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Psychological profiles of the mathematically talented: some sex differences and evidence supporting their biological basis

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Abstract. For over 20 years, above-level testing with the College Board Scholastic Aptitude Test (SAT) has been used to assess the abilities of well over 1 000 000 highly able 12–13-year-olds (students in the top 3% in intellectual ability). In this population, the predictive validity of the mathematical part of the SAT, SAT-M, for academic and vocational criteria has been demonstrated over 10-year gaps. Here, we document aspects of the psychological and achievement profiles of these highly able students, paying particular attention to sex differences. Males score higher on SAT-M (i.e., mathematical reasoning ability) than females; this difference is accompanied by differences between the sexes in spatial–mechanical reasoning abilities and in a number of lifestyle and vocational preferences. Collectively, these attributes appear to play a key role in structuring male–female disparities in pursuing advanced educational credentials and careers in the physical sciences. After profiling a number of the behavioural characteristics of the highly able, we examine some underlying biological correlates of these phenotypic manifestations. These include hormonal influences, medical and bodily conditions and enhanced right hemispheric activation.

1993 The origins and development of high ability. Wiley, Chichester (Ciba Foundation Symposium 178) p 44–66

Ever since its founding by Julian C. Stanley at Johns Hopkins University in 1971, the Study of Mathematically Precocious Youth's (SMPY's) research and educational programming has focused on exceptional achievements in mathematics, engineering, the physical sciences, and on the young individuals with the potential to produce them. These were fortuitous choices, given that our increasingly technological society requires many well-trained scientists in just these areas. Furthermore, the importance of mathematical ability for scientific achievement and creativity has become more evident with time.

Krutetskii (1976, p 6), for example, noted that 'the development of the sciences has been characterized recently by a tendency for them to become more mathematical . . . Mathematical methods and mathematical style are penetrating everywhere'. Kuhn (1962) was most probably correct in ascribing an overwhelming majority of 'scientific revolutions' to the work of mathematically brilliant individuals, criticisms of the selectivity of his examples notwithstanding.

Thus, individuals seen as having the most potential for high academic achievement and subsequent creative production in the physical sciences are those whose mathematical reasoning abilities are exceptionally high (Benbow & Arjmand 1990, Green 1989, Walberg et al 1984), the very individuals on whom SMPY chose to focus its research programme. Here, we present a psychological profile of the mathematically talented, especially as it relates to the constellation of personal attributes critical for the manifestation of exceptional scientific contributions, the sex differences found therein, and some biological foundations for these phenotypic manifestations. We begin with a discussion of mathematical talent and the importance of considering a label such as 'gifted' as a continuous rather than a categorical concept. A common arbitrary point for the label of giftedness is an ability level in the top 1%. Such a cut-off procedure can be misleading, because many people fail to appreciate the extent of individual differences within the top 1%. The top 1% of almost all ability ranges (for general intelligence, those with IQs from about 135 to over 200) cover a range just as broad as that from the bottom 2% to the top 2% (an IQ range of about 66 to 134).

Individual differences in the top 1%: their psychological implications

Many firmly hold that being within the top 1% in mathematical ability is sufficient for the production of exceptional scientific achievements (e.g., MacKinnon 1962, Renzulli 1986, Wallach 1976); that is, above a certain ability threshold (here, the top 1%, but many maintain lower levels apply), other factors become increasingly important for the emergence of advanced scientific achievements and creativity. What many educators and social scientists do not realize is that the range of giftedness includes about one-third of the *entire* ability range, and this range is seldom investigated systematically with the necessary methodological requirements (cf., Lubinski & Dawis 1992).

We (Benbow 1992) recently undertook the task of empirically determining if indeed there is such a point of diminishing returns in the distribution of mathematical ability, a point beyond which even greater mathematical talent has little usefulness. About 2000 students were identified by SMPY as being in the top 1% in mathematical reasoning ability in the 7th or 8th grade (13-year-olds), through use of out-of-level testing with the College Board Scholastic Aptitude Test-Mathematics (SAT-M) (i.e., 7–8th-graders took a test designed for above-average 11th and 12th-graders [16–18-year-olds]). These students had been included in SMPY's planned 50-year longitudinal study, which includes a total of 5000 students identified over 20 years, and, as part of the longitudinal study, had been surveyed five and 10 years after their identification at age 13 (Lubinski & Benbow 1994). We (Benbow 1992) elected to compare the mathematics–science achievement profiles of those students whose SAT-M scores placed them in the top quartile of the top 1% with those whose scores placed them in the bottom quartile of the top 1%. Sample sizes averaged 100 females and 367 males for the top 25%, and 282 females and 248 males for the bottom 25%. Data on a variety of criteria—earning a college degree in the sciences, intellectual level of college attended, academic honours, grade-point average, and intensity of involvement in mathematics and science—all favoured the top quartile, irrespective of sex. Of the 37 variables studied, 34 showed significant differences favouring the high SAT-M group, but, more importantly, most were substantively meaningful. The average effect sizes for the various types of variables studied are shown in Table 1. The differences averaged 0.64 standard deviations.

We (Benbow 1992) also conducted predictive validation assessments using the full range of talent in this sample, correlating the students' 8th-grade SAT-M scores with their College Board Achievement Test scores in mathematics or science attained at the end of high school (i.e., 4–5 years later). The correlations ranged from 0.16 to 0.57, with a mean of 0.40 for females and 0.45 for the males (approximate sample sizes are $n = 95$ females and $n = 223$ males, because different numbers of students elected to take specific tests). The predictive validities for Advanced Placement (AP) calculus examination scores averaged 0.43 for females and 0.38 for males. (It should be stressed that the above were raw correlations, not corrected for attenuation.)

TABLE 1 Average effect sizes for various tasks favouring the top quartile over the bottom quartile of a sample of 2000 children identified as being in the top 1% in mathematical reasoning ability in the 7–8th grade

Category	*d*	*h*
Standardized test scores	1.24	
Grade point average	0.50	0.54
Mathematics/science course-taking	0.42	0.65
Mathematics/science career goals		0.48
Educational aspirations		0.41
Non-class academic experiences		0.41
Prizes and awards	0.27	0.41

$d = \frac{\bar{x}_1 - \bar{x}_2}{SD}$

h, difference between arcsine transformation of two proportions.
d,h $\geqslant$0.2, small effect size; d,h $\geqslant$0.5, medium effect size; d,h $\geqslant$0.8, large effect size (Cohen 1988).

These data clearly reveal that individual differences in the top 1% in ability do have important psychological implications, yet such individual differences are seldom observed for the following reasons: (1) out-of-level testing is required to detect and separate the top 1%; (2) sample sizes of individuals within the top 1% tend to be small; and (3) the criteria themselves tend to lack sufficient ceilings (Lubinski & Dawis 1992). None the less, irrespective of the individual differences within the top 1%, it must be acknowledged that the most important attribute for successful performance in any highly select domain often has the least variation among the factors that contribute to achievement in that domain, a finding that transcends all types of talents or skills (Lubinski & Dawis 1992, Lubinski & Humphreys 1990a). This is because the variance in the critical attributes tends to be suppressed within elite educational and occupational populations through self-selection and institutionalized selection procedures. Thus, for individuals within the most prestigious scientific occupations, mathematical ability might have minuscule variation relative to the normal variation, but remain at centre stage. What then are some of the other factors that contribute to success? We turn to that issue next and the theoretical model guiding our work for some clues.

The theoretical model for SMPY's research

The conceptual framework guiding our research on mathematical talent draws on three already existing theoretical perspectives (Dawis & Lofquist 1984, Tannenbaum 1983, Zuckerman 1977), and incorporates some of what is already known about the development of talent and personal preferences for contrasting educational and vocational paths. Primarily, our work is based on a well-known model of vocational adjustment, the Theory of Work Adjustment, a model developed over the past 30 years by Rene V. Dawis and Lloyd H. Lofquist at the University of Minnesota (Dawis & Lofquist 1984, Lofquist & Dawis 1969, 1991). Although it is formulated to explain work adjustment, an especially attractive feature of this model is that it can be readily extended to critical *antecedents* to vocational adjustment, such as choice of college major and preferred density of course work in contrasting disciplines.

According to the Theory of Work Adjustment, to ascertain an individual's optimal learning and work environments one must first parse the individual's 'work personality' and the environment into two broad but complementary subdomains. An individual's work personality primarily comprises his or her (i) repertoire of specific skills or abilities and (ii) personal preferences for the content found in contrasting educational and vocational environments. In contrast, different environmental contexts (educational curricula and occupations) are classified in terms of (i) their ability requirements and (ii) their tendency to reinforce personal preferences. Optimal educational and work environments for an individual are those for which two levels of correspondence can be established, *satisfactoriness* and *satisfaction*. Satisfactoriness is the correspondence between an individual's abilities and the ability requirements of a particular educational or occupational environment, whereas satisfaction is the correspondence between an individual's preferences and the types of reinforcers provided by a particular occupation or educational track. The extent to which satisfactoriness and satisfaction are achieved determines educational and career choice, degree of commitment and occupational tenure.

An important implication of this model is that both abilities and preferences must be assessed, concurrently, to ascertain the suitability of a given individual for a particular educational or career track (cf., Lubinski & Thompson 1986). Similarly, both components of the educational and vocational environment (response requirements *and* reward systems) need to be evaluated to estimate whether both dimensions of correspondence are likely to be achieved.

Which abilities and preferences should be assessed when the educational or work environment is engineering or physical science? For these disciplines, as noted above, especially high mathematical reasoning ability is a requirement. High spatial-mechanical reasoning ability (probably the second most significant personal attribute and one that is frequently underappreciated; Humphreys et al 1993) is also important. Verbal ability is somewhat less critical, but still important. Investigative interests (scientific) and theoretical values (intellectual and philosophical) are among the most salient personal preferences of people who gravitate toward scientific environments, find their content reinforcing (for developing intellectual talent), and maintain a commitment toward these kinds of disciplines (Dawis 1991, Dawis & Lofquist 1984, Holland 1985, Lubinski & Benbow 1992, 1994, MacKinnon 1962, Roe 1953, Southern & Plant 1968). The physical sciences also require intense abilities and preferences for manipulating and working with sophisticated objects and gadgets. Individuals with pronounced or relatively high social values (or a stronger need for contact with people), gain less reinforcement in such environments.

If the abilities and preferences that are important for adjustment in scientific environments are not all in place, high achievement in the sciences is most unlikely. We propose that high achievement and creativity in science emanate from the following configural pattern of personal attributes: high mathematical reasoning ability, high spatial-mechanical reasoning ability, high theoretical values and investigative interests, and a relatively low need for contact with people in learning environments and vocational settings. These characteristics, coupled with an intense commitment to mastery of one's chosen discipline and energy for work (see below), are the *sine qua non* for high scientific achievement. For all of these attributes to be salient in any one individual is rare, but not as rare as noteworthy scientific achievements.

Possession of these personal attributes by themselves is insufficient. Those who have the personal potential to manifest exceptional achievement also require an environment appropriate to facilitate the emergence of world-class scientific accomplishment. Bloom (1985), for example, noted from his interviews of talented performers in a variety of disciplines that special experiences, sometimes interventions, were important in their development. (This is what we attempt to provide in our summer programmes for the gifted, described in detail elsewhere; Benbow 1986a, Stanley 1973, Stanley et al 1974).

Moreover, Zuckerman (1977), in her analysis of Nobel Laureates' careers, saw that their development or emergence fit well with the model of 'the accumulation of advantage'. That is, individuals with exceptional scientific achievements almost always show promise extremely early in their careers and this precocity appears not only to respond to but also to create greater opportunities for intellectual development. For example, most Laureates were advantaged in their graduate work by attending a distinguished university (10 universities produced 55% of the Laureates) and by studying with the best minds of the day—thereby begetting a pattern of eminence creating eminence.

Tannenbaum (1983) postulated that great performance or productivity results from a rare blend of superior general intellect, distinctive special aptitudes, the right combination of non-intellectual traits, a challenging environment and the smile of good fortune at crucial periods of life. (The first three components seem to parallel the abilities and preferences discussed in the Theory of Work Adjustment, and the latter two the work of Zuckerman.) According to Tannenbaum, success depends on a combination of facilitators, whereas failure results from even a single deficit. By virtue of its veto power, then, every one of the five qualifiers is a requisite for high achievement and none of them has sufficient strength to overcome appreciable inadequacies in the others.

The above serves as the scaffolding for our work on the dispositional determinants of scientific educational and career paths of the gifted. It is also the starting point for our attempts to facilitate the optimal development of their intellectual talents. However, a consistent finding from SMPY (and other research programmes studying the highly able or normal samples) is that these abilities and preferences, and commitment to work in general, differ between the sexes. An investigation of these sex differences led to the first evaluation of the Theory of Work Adjustment, with the results described below.

Sex differences organized around the Theory of Work Adjustment: a preliminary appraisal

Sex differences in abilities

Among SMPY's mathematically gifted 13-year-olds, differences favour males in mathematical reasoning ability but not in verbal reasoning, where there are no differences (Benbow 1988, Lubinski & Benbow 1992). Our gifted males score approximately one-half of a standard deviation higher than the females on the SAT-M, our measure of mathematical reasoning. Males' SAT-M scores are also

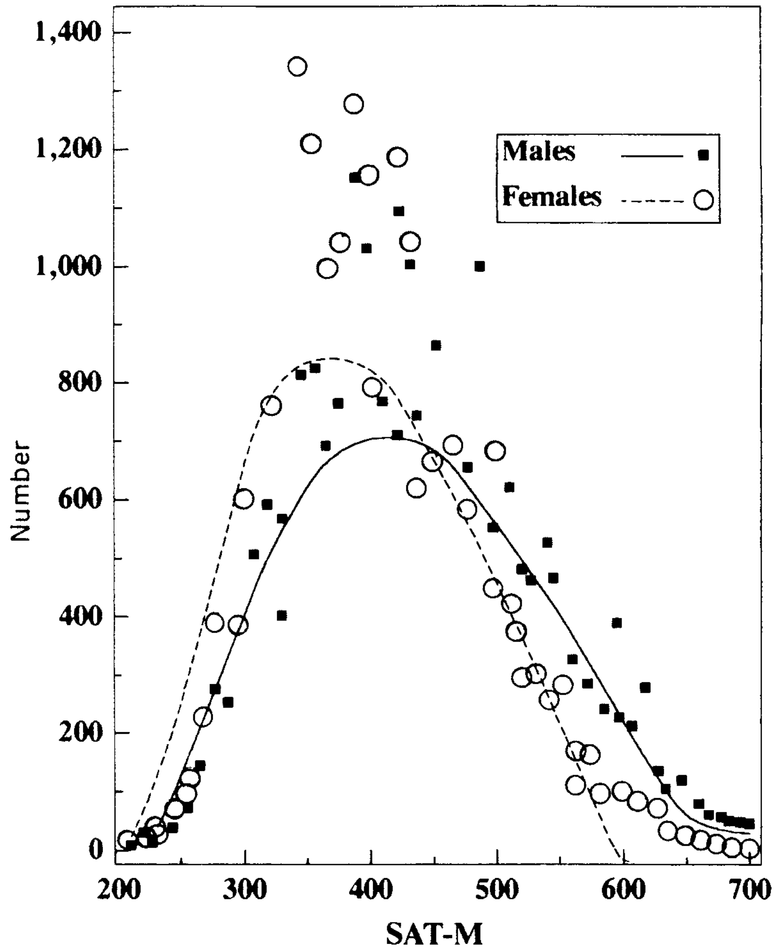

FIG. 1. A typical distribution of scores on the mathematical part of the College Board's Scholastic Aptitude Test (SAT-M) achieved by mathematically talented 13-year-old males (—■—) and females (---○---). Reproduced from Benbow et al (1988), with permission.

more dispersed; a typical distribution is illustrated in Fig. 1 (Benbow 1988). The resulting proportion of males and females at age 13 at various cut-off scores on SAT-M is approximately as follows: ⩾500 (average score of college-bound 12th-grade [18-year-old] males), 2:1; ⩾600, 4:1; and ⩾700 (top 1 in 10 000 for 7th-graders [13-year-olds], 13:1 (Benbow & Stanley 1983). These ratios have remained relatively stable over the past 20 years, and have now been observed among mathematically gifted students in the 3rd grade (eight-year-olds) (C. Mills, personal communication), and cross-culturally (though they are smaller in Asian populations; Lubinski & Benbow 1992). They have profound

**bility profiles of mathematically gifted students (aged 12–14) attending one of SMPY's summer academic pro
and 1992**

Sex	SAT-M (age adjusted)[a]			SAT-V (age-adjusted)			Advanced Raven's[b]			Mental rotation test[c]			Bennett m reasoning	
	n	$\bar{x}$	*SD*	*n*	$\bar{x}$	*SD*	*n*	$\bar{x}$	*SD*	*n*	$\bar{x}$	*SD*	*n*	$\bar{x}$
M	72	494	93	72	398	91	72	24.6	4.1	72	31.3	7.7	72	49.8
F	45	458	66	45	396	82	45	24.3	4.4	45	23.7	8.8	45	45.
M	84	486	91	84	395	88	85	24.4	4.2	83	31.6	7.5	83	49.
F	49	465	76	49	404	90	47	24.6	4.5	48	24.1	8.9	49	45.
M	68	532	101	68	426	78	68	25.1	3.9	68	29.9	8.1		
F	51	480	87	51	418	87	51	25.8	4.3	51	25.1	10.2		
M	107	579	101	101	413	81	92	25.2	4.2	95	30.0	8.1		
F	67	472	85	67	418	80	58	25.9	4.2	63	24.1	10.0		
M	69	537	100	69	415	79	69	24.5	6.5	69	29.2	9.1		
F	48	487	74	48	422	76	48	25.3	4.4	48	22.5	9.7		
M	87	545	96	87	415	79	82	24.6	6.8	80	29.8	8.8		
F	61	487	71	61	419	80	57	25.1	4.1	56	21.6	9.4		
M	20	585	86	20	441	98	20	27.3	4.4	20	24.9	9.9	20	40.
F	11	505	80	11	449	96	11	24.7	5.1	11	17.8	4.1	11	35.
M	43	593	95	43	446	78	21	27.0	4.4	40	23.8	9.7	42	42.
F	34	514	82	34	455	79	11	24.7	5.1	34	21.8	7.9	32	35.
M	57	562	81	57	435	59	57	26.6	3.8					
F	32	491	65	32	424	80	32	25.1	5.3					
M	72	571	85	72	440	62	66	26.8	3.7				8	39.
F	39	500	64	39	425	76	36	25.3	5.3				9	29.

ents in the 8th grade where adjusted to make them more comparable with scores earned by 7th grade students.
Raven's tests a person's ability to comprehend relationships among figures and is a measure of general intelligence. The ave
ersity student is 21.
rotation test the 50th percentile is a score of 16 for female adolescents and 26 for male adolescents.
core of 12th-grade students on the Bennett mechanical reasoning test is 37.4.
ho took all of the tests; 1, students who took at least one test.

implications for the mathematics–science pipeline, because far fewer females than males qualify for advanced training in disciplines that place a premium on mathematical reasoning.

The picture intensifies when the other cognitive abilities important for achieving advanced educational credentials in the physical sciences are examined. Although mathematically talented students, whether male or female, tend to have highly developed spatial and mechanical reasoning abilities, those of the males do appear higher (Benbow et al 1983, Benbow & Minor 1990, Humphreys et al 1993, Lubinski & Benbow 1992, Lubinski & Humphreys 1990b). Table 2, which is adapted from Lubinski & Benbow (1992), exemplifies these differences. It contains data on abilities of students tested through SMPY at Iowa State University from 1988 to 1992. Sex differences in mathematical reasoning ability are consistently found, paralleling findings described above for the entire nation. Although there are no meaningful differences in SAT-Verbal or Advanced Raven (a non-verbal test of general intelligence) scores, there are substantial differences between boys' and girls' in spatial and mechanical reasoning abilities, not unlike those observed 20 years ago by SMPY.

Thus, at age 13, sex differences in mathematical reasoning ability are compounded by differences in spatial and mechanical reasoning abilities. At the end of high school and college, these differences remain and are accompanied by differences favouring males in mathematics and science achievement test scores (Benbow & Minor 1986, Benbow & Stanley 1982, Stanley et al 1992).

Sex differences in preferences

Abilities are but one class of variables that affect educational and career decisions. Preferences for certain environments and occupational reinforcers are another. Accompanying sex differences in abilities are prominent differences in critical preferences for maintaining a commitment to careers in the mathematics–science area. Mathematically talented males as young as 13 are more theoretically oriented than females on the Allport–Vernon–Lindzey (1970) study of values (SOV) (Lubinski & Benbow 1992); furthermore, their primary interests lie in the investigative and (secondarily) the realistic (working with mechanical gadgets) sectors of Holland's hexagon of vocational interests (C. P. Benbow & D. Lubinski, unpublished work 1992, Fox et al 1976). 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 (C. P. Benbow & D. Lubinski, unpublished work 1992, Fox et al 1976, Lubinski & Benbow 1992). As Tables 3 and 4 show, it appears that females are more balanced and less narrowly focused in terms of their interests and values. Females have more competing interests and abilities, which draw them to a broader spectrum of educational and vocational pursuits.

'reference profiles according to the Allport–Vernon–Lindzey (Allport et al 1970) study of values of mathematic
d 12–14) attending one of SMPY's summer academic programmes between 1988 and 1992

		Theoretical		Social		Economic		Aesthetic		Political		Religio
Sex	*n*	$\bar{x}$	*SD*	$\bar{x}$	*SD*	$\bar{x}$	*SD*	$\bar{x}$	*SD*	$\bar{x}$	*SD*	$\bar{x}$
M	72	46.7	7.1	35.7	6.8	43.7	7.1	36.7	7.1	44.0	6.7	33.2
F	45	41.5	8.2	44.0	7.4	39.3	6.7	43.6	6.7	37.4	5.9	34.2
M	73	46.7	7.1	35.7	6.8	43.6	7.1	36.6	7.1	44.0	6.7	33.5
F	45	41.5	8.2	44.0	7.4	39.3	6.7	43.6	6.7	37.4	5.9	34.2
M	68	47.7	7.0	37.1	7.3	41.6	7.2	36.4	8.2	42.9	6.6	34.2
F	51	42.0	6.8	43.2	8.1	37.8	6.9	42.6	7.1	39.0	7.2	35.4
M	77	47.6	6.9	37.1	7.0	41.8	6.9	36.5	8.3	43.1	6.8	33.8
F	57	41.7	7.0	43.8	8.3	37.5	7.0	42.8	7.5	38.7	7.0	35.6
M	69	46.6	8.8	38.4	7.8	40.4	8.2	38.4	8.4	42.5	6.9	33.4
F	48	40.3	8.0	44.0	8.0	35.8	7.1	42.1	6.4	40.1	6.7	37.5
M	73	46.6	8.7	38.3	7.6	40.4	8.1	37.8	8.7	42.7	6.8	33.9
F	51	40.7	8.0	43.6	8.1	35.3	7.2	42.8	7.1	40.1	6.6	37.1
M	20	49.3	7.4	35.4	5.9	40.3	9.4	37.3	8.0	45.0	7.8	30.8
F	11	39.0	9.1	42.3	9.1	41.1	9.6	40.6	5.2	40.4	9.3	36.6
M	43	50.0	6.8	34.8	7.5	42.2	8.2	37.0	7.7	44.1	8.2	30.9
F	34	41.8	7.4	41.2	8.3	39.6	7.7	43.9	8.2	39.2	7.2	34.3
M	57	48.0	8.5	34.4	7.8	44.9	7.6	35.3	8.1	45.2	8.2	32.4
F	32	42.3	7.5	40.7	8.0	38.2	7.5	43.6	8.4	40.1	6.2	34.9
M	61	48.3	8.5	34.5	7.6	44.7	7.4	35.0	8.0	44.8	8.3	32.9
F	33	42.5	7.4	40.9	8.0	38.0	7.5	43.4	8.4	40.0	6.2	35.2

vho completed the entire test; 1, includes students with some scale scores missing.

TABLE 4 Vocational interests of mathematically precocious 13-year-olds assessed through SMPY according to Holland's hexagon (Holland 1985)

	Females $n = 83$	*Males* $n = 202$
Realistic	45.7	49.8
Investigative	53.0	54.0
Artistic	50.8	42.0
Social	45.1	41.1
Enterprising	44.5	47.0
Conventional	49.2	51.3

$7.5 < SD < 8.5$.

An alternative way to capture the essence of the sex differences in preferences is worth further elaboration. It takes us back to Thorndike (1911) and one of the most celebrated dimensions of individual differences, 'people versus things'. In normative samples, as well as among the gifted, females tend to gravitate towards the former, while males gravitate towards the latter (Lubinski & Benbow 1992, Lubinski & Humphreys 1990a); this dimension is found to be one of the best predictors of career choice among the highly able 10 years after its assessment (C. P. Benbow, D. Lubinski & C. Sanders, unpublished work). Given the female preference within the sciences for biology and medicine over the physical sciences (Lubinski & Benbow 1992), we have suggested that sex differences in vocational preferences are perhaps more precisely labelled as organic versus inorganic content (Benbow & Lubinski 1993, Lubinski et al 1993).

In conclusion, males are more likely than females to have a profile of abilities and preferences congruent with studying science, even among the mathematically precocious (see Lubinski & Benbow 1992). That is, in scientific disciplines, males are more likely than females to achieve correspondence for both satisfaction and satisfactoriness. The effect of this difference, however, is magnified by the huge difference between the sexes in commitment to full-time work, a difference which has remained fairly consistent over the last 20 years in SMPY investigations: 95% of gifted males versus 55% of gifted females plan to work full time until retirement (C. P. Benbow & D. Lubinski, unpublished work 1992). This latter difference is particularly important for scientific achievement because scientists of any note almost always devote extremely long hours to work. Thus, we propose that the differing ability and preference profiles and commitment to full-time work of males and females will lead them to find personal fulfillment in different careers. Moreover, given the nature of these differences (larger means and standard deviations for males in relevant abilities [Stanley et al 1992], plus larger mean differences favouring males on relevant interests and values), sex differences in science achievement should be especially pronounced at the exceptional levels.

Consequences of sex differences in abilities and preferences

Although students are not formally selected for advanced training on the basis of their theoretical values, their investigative interests, or their spatial and mechanical reasoning abilities (but they are on mathematical and verbal reasoning ability), students appear to self-select areas of concentration on the basis of these attributes, whether or not they are explicitly aware of their abilities and preferences (Humphreys et al 1993). Disparate male:female proportions in mathematics–science achievement thereby ensue. Indeed, that seems to be precisely the case for SMPY's mathematically talented individuals. SMPY's 10-year follow-up of its first cohort of mathematically talented students at age 23 revealed that more males than females were entering mathematics/science career tracks (51% versus 32%), especially in the inorganic sciences, and males had higher educational aspirations (Lubinski & Benbow 1992). Together, these trends lead to a somewhat startling result—less than 1% of females in the top 1% of mathematical ability from SMPY's first cohort are pursuing doctorates in mathematics, engineering or physical science. About 8% of such males were doing so. Similar discrepancies were found (C. P. Benbow & D. Lubinski, unpublished work 1992) for two other cohorts of mathematically talented students being surveyed by SMPY: among students with mathematical abilities in at least the top 0.5%, 12% of females compared with 27% of males were pursuing doctorates in mathematics, engineering and physical science, while among 18-year-old students in the top 1 in 10 000 in mathematical ability (SAT-M $\geqslant$ 700 before age 13) 77% of males and 47% of females were pursuing bachelor degrees in those areas. What are the prospects for the future? Will these large differences in career choice remain with us? As long as sex differences in critical ability and preference profiles remain stable, as they have done the past 20 years for the gifted, corresponding disparities along the mathematics–science pipeline will also remain.

SMPY's work in the area of sex differences suggests the Theory of Work Adjustment provides an adequate explanation of career choice among the gifted. Sex differences in achievement in the physical sciences seem to be a natural result of sex differences in personal attributes related to contrasting paths for fulfillment in the world of work—at least, that is what our data would suggest. Also, because differences in abilities and value dimensions between boys and girls are in place long before high school (Lubinski & Benbow 1992), we have suggested the hypothesis, and found evidence for it, that abilities and preferences may partly channel sex differences in specific course-work attitudes and course selection in high school and college and, in turn, directly contribute to male–female disparities in advanced educational credentials in mathematics and science (C. P. Benbow, D. Lubinski & C. Sanders, unpublished work).

Some possible biological linkages with mathematical talent

When one is confronted with sex differences such as those described above, especially those in the area of abilities, the natural question to ask is—why? Why do females, as a group, have poorer mathematical reasoning ability than males? This is a complex question, which cannot be given full justice here; we suggest the following. Our work with the mathematically talented leads us to ask not why females have poorer mathematical reasoning ability, but, rather, why there is an excess of mathematically talented males. Although most causal analyses of differences between the sexes in abilities (as well as preferences) stress socialization mechanisms (Halpern 1992, Lytton & Romney 1991), relevant variables may exist at more basic biological levels (Bouchard et al 1990).

Our investigations into the biological bases of mathematical talent have been guided by the work of the late Norman Geschwind (Geschwind & Behan 1982). Geschwind had proposed that prenatal exposure to high levels of testosterone would: (1) affect the thymus gland and, thereby, the immune system; and (2) affect the development of the left and right hemispheres of the brain in such a way as to enhance right hemisphere functioning, which, in turn, increases the likelihood of left-handedness. Geschwind put forward this theory to explain the relationship between left-handedness and various immune and autoimmune disorders as well as learning disabilities. We, however, used his theory to frame our biologically oriented work on mathematical talent, because mathematical reasoning has been suggested to be specialized within the right hemisphere of the brain. Our approach has been fruitful, leading us to identify several physiological correlates of extreme mathematical talent. These include left-handedness, immune disorders, myopia and enhanced right-hemispheric functioning (Benbow 1986b, O'Boyle et al 1991, O'Boyle & Benbow 1990, Lubinski & Humphreys 1992)—all consistent with Geschwind's hormonal hypothesis. This has now led to some electroencephalogram (EEG) studies, described below.

In two studies, patterns of brain activation or inhibition in relation to sex and precocity were investigated. EEG activity was monitored over the left and right hemispheres while gifted and average-ability subjects of both sexes viewed two types of stimuli, one type requiring verbal processing and the other requiring spatial processing. During verbal processing, gifted boys and girls exhibited greater activity than controls, with activation localized in the frontal lobes rather than in the temporal lobes, as in the subjects of average ability. During spatial processing, gifted and average-ability females did not differ from each other, but did differ from the two groups of males. However, gifted and average-ability males did differ, with gifted males demonstrating the capacity to selectively inhibit regions of the left hemisphere and thereby allow the right hemisphere to predominate in the processing. These findings suggest that different patterns of brain activation and inhibition underlie precocity and its expression in at least a subset of males, a finding that might eventually be tied to the sex differences described above. We hope that psychophysiologists and neuropsychologists will examine this possibility further in subsequent empirical research.

Conclusion

Exceptional achievements and creative contributions in mathematics, engineering and the physical sciences are within the exclusive purview of individuals with mathematical talent, a talent which can be reliably identified as early as age 13. Although many believe that being within the top 1% is sufficient for scientific excellence, there are vast individual differences within the top 1% of ability that are found to co-vary with a host of meaningful academic and vocational criteria when methods appropriate to reveal these relationships are used. Mathematical talent is not all that is necessary for the emergence of scientific eminence. Those who have the potential to manifest exceptional scientific achievements are those who also possess exceptional spatial and mechanical reasoning abilities, as well as a high theoretical orientation in combination with a relatively low social value orientation, coupled with high investigative interests. On the preference dimension for 'people versus things', exceptional physical scientists tend to be located on the 'things' end of this well-known spectrum of individual differences. Such individuals require special encounters with the appropriate environment to facilitate the emergence of world-class scientific achievement. Finally, mathematical talent seems to have biological co-variates, with the patterns of brain activation and inhibition underlying precocity and its expression differing between at least a subset of males and females.

Acknowledgement

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DISCUSSION

Sternberg: When we compare SAT or GRE test scores, we assume that the tests are equally valid for men and women, but in our sample of students admitted to Yale that wasn't true. The only test that predicted professors' ratings was that of analytical ability, but that was only for men. Nothing we looked at predicted the professors' ratings of the women. At least at the upper ability levels, the social pressures on women really are different from those on men. There is sometimes pressure on women not to do too well, and to be involved in other things such as family life, and this is as true now as it was 10 years ago.

Benbow: Many studies have shown that there is essentially no sex bias on the SAT-M test (see Benbow 1992, Benbow & Wollins 1995). We have tested this ourselves with our 13-year-olds. Basically, at the item level on SAT-M there are consistent differences favouring the males, that are small and normally distributed. The most important fact is that the SAT-M score predicts criteria at the age of 23 equally well for males and females. We can predict future academic achievement with the same precision for males and females, and we don't find, at the item level, any bias in the SAT-M test at 13 or 18.

Sternberg: Do you think our results are attributable to small sample size, or wrong criteria? The kinds of performance criteria we are talking about may be somewhat different. I know the Educational Testing Service has done a lot of studies predicting first-year grades.

Benbow: We can predict equally well for males and females whether they will choose to specialize in mathematics/science at college, amount of mathematics course-taking in high school and college, awards won, achievement test scores in science at the beginning of college, attendance at graduate school in the sciences, etc.

Sternberg: You are talking only about mathematics and some sciences. That may be one reason for the difference between your data and ours.

Benbow: There are tremendous differences between the sexes in the areas in which they choose to focus their energies and talents. Females do not choose to pursue high-level careers in the sciences with the same degree of commitment as males.

Sternberg: In psychology, at least, the women weren't doing worse, the prediction was simply worse.

Benbow: It's not the case that mathematically talented females like science or mathematics any less than such males. There are no differences between the sexes in the liking for mathematics among the mathematically talented—it's just that the females happen to like other areas just as much, that they have stronger competing interests than the males. Mathematically talented males tend to be narrowly focused on theoretical values and investigative career interests, and have less competing interests pulling them towards other areas. The females, however, score highly on theoretical, aesthetic and social values, and have investigative, artistic and social career interests. Also, they have stronger family commitments; almost half plan to work part time at some time during their life. Thus, the females have to make many more choices than the males.

Sternberg: Then you would actually expect the prediction to be different, whereas earlier you said there was no bias and the prediction was equal.

Benbow: I am talking now about sex differences in achievements, in terms of choosing a career. This is different from suggesting that scores on the SAT-M test are biased.

Sitruk-Ware: You referred to exposure to testosterone *in utero*. To my knowledge, testosterone can change only characteristics of external genital organs, phenotype and stimulate male behaviour and aggressiveness. Also, a female fetus exposed to testosterone would be born with sexual abnormalities. Could you elaborate on your ideas?

Benbow: Our ideas are based on Geschwind & Behan (1982) and Geschwind & Galaburda (1984, 1987). Geschwind showed that prenatal exposure to testosterone affected the thymus gland, and thus the immune system.

Gardner: My recollection of his hypothesis was that some sort of stress to the mother of a male in the prenatal period resulted in precocious release of testosterone.

Benbow: Geschwind, as I recall, thought that the fetus could be either highly sensitive to testosterone or exposed to high levels of testosterone.

Fowler: You described some of your findings, sex differences in EEG and similar findings, as biological. I'm perfectly willing to say that they are physiological, that you found real differences, but I'm interested in cause and consequence, and how you can determine whether boys and girls are born with such different patterns or whether they evolve in response to experiences that differentially channel their abilities.

Benbow: There is no way that you can tell. The children we studied were 13-year-olds, and a lot of things could have happened to them.

Fowler: This is an important question, though. To attribute everything simply to biology—full stop—is perhaps over-generalizing.

Hatano: Did you study strategic differences in problem-solving between sexes? For example, male students may use more visualization strategies which would induce greater activation of the right hemisphere.

Benbow: The boys may have done this. What we can pick up is that there are differences in activation patterns—that's the bottom line. Whether those differences have come about because of environmental factors or biological factors, we don't know, but what we can say is that at the age of 12 or 13, high ability girls and boys process these stimuli in different parts of the brain. Also, the way they process these stimuli differentiates them from students of average ability.

Fowler: Is there any overlap in your distributions of these physiological measures of difference between males and females? Do you find any females that look like males in these patterns, or vice versa, and, if so, what are the implications?

Benbow: There is obviously some overlap. I can only speculate on what these differences mean. The over-abundance of mathematically talented males, which is the way I like to look at the sex difference in mathematical talent, is, I believe, due to prenatal exposure to testosterone. The reason for the difference in patterns of brain activation between males and females is that there is an excess of males exposed prenatally to testosterone, and they are basically processing information in a different way from individuals not exposed to high concentrations of testosterone. This is highly speculative, of course.

Dudai: I don't really see the relevance of the testosterone theory to your findings. Norman Geschwind and Al Galaburda said that testosterone at an early age would increase or change the structure of the brain at certain loci. What you have shown is something which is in biological terms a gross finding of activation with a method which is no longer used. This tells you only about global activity, and nothing about the structure.

Benbow: Whether Geschwind & Galaburda are right or wrong doesn't really have any bearing on the validity of my findings. It was their work which prompted me to ask questions about intellectual talent and its relationship to brain activation patterns. One doesn't begin to measure EEG activity for no reason at all, without a theoretical rationale. Even if Norman Geschwind was wrong, it still behoves us to explain why I found these differences in brain activation patterns between gifted males and females, and between the gifted and those of average ability. These findings have been replicated.

Gruber: You mentioned honours and prizes. What were the honours and prizes that the top mathematical people won?

Benbow: There are many mathematics competitions at the high school level in the USA. Basically, we asked students to report how many awards they won in a mathematics area, or a science area, and so on. The awards were not necessarily specified. In my analyses I counted the number of and types of awards that the students had won.

Gruber: So are these the kinds of awards that students could normally win?

Benbow: We look from age 13 to age 23. The young person could have earned honours in his or her mathematics department, or could have won or participated in the Putnam competition, or have been in the International Mathematical Olympiad. We are dealing with academic achievement, not yet career achievement. We are now sending a 20-year follow-up questionnaire to these individuals so that we can begin to look at their career achievements.

Gardner: As I recall from earlier work, the figures are very different for Asian students. Something like half of all the mathematically high-scoring girls in the USA were Asian, I believe.

Benbow: That's true. Overall in the USA there are 13 males for every female who scores at least 700 on SAT-M before the age of 13 (though this ratio may have diminished over recent years). If you separate out the Asians and the Caucasians, the ratio becomes 4:1 for the Asians and 16:1 for the Caucasians.

We had the SAT-M test translated into Chinese and given to 13-year-old students in Shanghai and we found exactly the same ratio in China as for the Asians in the USA, 4:1. Perhaps the distributions of mathematical ability for Caucasians and Asians are separated by a standard deviation or so. Thus, if the top possible score on the SAT-M test was given a higher ceiling, say 1000 rather than 800, maybe we would find a ratio of 13:1 for the Asians too.

Gardner: This difference between Asian and Caucasian children is important, and we should think hard about what the causes might be. You have mentioned neurological differences, for example, at least in hemispheric activation, and I think there are probably differences in processing as well. Caucasian males and females probably use different strategies, though we should take care not to assume that this is a necessary condition. In countries in the South Seas, or in countries such as China and India, parents play with their children very differently. It might be that little girls might be strong in spatial ability in those places. It would be all too easy to go from your presentation to a headline in a magazine which says that 13:1 is the way it is, right hemisphere versus left hemisphere, testosterone and so on. We are asking these questions to try to get you to frame your presentation. Your claim that if we looked far enough among the Asians we would find a 13:1 ratio is pure speculation.

Benbow: Of course it is, just like your idea about playing. We just don't know. Our findings are controversial, and they can be misinterpreted, but there wasn't time for all the caveats in a 20-minute presentation.

Stanley: There's strong evidence from the International Mathematical Olympiad, in which teams of six high school youths from 50 countries compete, that females are not achieving to nearly the same extent as males. In 1988, for which full data have been published (Galvin et al 1988), only four out of the 17 females competing ranked in the medal-winning top 130. The other 13 were among the 138 who won no medal. There was one female from China in the International Mathematical Olympiad each year for four consecutive years. These four won one gold and three silver medals. The USA has *never* had a female on its International Mathematical Olympiad team, but other countries don't have many either. I suspect that the average sex difference in mathematical reasoning ability and achievement, although varying somewhat from country to country depending on the level at which elementary algebra and geometry are introduced, is international. One of the plus factors in China might be that mathematics is moved down to younger ages, enabling bright girls to handle an SAT-M-type test better because they have already studied some algebra and geometry (Stanley et al 1989).

Gardner: One of the things that my students have taught me is the importance of the millenia-long kinds of strictures about what girls and boys can and can't do. Take chess as an example. We could certainly have sat in this room 50 years ago and stated that a young woman could not be a chess player, and we would all be nodding our heads and there wouldn't be any women in the room. Now, we are beginning to see very good women chess players.

Fowler: From one family in particular. A Hungarian psychologist, believing that almost everyone could become a genius, started teaching his three daughters chess at the age of four. They are now in their late teens and early twenties and all are world-class chess players and have won numerous matches (Ingraham 1993).

Gardner: One family is enough. Once something has been established, the rules of the game can change. In domain after domain, whether play-writing, or painting or music, there have been, until this century, essentially no women, because we have had a sexist world. That doesn't mean that when the sexism disappears that there won't be any differences—I tend to agree with Camilla Benbow that there will be differences—but they could be totally different from what we could predict at this point.

Stanley: As I said, there has never been a young woman in the USA's International Mathematical Olympiad team. There is seldom one who ranks in the top eight in the country in the annual American High School Mathematics Examination (AHSME). We don't specially train students for the International Mathematical Olympiad in our country—we *choose* them carefully when they are juniors or seniors in high school. We choose the best, then train them for a month, whereas China and some other countries give a select few intense training over many years, from the age of 12 to 18 or 19 (Stanley et al 1989). It's a sort of *reductio ad absurdum* argument, anyway, to say there can *never* be a great female chess-player or mathematician. Recently, in the Putnam contest, a university level mathematics competition, in which a woman rarely ranks in the top 50, one woman ranked in the top 10. She was from Shanghai and had won a gold medal in the International Mathematical Olympiad. Prolonged, expert training does help, but it seems to take a lot more training for a female to reach the same level as a trained male.

Freeman: The Hungarian psychologist to whom Professor Fowler referred set up a foundation for training chess-players, and claims to be able to train *anybody* to the level of his daughters.

Howe: In Britain in recent years, a fairly small number of young mathematicians, perhaps half a dozen, have taken the A level examination, which is normally taken at around 18, at around eight, nine or 10. In every single case there has been very strong involvement by the father. Is that kind of involvement less common in the USA? Do you include cases such as these?

Benbow: The majority of the females in our study who scored at least 700 on the SAT-M test before the age of 13 do choose careers in mathematics and science, although the proportion who do so is smaller than the proportion of males. Those who do seem to be influenced very much by their fathers. Our mathematically talented females choose careers like those of their fathers, even if they have a professional mother with a PhD. I have noticed this paternal influence in our sample, though how you measure it and what it's impact is, I don't know.

People always claim that I am a total believer in biology. Personal attributes are the result of biological predispositions that have interacted with the environment. Of course, the environment is important; Julian Stanley and I wouldn't conduct the type of programmes that we do if we didn't believe in environmental influences. I hate being pushed into this corner. I just feel motivated to make the point that there are some biological or physiological factors that we need to reckon with.

Sitruk-Ware: We should be extremely careful before saying that physiological differences between males and females are due only to testosterone or oestrogen. The social values, the environment and the education of little boys and girls are so different and could be so important.

Benbow: I agree, but it is equally dangerous to take the other position. I was sent a letter from a female who has read our work, who said that just because she was mathematically talented people kept telling her that she should apply this ability and become a physical scientist, and she was pushed and encouraged—those were her words. Then, she participated in a talent search and was pressured even more to use her talent for mathematics. She followed all this advice, entered the Air Force Academy, and started studying mathematics. Although she did well, she did not like it. Despite all the pressures on her, she was interested in psychology, and she changed to psychology. She said she always felt guilty about leaving mathematics and not developing her mathematical talent, until she read an article David Lubinski and I had written (Lubinski & Benbow 1992) and understood why she had taken the direction she had.

There are also dangers in saying that society is responsible for all individual differences. People are born into this world with some biological predispositions, and we should allow them to develop according to their abilities and preferences. If a mathematically gifted female chooses to become a psychologist rather than a mathematician, and she is fully satisfied in her career choice, even when she looks back to it when she's 60, then that was the appropriate thing for her to have done, even if disparities between the sexes ensue. Let me be clear. I am not saying that society is perfect today or that females are making fully informed decisions. I am just highlighting the point that societal goals for equal representation of the sexes across disciplines are somewhat at odds with the notion of each individual being able to achieve personal fulfilment.

Sternberg: The argument has been made that because both women and men receive training but women are still represented in low proportions, the basis of the difference is more likely to be biological. But boys and girls are not always treated in the same way in classrooms; even though they may receive the same so-called training, their subjective experiences are not the same. Different effects can result from an objective stimulus.

Bouchard: The problem with those studies is that they never show that the treatment is correlated with the effect, so they have no explanatory power.

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Genetics and high cognitive ability

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Abstract. More is known about the genetics of general cognitive ability (*g*) than any other trait in psychology. Recent findings on the genetics of *g* include the following three examples: (1) heritability increases throughout the lifespan; (2) heritabilities of performance in cognitive tests are strongly correlated with the tests' loadings on a *g* factor; and (3) genetic effects on scholastic achievement largely overlap with genetic effects on cognitive ability. This body of genetic research addresses the aetiology of individual differences in the normal range. Much less is known about the genetics of the high end of the distribution. Finding heritability in the normal range of cognitive ability does not imply that high ability is also genetic in origin. However, the first twin study of high IQ children, which uses a new technique that analyses the average difference between extreme groups and the rest of the population, suggests that high IQ is as heritable as individual differences in the normal range. We are currently engaged in a molecular genetic study that attempts to identify specific genes that contribute to high ability.

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In this chapter we consider the genetic contribution to individual differences in cognitive abilities. The high end of these dimensions is what we denote as high ability. For three reasons, we shall focus on general cognitive ability (*g*, assessed as a first unrotated principal component or as a total score on an IQ test) rather than on specific cognitive abilities. First, more is known about the genetics of *g* than any other behavioural dimension. Second, *g* appears to be more highly heritable than any other behavioural dimension. Third, a consideration of specific cognitive abilities is not possible in a chapter of this brevity (for a review of the genetics of specific cognitive abilities in the normal range of variation, see Plomin [1988]; little is known about aetiology at the high end of these distributions).

Quantitative genetics and *g*

Quantitative genetic methods are those that involve family, twin and adoption designs that use relatives' differing degrees of genetic relatedness to estimate