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Acknowledgements
This research was supported by ONR contract N000014-83-K-0601. DEP is a Monsanto Fellow of the Life Sciences Foundation.

Possible biological correlates of precocious mathematical reasoning ability

Extreme mathematical reasoning ability, a critical component of mathematical talent, has possibly six biological correlates. These are left-handedness, allergies, myopia, and gender (i.e. being male) and possibly hormones and bihemispheric representation of cognitive functions. Extremely high verbal reasoning ability shares these same biological correlates, except gender. These results may bear on the etiology of extreme intellectual abilities.

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A majority of the events described by Kuhn[1] as 'scientific revolutions' can be ascribed to the work of individuals who were extremely talented mathematically. For this reason alone, it is important to understand the bases of extreme mathematical talent. Gardner[2] has posited that mathematical talent involves the ability to manipulate and comprehend long chains of reasoning. This mathematical reasoning ability, as distinct from the ability to apply previously learned concepts, may be a critical component of extreme mathematical talent. By contrast, computational ability seems insignificant[3].

Mathematical testing

Few tests measure mathematical reasoning ability. A highly relevant test of that ability is administered several times a year under the auspices of the College Board (i.e. by the Educational Testing Service, Princeton, New Jersey) to more than a million 16–18-year-old applicants. It is called the Scholastic Aptitude Test (SAT). Julian Stanley and his associates have used it since 1972 to find exceptionally talented youths. In the United States, some 70 000 bright students aged 13 years old or less now take the SAT each year at local administration centers. It is a secure, three-part multiple-choice test of developed ability, not primarily learned subject matter, designed for approximately the more able half of twelfth-grade students throughout the country, most of whom are 17 or 18 years old.

One part of the SAT, called SAT-V, is verbal. It consists of reading passages, antonyms, verbal analogies, and incomplete sentences. The chief purpose of SAT-V is to test the type of reading and verbal reasoning ability needed for success in a United States college or university. The other major part, SAT-M, tests mathematical reasoning ability and consists of 60 multiple-choice items to solve in 60 minutes. Only rudimentary knowledge of algebra and geometry is necessary to be able to solve the items on the SAT-M. When given to intellectually talented 12-year-olds, who have not had much experience with abstract mathematics, it is an especially good measure of mathematical reasoning. Such students have not been exposed to the content of the test and, thus, must figure out by themselves how to solve the problems (see Ref. 4). Below is a sample item from the test:

The town of Mason is located on Eagle Lake. The town of Canton is West of Mason. Sinclair is east of Canton, but west of Mason. Dexter is east of Richmond, but west of Sinclair and Canton. Assuming all these towns are in the United States, which town is farthest west?

(A) Mason (B) Dexter
(C) Canton (D) Sinclair
(E) Richmond

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In this review I shall focus on biological correlates of extreme mathematical reasoning ability, as measured by the SAT-M. This does not imply that environmental factors are unimportant since they obviously are. Instead, I wish to address the unfashionable question of whether there are *any* biological factors which are important for extreme mathematical talent.

Little research on the biological correlates of extremely high mathematical reasoning ability has been carried out. Most of it has arisen from one group, the Study of Mathematically Precocious Youth (SMPY), now located at Iowa State University and Johns Hopkins University. Four biological correlates of that ability have been identified so far. These are left-handedness, symptomatic atopic disease (allergies), myopia, and gender. Some or all of these biological correlates may be related to bihemispheric representation of cognitive functions or the influence of fetal hormones. If so, these may be two additional biological correlates of extremely high mathematical reasoning ability.

Left-handedness

Although no overall differences in general intellectual functioning between left- and right-handers have been generally found[5], there may be differences in certain aptitudes. It was previously believed that right-handedness was advantageous. Left-handers were believed to be 'psychoneurotic, epileptic, stutterers, reading-disabled, mentally retarded, mirror writers, poor in penmanship, deficient in spatial and artistic sense, stubborn, resistful of authority, inclined to lives of crime and moral dissolution, dirty, homosexual or bisexual'[6]. More recently, however, it has been found that left-handers may show high performance levels on tasks mediated by the right hemisphere of the brain. The traditional view is that among right-handers the right hemisphere is specialized for non-verbal tasks and the left for verbal, although these differences are quantitative rather than absolute. Thus, non-righthandedness has been positively associated with spatial ability and musical ability[7,8] (although there are opposing viewpoints; see, for example, Ref. 9). Moreover, higher frequencies of left-handedness have been found among university mathematics teachers and students, music students, artists, astronauts, and architects[8,10,11].

Mathematical reasoning ability, in contrast to computational ability, is probably more strongly under the influence of the right hemisphere in normal right-handers[2,3,12,13]. Thus, it would seem reasonable to expect that left-handers have an advantage in such tasks. Indeed, a slight advantage favoring left-handed school children on a numerical reasoning test has been found[14]. Moreover, left-handedness (and mixed-handedness) has been related to extreme mathematical talent[12,15]. Compared to their parents, siblings, a comparison group of same-age students, and population norms, young adolescents who had scored extremely well (top 1 in 10000) on a test of mathematical reasoning ability were much more frequently left-handed[12,15].

A counter-intuitive result is that extremely high verbal reasoning ability (top 1 in 10000) has also been associated with an increased frequency of left-handedness[12]. This seemingly anomolous result might be explained by the fact that the ability measured was verbal *reasoning*. Because verbal reasoning ability involves comprehension, analogical reasoning, and the understanding of difficult words, it is probably more under the influence of the right hemisphere than language production or syntactical aspects of verbal ability[16].

The comparison group used in the above study on left-handedness[12] was well above average in ability, but not extremely intellectually talented. Since there was not an especially increased incidence of left-handedness in that comparison group, it may be that left-handedness is simply associated with extremes in ability at either ends of the scale. Indications are that both dyslexia and acalculia (learning disability in mathematics) are also associated with left-handedness[17]. This may explain why no *overall* differences in general intellectual functioning between right- and left-handers have been consistently reported.

Symptomatic atopic disease

Symptomatic atopic disease (allergies) is another trait associated with extreme ability. As with left-handedness, extremely precocious mathematical or verbal reasoners were about twice as likely to have allergies as members of the general population[12]. Such extremely able students were reported by their parents to have a higher incidence of allergies than the parents themselves, their siblings, or a comparison group of students. Although this finding is consistent with widely held stereotypes about the gifted, no other study has formally reported this relationship, as best could be determined.

Myopia

Myopia has been frequently correlated with higher general intelligence[18,19]. A slight difference in IQ scores favoring myopic individuals has been reported. In my study of extremely high mathematical and verbal reasoners, a dramatically increased rate of myopia was found[12]. Extremely high ability students were about four times as likely to be myopic as were high school students in the United States and were again much more frequently myopic than their siblings and a comparison group.

Gender

A rather controversial and emotional topic is whether extremely high mathematical reasoning ability is or is not a biological correlate of an individual's sex. Many studies have reported sex differences in mathematical aptitude and achievement[20,21]. These studies indicate that sex differences in mathematics do not seem to occur consistently until after or at puberty and only then in areas requiring reasoning[21]. More than one major study has, however,

reported differences for seven- to nine-year-olds (Dougherty, K., Herbert, M., Edenhart-Peper, M. and Small, A., unpublished observations). It is important to emphasize that no sex differences have been found in computational ability or the ability to apply already-learned concepts[21].

Sex differences in mathematical reasoning ability have been reported among highly talented pre-adolescents[4,22]. In those studies, a test of mathematical reasoning ability (i.e. SAT-M) was administered to 49 747 gifted pre-adolescents. In the 9 administrations of that test over a period of 11 years, males have scored consistently higher than females by approximately one-half standard deviation[4,22]. Since then more than 100 000 additional students have been tested across the United States with similar results, and these findings have been replicated in other countries as well. Although the consistent mean difference favoring males has important implications, the significant result is that the sex difference is especially large among the most talented. There were many more extremely mathematically talented boys than girls (e.g. at the top 1 in 10 000 level there are about 12 males for each female). This large sex difference seems to have important long-term consequences[23].

That biological factors may be involved in causing the sex difference is given credence by the fact that solely environmental explanations of those results have proven lacking[4,15,22,23]. For example, among students who took the mathematical reasoning test, there were no sex differences in attitudes towards mathematics[23,24] and course-taking[22,23]. Additionally, there was no evidence on the basis of sex for any differential encouragement by parents for the study of mathematics[25,26].

Hormones

Male and female hormones (androgens and estrogens, respectively) have been frequently implicated in the production of sex-related differences in spatial ability. (Spatial ability is considered to be a function more efficiently carried out by the right hemisphere[27] and to be possibly related to mathematical performance.) Androgens appear to exert permanent organizing effects on the structure of the central nervous system, including the brain[28]. Moreover, performance and intelligence varies among hormonally different groups in a manner consistent with the hypothesis that androgens before or at puberty are importantly related to the development of spatial ability[29,30]. Since very high androgen levels are associated with low spatial scores among males and with high spatial scores among females[31,32], there may be an optimal androgen–estrogen ratio. For the related hypothesis that onset of physical maturation is associated with the development of cognitive abilities, Waber[33] has recently failed to find support.

Hypotheses dealing with prenatal exposure to hormones and their effect on brain development have fared better, however. It has been shown that progesterone exposure enhances numerical ability[34]. Levy and Gur[35] proposed that high levels of fetal sex hormones promoted the maturational rate and cognitive capacity of the right hemisphere. Interestingly, first-borns compared to later-born siblings are exposed to higher levels of hormones prenatally[36] and have frequently been found to score higher on intelligence tests. Moreover, Geschwind and Behan[17] have postulated that left-handedness and immune disorders, such as allergies, are related to exposure to high levels of testosterone in fetal life or to high fetal sensitivity to testosterone. They have suggested that testosterone slows the development of the left hemisphere and thereby enhances the development of the right hemisphere. It simultaneously affects immune development. It was in response to this hypothesis that we studied left-handedness and immune disorders among intellectually talented youth. Since left-handedness and allergies were related to extremely high levels of mathematical or verbal reasoning ability, pre-natal exposure to high levels of testosterone may be another correlate of extreme levels of those abilities. Moreover, special talents have been exhibited by learning-disabled individuals, who are also more frequently left-handed[37]. Geschwind and Galaburda[37] in an extensive review discuss the above issues at length. It should be kept in mind, of course, that overall intelligence is a multi-faceted trait and that these studies deal with but portions of it.

Bilateralization

The above left-handedness findings have implications for brain functioning. Left- and mixed-handers and right-handers with left-handed relatives (perhaps only among males) have been found more frequently to have bilateral representation of cognitive functions[27,38]. Thus, it has been proposed that bilateral or diffuse representation of cognitive functions (rather than greater specialization of the hemispheres) is associated with extremely high mathematical and verbal reasoning and spatial ability[7,12,15,38]. A preliminary study using a computer simulation of a tachistoscope was consistent with this view[39]. The lack of a control group, however, limits the interpretation of the experiment. Nonetheless, bilateral representation of cognitive functions may be another biological correlate of extremely high mathematical reasoning ability.

Such a connection becomes even more intriguing in the light of recent results by Witelson[40]. She found that the corpus callosum, the main fiber tract connecting the two cerebral hemispheres, is larger in left- and mixed-handers than in right-handers. Thus, the 'greater bihemispheric representation of cognitive functions in left- and mixed-handers may be associated with greater anatomical connection between the hemispheres'[40]. Can this relate to extremely high mathematical or verbal reasoning ability as well?

Conclusion

In conclusion, several biological correlates of extremely high mathematical reasoning ability have been identified. These are left-handedness (and mixed-handedness), immune disorders, myopia, and gender (i.e. being male). We hypothesize that possibly bihemispheric representation of cognitive functions and prenatal hormones (e.g. prenatal testosterone exposure) may also be biological correlates. In addition, all except gender may be associated with extremely high verbal reasoning ability.

Geschwind[17,37] postulated that prenatal exposure to high levels of testosterone may affect immune development and also enhance right hemispheric functioning and thereby increase the likelihood of being left-handed or mixed-handed. Although the effect of testosterone could specifically enhance the development of the right hemisphere of the brain, it may also work to make individuals more variable. This has been previously suggested for physical maturation[33]. If linkage of prenatal testosterone exposure to left-handedness, intellectual precocity, learning disabilities, and immune disorders is established, as it has been for being a male, then it would be consistent with this viewpoint. Males have been found to be statistically more variable than females in a number of traits.

The basis for the relationship of myopia to extremely high mathematical and verbal reasoning ability, as well as high general intelligence, is obscure. A hereditary component, not related to left-handedness and allergy, has been implicated[12,18]. Although hormonal explanations for the emergence of myopia have also been offered, they generally have not received scientific support.

Ethnicity may be another correlate of extreme mathematical reasoning ability. There is an over-representation (at least 13 times as many as expected) of Asian-Americans among extremely talented mathematical reasoners, whereas this group was only slightly over-represented among the extremely able verbal reasoners[12]. Although this latter finding is interesting, it is difficult to interpret. Asian-Americans immigrating to the United States, especially from Taiwan, Korea, and India, Pakistan and Banghladesh, tend to be highly educated and highly motivated to achieve. Finally, bloodtype was not found to be a biological correlate of either verbal or mathematical precocity, although it was found to be related to social class in England[15].

In summary, four biological correlates of extremely high mathematical reasoning ability have been identified so far and two hypothesized in an area still in its infancy. These are left-handedness, allergies, myopia, gender, and possibly hormones and bihemispheric representaion of cognitive functions.

Acknowledgements
I should like to thank Robert M. Benbow, Linda E. Brody, Lola L. Minor, and Julian C. Stanley for comments and helpful suggestions and Lois S. Sandhofer for preparation of the manuscript. Support was provided by the US Department of Education and the National Science Foundation (MDR-8651737).

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