	25.3	5.3				9	29.0	7.2	33	42.5	7.4	40.9	8.0	38.0	7.5	43.4	8.4	40.0	6.2	35.2	10.2

● Students who took all of the tests ■ All students who took any one test

Table I Ability/preference profiles of intellectually gifted students (top 5%) attending a summer academic program across four separate years by gender.[1]

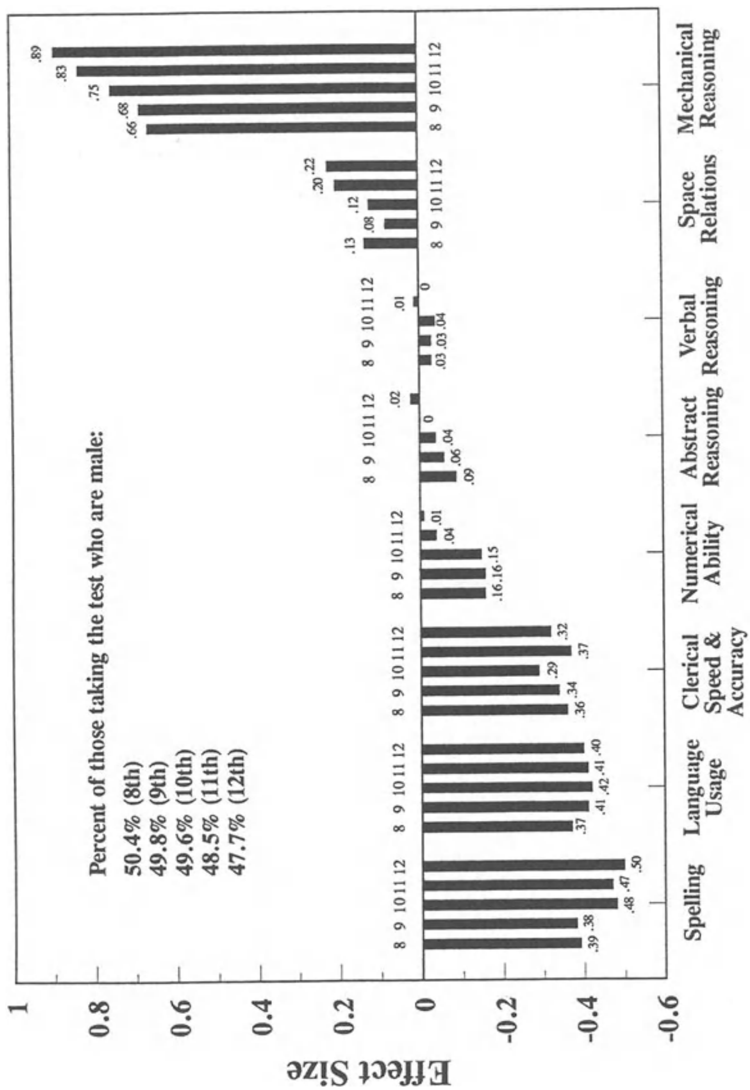

Figure 2 Effect sizes for differential aptitude tests (DAT). Effect sizes represent the standard deviation difference between the genders in the ability in question (it is computed by subtracting the female mean from the male mean and dividing by the pooled standard deviation). (Adapted from Stanley et al., 1992).

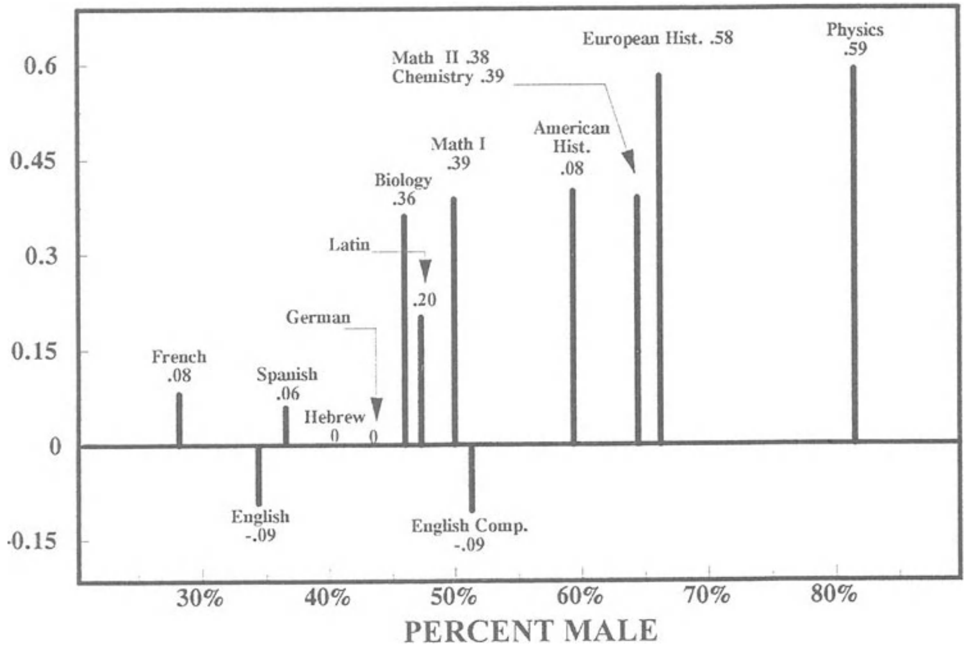

Figure 3 Average standardized gender differences on each of the 14 college board achievement tests for the years 1982-85, plotted against the medial percent of those taking the test who were male (r = 78). (Adapted from Stanley et al., 1992).

Contrary to the claims made in recent reports, there is no evidence that these differences are diminishing among the gifted. Rather, they have remained rather stable over the past 20 years. An often overlooked explanation for these findings, even if contemporary meta-analytic reviews are accurate about the genders converging toward a common mean on most abilities, is the following. Males tend to be more variable on measures of cognitive functioning, even on tests for which females have *higher* means (Feingold, 1992; Lubinki and Dawis, 1992; Stanley et al., 1992). As a result, males are more frequently found at the extremes, both in the retarded and talented tails of ability distributions (Lubinski and Benbow, 1992; Lubinski and Dawis, 1992). Consumers of meta-analytic reviews *must* keep in mind that overall effect sizes assess only gender differences in group means. If there are also gender differences in dispersion (or variability), male/female proportions at high levels of an attribute can, and often do, differ markedly. This, we believe, is one of the most under-appreciated points in the assessment of gender differences in human abilities.

Preferences : values and interests

Abilities are only one important class of variables that affect educational and career decisions. Preferences for certain environments and occupational reinforcers are another. In this section, we illustrate how gender differences in mathematical reasoning are accompanied by gender differences in values and interests. Two of the more useful schemes for analyzing interests and values are Holland's (1985) hexagon (consisting of investigative, artistic, social,

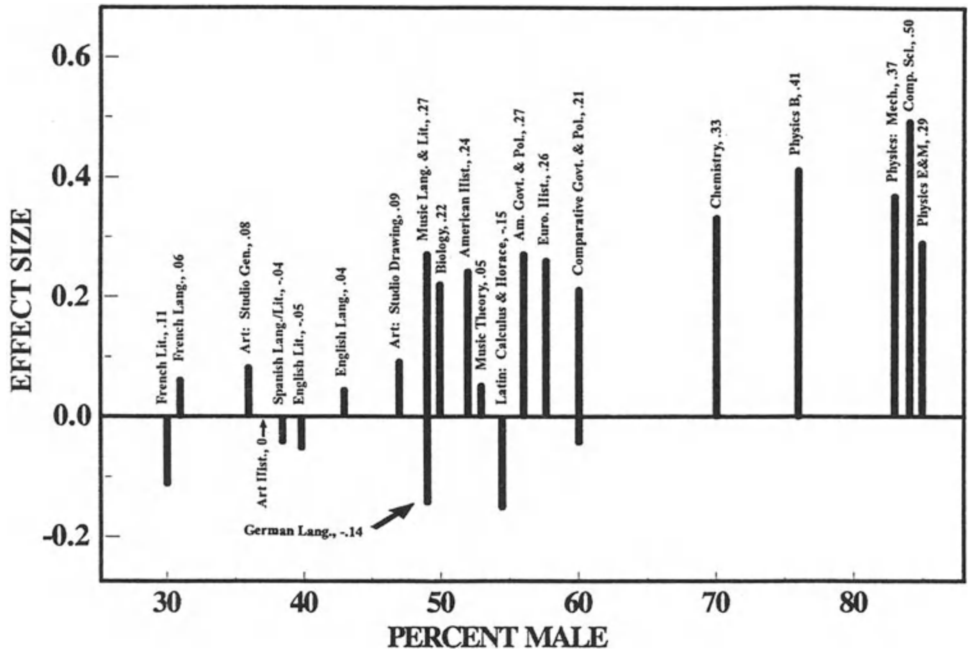

Figure 4 Average standardized gender differences on each of the 26 college board advanced placement program examinations for the years 1984-86 (1987 for american government and politics, and comparative government and politics), plotted against the median percent of those taking the examination who were male (r = .75). (Adapted from Stanley et al. 1992).

enterprising, conventional and realistic vocational interest themes) and the Allport et al. (1970) Study of Values (SOV), six value dimensions based on Spranger's (1928) *Types of Men* and sharing appreciable overlap with Holland's model. The SOV "evaluative attitudes" are theoretical, aesthetic, social, economic, religious, and political. (Readers interested in more detailed discussions of these critical preferences for structuring contrasting educational choices and career paths are referred to Lubinski et al., in press).

Vocational interests and personal value orientation function to determine the focal content domain of one's academic area of concentration. Investigative interests and theoretical values are among the most salient personal preferences of physical scientists. Moreover, a high theoretical complemented by a high aesthetic orientation is correlated with scientific creativity (MacKinnon, 1962; Southern and Plant, 1968).Table I reveals how theoretical values, which are characteristic of physical scientists, are much more characteristic of gifted males than females. Social values, which are negatively correlated with interests in physical science, are more characteristic of gifted females than males. Benbow and Lubinski (1992) presented similar data on Holland's vocational interest themes. They found for mathematically talented students (top .5 %) that there were no gender dfferences in investigative interests. Nonetheless, an interesting pattern of gender differences emerged : males' interests were primarily focused around investigative careers (i.e., preference for academic pursuits involving math and science) and secondarily in realistic areas (a strong preference for working with things or gadgets). The interest pattern of gifted females', in contrast, was more evenly distributed across investigative, artistic (writing and artistic forms of self- expression), and social areas (considerable people contact or social service). These findings seem to reflect gender differences on one of the most celebrated dimensions of individual differences, "people versus things" (Thorndike, 1911). Mathematically talented females tend to gravitate toward the former, while mathematically talented males gravitate toward the latter (cf. Lubinski and Humphreys, 1990b). Might it be more precise to say that gender differences in vocational preferences are structured around organic versus inorganic content domains ? Regardless, this dimension of individual differences has predictive utility for familiar educational and occupational categories.

Although students are not formally selected for advanced training based on their theoretical values, their investigative interests, or their spatial and mechanical reasoning abilities (but they are on mathematical reasoning ability), students appear to self-select areas of concentration based on all of these attributes, whether they are explicitly aware of their abilities and preferences or not. Gender differences in mathematical reasoning are, therefore, compounded by gender differences in spatial visualization and mechanical reasoning, and disparate male/female proportions in math/science achievement created by these abilities are intensified by gender differences in values and interests critical for forming a commitment to these disciplines. In addition, at least one other factor exacerbates these disparities ; for intellectually gifted subjects, there are huge gender differences in commitment to full-time work : 95 % of the males versus 55 % of the females say they plan to work full-time until retirement (Benbow and Lubinski, 1992). This finding must be taken into account when addressing all forms of gender differences in achievement and career advancement ; as long as the genders differ so markedly in their commitment to full-time work, marked differences in achievement and promotion are sure to remain, even among males and females whose relevant ability/preference profiles are equivalent.

Gender differences in math/sciences career choices

The data in Table II show the current gender discrepancy in math and science educational credentials for a sample of SMPY participants in the top 1 % of mathematical ability. More males than females are entering math/science career tracks, especially the ("inorganic") nonbiological/behavioral sciences ones, and they hold higher educational aspirations. Yet perhaps the most startling finding in Table II is that less than 1 % of females in the top 1 % of mathematical ability are pursuing doctorates in mathematics, engineering, or physical science. Approximately 8 % of such males are doing so. Similar discrepancies were reported by Benbow and Lubinski (1992) for two other cohorts of mathematically talented students surveyed in the 1980's/1990's. Among students with mathematical abilities in at least the top .5 %, Benbow and Lubinski reported that 12 % of females compared to 27 % of males were pursuing doctorates in mathematics, engineering, and physical science. Even among 18 year-old students in the top 1 in 10,000 in mathematical ability (SAT-M > 700 before age 13), we find 77 % of these males but only 47 % of the females pursuing bachelor degrees in mathematics, physical science, and engineering. As the following theoretical discussion will reveal, as long as gender differences in critical ability/preference profiles remain stable, as they have over at least the past 20 years for the gifted, corresponding disparities along the math/science pipeline are predicted to continue. Moreover, given the nature of the gender differences (larger means and standard deviations for males in relevant abilities, plus larger mean differences favoring males on relevant interests and values), gender differences in achievement should be expected to become more pronounced at higher educational levels.

Educational and vocational decision making and adjustment

It is helpful to organize the above findings around a well-known model of vocational adjustment. This model is useful for several reasons. One especially attractive feature is that it is readily extended to critical antecedents of vocational adjustment, such as choosing a college major. According to the Theory of Work Adjustment (TWA), one's psychological adjustment to any given educational or career track is a joint function of two broad dimensions of correspondence, *satisfaction* and *satisfactoriness* (Dawis and Lofquist, 1984; Lofquist and Dawis, 1991). The latter is defined by the extent to which abilities correspond to the ability requirements of a given occupation, and the former is defined by correspondence between one's personal preferences (interests, needs, values) and the rewards offered by the discipline or occupation.

	Highest Degree / Major	Bachelor		Advanced (Less than Doctorate)		Doctorate		Total (Across Degrees)	
		Males	Females	Males	Females	Males	Females	Males	Females
Math and Science	Mathematics	3.4	3.5	0.3	0.7	0.5	0.0	4.2	4.2
	Engineering	16.2	7.6	7.9	3.0	3.4	0.7	27.5	11.3
	Physical Science	2.2	1.5	0.5	0.4	3.7	0.2	6.4	2.1
	Biology	2.2	5.4	0.3	0.4	1.1	1.5	3.6	7.3
	Medicine					8.7	5.9	8.7	5.9
	Social Science	4.8	6.1	0.4	2.0	1.9	0.9	7.1	9.0
	Humanities	2.5	5.0	0.1	2.4	0.8	1.7	3.4	9.1
	Law					6.4	4.1	6.4	4.1
	Business	7.1	11.1	4.5	5.0	0.8	0.7	12.4	16.8
Total	All Majors	42	52	15	17	28	17	85	86
	Math/Science Majors	24	18	9	5	18	9	51	32

Table II Longitudinal data for mathematically talented students (top 1%), identified by a SMPY talent search at age 13. Percentages reflect students' current level of educational attainment or pursuit (at age 23) by gender.[2]

Correspondence between both of these dimensions is critical for an individual to be adjusted to a particular educational or work environment (see Figure 5).

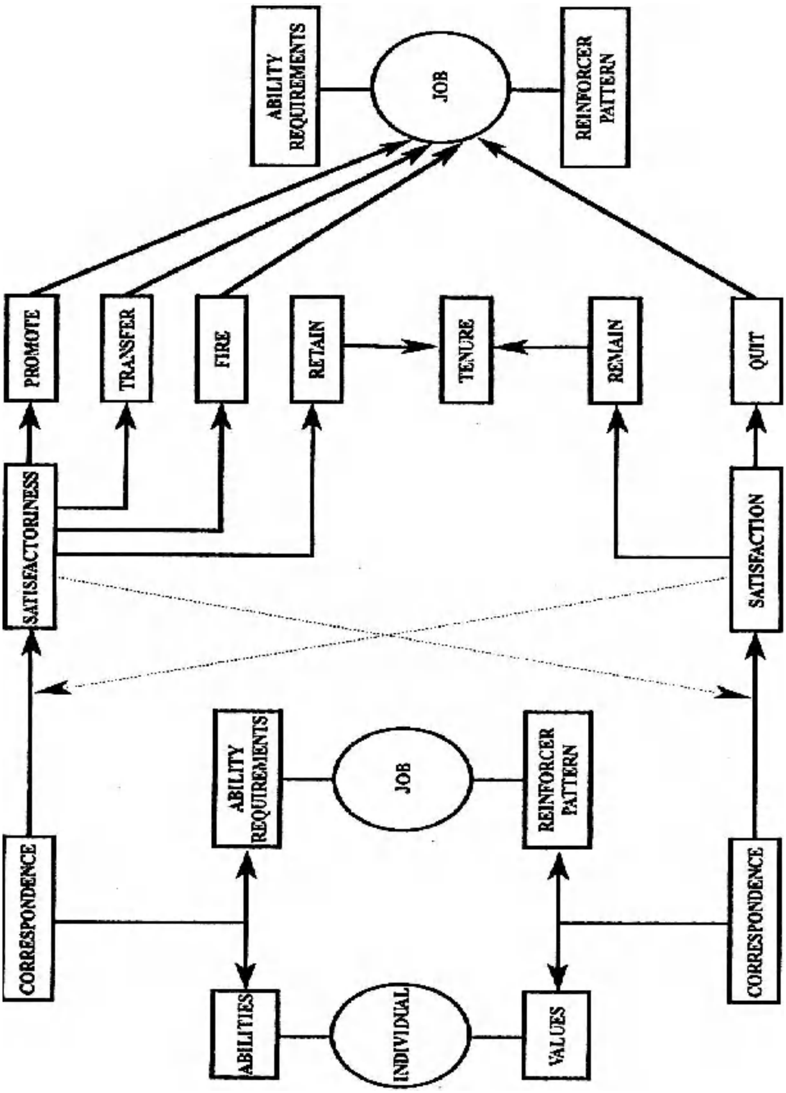

Figure 5 A depiction of the Theory of Work Adjustment. (Adapted from Dawis and Lofquist, 1984). The dotted lines serve to illustrate how satisfaction and satisfactoriness function jointly to determine educational/career tenure. When an individual is not satisfactory, the environment is motivated to transfer or fire the individual, whereas if the individual is not satisfied, the person is motivated to leave.

Figure 5 highlights how mutually complementary people and their environments are when an individual is adjusted to work. Just as individuals have abilities and needs, so do environments. Environments can be described in terms of their response capabilities (to provide reinforcers attractive to individuals with correspondent needs) and in terms of their needs (or demands for individuals having correspondent abilities). School and work environments are, essentially, molecular ecologies defined by 1. their capability to reinforce and 2. the response requirements that they demand (Lubinski and Dawis, 1992; Lubinski and Thompson, 1986).

As noted above, gifted males compared to gifted females tend to have ability and preference profiles more congruent with optimal adjustment in math and science careers. As a result, one would expect more males and females in such careers, which is what we demonstrated above. The important message to take from this discussion is that, given the basic gender differences reviewed As noted above, gifted males compared to gifted females tend to have ability and preference profiles more congruent with optimal adjustment in math and above, to an appreciable degree males and females are most likely to thrive, disproportionately, in somewhat different occupational environments. To be sure, there will be overlap ; but disparate proportions are to be expected. Given that most vocational counselors underscore the importance of both abilities and expressed preferences throughout the educational and career decision making process, stressing the importance of vocational counseling is not likely to attenuate these differences. This basically is the main thrust of SMPY, to stress to gifted adolescents the personal significance of both satisfaction and satisfactoriness when choosing a college major or possible career, irrespective of whether male/female disproportion's ensue. If mathematically gifted females prefer to secure advanced degrees in biology, the humanities, law, or medicine (choices more congruent with their interests and values) and other disciplines for which they are likely to find more correspondent with their personal attributes, we see no problem with gender disparities. Here, our unit of analysis is the individual. Our goal is to facilitate individual development in ways that both the individual and the environments they choose find satisfying and satisfactory.

Yet, as a corollary to optimal intellectual development among the gifted, SMPY, because of the nature and scope of its data-collection operation, is often in a position to test more basic hypotheses and theoretical conjectures in psychological science. Some of these include postulated connections between intellectual precocity and underlying biological mechanisms. We turn next to our findings in this important area.

Possible underlying reasons for the gender differences

In most treatments of causes for gender differences in abilities, interests, and values, socialization hypotheses have been emphasized (Halpern, 1992). This is perhaps due to the erroneous assumption that, if gender differences are environmentally determined, they are somehow more readily modifiable. Whether individual differences in a behavioral trait are pirmarily determined by biological or environmental factors is not what determines how responsive the differences will be to environmental intervention (Meehl, 1972). Nonetheless, SMPY and several other investigators have devoted considerable effort to identifying environmental determinants for gender differences in mathematical talent (Benbow, 1988). Although subtle effects of socialization could not be tested, the research conducted over the past 20 years has been unable to produce results consistent with an exclusively environmental explanation for the sex difference in SAT-M scores (Benbow, 1988).

Moreover, Lubinski and Benbow (1992) listed a number of findings that would appear curious if purported social influences are operating exclusively to attenuate in females the development of key attributes associated with satisfaction and satisfactoriness in engineering, mathematics, and the physical sciences. For example, females are superior to males on tests of arithmetic computation and they also (as a group) tend to get better grades in math courses. Some hypotheses attribue sex-role identification to gender differences in mathematical reasoning ability, but adolescents gifted in spatial and verbal abilities, like their mathematically gifted peers, are less gender stereotyped in nonacademic interests than the typical adolescent (cf. Lubinski and Humphreys, 1990b) ; and a recent meta-analytic review has called into question parents' differential socialization of boys and girls with respect to a number of abilities and social behaviors (Lytton and Romney, 1991). These factors led SMPY to begin exploring possible biological correlates of superior mathematical reasoning ability, hoping to stimulate subsequent and more sophisticated investigations into the underpinnings of precocity and the gender differences observed in several of its facets. This approach appeared fruitful, inasmuch as a genetic contribution to both abilities and preferences has been clearly documented (Benbow et al. 1983; Bouchard, 1991; Bouchard, et al., 1990; Lykken, 1982). SMPY's work in this area began with a neuropsychological investigation.

Hemispheric specialization

The human brain is split into two parts, the right and left hemispheres, which are connected by the corpus callosum. The left hemisphere is specialized for language production, is analytical and sequential in processing of information, and is compartmentalized for various sensory modalities (Semrud-Clikeman and Hynd, 1990). The right hemisphere is specialized for nonverbal abilities (e.g., spatial ability and judging emotions) and the distribution of attention across space (Kosslyn, 1987). It tends to be more holistic in the processing of information and integrates information across multiple modalities simultaneousy. SMPY's early work revealed that exceptionally precocious youth tend to be more frequently left-handed than their parents and siblings, average-ability students, and modestly gifted students (Benbow, 1986; Benbow and Benbow, 1984). Because the specialization of cognitive functions in the right and left hemispheres tend to be more diffuse in left than right handers, this finding had special significance for theoretical conjectures about brain organization (Bradsha and Nettleton, 1983). It led to a proposal that bilaterality or enhanced right hemispheric functioning may be associated with extreme intellectual precocity (Benbow, 1986; O'Boyle and Benbow, 1990). A series of studies has now provided support for this view.

Benbow and Benbow (1987) analyzed data from the visual modality. These date were obtained by tachistoscopically presenting stimuli (verbal and spatial) to each visual field and measuring reaction times. Results seemed to indicate that, indeed, the organization of skills within the two hemispheres was somewhat different for the intellectually gifted compared to typical students. O'Boyle and Benbow (1990) explored this idea further. They reported results of two experiments in which intellectually gifted and average-ability subjects (12 to 14 year-olds), all of whom were right handers, performed a verbal dichotic listening task and a free-vision chimeric face task. Typically, one would expect for right handers a right ear/left hemisphere advantage for the verbal dichotic listening task, while for the chimeric face task (a task involving the judging of emotions) a significant right hemisphere bias would be anticipated. For O'Boyle and Benbow's average ability control subjects, this was indeed the case. But the intellectually gifted subjects exhibited a quite different pattern. In the dichotic listening task, gifted subjects failed to show the usual left hemisphere advantage. Both hemispheres were equally effective in dealing with linguistic stimuli. For the chimeric face task the gifted, just like the average-ability subjects, also exhibited a right hemisphere advantage. This right-hemispheric bias for the gifted was, however, appreciably stronger by a magnitude of four than that revealed by the average-ability students.

O'Boyle and Benbow (1990) concluded from the above findings that the right hemisphere of the intellectually precocious is particularly engaged during cognitive processing. To lend further credence to this idea, more basic physiological data were collected. O'Boyle et al. (1991) conducted a preliminary electroencephalographic (EEG) investigation to determine if the pattern of hemispheric activation characterizing mathematically precocious males is different from that of average ability males. All subjects were right handed, and alpha activity at four brain sites was monitored. At baseline (looking at a blank slide) the left hemisphere of the precocious group compared to the average-ability group was found to be more active at all four sites. For the chimeric face task, the right hemisphere was markedly more active than the left, especially at the temporal lobe, while for the average ability students the left hemisphere was somewhat more active (see Figures 6 and 7). For the verbal task, the right hemisphere of the extremely precocious was somewhat more active with the opposite pattern for the average-ability subjects. A replication of this work, using both males and females as subjects, has now been completed (Alexander, 1992). The findings for males did replicate. Intellectually precocious males show enhanced right hemisphere

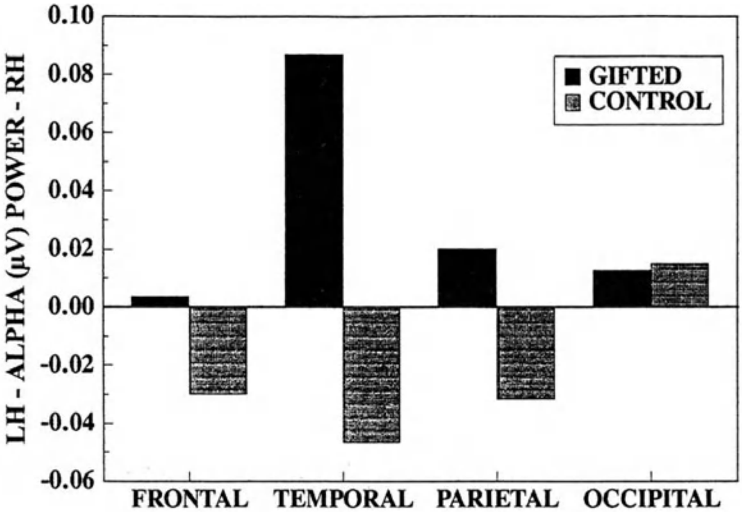

Figure 6 Alpha power reduction (i.e., the reduction of alpha brain wave activity) (μV) for mathematically gifted and average ability control youths during the chimeric face task. (Adapted from O'Boyle et al., 1991).

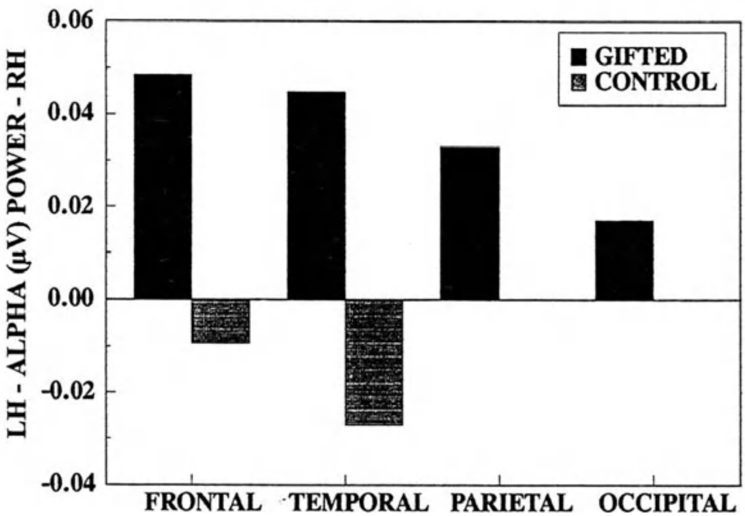

Figure 7 Baseline alpha power (alpha brain wave activity) for mathematically gifted and average ability control youths. (Adapted from O'Boyle et al., 1991).

functioning, but the females did not. In sum, evidence is beginning to emerge indicating that the organization of cognitive functions within the left and right hemispheres in intellectually precocious males differs from that found for individuals with average abilities. These findings provide an especially attractive rationale for subsequent work involving recent advances in Positron Emission Topography (PET) technology.

Nonetheless, a question remains : why does enhanced right hemisphere functioning characterize males but not females? We offer the following hypothesis : we suggest that it may have something to do with prenatal exposure to high levels of the hormone *testosterone* (Benbow, 1988). Further,we suggest a re-framing of the question, "Why do so few females possess exceptional levels of quantitative sophistication ?" The question might better be posed as : "Why is there an *overabundance* of mathematically gifted males" ?

Although purely speculative at this point, the excess of mathematically precocious males may be due to the more frequent exposure of males than females to high levels of fetal testosterone. Levy and Gur (1980) proposed that high levels of fetal sex hormones promote the maturational rate and cognitive capacity of the right hemisphere, and Gardner (1983) and Troup et al. (1983) reported that mathematical reasoning ability may be more directly under the influence of the right than left hemipshere. It may be that, just as there are continuous and taxonic avenues from which mental retardation can be traced (namely, simply systematic sources of individual differences at the low end or Mendelian inheritance, respectively), intellectual giftedness may stem from systematic sources of individual differences at the high end and, *possibly*, from underlying hormonal influences that function to produce discontinuities at the phenotypic level indicative of a taxonic phenomenon.

The work of Geschwind and Behan (1982) provides the theoretical basis for our speculations. Geschwind and Behan reported that left handers suffer more frequently from immune disorders, learning disabilities, and migraines than do right handers. The proposed explanation for this association involved prenatal exposure to testosterone. They suggested that if the developing fetus is exposed to high levels of testosterone or has an increased sensitivity to testosterone, at least two sequenced manifestations result. Testosterone affects the development of the thymus gland and, thereby, leads to increased susceptibility to immune disorders, such as allergies. Moreover, testosterone was predicted to enhance the development of the right hemisphere of the brain, which would lead to an increased likelihood of becoming lefhanded. Benbow (1986) and Benbow and Benbow (1987) presented data consistent with this hypothesis. Although, overall, intellectually precocious youth tend to be physically healthier than their normative peers (Lubinski and Humphreys, 1992), they also are more frequently left-handed, suffer more frequently from allergies (as well as other immune disorders), are more often first-born, and (quite curiously) tend to be born during a specified period of the year (February through July, with a peak in June), all findings that were predicted from the

Geschwind hormonal hypothesis and discussed in more detail by Benbow and Benbow (1987).

Conclusion

Herein we have documented that gender differences among the giften have not diminished over the past 20 years in contrast to some recent reports that they may be disappearing in normative samples. Among the gifted there are gender differences at age 13, favoring males, in mathematical reasoning ability, that are accompanied by gender differences in spatial and mechanical reasoning abilities. (At the end of high school and college, there also are gender differences, favoring males, in mathematics and science achievement test scores). These differences at upper ability ranges are important and psychologically meaningful; even among SAT-M scores in the top 1 %, Benbow (1992) has demonstrated their predictive validity across 4-10 year temporal gaps for a host of academic achievement criteria.

In addition, there are differences in values and interests among the gifted at age 13 ; mathematically talented males are more theoretically oriented on the SOV and have primary interests in the investigative and realistic dimensions of Holland's Hexagon. In contrast, mathematically talented females are more socially and aesthetically oriented and have interests that are more evenly divided among investigative, social, and artistic pursuits. Thus, at age 13 more males than females possess ability and value profiles congruent with pursuing careers in the malth/sciences. This leads to gender disparities in educational attainment and in pursuing careers in math/science. These disparities become more intense at higher educational/professional levels, in part because males also demonstrate a stronger commitment to full-time work. Indeed, by drawing on longitudinal data available from SMPY on these students, we revealed that at age 23 more than twice as many males than females are pursuing advanced schooling and careers in the areas of mathematics, engineering, and physical science. The ability differences partially responsible for male/female disparities in physical science disciplines may have a biological basis. Mathematically talented males appear to possess enhanced right hemisphere functioning.

Notes

[1] All subjects were identified by a talent search at age 13 and subsequently enrolled in a summer academic program for the gifted at Iowa State University (ISU). Students were qualified for this program if, as seventh graders, they earned scores of at least 500 on the mathematics SAT (SAT-M) or 430 on the verbal SAT (SAT-V). Only students with SAT-M > 350 (roughly the top 2% in mathematical reasoning ability) are included here. (Note that the group of students who took all of the tests is also included in the group who took at least one test). ISU's Talent Search is particularly noteworthy because it has the highest participation rate in the nation (more than 75% of all eligible students) and the highest ability scores. Students in these programs tend to be (personally) motivated and (family) supported : except for limited-income families, parents pay for them to attend.

Tests : College Board Scholastic Aptitude Test (mathematics = SAT-M; verbal = SAT-V; for participants beyond the seventh grade, SAT scores were adjusted downward 4 points/month); Raven's Progressive Matrices (Advanced), a nonverbal measure of general intelligence; Vandenberg Mechanical

Comprehension Test (Form AA), a test designed to assess inferences based on primitive kinds of physical mechanisms (gears, pulleys, springs etc.); Allport, Vernon and Lindzey (1970) Study of Values, a measure designed to assess the relative intensity of six "evaluative attitudes" used to approach life theoretical, aesthetic, social, economic, religious and political.

[2] The students in the sample were identified by a talent search requiring junior-high math achievement scores in the top 2% and had scores of at least 390 on the mathematics SAT or 370 on the verbal SAT when in seventh or eighth grade (years 1972-1974). The students were surveyed 10 years later (i.e. at age 23). The two bottom rows are rounded to the first whole number. The bracketed cells reveal the low rate at which mathematically gifted females pursue doctorates in mathematics or physical science. Samples defined at this level of mathematical reasoning have special significance for the math-science pippeline because these students earn degrees in math and science at 10 times the national rate. The all majors row includes low-frequency majors not reported in the above categories. (Adapted from Lubinski and Benbow, 1992)

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