THE ORIGINS AND DEVELOPMENT OF HIGH ABILITY

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Contents

Symposium on The Origins and Development of High Ability, held at the Ciba Foundation, London, 25–27 January 1993

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Novartis Foundation Symposium
Edited by Gregory R. Bock, Kate Ackrill

Introduction

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> *Genius . . . is the capacity to see ten things where the ordinary man sees one, and where the man of talent sees two or three,* plus *the ability to register that multiple perception in the material of his art.*
>
> Ezra Pound 1935

It is my pleasure to call this symposium to order, and, in particular, to thank the trustees, executive council, and staff of the Ciba Foundation for their gracious hospitality. In the course of hundreds of occasions since its first scientific meeting in 1949, the Foundation has more than fulfilled Lord Beveridge's promise of a 'laboratory for mixing scientists'; it has been a major catalyst in the discovery process. I am sure that I speak for those present, and many who are not, in commending the Ciba Foundation for its outstanding contribution to the scientific enterprise.

We are here as guests of the Foundation to discuss the origins and development of high ability. For the purposes of these introductory remarks, and in keeping with the spirit of the papers to be presented, I would prefer to address the topic of high ability in terms of its limiting case: *genius.* This may seem an old-fashioned word, which some might fear carries too much baggage from bygone scientific excursions, but 'genius' has the virtue of evoking the 'big picture', reminding us that these discussions bear upon long-standing, fundamental, and largely unresolved issues of human psychology. Until proven wrong, therefore, let me assume that the terms 'high ability,' 'giftedness,' and 'genius' can be treated as synonymous—and that it is useful to do so, lest we find ourselves either mired in semantic debates or waffling on the distinctiveness of our subject-matter.

The phenomenon of genius has provoked thinkers for many centuries, probably because it presents itself as inexplicable. In antiquity, the Romans spoke of the genius of a person or *place*, meaning its indwelling, protective demon or tutelary spirit. By the sixteenth century this idea had been metaphorically extended to describe the innate capacity of a person (Onions 1966, p 393). Since the eighteenth century, the word has come to refer chiefly to extraordinary native intellectual power, and, ironically, the original, spatialized meaning is now a source of metaphoric usages (e.g., 'the genius of the nation').

This drift in meaning did not affect the essential property of genius, however, which is its singularity *vis-à-vis* normal intelligence and conventional ways of thinking. Whether viewed as rising mysteriously from within ('native') or mysteriously from outside ('demonic') the psyche, genius is *special*; it is both different and rare.* This feature makes the 'genius of genius,' so to speak, especially difficult to capture. We cannot predict where genius will occur or how it will manifest itself. We do not know its causes or correlations, or, with any certainty, how to measure it. We are not even sure what it is—but we know genius when we see it.

Paraphrasing Whitehead, one can ask: what can be done to obscure the vast darkness of this subject? Before the members of this symposium move to answer this question, let me briefly indulge a chairman's privilege by proposing a few framing issues.

The largest of these issues—one of the largest in all of the twentieth century behavioural science—is that of Nature versus nurture. Depending on the view one takes of genius in this respect, various subsidiary questions follow. Thus, if genius is innate, existing from birth, is it a product of genetic mutation or some other genetic event of extremely low probability, or is it inherited in a more or less normal fashion?

What are the evolutionary implications of these alternatives? The rarity of genius suggests that if it is subject to normal inheritance processes, it is not a trait or combination of traits for which there is strong positive selection. This would not be surprising, in view of the conservative nature of most human populations, for most of human history. In contrast with normal high intelligence, which has probably enjoyed Nature's favour throughout human phylogenetic history, persons of strikingly different and unpredictable mental habits might well be at a disadvantage in the game of reproduction and survival. Seneca's famous comment that there is no great genius without some touch of madness reflects a widespread wariness in folk attitudes, one which over the aeons may have contributed to maintaining the rarity of genius.

All of this might soon change. Nowadays, sperm banks with designer genes, *in vitro* fertilization, futuristic cloning techniques, and other biomedical technologies have created a eugenics that could significantly increase the incidence of genius in the population. As we speak, the Human Genome Project is deciphering the hiddenmost codes of mental functioning. Purposive evolution is a risky, ethically troubled business, but we can be sure that if the technology exists to maximize the chances of genius among offspring, many aspiring parents will avail themselves of it. Given that such procedures are likely to remain expensive, such tinkering can only widen the disparities between rich and poor, the educationally advantaged and the educationally deprived.

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*Note that the word 'gifted' displays the same ambiguity as to where the 'gift' comes from.

In both evolutionary and contemporary terms it matters how society interprets genius, and also how genius interprets itself. Whether in a social setting or in the privacy of one's self-image, differentness may be an unwelcome, disturbing feature—something construable as eccentricity, inadequacy, or, as we have seen, madness. In a society that exalts intellectuality and tolerates personal differences, genius can realize itself; but such societies are rare in human experience, and we must believe that genius has been stifled, wasted and destroyed far more often than it has flourished. What cautionary lessons can be learned from the *failed* genius of individuals or entire cultures, prodigious abilities that withered before their time?

If genius is not innate, or not necessarily so, other problems arise. The move to generalize from singular instances cannot proceed without some common features among those instances, and yet the environmental factors that produce genius are far from clear. Present understanding of the intrauterine environment allows only a gross assessment of how hormones, nutrients, toxins and other factors affect later mental ability. Biographies, notoriously, are as unique as the individuals they describe, blurring any identifiable pattern among the remembered childhoods of adult geniuses. The anthropologist Paul Radin once speculated that genius occurs with about equal frequency in all societies; what differs are the intellectual and material conditions under which it may or may not manifest itself (Radin 1927).* Although lacking in hard evidence, such a view does blend the innate and the acquired in a plausible way, implying that education can, in principle, maximize the *realization* of genius when and if it occurs in a population. Would Mozart or John Stuart Mill have been prodigies or adult geniuses without rigorous parental discipline and hard work on their part? Not according to Thomas Edison, who described genius as 'one per cent inspiration and ninety-nine per cent perspiration'. But that one per cent makes all the difference, leaving us again with the problem of how to account for that crucial factor. Not only for the sake of scientific discovery, but also in the hope of elevating the quality of mental functioning in human populations generally, it is important that we continue to bring new concepts and methods to this challenge.

In closing, let me recall the prologue from Ezra Pound, for it anticipates a more modern, perhaps more fruitful, line of approach to our topic. Whatever may be its origins in Nature and/or environment, whatever may be its relationship to normal intelligence, giftedness embodies a remarkable *style* of thinking. Whether the domain is mathematics, music or chess, the cognition underlying 'genius' is marked by unusual modes of perception, mental

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*Following in the tradition of Spengler and Toynbee, Alfred Kroeber (1944) tried unsuccessfully to devise a theory of culture history that would account for bursts of creative genius.

integration, memory retention and memory deployment.* With rapidly developing advances in parallel-distributed processing, neuropsychology and other areas of cognitive science, we may be on the verge of solving, or productively reformulating, some of the old problems of genius, once and for all.

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*Similarly, Arthur Koestler (1964) has argued that moments of creative insight involve a 'bisociative' merging of two or more separate, seemingly incompatible frames of reference.

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The concept of 'giftedness': a pentagonal implicit theory

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Abstract. This paper presents a pentagonal implicit theory of giftedness and a set of data testing the theory. The exposition is divided into five parts. First, I discuss what an implicit theory is and why such theories are important. Second, I describe the pentagonal theory, specifying five conditions claimed to be individually necessary and jointly sufficient for a person to be labelled as gifted. These conditions not only help us understand why some people are labelled as 'gifted', but also why some others are not. Third, I consider the relation of the pentagonal theory to explicit theories of giftedness. Fourth, I present data supporting the theory. Finally, I discuss some implications of the pentagonal theory for gifted education.

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Why is a child who scores in the top 1% on the Wechsler Intelligence Scale for Children much more likely to be labelled as 'gifted' than one with a 100 metre sprinting time in the top 1% of his or her age cohort? Why is a physicist who is considered number 1 in the country by his peers or another panel of judges considered gifted, whereas the criminal at the top of the police's most-wanted list is not? Why do contestants in major beauty contests, such as the Miss America Pageant, have to answer questions about issues perceived to be of domestic or international importance, whereas contestants in the major scientific competitions, such as the Westinghouse Science Talent Search, do not have to submit to judgments of their personal attractiveness? The pentagonal implicit theory of giftedness (Sternberg 1994), described herein, seeks to answer these and related questions.

The nature of implicit theories

Implicit theories are not public or formal; rather, they are intellectual constructions that reside in individual people's minds (Sternberg 1985a, Sternberg et al 1981). Such theories can be discovered through questions and inference, and are often revealed by behaviour. Typically, however, we do not examine our implicit theories closely until questioned; we simply employ them in making our everyday judgments of the world and of those who inhabit it. For example, we each have an implicit theory of what constitutes charisma, and when we meet other people, we judge them against the standards of this unspoken construct. Similarly, we each have an implicit theory of what constitutes giftedness.

Contrasting with implicit theories are explicit theories, the constructions of psychologists or other scientists that are based or at least tested, in psychology, on data collected from people performing tasks presumed to measure psychological functioning. Explicit theories have dominated the literature on giftedness (see Sternberg & Davidson 1986 for a collection of such theories). Theorists specify what they believe to be the elements of giftedness, and then try to verify that their claims are psychologically or educationally valid.

Why even bother to study implicit theories of giftedness? What difference does it make what a layperson thinks when there are well-informed theorists who have devoted their professional lives to studying and judging the problem? There are at least four reasons why it is worthwhile to understand people's conceptions (implicit theories) of giftedness. First, discovering such implicit theories can be useful in helping to formulate the common cultural views that dominate thinking within a society—what we mean, for example, by 'giftedness'. Second, understanding implicit theories can also help us understand or provide bases for explicit theories, because explicit theories derive in part from scientists' or other researchers' implicit theories of the construct under investigation. Third, implicit, not explicit, theories have the most influence on actual everyday life and practices. People's generalized implicit theories of giftedness, for example, determine how decisions about identification are made. Fourth, if we want to change our ways—to improve our criteria for identifying the gifted—we need to know exactly what those ways are.

Implicit theories of giftedness are important, because they provide a dimension of understanding that cannot be obtained through the study of explicit theories. This does not mean that explicit theories are unimportant. Rather, both kinds of theory are needed, and they should be studied in conjunction. Implicit theories provide the form or structure by which we define giftedness, whereas explicit theories provide the content that is embedded within that form or structure.

The pentagonal implicit theory of giftedness

The goal of the pentagonal implicit theory of giftedness is to capture and systematize people's intuitions about what makes an individual gifted. The theory, summarized in Fig. 1, is that in order to be judged as gifted, a person needs to meet five criteria: (1) the excellence criterion, (2) the rarity criterion, (3) the productivity criterion, (4) the demonstrability criterion, and (5) the value criterion.

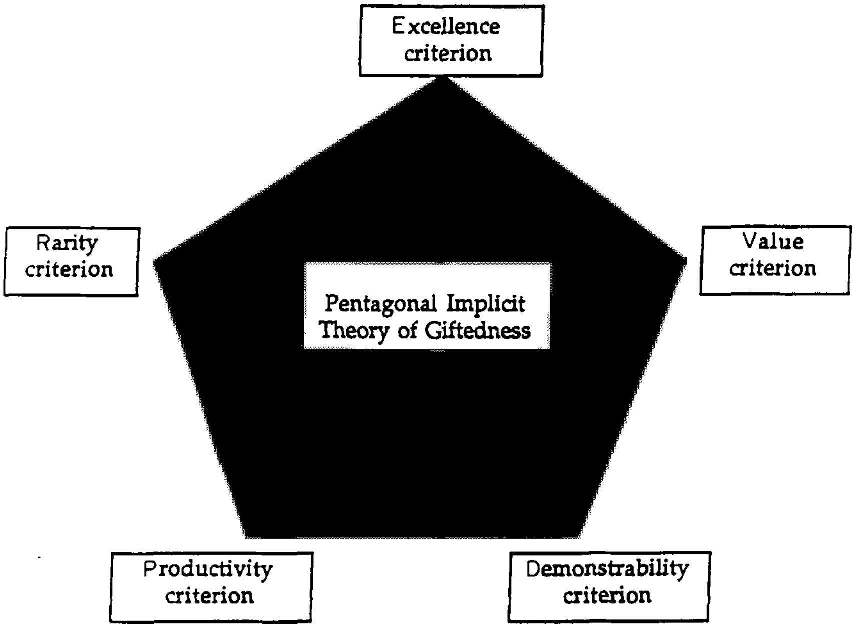

FIG. 1. The five individually necessary and jointly sufficient criteria of the pentagonal implicit theory of giftedness.

The excellence criterion

The excellence criterion states that gifted individuals are *superior to their peers in some dimension or set of dimensions.* To be gifted, one has to be extremely good at something, in psychological terminology, high in a judged dimension or dimensions. The qualification that this must be relative to peers is necessary because the designation of excellence depends upon the skills of those against whom one is judged. A 10-year-old's raw score on an intelligence test might convert into a very high score relative to children of the same age, but would seem unexceptional in comparison with children five years older. Similarly, a musical performance that would be exceptional for an eight-year-old taking weekly music lessons at school might be quite undistinguished for an eight-year-old who has been trained at a conservatory since the age of four.

The rarity criterion

For individuals to be labelled as gifted, they must show a *high level of an attribute that is rare amongst their peers.* The rarity criterion is needed in addition to the excellence criterion, because even if a person performs well in a given area, the person will not be viewed as gifted unless a high performance in this area is rare. Suppose we give a test of mastery of the basics of the English language to a class of students at a good university. They should all receive high scores on the test, because all should be fully proficient in the basics of English. But even if all of them got perfect scores, we would not say that they were all therefore gifted. Thus, one may display excellence, but unless such excellence is rare, one is not likely to be viewed as gifted.

The productivity criterion

The productivity criterion states that *the dimension(s) along which the individual is evaluated as superior must lead to or potentially lead to productivity.* Consider again the contestants in the beauty contest. Why is it that they must answer questions about issues of the day, rather than merely being judged solely on their appearance? Appearance is probably the major determinant in the contest, so why is it not sufficient? Despite the fact that the contest is really about beauty, beauty in itself is not perceived as productive or potentially productive. The contestant needs to demonstrate that she can *do* something beyond simply looking good. In contrast, the contestant in a scientific competition is not judged on other dimensions such as personal appearance, because the scientific work itself—the basis of the contest—is viewed as productive.

The productivity criterion generates disagreements over exactly who should be labelled as gifted. Some, for example, believe that a high score on an intelligence test is not sufficient grounds for viewing a person as gifted; scoring highly does not show that the person can 'do' anything (e.g., Gardner 1983). To others, getting a high score on the test is considered as doing something in and of itself; at worst, it shows only the person's potential for productivity.

In childhood, of course, it is possible to be labelled as gifted without having been productive. In fact, children are typically judged more on potential than on actual productivity. As people get older, however, the relative weights of potential and realized potential change, with more emphasis being placed on actual productivity.

The demonstrability criterion

The demonstrability criterion states that an individual's *superiority in the dimension or dimensions which determine 'giftedness' must be demonstrable through one or more tests that are valid assessments.* The individual needs to be able to demonstrate, in one way or another, possession of the abilities or achievements which led to the judgment of 'giftedness'. Simply claiming giftedness is not enough. Thus, a person who scores poorly on all measures used in assessment, and who is unable to demonstrate possession of special abilities in any compelling alternative way, will not be viewed as gifted.

The assessment instrument used, however, must be valid, that is, each instrument must measure what it is supposed to measure. Suppose that a job candidate gives a brilliant talk, suggesting unusual gifts both in research and in presentation, but then, when asked about the content of the talk, is unable to answer even the simplest of questions. Members of the audience will gradually conclude that the candidate was somehow ‘programmed’, probably by his adviser. The talk would then be invalid as a measure of the candidate’s abilities, because it did not actually reflect his gifts (or lack thereof).

The validity issue has become extremely important in recent years in the identification of intellectually gifted schoolchildren. In the past, many schools were content to use standardized intelligence tests, and perhaps grades in school and scores on achievement tests, as bases for identifying children as intellectually gifted. As the focus of testing has been shifting more and more towards an emphasis on performance- and product-based assessment, however, some have questioned the validity of the traditional measures (e.g., Gardner 1983, Renzulli 1986). Someone who would have been labelled as gifted under traditional measures might not be so labelled now. The implicit theory of giftedness may not have changed, but what is considered as a valid demonstration of giftedness may have.

The value criterion

For a person to be labelled as gifted, *that person must show superior performance in a dimension that is valued by his or her society.* The value criterion restricts the label of giftedness to those with attributes that are valued as relevant to giftedness. The individual at the top of the police’s most-wanted list might be superior in one or more dimensions, possessing a rare ability to perform certain malevolent acts, and able to demonstrate this skill upon demand. The individual may even be highly productive, if in a criminal way. But because what he is so good at is not valued by society at large, he is not likely to be labelled as gifted by the general population, though he might well be by a pack of thieves. The pentagonal theory allows that what is prized as a basis for giftedness may differ from one culture or even subculture to another.

Implicit theories are by nature relativistic—there is never any guarantee that people’s personal values will match across time and space—but implicit theories, as noted above, provide the best practical form or structure by which to identify the gifted. For a judgment to occur according to strict standards, one needs to add content to implicit theories. This is the role of explicit theories, considered next.

The role of explicit theories

Implicit theories are necessarily relativistic, because perceptions are often dependent on time and culture. Consider, for example, intelligence. We know from studies of implicit theories that what people consider to be intelligent differs across time and place (Berry 1984, Serpell 1974, Wober 1974). In contrast, explicit theories of intelligence attempt to specify just what intelligence is, so that whether a given person is *actually* intelligent—according to a given explicit theory—will depend upon the person's standing as measured by that theory. Note the importance of the qualifier, 'according to a given explicit theory'. The judgment made is still relative to an explicit theory, and, as we know, such theories differ.

Consider, for example, two contemporary theories of intelligence, that of Gardner (1983) and that of Sternberg (1985b). According to Gardner, a person of extraordinarily high musical ability is *intellectually* gifted by virtue of the superiority of his or her *musical* ability. According to Sternberg, such a person is musically gifted; the person is *not* intellectually gifted by virtue of the superior musical ability, although that individual might well be intellectually gifted on the basis of further information.

In short, explicit theories provide definitions of content, but we are still left with the judgments that the explicit theory is derived from. The problem is that in the science of understanding human gifts, we do not yet have certainties. There are no explicit theories known to be totally and absolutely correct, and there are not likely to be any in the foreseeable future. Nevertheless, the combination of implicit and explicit theories can help us understand both the structure people instinctively use for labelling others as gifted, and the more objective content (or specific scales) they use to give force to these labels.

The weakness of current explicit theories is shown, I believe, by a study now in progress that I am conducting with Wendy Williams. We looked at scores on the Graduate Record Examination (GRE), a test widely used in the USA for admission to graduate schools, for all students admitted to Yale University's graduate (PhD) programme in psychology over the past 12 years. The test yields four scores: verbal, quantitative, analytical and achievement (in our case, in psychology). We used these scores to predict a variety of dependent measures: (a) grades in the first and second years of graduate study; (b) dissertation advisers' ratings of their principal advisees' analytical, creative, practical, overall research, and overall teaching abilities; and (c) dissertation readers' ratings of graduate students' dissertations. The group of readers does not include the dissertation adviser. We found that the GRE score predicted grades, but only in the first year of graduate study. Of the four subtests, only the analytical provided significant, though relatively weak, prediction of faculty ratings, and the significant prediction was for males only. Thus, the standard kind of psychometric theory giving rise to the GRE did not provide meaningful prediction of performance in our psychology graduate programme. Moreover, a similar study in the economics department at Yale yielded similar results.

Of course, our graduate students are relatively gifted, and one might argue that with somewhat more range, better prediction would be obtained. To test this hypothesis, we repeated the prediction analysis, but using only the top and bottom quartiles of the sample, which greatly increased the standard deviations of our test scores. Using this procedure, we found that although prediction of grades in the first year increased, prediction of faculty ratings did not. In fact, the only significant correlations we had found earlier with faculty ratings—those for GRE analytical with male subjects—were not significant in the more extreme sample. Using the top and bottom and deciles greatly increased prediction of the first-year grades, but again had no effect on prediction of faculty ratings. Thus, restriction of range seems to have reduced correlations with grades, but not with faculty ratings, which are the more meaningful assessment of student performance in graduate school. Indeed, in the US system, graduate grades in doctoral programmes are usually considered of relatively little consequence, and when students apply for faculty positions their grade record is often not even required, because research and teaching abilities are seen as paramount, not grades.

In contrast, a strong explicit theory can have real educational value. In another study conducted with Pamela Clinkenbeard, high school students (generally age 16–17) were admitted to a summer programme for gifted students run at Yale on the basis of outstanding analytical, synthetic–creative or practical–contextual abilities, along the lines of the triarchic theory of human abilities (Sternberg 1985b). Students admitted to the programme were taught introductory psychology via techniques that emphasized either analytical, synthetic–creative or practical–contextual applications of the material. Students were randomly assigned to sections, so that a student high in a particular ability might or might not be placed in a course section corresponding to his or her strengths. The progress of all the students was evaluated with assessments that stressed analytical, synthetic–creative and practical thinking. We found that students did better in the course when they were matched to a section corresponding to their strengths, especially when they were evaluated in terms of their stronger abilities. Thus, we found matching between type of giftedness, on the one hand, and methods of teaching and assessment, on the other. In other words, when a strong theory is used to identify, teach and assess the gifted, one can get better educational outcomes than when such theory-based intervention is absent.

The GRE measures primarily analytical as well as memory abilities. The Triarchic Abilities Test we used in the high school summer identification programme measured synthetic–creative and practical–contextual abilities as well. But do people look for excellence in any kinds of ability at all when drawing on their implicit theories of giftedness? The data described below address this question.

Data

Does the pentagonal implicit theory actually capture people's intuitions about giftedness? Do people really use these criteria in making their evaluations of others? We decided to find out. In the spring of 1992, we tested two groups of subjects: 24 students, 12 male and 12 female, at Yale University, and 39 parents of gifted children (of whom 18 were male and 21 female) in Connecticut, USA. Roughly half of the males and half of the females evaluated boys; the other half evaluated girls. We gave each subject brief descriptions of 60 imaginary schoolchildren. Each description included the following items:

(1) How the child scored nationally on a given standardized test (described as 'good', 'mediocre', 'excellent', etc.).

(2) How this score ranked within the child's school (e.g., in the top 20%).

(3) How accurate the school felt the given test was in predicting gifted performance.

(4) What value the school placed on a given test as a measure of giftedness.

(5) The number of independent projects (pre-screened for high quality) a child submitted.

(6) What value the school placed on independent projects as a measure of giftedness.

The subjects then made two evaluations. On a scale of 1–6 we asked them to rank (1) *How likely* it was that *the school* would identify this child as gifted and (2) *How likely* it was that *they personally* would identify this child as gifted.

The experiment was designed to allow use of multiple regressions to predict ratings of likelihood of the schoolchildren being identified as gifted (the dependent variable) from the six independent variables in each description. The six independent variables fit into the pentagonal implicit theory as shown: (1) excellence, Statement 1; (2) rarity, Statement 2; (3) productivity, Statement 5; (4) demonstrability (i.e., validity), Statement 3; (5) value, Statements 4 and 6. Thus, a significant regression weight for any criterion would indicate its use in judgments of giftedness.

Among the 24 students, overall mean ratings on the six-point scale were 4.26 for girls/school rating, 4.13 for girls/self rating, 4.15 for boys/school rating, and 4.07 for boys/self rating. Mean ratings of boys and girls did not differ significantly. Among the 39 parent subjects, these means were, in the same order, 3.99, 4.18, 3.85 and 4.08. Of greater interest here, though, are the results of the multiple regressions, which are summarized in Tables 1 and 2. The results are practically identical for the two samples.

Statistically significant regression weights were assigned to excellence, rarity, productivity and value of the test in all four multiple regression analyses.

TABLE 1 Summary of multiple regression analyses: Yale University students sample

	β (Standardized regression coefficient)			
Rating (statement)	*Girls/school*[a]	*Girls/self*[b]	*Boys/school*	*Boys/self*
Excellence (1)	0.32***	0.73***	0.28***	0.55***
Rarity (2)	0.45***	0.38***	0.25**	0.23***
Productivity (5)	0.37***	0.22***	0.44***	0.58***
Demonstrability (3)	0.00	0.13**	0.03	0.28***
Value (4)	0.49***	0.26***	0.50***	0.19***
Value (6)	0.26***	0.10*	0.28***	0.07
R^2	0.78***	0.91***	0.68***	0.87***
Root-mean-square error	0.46	0.33	0.60	0.38

[a]Test subjects were asked to rank the likelihood of an imaginary girl's school identifying her as gifted.
[b]Test subjects were asked how likely it was that they personally would identify this girl as gifted. (See text for further details.)
*$P<0.05$; **$P<0.01$; ***$P<0.001$.
$n=24$ students.

TABLE 2 Summary of multiple regression analyses: sample of parents of gifted children

	β (Standardized regression coefficient)			
Rating (statement)	*Girls/school*	*Girls/self*	*Boys/school*	*Boys/self*
Excellence (1)	0.33***	0.53***	0.34***	0.49***
Rarity (2)	0.29***	0.35***	0.24**	0.37***
Productivity (5)	0.34***	0.50***	0.44***	0.67***
Demonstrability (3)	0.02	0.25***	0.00	0.11**
Value (4)	0.50***	0.28***	0.43***	0.18***
Value (6)	0.44***	0.20***	0.35***	0.13**
R^2	0.76***	0.90***	0.68***	0.91***
Root-mean-square error	0.49	0.24	0.66	0.26

*$P<0.05$; **$P<0.01$; ***$P<0.001$.
$n=39$ parents.

The weight for the independent projects (Statement 5) was statistically significant in all but one regression. Interestingly, our subjects believed that *they* would take validity (demonstrability) into account in their evaluations, but that the *school* would not. Subjects also believed that they took excellence into account more than would the school, whereas the school's system of values

(Statements 4 and 6) was clearly seen as more important to the school than it was to the subjects doing the ratings. Patterns of weights were similar for evaluations of boys and of girls.

Overall levels of prediction were quite high, with R^2 values varying from 0.68 (corresponding to a multiple correlation of 0.82) to 0.91 (corresponding to a multiple correlation of 0.95), with a median of 0.82 (corresponding to a multiple correlation of 0.91). These values were somewhat higher for the self ratings than for the school ratings, which makes sense, because subjects are more likely to believe they know their own implicit theory than that they know the implicit theory of the school.

These results are generally consistent with the pentagonal implicit theory. They suggest that people take into account the five points of the theory in making evaluations, and believe that the school takes into account all of the points except instrument validity (demonstrability). Of course, our population of subjects was a limited one, and we plan to do further research with other populations.

The implications for educational practice

Consider how the pentagonal theory, in combination with explicit theories, helps us to address standard questions of identification and instruction that arise about the education of the gifted. The pentagonal theory does not answer these questions, but rather suggests directions that answers might take.

What percentage of children should be identified as gifted?

This question is often asked as though there is a 'right' answer, when of course there isn't. The pentagonal theory helps us address this question by separating two often-confounded concepts that ought to be distinguished: excellence and rarity.

Our use of norm-based measurement, which practically equates these two concepts, leads us into confusion. All of us who have taught know that in one year we may have an 'excellent' class, in which many or even most of the students perform at a very high level, whereas in another year we may have a weak class, in which few do well. One way of using the pentagonal theory is to suggest that we identify as gifted that percentage of students whose performance on some set of standards meets a pre-set criterion of excellence, and for whom we have the resources to provide special services. We will thereby acknowledge that our limitations in identification reflect not only students' abilities, but also our own ability to serve such students.

What constructs or measures should we use to identify the gifted?

The pentagonal theory makes clear that there is no one 'right' construct measure, or even set of constructs or measures, that we 'ought' to use. Rather than simply doing what we do because it has always been done that way, we need to take responsibility for stating explicitly just what it is that we value and why. If we care about the potential of an individual to contribute to himself, others, and society in a productive way, we need to justify why the measures we use will help to identify such potentially productive individuals.

What kind of educational programme is ideal for gifted children?

Debates about the best programme for gifted children take on a different character when viewed from the standpoint of the pentagonal theory. Again there is no 'right' answer to the question; rather, we again need to ask ourselves what we value. If we value rapid learning, then acceleration makes sense. If we believe that what matters is the depth or care students take in probing into what they learn, enrichment will be preferable. If both are prized, a combination might be best. Whatever we do, we should ensure that the values expressed in the instructional programme are the same as those expressed in the identification programme.

In conclusion, the pentagonal implicit theory provides a basis for understanding how people assign the label of giftedness to some individuals but not to others. It suggests the framework supporting such judgments, whereas explicit theories fill in possible and alternative contents. By understanding implicit as well as explicit theories, we obtain a better grasp of what giftedness might mean, not only as specified by psychological or educational theorists, but also by the people who make the day-to-day decisions about giftedness. For they are theorists too—in fact, the ones who most affect the lives of us and our children.

Acknowledgement

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DISCUSSION

Freeman: Many teachers are not encouraged to use their implicit theories and are actually taught how to recognize gifted children. My reading suggests there are two distinct kinds of stereotype about gifted children either side of the Atlantic. The image of a gifted child in the USA would be one who is taller than average, probably blond and blue-eyed, male, of course, good at sport and what they call in the USA 'leadership', with straight A grades in everything, a child who is very popular and will go on to do well. The British stereotype is completely different. It is male, again, but small, rather thin, what we would call weedy, wears glasses, and is quite incapable of relating to other people and so is known as a loner. Such a child would be good at one thing, probably mathematics, music, or some other intellectual pursuit.

How can you assess gifted children with your pentagonal implicit theory of giftedness? How can children fulfil the productivity criterion and demonstrate their giftedness in the same way that adults can?

Sternberg: In studying implicit theories, one is trying to find out what the stereotypes are, to find out how people process the information. It is important to know this, in part so that one can know where interventions should be made.

I don't see any reason why younger children can't do basically the same kinds of projects that older children do, but at a lower level. I have worked with elementary school children to guide them in developing psychology experiments. Often teachers of the gifted have the idea that the children cannot do anything creative, and so feel that all they can do is to provide faster presentation or more difficult presentation of the usual material. After watching me work with their children, the teachers are often surprised that the children can come up with ideas for experiments and how to execute them more easily than can many undergraduates and early graduate students. The conventional wisdom is that the children later have the creativity knocked out of them. If you work with young children along the lines I suggested, there's no reason why they can't do, at an appropriate level, the kind of project work that an adult might do. They won't be as sophisticated, but they can deploy the same skills. In some of our studies of creativity, young children in the upper elementary grades (age 9–12) do just fine on science projects, producing advertisements or writing short stories.

Fowler: Are you dealing with a question of alternatives, IQ or GRE or SAT (scholastic aptitude test) versus some other performance-type measure? Can there be a combination? Can one have a high IQ and also be creatively gifted?

Sternberg: In my triarchic theory of intelligence, which specifies analytical, creative and practical abilities, the three kinds of abilities often have a low correlation. There's no reason for them to be uncorrelated, because, according to this theory, the same basic processes underlie all three. What differs is levels of experience. With creative abilities, what's novel for one person may be familiar for another. Moreover, test content that's familiar in one culture often is not in another. With respect to practical abilities, what's contextually relevant for one person may not be for another. We have studied practical intelligence in managers and salespeople, to test their tacit knowledge of what is needed for success in a practical setting. We have found no correlation of results on our tests with IQ within the ranges in which we have looked. We think that within a given context, those people who are able to take advantage of the environmental resources are not necessarily the people with high IQs.

Gruber: Could you speculate a little about effect size? In your study of GRE results those correlations which were significant were still only about 0.25 or 0.30, and that would reduce their importance for practical implementation. In other words, the effect size is small. One conclusion you have drawn from your triarchic model is that the abilities of the student should be matched to the teaching method. This is a very promising and interesting idea, but how much do you hope for from it in the light of the low correlations?

Sternberg: I'm not really interested in whether or not GRE scores predict grades. We included grades as a criterion as an afterthought, because I knew someone would say that GRE scores don't predict anything at all because of restriction of range. So, I thought it would be better if I could show they predict something; and what they predict is grades. The prediction is meagre. I'm claiming that GRE scores weakly predict something, so that you can't say that their failure to predict more interesting criteria is due to the fact they don't predict anything. The effect size is small, but that's all that anyone has ever found, at the graduate level. Our correlations are similar to those obtained by the Educational Testing Service for predicting graduate study grades.

The idea of matching abilities to teaching is, I think, significant. Creative children, who have a lot of potential, tend to be put into an accelerated curriculum, where they are taught the same material as in school, but faster.

That approach will not help them to take advantage of their creative giftedness. In contrast, it makes a lot of sense to put analytically gifted children in an accelerated curriculum, to the extent that you want them to benefit maximally from the form of giftedness they have.

Consider some of our major business executives and entrepreneurs. A lot of these people later don't give money to universities or schools. They say, 'Look, here I am, making $700 000 a year, whereas that nerdy PhD is making $50 000 a year, though he was the one who got all the awards in school'. The idea behind this matching is that there may be people who are practically gifted in such a way that they could be the entrepreneurs, managers or leaders of the future, even if they are presently not recognized as gifted. My idea is to try to recognize these people, then teach them through a curriculum that enables them to show what they are good at. We need to make sure that we assess them appropriately. If we teach them in a practically based curriculum, but then give them a multiple-choice memory test at the end, they won't be able to show what they've learned. Even in our gifted programmes in the USA there are often bad mismatches, where a child is identified as gifted by a broad method but then appears stupid in the class because the instruction and assessment don't match the method of selection. Another example is a child from a low socio-economic class who may have developed practical skills. You might not identify such children as strong analytically, but they may appear strong practically. They can use mathematics in their everyday lives, working as street vendors or, for that matter, dealing in drugs, but this wouldn't be revealed by conventional tests.

Hatano: I wonder if in people's naive theories of competence being gifted is synonymous with having high ability or being expert. Your five criteria can be applied to all three concepts—high ability, giftedness and expertise—but maybe the discounting principle works differently. To be characterized as gifted, one needs not only to meet those five criteria, but also to do so with a minimal amount of practice or without good environmental support. High ability does not presuppose minimal practice. That's why the Japanese are not very interested in the measurement of giftedness. We believe it is difficult to measure giftedness, because we do not usually know how much we should discount, whereas it's quite possible to measure high ability. In our society, when a test or exam is set, many students treat that test as a target and practise for it. This makes it almost impossible to measure their giftedness.

Sternberg: If you have a test assessing the actual criteria directly, maybe practice is not such a bad thing. If you are interested in developing the ability to write short stories, or to do artwork, or to come up with science experiments, and you are using those as criteria for admissions also, what's wrong with practice? If the students are studying for aptitude tests measuring less criterion-relevant behaviour, you might argue that their time would be better spent in philosophy, history and sciences courses, and so on. If the criterion is what you are assessing, then the practice is time well spent.

You asked why we should identify gifted children anyway. I can speak better for the USA. I have two children at a local school, who are bored out of their minds, doing the same things again and again, learning hardly anything, and we are now considering putting them into fee-paying schools. One of the reasons for doing this, at least in the kind of slowly moving educational system that we seem to have, is to try to get these children into situations where they can have better learning experiences, where they're not bored, and where they don't turn off intellectually. The advantage of having some form of identification of the gifted is that, ultimately, one of the best resources that a society has is its very gifted people. If we can help them develop their talents by matching instruction to ability, and if we can then assess them appropriately, we may find that we have a lot more productivity than we do in a society in which we stick them all in a classroom and hope for the best.

Gardner: I thought your results about the GRE were quite stunning, but imagine you had presented them to a group of graduate admissions committee heads in psychology or chemistry or English literature. How do you think they would react?

Sternberg: I have done so, so I can tell you what happened! I presented my findings to the directors of graduate studies of the various graduate programmes at Yale. As I mentioned, the economics department had done a similar but more limited study, with similar results, suggesting that the lack of meaningful prediction is not limited to psychology. Most of the people were, I think, impressed, but there is likely to be less change in action than in conceptualization—it's a very entrenched system. The best predictor of how the directors felt about the GREs after my talk was how they felt before. Those who were somewhat sceptical became more sceptical; those who were strong believers could always find some other variant or some other study that would make you more confident about the results.

Gardner: The crucial question is, if you could show them a better predictor, would they use it? My more cynical inclination is to think that these instruments fit political, social and economic purposes which don't have much to do with their predictive power. Admission practices would be hard to change no matter what the results were.

Sternberg: After getting these results, we got permission from the Dean of the Graduate School to go back to the admissions files and code other sources of data, such as the students' application essays, their past research experience, their letters of recommendation, the qualifications of the people who wrote these letters and various other things. We are hoping to discover whether there are other, better predictors of meaningful graduate performance in their records. I doubt anything will change soon. There's a lot of vested interest in the existing tests.

Fowler: I'm not against identifying giftedness in any form, or trying to expand and diversify learning experiences, but I would hate to give up on the general population. When people like Herbert Kohl (1968) get into ordinary classrooms and open things up a bit, they discover that lots of children can be creative. Are we to give up on our whole educational system? Can't we try to diversify learning experiences for almost everyone?

Sternberg: I'm not going to get into a genetics versus environment argument—obviously there are genetic contributions to intelligence—but within the environmental portion, we can do a lot to help people develop and make the most of whatever abilities they have, through what Reuven Feuerstein would call mediated learning experience, or what Lev Vygotsky called internalization. If mediators—parents and teachers—interact with children in ways that emphasize higher level responses to questioning, they can help in the development of children's giftedness.

With Howard Gardner, we have developed a programme to encourage practical and creative intelligence in children in the sixth grade (about 11–12 years). I do believe that we can help kids take what they have and make the most of it. However, these programmes don't eliminate individual differences. How an individual changes and what happens to mean levels of performance are different questions.

Hautamaki: In your triarchic theory you make the division between analytical, creative and practical ability. From my experience, any attempt to match the developmental level of a child to the formation of mental abilities requires a developmentally open process. You have to be attentive to the child's needs and goals, and this requires, from the perspective of intervention, a close relationship between the meaning of a mental act and its objective content. This dual position affects the growth of abilities. How do you think these three aspects develop?

Sternberg: I think that they do develop, and that rank orders can change with time. Motivation is important too, as is personality. In our creativity work, we include in our theory facets of intelligence and knowledge, but we also include facets of thinking styles, personality, motivation and the environment. Intelligence is only a part of the total picture. Consider language learning. I used to think that I couldn't learn another language, and I was tottering along trying to learn Spanish, and then I met Alejandra, now my wife, who spoke only Spanish, and discovered that I was a good language learner. If you are motivated, very often, whatever your ability or achievement level, you can do much better.

Stanley: In any prediction system in which you use various variables for prediction, they're not usually treated independently. For example, a student with a low SAT score admitted to a school such as Johns Hopkins would probably have had very good grades in high school. The same is probably true for graduate school; the correlation is not restricted only by restriction of range explicitly, but also by the fact that compensatory criteria are used. For a student with a 340 score on SAT-Verbal to be admitted, he or she must have shown overwhelming superiority in other areas.

Sternberg: I totally agree with you. This is an important point. For every student with a score of 340 who was admitted, and there were a few, there were many not admitted who had done other things which were equally or more outstanding, but who hadn't got in *because* of their 340 score. I'm not claiming that the people admitted with low scores are a random sample of people with those low scores—clearly they're not. What I am concerned about, though, is that there are people who have high creative and practical or even analytical abilities that are not revealed by examinations, and few of these people will make it through the admissions barrier. I'm concerned about the misses, not the false alarms. The false alarms, those with high GRE scores that can't do anything else, merely waste some money and some faculty time, then they go off and do something else. There are lots of children, the misses, who don't make it on the standard kinds of assessment—the A levels in the UK and the GREs and the SATs in the USA—who might be absolutely outstanding on other kinds of measures but will never have the chance to make the contributions to society of which they might be capable. These test scores contaminate you. Once you have those numbers, even if people acknowledge that the numbers provide only one measure among many, they still use them, and they use them heavily. Let's give those people who are outstanding in ways other than test results a chance.

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Giftedness and intelligence: one and the same?

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Abstract. Giftedness, like other rare phenomena, is often explained by principles beyond those used to explain the normal variation of mental ability. Before parsimony is abandoned and additional principles are invoked, the following five points should be considered. (1) Gifted samples often have restricted ranges, reducing correlations with intelligence and making standard tests insensitive to relationships that may exist. Though this is an obvious point, it is frequently overlooked. (2) Theories of intelligence that view *g* as a single global ability are inadequate. Intelligence is better seen as a complex system of independent but interrelated parts. Measures of *g* are global ratings of system functioning, but global measures do not explain mental ability in terms of either more basic cognitive abilities or underlying brain functioning. More basic explanations of intelligence are essential for understanding giftedness. (3) Correlations among intellectual abilities are lowest for persons of high intelligence. Specific skills will be less highly correlated among the gifted. (4) Heritability of cognitive abilities may differ across the intelligence range, though evidence on this point is mixed. (5) Achievement and intelligence are different things. Discrepancies between intelligence and achievement are due to environment. Such a finding is consistent with the idiosyncratic development of giftedness.

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There is no more important topic today than the treatment of gifted individuals in developed countries. The topic has immense importance to the entire world. As the technical revolution advances in industrialized countries, there will be fewer and fewer jobs which require simple repetitive activity or back-breaking labour. The fate of nations competing in an international arena will depend on the quality of their work-forces. By 'quality' of the work-force, I mean the cognitive ability of the work-force. Intelligence is what will be important. Companies and countries will succeed by innovation. Innovation within a company or country will depend on how much talent it has available and on how well it can cultivate that talent. There may come a day when countries compete as ferociously for talent as they now compete for territory.

Not surprisingly, the study of outstanding ability is in its infancy. By definition, outstanding ability is rare. Things like large earthquakes, volcanic eruptions, tornadoes and exceptional human achievement are hard to study because they are rare. Rarity does not mean that these phenomena require special explanatory principles. It is my thesis that we should first attempt to explain exceptional human accomplishment using the same principles that apply to intelligent behaviour across the entire range of ability. The important question is how much of exceptional achievement can be accounted for by contributions from variables such as intelligence, personality, motivation, etc. When we have a full understanding of outstanding achievement, it is my guess that the largest single portion of difference among people will be due to intelligence. I predict that over 50% of the variance in exceptional achievement will be predicted by intelligence in the full range of ability.

There is a tendency, particularly in the USA, to underrate the importance of native talent in accomplishing exceptional achievement. For example, Thomas Edison claimed that genius consisted of 1% inspiration and 99% perspiration. Although that may have been true for Thomas Edison, for the rest of us, inspiration might be harder to come by.

The full range of ability is seldom considered when exceptional achievement is studied. Usually attention is focused on a highly selected group of subjects. An appreciation of the problems of studying exceptional ability requires an understanding of the complications that can occur when only one extreme of the distribution is studied. I shall discuss five issues that are important to keep in mind when attempting to account for exceptional achievement.

Restricted range and test insensitivity

The first, and, I hope, most obvious, difference in studying outstanding accomplishment is that outstanding persons come from an extremely restricted range of ability. Consider outstanding musical accomplishment. Suppose someone develops a music IQ test that rates people's musical accomplishment on the same scale as an IQ test. This music IQ test will have a mean of 100 and a standard deviation of 15. A large sample of people are given the test and a researcher selects 100 persons who have musical ability that is more than five standard deviations from the mean. In other words, all subjects in the sample score more than 175 on the music test. Now the researcher gives each person an IQ test. A correlation of 0.10 between IQ and the music IQ test is found. Is it reasonable for the researcher to conclude that IQ has no relationship to musical ability? No—that would be the wrong answer. When the correlation is corrected for restriction in range, a value of 0.65, a substantial relationship, is obtained.

The reason it is so easy to be wrong about correlations in restricted samples is shown in Fig. 1. As a group is selected with increasingly strict restrictions,

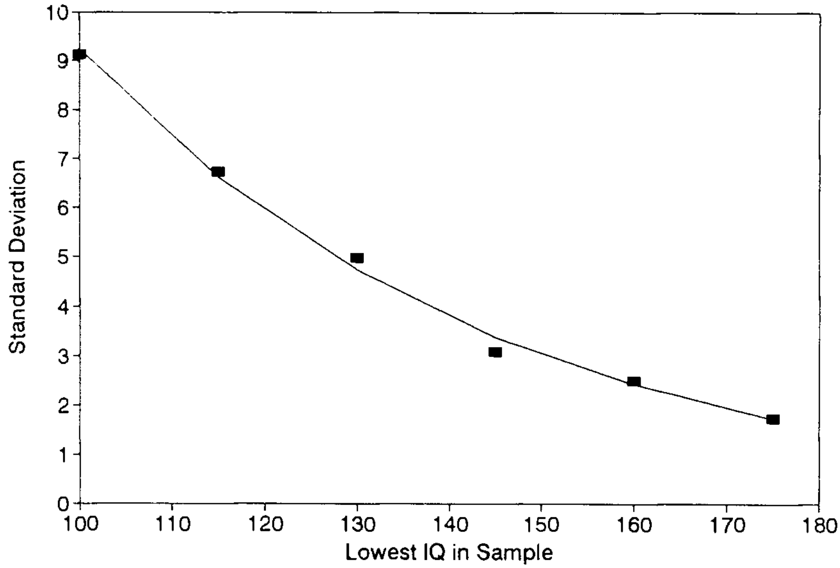

FIG. 1. An exponential fit of Monte Carlo data (left-most four points) of the standard deviation (y-axis) obtained when samples are selected from 3000 cases so that all cases are above a certain score (x-axis). The population standard deviation is 15 and the mean is 100. (The right-most two points were obtained by extrapolation because Monte Carlo samples did not generate sufficient numbers of cases.)

the standard deviation of the group decreases. Figure 1 shows the standard deviations for groups of increasing restriction. The x-axis shows the cut-off used to form the group. The point at $x = 100$ shows the standard deviation of a group selected so that all subjects obtain a score of 100 or higher. The second point shows a group composed of subjects with scores of 115 or higher. These points were obtained by averaging five Monte Carlo samples selected from an overall sample of 3000 subjects. Figure 1 clearly shows the effect restriction of range has on the standard deviation. As the sample becomes more restricted, the standard deviation decreases. This is important for correlational studies, because the sample correlation is not an accurate estimate of the population correlation unless the sample and population standard deviations are the same. For a given population correlation, the sample correlation decreases in proportion to the decrease in the standard deviation caused by the restriction in range. Most researchers appreciate this fact, but many are not aware of the size of its effect.

Figure 2 shows what the population correlation would be for different sample correlations and for different degrees of restriction in range. The previous example had a sample correlation of 0.1 and a cut-off of 175. The point at $x = 0.1$ for the curve labelled '175' shows a population correlation of about 0.65. This example may seem extreme, but consider a restriction of range only two standard

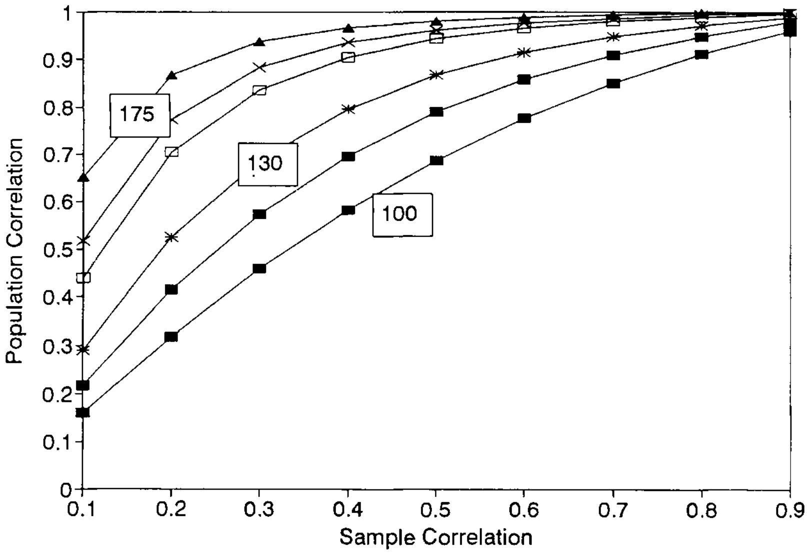

FIG. 2. The relationship between sample correlations (x-axis) and population correlation (y-axis) for various degrees of restriction of range. Each curve represents an additional standard deviation of restriction of range where the standard deviation is 15 and the mean is 100. Scores in boxes are the lowest score in the restricted sample.

deviations from the mean. Subjects are picked who have a musical IQ equal to or above 130. Now, suppose the correlation between musical IQ and standard IQ for subjects in this restricted sample is 0.1. What is the population correlation coefficient? According to Fig. 2, the population correlation is about 0.3, a not insignificant correlation, about as high as the correlation between the scholastic aptitude test (SAT, a college selection test) and college grades. When moderate degrees of selection cause moderate restriction in range, the effect on correlations can be large enough to change the interpretation of results. No one would pay much attention to a correlation of 0.1, but correlations of 0.3 and 0.65 are another matter.

The effect of restriction of range on correlations means that caution is required in the study of extreme groups. Intelligence is probably an important causal variable of many exceptional human abilities. It is inappropriate to exclude intelligence as a cause in favour of less parsimonious explanations because of low sample correlations. That would be like saying that mental retardation has nothing to do with intelligence because there are low restricted range correlations of adaptive behaviour with IQ, or that height is unimportant in basketball because height at NBA (National Basketball Association) centres has a low correlation with basketball skills.

Another danger is that curtailed ranges can lead to absolutely wrong conclusions about which variables are causal. Graduate students are heavily selected on intelligence, but the sample correlation of IQ with accomplishment in graduate school is low. Performance in graduate school is probably better predicted by personality and motivational variables, given that students have already been selected on the basis of intelligence. It is wrong to conclude that personality and motivation are the primary causal factors in graduate student accomplishment. Anyone who believes that should admit graduate students from the full IQ range and see what happens.

A failure to understand the effects of curtailed range on causal variables may lead to inappropriate conclusions being drawn about what the causal variables really are. I predict that much attention will be devoted to motivational and personality variables in many fields of exceptional achievement. It is so easy to overlook the primary causal variables by examining sample correlations without taking into account the effects of restricted range. Such an emphasis on secondary variables can lead to the conclusion that anyone can be a person of exceptional accomplishment if they are properly motivated and do the right things. Personality and motivation should be studied to understand what differentiates people of the same intellectual ability. These variables are not the primary determinant of graduate school performance—they cause differences among matched subjects. The same line of reasoning applies to any study of samples of restricted range.

A partly related issue is the discrimination of tests. Current tests are developed with a normal sample of perhaps 3000 persons. In a sample of that size there are likely to be few persons with an IQ of 145 and none with IQs of 160 or 175. The deviser of the test selects items to discriminate best among members of a normal sample. That means that test items discriminate less well at the extremes where there are fewer persons than in the centre of the distribution where there are more. Most tests will not provide the kind of discrimination needed to study groups who are extreme in the ability being tested. Many researchers overlook the implications of this obvious point. Suppose musical ability is perfectly correlated with IQ within a group of subjects with extremely high musical ability. The correlation between IQ and muscial ability will be zero according to standard tests of intelligence because IQ tests are not designed to discriminate among people of very high ability.

Theories of intelligence

Another issue in the relationship between intelligence and exceptional ability is the theory of intelligence often implicitly adopted. Spearman's *g* is a virtually undeniable empirical phenomenon. A battery of mental tests will always produce a large, general first factor when factor-analysed.

This empirical fact suggests to some (e.g., Eysenck 1982) that Spearman's *g* is a single ability. This interpretation makes it hard to understand how exceptional individual abilities exist unless they are different from intelligence.

How can the idiot savant be explained by g? How can the mathematical genius who has trouble making his own breakfast be explained by g? Spearman's g, viewed as a single ability, predicts uniform levels of performance across mental skills for a single person.

Spearman's g need not be interpreted as a unitary ability. I suggest (Detterman 1982, 1986, 1987a,b, 1992, Detterman et al 1992, Kranzler & Jensen 1991) that Spearman's g represents several independent basic cognitive abilities combined in a complex system. The key to understanding intelligence and exceptional ability is understanding the basic cognitive skills within the system in which they are embedded.

Intelligence is similar to any other complex system. Cities are complex systems. Global ratings of the desirability of living in cities in the USA are available. Such a ranking is published regularly in *Place's Rated*. The global rating of a city is equivalent to IQ. Both IQ and the city rating are global ratings of the efficiency of a system.

Systems are better understood, though, in terms of more basic properties. Figure 3 shows how the global ratings of both cities and intelligence might be related to more basic processes. Such basic variables are the key to understanding how either intelligence or cities operate.

Difference in correlations across the range of ability

Another frequent assumption is that the structure of intellectual ability is the same for all persons across the range of ability. This assumption seems to be wrong. We (Detterman & Daniel 1989, Detterman 1991) have found that the correlation among subtests for IQ tests and cognitive ability is higher for low ability subjects than for high ability subjects.

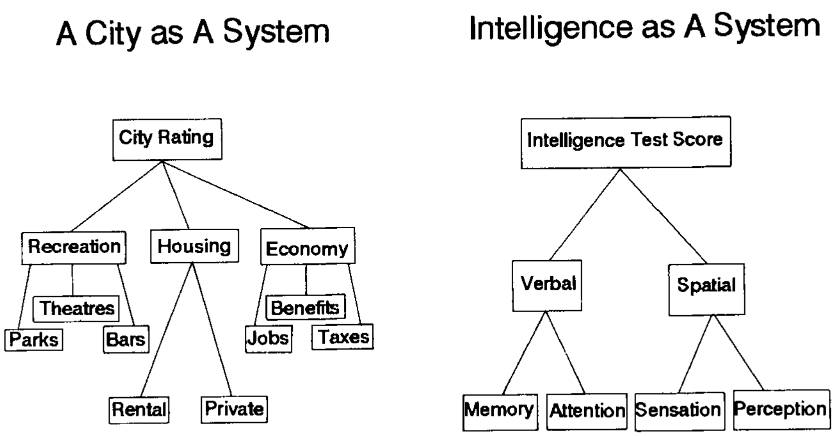

FIG. 3. A city and human intelligence as complex systems. The top box for both systems represents a global rating that is best understood in terms of more basic processes.

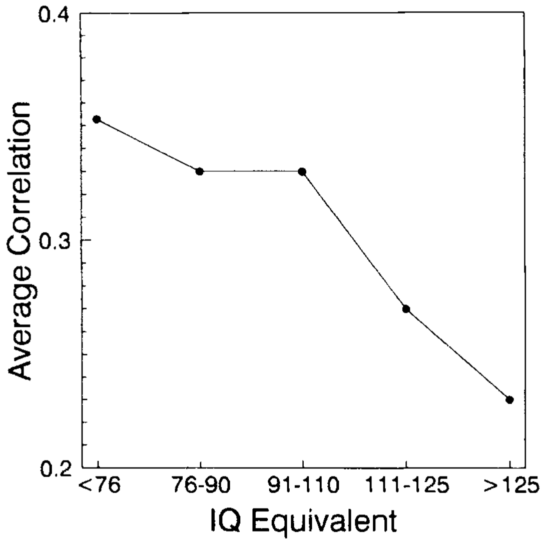

FIG. 4. Differences in correlations among subtests for different ability levels for the Kaufman-ABC standardization sample. Correlations were corrected for restriction in range. Lower ability groups show higher average correlations among subtests than higher ability groups.

These results have been replicated for the Kaufman-ABC (D. K. Detterman & M. Persanyi, unpublished work 1990), an intelligence test widely used in the USA. One subtest was used to split the normative group subjects into five groups varying in ability. Correlations among all other subtests were then assessed within each of these ability groups. The correlations obtained were corrected for restriction in range. The corrected correlations were then averaged across subtests. This procedure was repeated with each subtest to form the ability groups.

Figure 4 shows the results. Lower IQ children and adults show much higher subtest correlations than high IQ subjects of the same age. This finding is consistent with data for other intelligence tests and basic cognitive ability tests that have been analysed. I have not found this effect for achievement tests.

The differences in correlation across IQ level are consistent with the systems theory of intelligence (Detterman 1987a). In this theory, lower IQs result from deficits in important cognitive processes. Because these processes are part of a system, they affect the functioning of other parts of the system. If these important processes are deficient, the parts dependent upon them will also be impaired. Essentially, a deficit in an important process will put an upper ceiling or limit on the efficiency of the operation of other parts of the system. That means that all parts of the system will be more similar if there is a deficiency in an important process. This forced similarity in abilities is what causes a higher correlation among IQ subtests for low IQ subjects. Higher IQ subjects show more variability in abilities because their abilities are not limited by an artificial ceiling imposed by a deficit.

The lower correlation among ability measures for high IQ subjects has important implications. High IQ subjects will show a much wider variety in patterns of cognitive skills than low ability subjects. It would not be surprising to find a person with a high IQ whose mathematical ability far exceeds his verbal ability, but it would be surprising to find a difference of the same magnitude between mathematical and verbal ability among low IQ subjects. A professor of mathematics whose verbal skills are several deviations below his mathematical skill may not be unusual; one would be unlikely to find a person of low IQ who showed the same degree of deviation, though.

These findings have other implications. Should methods of education be different for low and high IQ persons? Should different methods of assessment be developed for high IQ persons? Current methods are best at assessing global functioning, not particular individual skills.

Differences in heritability

Detterman et al (1990) examined heritability across the IQ range in a preliminary sample of twins. They found higher heritability of Spearman's *g* at the low IQ end of the distribution. Since that study, every possible outcome has been obtained by others and by the original authors with their complete data set. About the only conclusion that can be drawn is that IQ may not be equally heritable across the ability range, but firmly establishing this will require large sample sizes.

It makes sense that heritability of IQ might differ across ability levels. The other side of this coin is that environmental influences are greater if heritability is less. Perhaps what a mentally retarded person is able to accomplish is more a function of genetic influences than environment whereas those with higher IQ might be more influenced by environment. It is also possible that mentally retarded persons would have more trouble finding appropriate environments on their own. Environmental interventions would have greater impact. Educational theorists who suggest that mentally retarded persons need extra educational help adopt this latter viewpoint.

Achievement and intelligence are different

Thompson et al (1991) found that general levels of achievement were highly predicted by the heritable component of Spearman's *g*. Evidently, both achievement and IQ are based on a common set of genes. Discrepancies between IQ and achievement, however, were associated with environmental differences.

Thus, much of the achievement is due to inherited ability, but when a person fails to achieve as expected from their IQ, the difference probably results from environmental influences. This finding makes a great deal of common sense, suggesting as it does that optimum environments will result in minimum discrepancies between IQ and achievement. Even with individually optimum environments there will be big differences in achievement between persons. Education, even at its very best, will never erase the ability differences between people.

Conclusions

These five points suggest that understanding the role of intelligence in exceptionality will not be easy. It is important to remember that the fact that intelligence doesn't have a simple relationship to exceptionality doesn't mean that there is no relationship.

When exceptional people are studied, it is natural to concentrate on what makes each person in the group unique. A question that should not be neglected in the process is why these persons are exceptional in the first place. Only when we understand the differences between and within groups will we know how important intelligence is to giftedness.

Acknowledgements

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DISCUSSION

Gardner: It would be uncontroversial to say that general intelligence a standard deviation above the mean is necessary if a person is to do something distinctive or remarkable. Beyond that, I wouldn't think that general intelligence is much of a factor. The last part of your talk, and some of your written work, said, as I would tend to, that a person needs a certain general intelligence, but that a much more specific type of intelligence determines where a person goes, whether into a language area, or a spatial area, or a musical area. How highly do you rate a person's general resource capacity in comparison with other more specific factors?

Detterman: Data I have collected show that *g* will be more important at the low IQ end. *g* will be extremely important for persons of low IQ, and will become less important as ability increases. That doesn't mean that individual cognitive abilities don't work as a single unified system. It just means that the individual abilities are working together better in a well-functioning system than in a poorly functioning system. The brain works as a unified system, and if we understood the parts of that system, we could explain exactly why somebody becomes what they are.

Bouchard: You really do need both *g* and special mental abilities. Giftedness is probably a combination of both, plus motivation. There are compelling reasons to think that there are specialized units in the brain that deal with spatial ability or verbal ability, etc. The brain is an integrated organ; the central nervous system integrates the behaviour of the organism as a whole. When evolution was selecting us for particular spatial skills (primates lived in trees) and for certain kinds of verbal abilities, it was working with some fundamental units—neurones and particular biochemical properties. The brain is permeated by those things. Thus, there are some features common to each of the specialized skills. So, there are both specialized units and commonality.

That has implications for whether general intelligence is more important at the higher end or the lower end of the dimension. It's probably equally important at the high and low ends. At the low end, the specialized units are not functioning as well, *and* the integration, the functional activity of the nervous system, is not as good. At the high end, both are functioning well.

Detterman: In system theory, some processes are considered to be more central than others. Systems theoreticians talk about 'centrality', which can be measured. Centrality of a particular part of the brain is high when that part influences many other parts of the system. If centrality equals one, that part of the brain affects everything. There may not be processes with a centrality of one in the brain. What you are really saying is that there is a central process in the brain that affects everything. I'm not sure a brain constructed in that way would be a good brain.

Bouchard: Consider this question from the point of view of an evolutionary psychologist. What was the context in which human organisms survived and evolved? For survival in a Pleistocene environment we probably did have features of our brains with a centrality of one. In a Pleistocene environment, if spatial ability fails you're kaput! If the integrative function of the brain fails, you're kaput! In the modern world in which we live that's no longer true; we can live with one peculiarly specialized function and survive, but we wouldn't have done so in a Pleistocene environment.

Eysenck: Spearman did not think that intelligence was a thing, and was opposed to the reification of intelligence. He always thought that intelligence was a concept, and he contrasted it with other concepts. You are saying that concept relates to related but independent parts, which seems to me an oxymoron *par excellence*. Things are either related or independent—they can't be both.

Detterman: They can be both. They can be measured independently, but still be related by the processes that go on within the system. The number of theatres in London could be measured independently of other aspects of London. Across cities, the number of theatres might not be correlated with other aspects of cities, yet the number of theatres would contribute to the global rating of a city.

Eysenck: In that case, how would you experimentally differentiate the two concepts and show that one is correct and the other is not? The theory that Spearman and Thurstone finally agreed on was that there is a general factor which is defined as *g* and shown by getting a matrix of rank one for the intercorrelation between the different primary abilities. That seems to me a strong proof that there is a general factor, *plus* a number of independent abilities—spatial, verbal, numerical, etc. I still find it difficult to see how one can get away from this kind of conception which is also, for example, found when you go away from factor analysis to multidimensional scaling. You get a very clear picture of the central region in the scaling pattern, which defines your general factor and the various group factors or primary abilities lying outside it.

Detterman: The answer to that is gigo—garbage in, garbage out—and it's the same principle that applies to computers: what you get out depends on what you put in. What you put into the factor analysis is what you will get out. People like Thurstone (1935, 1938) and others agree that factor analysis of complex tests was just a beginning. What factor analysts have suggested since the beginning of factor analysis is that the processes should continue, with the refinement of tests to make them more explicit, then repetition of the factor analysis. The problem is that we stopped doing factor analysis with complex tests. We have never analysed the more basic processes that Spearman, for example, was interested in analysing. We need more specific tests, and we need to find out how these specific tests relate to the more complex tests.

Eysenck: Of course we do, but you were implying that we had already done this, that there was direct evidence for your kind of conception, as opposed to Spearman's conception.

Detterman: There is some evidence, including a study that I have just published (Detterman et al 1992, Detterman 1992). Kranzler & Jensen (1991) factor-analysed a set of cognitive tests, and showed that the first and second factor accounted for significant parts of general intelligence. The Kranzler & Jensen study shows that cognitive abilities are not the same as *g*. If they were, *g* and the first factor of cognitive abilities would be identical. I consider that to be strong evidence. I know you probably don't, and I know there are others who don't.

Eysenck: I would like to raise one other point, about correlations between tests being higher in the low IQ range.

Detterman: I should point out that I have been told since we made this finding that Spearman also noted the effect.

Eysenck: The problem here is the assumption that the distribution of IQ is normal. Burt showed fairly clearly that it is not really normal, but follows the Pearson formula 4 distribution (Burt 1963). If that is so, the deductions you make from a normal distribution wouldn't strictly apply. The real difficulty is that there are few cases of IQ above 140, so the actual distribution is notional, you don't really know what it is, how many cases of IQ of 180 you would find and so on. If you take a Pearson type 4 distribution you might get quite different results. I haven't tried that, though.

Detterman: Neither have I.

Stanley: Howard Gardner brought up a point that needs to be discussed widely here, about the threshold IQ above which a higher IQ doesn't make much different to achievement. Some people have suggested this is as low as 120, but the work of Ann Roe (1953) doesn't agree with that at all, nor does that of Harriet Zuckerman (1977). The work that Camilla Benbow and I have done with youngsters with high mathematical reasoning ability, those who before the age of 13 scored at least 700 on the Scholastic Aptitude Test mathematics section (SAT-M), about one in 5000 males and one in 30 000 females, doesn't go along with that notion either.

Detterman: So you would argue that the higher the IQ the greater the potential for exceptional achievement.

Stanley: Yes. The higher the IQ is, the greater is the potential, though a lot of that potential is not realized because of environmental deficiencies.

For example, US participants in the International Mathematical Olympiad, who are normally 17 or 18 years old, seem almost never to have scored poorly on SAT-M at the age of 12. They usually scored in the high 700s.

Gardner: Samuel Johnson said that a genius is an individual of large general powers accidentally deflected in one direction or another. In the scholastic domain, it's quite likely that the threshold of unusual accomplishment would be higher than 600 in a College Board aptitude test. But we should look at a much wider range of performances than simply scholastic. If you looked at great poets, great painters, great musicians, great leaders, would you continue to find that the intellectual scholastic threshold is at the level you're implying or at the level that I'm implying? The question is, how wide is the array of talents which has to be included when you are trying to figure out your threshold of outstanding performance? I would be surprised if, among people who are successful in a school subject, such as mathematics, those with an IQ of 120 were different from those with an IQ of 150. It is also important to look retrospectively, to look at people who have achieved highly in an area like mathematics and see what their earlier scores were like. I assume, Professor Stanley, that when you talk about Anne Roe and Harriet Zuckerman's work, you are talking about people who were successful scientists and who had their intelligence tested as adults.

Stanley: Yes, but there is much early evidence too.

Howe: Professor Detterman, I still have some difficulty understanding what it really means when you talk about abilities being due to general intelligence or caused by intelligence. All one has is measures of performance, never more than measures of performance, whatever kind of analysis is carried out on those measures. As you say, what goes in is what comes out. You took an example of a good city. Presumably, no one would ever pretend that the final measure you end up with is anything but a summary indication. One wouldn't dream of making any causal inferences on the basis of that measure. With intelligence one is always making these kinds of causal inferences. Perhaps people slip into the habit of saying 'due to' when they don't really mean it.

Detterman: I agree. In fact, I hope I made a major point of saying that we would be much better off understanding the cognitive abilities that contribute to and explain intelligence than the global functioning reflected in an IQ score.

Howe: It seems to be implicit in psychometrics that somehow intelligence measures are a more indirect indication of underlying determinants than other things, such as achievement. I know there's a history of argument about this.

Detterman: That is what I am arguing. Cognitive abilities are more direct measures that will predict subsequent achievement. To understand cognitive processes we should not look at groups with restricted ranges and talk about personality factors or why a person is deflected in one direction or another. We must understand the cognitive abilities that contribute to that intellectual power.

Bouchard: Some of us do see IQ as a causal agent, explicitly, overtly, and we don't slip into that by accident—that's exactly our position. I often get accused of making a reification mistake. It's *not* a reification mistake, but a theoretical construct in which I really believe. I think it has implications, and it's causal, and I don't apologize one iota for that.

Heller: Professor Detterman, I would be interested to hear your answer to the question of whether the term 'gifedness' and the term 'talent' are the same. You probably know Gagné's (1991) model of giftedness and talent, which includes intrapersonal and environmental catalysts (moderator variables).

Detterman: I used the term 'high ability' throughout, because calling someone gifted is probably a retrospective decision that we make because that person happens to have turned out one way or another. Giftedness is not often an *a priori* prediction. Too often when we talk about giftedness, we are talking in the biographical sense. When a person performs an outstanding accomplishment, he or she is then called gifted. I talked about ability that would explain a portion of the variance in giftedness. High ability is what could develop into giftedness.

Heller: In Gagné's model giftedness and talent are different constructs. Abilities (aptitude domains) are incorporated in the term giftedness, whereas talents are seen as domain-specific, realized abilities. This model also includes assumptions of catalyst variables which moderate the relationship between intelligence predictors and achievement criteria. It's useful, for example, for prediction of excellence in domain-specific fields of talent. Could your conception of giftedness or intelligence fit into this model?

Detterman: What Gagné calls giftedness I would call high ability, and what is talent in this model I would call achievement or giftedness. What I'm most interested in knowing is what proportion of the variance each of these factors accounts for. I think the cognitive abilities that compose intelligence will account for over half the variance in giftedness. The other half of the variance can be understood in terms of other processes, which are also important and include things like personality and motivation. If you look only at a highly talented sample, it's likely that you will ignore intelligence, because the group has been so highly selected on intelligence. What is likely to attract attention are differences in personality, motivation and other factors not selected for.

Sternberg: One of the basic methodological issues is whether we measure longitudinally or cross-sectionally. The way you evaluate something early in a system is not necessarily the way you evaluate it later on. A theoretical framework that would incorporate a lot of what you said and also some of the comments that have been made is one that goes back to 1946, Garrett's differentiation theory. The idea is that at younger levels and perhaps at lower levels of intelligence, *g* is more important. You mentioned that with lower IQ there might be limitations in the system. I might look at such limitations in terms of higher order executive processes, and others might look at them in terms of basic processes, but it seems that in retarded children or very young children those higher order executive processes are a major source of individual differences and they may contribute to differences in IQ. IQ, after all, is a construct that was originally designed for assessment of mentally retarded children in schools. As people grow older and become brighter, as they become more differentiated, general ability may become less important. That's consistent with what a lot of people have said, yourself included, when you gave the example of the basketball players. It maybe that that extra height in the 7′ versus 7′6″ person will make some difference, but it probably matters less than the differences at lower heights. At higher levels, more specialized kinds of things, more differentiated abilities, would become more important.

Detterman: That *has* to be the case.

Sternberg: Julian Stanley talked about physicists and mathematicians. In our studies of tacit knowledge in salespeople, the only score correlated with IQ was a score that did not predict sales performance, whereas what was predicted by a measure in terms of sales performance was not predicted by IQ. Perhaps in certain aspects of life, as Howard Gardner was saying, IQ not only doesn't matter, but also may even be a negative predictor. For leadership, having a high IQ helps in conditions of low stress, but in conditions of high stress it actually makes things worse. If our focus here is on giftedness and higher levels of performance, we should look at some of the more specialized kinds of ability.

Detterman: The salesperson example is a good one. Perhaps you came to the wrong conclusion because of selection on intelligence. To be convincing, a study about salespeople would have to take a random sample of individuals from the population, make them into salespeople, and then look at what abilities predict proficiency as a salesperson.

Sternberg: These people are certainly not highly selected for IQ. What's really of interest is not the whole range, but the range of people who actually go into the field. If I'm studying business executives, I have no right having retarded individuals in my population to increase the correlation. I should look at the population of interest, people who are potentially or actually business executives. If I'm looking at sales, I should investigate people who are studying to be salespeople, not people who decide to be physicists, or people with IQs of 40 who are in an institution.

Detterman: As long as you are clear about that, that's fine. Of course, when you select graduate students, you have to select them on some basis, and if you are choosing among the graduate students that have been selected, you would be crazy to base your selection solely on GRE scores. You would want to select motivated graduate students.

Sternberg: The managers and salespeople and lawyers and waitresses in our studies weren't selected by GRE scores.

Detterman: They were selected by devices like GREs. You cannot say that they represent the full range of ability.

Sternberg: These are the people who ring your doorbell and try to sell you insurance.

Detterman: They have been more heavily selected than any of us, because they are selected on the basis of commission.

Sternberg: But not on IQ.

Detterman: They won't make a living if they can't sell and that ability may be related to intelligence.

Sternberg: We agree they're selected, but they are selected according to traits that happen not to be correlated with IQ. All I'm saying is that when we talk about more meaningful forms of giftedness, whether in adults or in children, we may want to get away from general ability notions and more toward notions of specialized abilities, such as the things that salespeople are selected for.

Detterman: But you cannot come to the conclusion that they were not selected on intelligence unless you begin with an unselected group. Even if you're more interested in what differentiates people within the group, you cannot say that intelligence is not important in bringing these people to where they are. If you do, people will think that intelligence isn't important and that we can train everybody to be a Nobel Laureate or a salesperson. That is simply not the case.

Sternberg: You are distorting what I'm saying. Intelligence is important, but the kind of practical intelligence these people have is different from the kind you are talking about when you rate the IQ test score at the top of the hierarchy and make it sound as if *g* is everything. Yes there's a *g*, but it's a limited *g*. There's a *g* in some of our practical intelligence measures for managers. It's also another limited *g*.

Detterman: You are not listening to what I am saying, either. What is important depends entirely on your point of view. Within a group, you are absolutely right that personality, practical intelligence and other things will be important in explaining differences within the group. Across the wide range of human ability, it is *g* that's important. I would give *g* primary importance in differences between groups. As people are selected into groups, intelligence becomes less and less variable. There's nothing else that can happen but that other things become important.

Sternberg: That's simply not true in our samples of salespeople and managers. There is range in IQ.

Detterman: Sales is an unusual example, which has presented problems for prediction for as long as it has been studied. For graduate students, I don't think there's much variability though.

Sternberg: There's a problem of prediction because we are using the same stupid measures! If you use measures of tacit knowledge for sales, you can get much better prediction of performance. I agree that if you use an IQ test you will have a problem predicting success.

Gruber: The geneticist Dobzhansky (1973) pointed out that in a population of clones, heritability would be zero; they would all have identical heredity, but the measure of heritability would be zero. Likewise, you can imagine a measure of heritability that would be maximized at the other extreme. Heritability is not a fixed quantity, but a quantity that depends on historical and other circumstances. Imagine Einstein, Poincaré and Max Planck together in one room having a discussion, and that you wanted to predict which one of them would develop the theory of relativity, or that you wanted to understand why it was that it was Einstein who did so. You would not look at their intelligences, or peculiar evidence of minor differences between them. They were all great problem-solvers. You would consider their philosophies of science and their understanding of what's right.

You said that attenuating the range leads to low correlations, then went on to say that because that's the case, we should not allow ourselves to be misled into looking at social factors or personality or such other vague factors, and that when all is said and done what really counts is *g*. It seems to me that once you have attenuated the range, and got a small, specialized group, it is *just* these other factors that have explanatory power. We need a theory that doesn't deny the importance of levels of ability, in your sense of the word, but which also pays close attention to the way in which people develop within a field, taking into account not only their abilities but also their orientations and senses of purpose. Those factors should not be dismissed because of statistical arguments.

Detterman: It was not my intention to dismiss them. They are extremely important within the group, by statistical necessity, because selection has taken out the variability due to intelligence. If you optimized the environment, the only thing that would be important would be genetics. In a similar fashion, if you removed intelligence by selection, what would be important are the kinds of factors you mentioned. This doesn't mean that intelligence is not important for accomplishment. I still hold that intelligence will account for over half the variance in exceptional achievement.

Ericsson: If I understand you correctly, when you talk about *g*, you are relating *g* to its components, such as memory, attention and sensation, which are not modifiable. Only the sequencing of the components (their programming) can be influenced by environment.

Detterman: Some of them may be highly modifiable.

Ericsson: As I understand your argument, you would maintain that these components are related to higher performance even in restricted samples. I don't know of any studies showing that estimates of basic processing capacities are good predictors of expertise and excellence.

After practice and training, even short-term efforts, performance on tests of basic processing capacity can be changed, and large improvements are possible, in normal college students, at least.

Detterman: There's a substantial, growing, amount of evidence about the relationship between basic cognitive abilities and higher intellectual performance and performance in other domains. The US Air Force's Project Lamp, for example, is predicting specific skills such as computer programming from basic cognitive skills.

Ericsson: In my opinion, that's not a project studying high levels of expertise. Would you call the high aptitude groups in those studies experts?

Detterman: Some of the studies have been done on high achievement groups in a particular domain, if you consider outstanding computer programming as high achievement. That depends on your definition. Your second point was that you can teach the test, and improve performance through practice.

Ericsson: The cognitive processes that can be acquired as a result of training are actually quite different from any kind of simple sequencing of basic processes. Large increases in performance resulting from practice on tasks measuring basic processing capacities imply mechanisms different from the simple sequences of fixed basic processes that you are talking about.

Detterman: Are you saying that you can teach anybody anything?

Ericsson: I don't think so. In those tests with which I'm familiar, there is clear evidence that there are ways in which knowledge and skill can be acquired, especially with experience, that allow subjects to overcome the basic limits.

Detterman: Could you give me a more concrete example?

Ericsson: Consider typing expertise. Expert typists overcome the sequential processing constraints of serial movements by processing ahead, up to six or seven letters ahead. If you reduce that ability to plan ahead by limiting the preview of the ensuing text, you can actually reduce expert typists to the levels of novice typists. Hence, it is not the speed of the elementary movements, the basic components, that determine the speed of expert typists. Essentially, experts have acquired new skills to perform tasks that allow them to circumvent the basic limits of untrained subjects. If one views g as a direct measure of the basic components, it should not be possible for it to predict exceptional performance.

Detterman: Surely you wouldn't argue that someone with basic motor impairment would be able to type 100 words per minute?

Ericsson: A handicapped person obviously couldn't. Other obvious handicaps include sensory deficits such as blindness or deafness. I would ask you to point me to good evidence for abilities that are not obvious and do not reflect physical deformity. In your definition of g you referred to mental capacities such as attention and perception.

Detterman: Let me ask you another question. Can you teach anybody to type 100 per words a minute?

Ericsson: I don't know.

Detterman: I would seriously doubt that you could, and I would bet that the likelihood of success is related, at least to some extent, to the person's cognitive potential, to working memory capacity, at least, which is highly correlated with IQ.

Ericsson: I believe there are other constraints on the acquisition of skills that have nothing to do with basic mental capacities, but concern the motivational and intentional factors determining improvement of performance during training.

Mönks: Professor Detterman, you said that achievement and intelligence are different.

Detterman: They depend on some of the same genetic processes.

Mönks: But achievements can differ from the potential, i.e., intelligence. My question is, what do you actually mean when you say that achievement and intelligence are different? What is your message?

Detterman: There are hereditarily determined, biologically determined, characteristics of intelligence that will provide a measure of potential if we can measure them. That's not to say that intelligence is not modifiable by the environment. That's what the discrepancy between measured intelligence and achievement shows. The expression of biological potential is highly modifiable by environment.

Mönks: So intelligence stands for potential.

Detterman: Not entirely. Intelligence currently is an environmentally measured concept. Intelligence is a phenotypic trait. If we could measure potential separately from achievement, we could all go home, because we would understand education, intelligence and achievement completely.

Mönks: What is the input or the role of motivation?

Detterman: I'm sure that motivation is important, but I don't know how to describe it or how it affects intelligence.

Lubinski: I was pleased that you brought up the issue of restriction of range, because people underappreciate its importance. Your example of the basketball players is a good one. The problem is also exacerbated by restriction of range in the criteria. The variance in quality of psychology PhDs is a lot smaller at Yale then it is across the USA. Another problem with Bob Sternberg's study is that the ratings on the criterion variable were made by one rater on a one-item scale, retrospectively. One-item scales are notoriously unreliable, and are certainly not reliable beyond 0.6. You can't get high correlations using measures with reliabilities in this region. Also, different raters rate different students. In addition, some of the raters were aware of the students' GRE scores. I'm not impressed by the low correlation between graduate students' GRE scores and one-item ratings on the quality of their dissertations. I would expect that.

Sternberg: It's true that range differs in different programmes, which is why I looked at the top 25% and bottom 25% as well as the top 10% and the bottom 10%. However, if we want to address giftedness, the students in our programme cover a sensible range because they are among the gifted.

The point I was trying to make is that if nothing predicted the professors' ratings, you could say they were non-predictable. In fact, the professors didn't know what each others' ratings were, yet other professors' ratings of the dissertations, and the ratings of the advisers of the students, were correlated. Moreover, the first-year grades were correlated with the professors' ratings. This at least suggests that it's not impossible to get correlations.

Also, I think you would find that almost no one knows the GRE scores when they make their ratings.

Detterman: But retrospectively raters know who got the plum job, or who's publishing a lot. The raters were not blind to variables intelligence might predict.

Sternberg: Well that's fine. In the field, that's how people are really evaluated, through ratings of analytical ability, creative ability, practical ability, research ability and teaching ability. I'm not saying that everything is incorporated into those five things, but they are important.

Gardner: In trying to portray where I find parochialism in the discussion, I want to suggest a thought experiment. Imagine that the Stanford-Binet never existed, but that about 50 years ago a man named Alfred Sloan invented the SQ. Alfred Sloan was president of General Motors and wanted to figure out who would be good salesmen. He hired Robert Sternberg, and tested people with telephone calls and poker games and other ways in which other people can be influenced, and came up with the SQ. The SQ turned out to appear in anything that Sloan was interested in. The only exception was that it wasn't good at predicting who would be a good scholar, but he didn't care about scholars, so invented something called the *g* or goofy measure for people goofy enough to become scholars.

We place far too much weight on a measure that was devised for a specific purpose, to predict which children would have difficulties in school. From the point of view of society, the SQ would have been much more portable, because being able to convince people to do things, which is what salespeople do, is more important. When you put down the salesman, you are not taking a sufficiently broad view of what makes society tick.

Detterman: I would say exactly the opposite. *g* is the ability that brings you to the portal of the occupation you want to be in. We are in this room because we have all gone through selection processes. Without them, we would not be here. The parochial view would be to assume that anybody can accomplish what's been accomplished by people in this room. We tend to do that, but it is not the case. I work with mentally retarded people and can assure you that is not possible for a mentally retarded person to accomplish what you have accomplished even under the best of conditions. It would be unfair to expect as much from a mentally retarded person as is expected of you.

Gardner: You are missing my point. Getting to this room isn't important from the point of view of society at large.

Sternberg: We are here because we can sell our point of view. This is still about sales!

Detterman: Being in this room *is* important to society. The influences that brought us here are also important. One must investigate the full range of ability before one can decide what is important for achievement in life. Studies that look only at variables that differentiate people within highly selected groups cannot tell us what produces outstanding achievement.

Stanley: The index that Howard Gardner 'invented' actually existed. Long ago, the Life Insurance Management Association developed an empirically keyed measure of aptitude for selling life insurance. It included questions such as, how many children do you have? If you had none, if you were a bachelor, you were probably a poor prospect who wasn't going to work hard enough; if you had 10, you probably had too many and would have to stay at home too often. Another question was, if you inherited a million dollars, what would you do with it? Giving it to charities was a bad answer—you should spend it on yourself and your creature comforts!

Colangelo: Professor Detterman, you mentioned optimizing the environment (p 38). I would like to hear some explanation about what it means to optimize the environment. This seems to be a cure-all for whatever ability doesn't take care of. Is optimization simply having the materials around? Did we all come from optimal environments? The inventors I have studied didn't come from optimal environments. Do you consider that simply having the resources available makes the environment optimal?

Detterman: All I can give you is my opinion. We don't know much about this, because the effects are small and often idiosyncratic, and difficult to study. We know far less about environmental variables than we do about the genetic side of the equation.

Bouchard: Howie Gruber put Einstein, Poincaré and Max Planck in a room together, selecting some of the most brilliant people that ever came along, and tried to explain why one of them invented the theory of relativity. I would assert that we deal with this problem often. We take gifted children, and ask why one did this while another did that. We make up reasons. We look through the data and pick things out. Then we purport to have explained things. We need appropriate scientific controls at that level also. In most cases the explanations are nothing but anecdotes, and chance is a powerful alternative predictor of many of those things. We get to the descriptive level and we stop doing science and resort to anecdotes.

Freeman: I have done a study (Freeman 1983, 1991) in which I used the Raven's Matrices (Raven 1965), a non-verbal, supposedly culture-free, test as a basis, and compared this with the Stanford-Binet IQ scores of the same 210 children. At the same time I went to their homes and rated, albeit subjectively, their environments. I talked to their parents and rated the parents' attitudes towards the children's education. I also rated the schools' attitudes to the children's education. Even when children were of the same measured ability on the Raven's Matrices, there were distinct differences in their IQ scores, and those distinct differences were entirely related to their environmental circumstances. It's not often that one looks at this difference from the environmental rather than the genetic point of view, but this does very much support what Professor Detterman was saying. At the higher ranges of the 95th percentile of basic intelligence, or whatever one wants to call it, one might expect the IQ score to be accordingly high, given that the circumstances are equally good, because of the exceptionally high ability to take in more information. If the procedures within the nervous set-up are working well, more information will be taken in, and therefore the IQ will go up. I do believe that the IQ score is a measure of achievement. It contains so much 'pollution' by acquired information, which must come from the environment.

Gardner: Are you claiming that the Raven's test isn't a measure of achievement?

Freeman: It is the closest to a culture-free test we have. It must include achievement, of course, but less so than a vocabulary test, for example.

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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.

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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

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

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

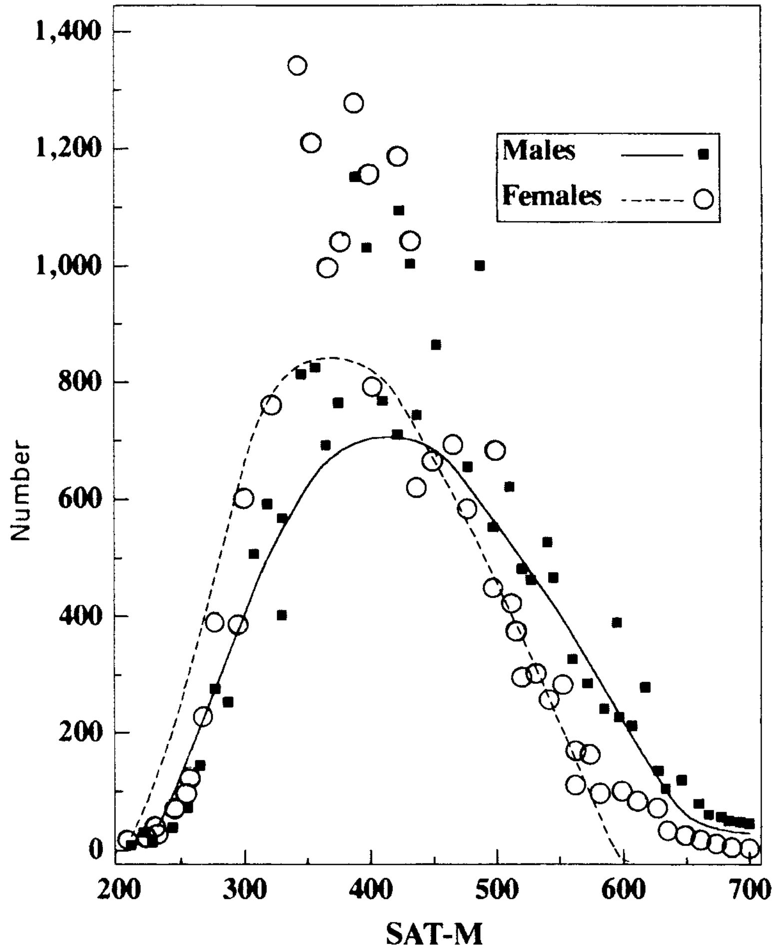

FIG. 1. A typical distribution of scores on the mathematical part of the College Board's Scholastic Aptitude Test (SAT-M) achieved by mathematically talented 13-year-old males (—■—) and females (---○---). Reproduced from Benbow et al (1988), with permission.

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: $\geqslant$500 (average score of college-bound 12th-grade [18-year-old] males), 2:1; $\geqslant$600, 4:1; and $\geqslant$700 (top 1 in 10000 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

	SAT-M (age adjusted)[a]			SAT-V (age-adjusted)			Advanced Raven's[b]			Mental rotation test[c]			Bennett m reasoning	
Sex	*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

who 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.

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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 the genetic contribution to individual differences. For example, identical twins are identical genetically, and, roughly speaking, the genetic correlation between dizygotic twins is only 50%. In the case of adoption, some family members are genetically unrelated but reared together, such as adoptive parents and their adopted children. Other family members are genetically related but reared apart, such as genetic parents and their children adopted by others. If genetic differences among people contribute to observed *g* differences among them, the resemblance of relatives should vary as a function of their genetic relatedness, regardless of their rearing status. Details of quantitative genetic methods and their application to behaviour are available in introductory form (Plomin 1990a) or in textbooks (e.g., Plomin et al 1990).

As environmentalism waned in the 1960s, human behavioural genetic research began to gain momentum. However, the existence of the fledgling field was threatened by the furious response to Arthur Jensen's 1969 paper that broached the topic of genetic differences between ethnic groups. The 1970s were a time of turmoil for the field, but during the 1980s a remarkable turn-round occurred, antipathy towards human behavioural genetics changing into acceptance. For example, a survey of more than 1000 social and behavioural scientists and educators indicated that most had accepted the evidence for a significant effect of heredity on IQ scores, traditionally one of the most controversial areas in behavioural genetics (Snyderman & Rothman 1987). This acceptance was fostered in part by two reviews of the literature on the genetics of *g* published in *Science* (Erlenmeyer-Kimling & Jarvik 1963, Bouchard & McGue 1981). Model-fitting analyses of these data consistently yield evidence for significant genetic influence (Chipuer et al 1990, Loehlin 1989). As in all science, we can go beyond statistical significance to address the issue of effect size. In quantitative genetics, the estimate of effect size is the descriptive statistic called heritability, which estimates the portion of variance on a measure of *g* that can be ascribed to genetic factors. Model-fitting analyses typically estimate heritability to be about 50%.

It should be emphasized that heritability describes 'what is' in a population—the genetic and environmental provenances of measured differences among individuals as they exist in a particular population with its particular mix of genetic and environmental influences. Heritability does not predict 'what could be', nor does it prescribe 'what should be'. If this is understood, the following statement will not sound paradoxical: cognitive ability can be highly heritable in a population and yet change dramatically in an individual who undergoes intense training. Heritability denotes probabilistic genetic influence for a population, not predeterminism or immutability for an individual.

The general acceptance that there is an important genetic contribution to individual differences in *g* makes it possible to go beyond this most basic nature–nurture issue to ask more interesting questions. Three examples will be mentioned briefly. The first concerns development, the second multivariate genetic analysis and the third school achievement.

Developmental genetic analysis: genetic change as well as continuity

Behavioural genetics began with Sir Francis Galton's work just a few streets away from the Ciba Foundation. When Galton first studied twins (1876), he investigated the extent to which the initial similarity or dissimilarity between twins changed during their development. Other early studies were also developmental but this developmental perspective faded from genetic research until recent years.

Two types of developmental question can be addressed in genetic research (Plomin 1986). First, does heritability change with age? It is reasonable to suppose that environmental factors increasingly account for variance in *g* as experiences accumulate during the course of life. In fact, genetic research suggests that the genetic influence on *g* increases in a near linear fashion from infancy through early childhood (Fulker et al 1988) and perhaps continuing throughout the lifespan (McGue et al 1993, Plomin & Thompson 1987). For example, a recent report of the first genetic study of older adults which used the powerful design of comparing twins reared apart and twins reared together suggested a heritability for *g* of 80% (Pedersen et al 1992).

The second type of developmental question concerns genetic contributions to changes with age and continuity in longitudinal analyses. Although genetic effects contribute substantially to the stability of *g* during childhood, what is more surprising is the extent to which genetic effects appear to contribute to changes with age (Fulker et al 1993). Particularly interesting is the suggestion of substantial new genetic variation that appears during the transition from early to middle childhood.

Multivariate genetic analysis: genetic *g*

A second example of research that goes beyond the basic nature–nurture question is multivariate genetic analysis, which extends the univariate genetic analysis of the variance of a single trait to multivariate analysis of the covariance between traits. Multivariate genetic analysis makes it possible to estimate the extent to which genetic effects on one trait overlap with genetic effects on another trait. Analyses of this type in the realm of cognitive abilities indicate that specific tests and group factors show some genetic effects unique to each test and factor. Nonetheless, much of the genetic effects are shared across diverse tests and factors (Cardon & Fulker 1993).

Another recent finding makes a related point. The heritability of performance in a cognitive test is strongly correlated with the test's *g*-loading, its factor loading on an unrotated first principal component (Jensen 1987); the more a test measures *g*, the more heritable the test is. For example, in the study mentioned earlier of twins reared apart and twins reared together, the correlation between heritabilities of the tests and their *g*-loadings was 0.77 after differential reliabilities of the tests were controlled (Pedersen et al 1992).

Achievement at school and *g*: same genes, different environments

The third example also involves multivariate genetic analysis, but is especially relevant to the origins and development of ability. Achievement at school is interesting from a genetic perspective because it is widely assumed that achievement and ability are different, almost by definition. Achievement is what a student achieves by dint of effort, whereas ability is thought to involve inherent talent. For this reason, achievement test scores are assumed to be environmentally determined. However, a neglected finding is that performances in achievement and ability tests are moderately correlated, which raises the possibility of genetic overlap between the two domains.

Although there have been several studies of scholastic achievement in adolescent twins, until recently there had been no reported research in middle childhood. In the Western Reserve Twin Project (WRTP), specific cognitive abilities and school achievement were investigated for a sample of 146 pairs of monozygotic twins and 132 pairs of dizygotic twins from six to 12 years of age (Thompson et al 1991). School achievement test scores showed significant heritability. However, heritabilities of scores in achievement tests were much lower than heritabilities for specific cognitive abilities—about 0.20 versus about 0.70. More surprising are the results of multivariate genetic analysis: the well-known correlation between cognitive abilities and school achievement test scores is due almost entirely to genetic factors common to the two domains. Conversely, ability–achievement discrepancies are environmental in origin.

Quantitative genetics and high cognitive ability

The research described above addresses the aetiology of differences in *g* between individuals in the normal range of ability. Much less is known about the origins of high ability (Feldman 1986, Simonton 1989, Howe 1990, Storfer 1990). It cannot be assumed that aetiology at the extremes of a dimension is the same as that for the rest of the distribution. For example, at the low end of the ability spectrum, severe retardation shows little familiality, in contrast to the rest of the IQ distribution (Plomin 1991).

A year before Mendel's seminal paper on the laws of heredity, Francis Galton (1865) published a two-article series on hereditary genius that he expanded into the first book in the field of behavioural genetics, *Hereditary genius: an inquiry into its laws and consequences* (Galton 1869). Using mere reputation as an index, Galton suggested that ability, brains as well as brawn, ran in families. He greatly overinterpreted the results to support his belief that genius is hereditary, although in 1874 he toned down his extreme position (Galton 1874). Galton believed that 'ability will out' regardless of environment. A contrary influential view was that high intelligence is not heritable because highly intelligent people learn easily and thus reflect differences in their experience to a greater extent than other people (Jennings 1930).

The issue is whether genetic factors affect high ability and how the magnitude of this genetic influence compares with the magnitude of genetic factors that contribute to individual differences in the normal range. The issue is not the heritability of high ability in the usual sense of genetic contributions to differences among individuals of high ability. The reason why one child has an IQ of 150 and another an IQ of 145 is less interesting than understanding why both children have IQ scores so much higher than the rest of the population.

This question can be addressed using a new approach that generates an estimate of what is called *group heritability*, in contrast to the traditional heritability statistic, which could be referred to as *individual heritability*. Group heritability is the genetic contribution to the average difference between a selected group such as children of high ability and the rest of the population. The typical approach to group heritability in genetic research on disorders is to establish a cut-off score as a diagnostic index of the disorder (that is, normal versus abnormal). Degrees of concordance can be calculated and compared for monozygotic and dizygotic twins, or liability (tetrachoric) correlations can be used, which assume a continuous distribution even though the data, as they are used, are discontinuous.

A far superior approach has been developed by DeFries & Fulker (1985) and has been dubbed DF analysis for that reason as well as because of the lack of a more descriptive moniker (Plomin & Rende 1991). DF analysis assesses group heritability as the differential regression to the population mean of the co-twins of monozygotic and dizygotic twins selected on the basis of a quantitative measure (probands). IQ scores of co-twins of probands with high IQ scores are expected to regress toward the mean of the unselected population, but, to the extent that high ability is due to genetic factors, the regression to the mean will be less for monozygotic co-twins than for dizygotic co-twins. DF analysis was first applied to reading disability (DeFries et al 1987). Group heritability for reading disability was found to be only about half the magnitude of individual heritability for reading ability, suggesting that the disorder, reading disability, is aetiologically different from the dimension of reading ability.

Is group heritability of high ability significant, and what is its magnitude? The WRTP twin sample was used to estimate group heritability (Thompson et al 1993). The DF approach was applied to IQ scores from traditional intelligence tests (Weschler Intelligence Scale for Children-Revised and the Peabody Picture Vocabulary Test) expressed as a composite standard score with a mean of 0.0 and a standard deviation of 1.0. High ability was operationally defined as an IQ score 1.25 standard deviations above the sample mean.

In a preliminary analysis, concordance was calculated separately for monozygotic and dizygotic twin pairs in which at least one member of the pair (the proband) scored 1.25 standard deviations above the sample mean. The total number of affected (high ability) individuals in concordant pairs was divided by the sum of the total number of affected individuals in concordant and discordant pairs, to give the 'probandwise concordance'. The probandwise concordances were 62% (18/29) for monozygotic twins and 25% (6/24) for dizygotic twins, suggesting genetic influence on high ability.

These twin concordances suggest that group heritability for high ability is additive, because the dizygotic twin concordance is only slightly less than half the magnitude of the monozygotic concordance. This does not contradict the hypothesis that rare genius may be epistatic (Lykken et al 1992). The genetics of genius may differ from the genetics of high cognitive ability. Specific constellations of many genes may be required for genius. The hallmark of such epistatic interactions is resemblance between monozygotic twins but not between first-degree relatives.

DF analysis provides an estimate of the magnitude of group heritability using continuous IQ scores rather than by dichotomizing the scores. The results of DF analysis are illustrated in Fig. 1. As shown in this figure, the mean IQ of the monozygotic co-twins of probands regresses less far to the population mean than does the mean of the dizygotic co-twins of probands. This supports the suggestion of group heritability for high ability that emerged from the comparison of twin concordances.

In DF analysis an elegant regression model is used to test the differential regression to the mean for monozygotic and dizygotic twin probands, taking into account mean differences between the probands. The analysis yields estimates of group heritability and standard errors of these estimates. DF analysis, described elsewhere (DeFries & Fulker 1985, 1988), estimates the group heritability of high ability as 0.67 ± 0.24. This significant group heritability suggests that about two-thirds of the difference between the IQs of the children in the high ability group and the average IQ in the sample can be attributed to genetic factors.

This estimate of group heritability is similar to the traditional individual heritability for *g* in the same sample (Thompson et al 1993). Together, these results suggest a hypothesis with far-reaching implications: in terms of genetic influence, high cognitive ability may be merely the extreme of the normal continuum of *g*.

Molecular genetics and high cognitive ability

We are at the dawn of a new era in which molecular genetics techniques will revolutionize genetic research on behaviour by identifying specific genes that contribute to genetic variance in behavioural dimensions and disorders (Plomin 1990b). We have begun to use these techniques in our research to identify specific genes that affect high cognitive ability (Aldhous 1992).

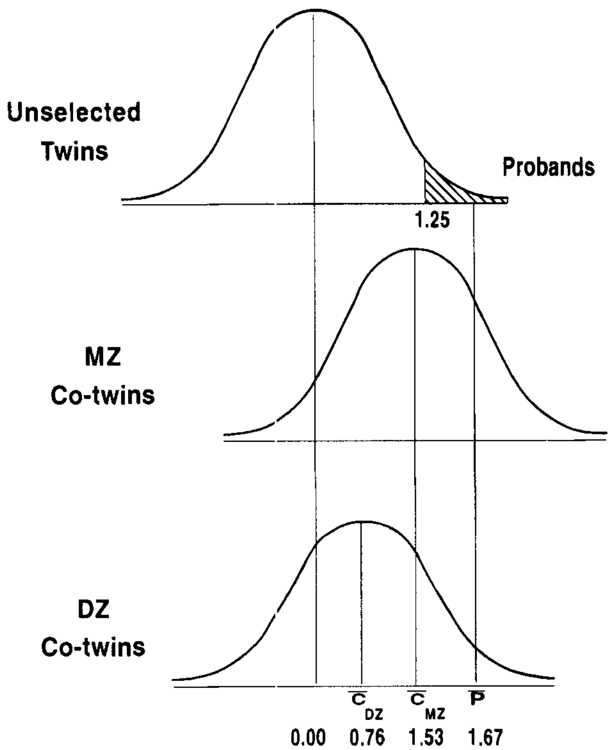

FIG. 1. IQ distributions for an unselected sample of twins and the monozygotic (MZ) and dizygotic (DZ) co-twins of probands selected for high IQ. The top distribution is an idealized normal distribution for an unselected sample. Individuals of high ability, probands, were defined as those with an IQ score 1.25 standard deviations above the sample mean of 0.0. The two distributions below are those for monozygotic co-twins of probands (MZ) and dizygotic co-twins of probands (DZ). The MZ co-twin mean (1.53) regresses less far towards the mean of the unselected population than does the DZ co-twin mean (0.76), suggesting heritability for high cognitive ability.

It was only ten years ago that the now-standard techniques of the 'new genetics' were first used to identify genes responsible for single-gene disorders. As described elsewhere (e.g., Plomin et al 1990), the discovery of restriction enzymes, which led to recombinant DNA technology and the ability to sequence DNA, also produced thousands of new DNA markers, genetic differences among people that involve DNA itself rather than gene products such as blood group antigens. These new DNA markers can be used to identify the chromosomal region and, eventually, to isolate the gene and its product responsible for single-gene disorders.

Notable early successes include cystic fibrosis and Duchenne muscular dystrophy. These are dichotomous traits, like Mendel's smooth/wrinkled seeds, in which one gene is necessary and sufficient to explain the observed difference. Several thousand single-gene disorders, most very rare, have been reported, but behaviour is much more complex. Behaviour reflects the functioning of the whole organism and it is dynamic, changing in response to the environment. Genes that affect behavioural traits are transmitted hereditarily according to Mendel's laws in the same way as genes that affect any other phenotype, but behaviour is special in three ways. First, unlike Mendel's smooth and wrinkled seeds, most behavioural dimensions and disorders are not distributed in simple either/or dichotomies, although in psychopathology we often pretend that there is a line which sharply separates the normal from the abnormal. Second, behavioural traits are substantially influenced by non-genetic factors: heritabilities rarely exceed 50%. Third, behavioural dimensions and disorders are likely to be influenced by many genes, each with a small effect. Each of these points applies to dimensions of cognitive ability and to the dichotomy of convenience that we call high cognitive ability. The challenge is to use DNA markers to find genes in complex systems such as these which involve multiple genes as well as multiple non-genetic factors. Such genes of varying effect size that contribute to quantitative traits are called quantitative trait loci (QTL).

Linkage

For a single-gene trait, linkage analysis is guaranteed to find the chromosomal location of the gene, even when nothing is known about the gene product. Linkage traces the co-transmission of a marker and a disorder within a family pedigree. The exemplar is Huntington's disease, which was the first disorder mapped to a chromosome using the new RFLP (restriction fragment length polymorphism) markers. Huntington's disease has long been known to be attributable to a single dominant gene that is lethal later in life regardless of a person's other genes or environment. Other single-gene disorders are quickly being put on the genome map through the use of linkage.

The problem is that behavioural dimensions are different. Most importantly, they show no suggestion of simple single-gene inheritance. Linkage can identify only a major gene that is largely responsible for a disorder. For the analysis of behaviour, relying on linkage techniques that can detect only major-gene effects is like losing one's wallet in a dark alley but looking for it in the street because the light is better there. It is now generally recognized that no major gene for behavioural dimensions or disorders is likely to be found in the general population. However, current linkage research assumes that a major gene can be found in certain families. Linkage studies focused on large pedigrees with many affected individuals may find a gene which is largely responsible for the disorder in a particular pedigree. Multiple-gene influence would still be seen at the population level if different major genes were responsible for the disorder in different families.

The alternative view, espoused here, is that major genes will not be found for behaviour, either in the general population or in a family. Rather, for each individual, many genes make small contributions to variability and vulnerability. Thus, the genetic quest is to find not *the* gene for a behavioural trait, but the QTL that affect the trait in a probabilistic rather than predetermined manner. Although some sledgehammer effects of major genes may be found, it seems more likely that many other alleles nudge development positively and negatively for many individuals.

Behaviour is not too complex for us to take advantage of the new DNA markers, but we need to bring the light of molecular biology into the dark alley. New strategies are needed to identify genes that affect behavioural traits, even when the genes account for only a small amount of variance, when non-genetic factors are important, and when the traits are quantitatively distributed. We need to use molecular genetic techniques in a quantitative genetic framework.

Allelic association

The breathtaking pace of technological advances in molecular genetics means that at the turn of the century we will most probably be investigating multiple-gene influences for complex dimensions and disorders using techniques completely different from those in use today. One strategy that we are using in the meantime is called allelic association. Linkage refers to loci rather than alleles—linked traits such as haemophilia and colour-blindness do not occur together in the population. In contrast, allelic association occurs when a DNA marker is so close to a relevant gene (or is part of the gene) that affects a trait that a marker allele is correlated with the trait in unrelated individuals in the population.

The best case is when the marker is the relevant gene itself, when the marker is in the coding region of a gene and thus encodes actual polypeptide differences among people. Most DNA consists of non-coding regions between genes that are not transcribed into messenger RNA and thus are not translated into amino acid sequences. Moreover, much of the gene sequence that is transcribed is spliced out (so-called introns) and is not translated into amino acid sequences that form polypeptides. Of the thousands of known markers, only a handful are known to be in coding sequences (exons), for example, markers for two of the five types of dopamine receptor, D_3 and D_4 dopamine receptors. Binding to the D_4 receptor is different in people with different marker genotypes. However, the vast majority of known markers are likely to be in non-coding regions because natural selection permits much more variation in non-functional DNA than in functional DNA. Finding such functional markers is a high priority for research because of the power they provide for finding QTL (Sobell et al 1992).

Allelic association makes it possible to use markers that are not functional themselves but are very close to sites of functional genetic variation. A marker allele and a functional variation in DNA on the same chromosome are rarely separated by recombination (meiotic crossing over of chromosomes) if their loci are very close together on the chromosome.

Allelic associations have been found between disease states and markers in the HLA histocompatibility complex (Tiwari & Terasaki 1985). In other words, particular HLA alleles are indicative of an increased risk for certain diseases. For normal variation, the best example of allelic association is serum cholesterol levels, for which about a quarter of the variance can be explained by four apolipoprotein gene markers (Sing & Boerwinkle 1987). In several psychiatric studies, a marker in the D_2 dopamine receptor has been found to be associated with alcoholism (Cloninger 1991). The frequency of this allele appears to be greater in severe alcoholics than in controls, although failures to replicate this result have been reported.

A major advantage of allelic association analysis is that it can be used with samples of unrelated individuals, whereas linkage requires pedigrees of related individuals. In addition, allelic association is just as applicable to quantitative traits as to disorders. Finally, because unrelated subjects are relatively easy to obtain, sample sizes can be increased such that association analysis is powerful enough to detect small genetic effects.

One problem is the large number of DNA markers. The allelic association approach is like searching for a few needles in a haystack. Linkage can detect a major gene far away from a marker, whereas allelic associations can be detected only when a marker is very near a gene that affects the trait. For behavioural traits, which are influenced by many genes as well as non-genetic factors, a near-sighted strategy such as association may be needed to see the fine details of the landscape near a marker even though the ability to see distant mountains must be sacrificed. In fact, this is no sacrifice, because there are no mountains to be seen, but there are so many markers that randomly drawing straws from the haystack is unlikely to pay off. The odds can be stacked in our favour if we begin the search using markers in or near genes of neurological relevance, and use large samples and well-measured extreme groups, which increases the power to detect small effects. The goal is to identify some, certainly not all, genes that contribute to the ubiquitous genetic variance found for behavioural traits.

Allelic association and high ability

We are using this allelic association approach in an attempt to identify QTL associated with high ability, investigating DNA markers in or near genes with possible neurological relevance such as the many neuroreceptor genes and the genes involved in their regulation. From the WRTP sample of more than

500 children we selected three groups of Caucasian children: the 24 children with the highest IQ scores, 21 with average IQ scores, and the 18 with the lowest IQ scores. The average IQ scores of the three groups were 130, 104 and 80, respectively.

We established permanent cell lines from blood from these children by transforming the lymphocytes with Epstein–Barr virus. Such cell lines provide unlimited amounts of DNA for marker analyses as well as a permanent resource for future DNA analyses. We have compared allelic frequencies for these groups for more than 20 DNA markers, including dopamine receptors 1 and 3, monoamine oxidase B, neurofilament protein and fragile X repeat length. Although interesting preliminary results are beginning to emerge, we have agreed not to publish these results until we have replicated them in an independent sample. Our replication sample includes 30 children with even higher IQ scores (mean IQ of 142), as well as 30 children with even lower IQ scores (mean IQ of 74).

Nearly all molecular genetic research focuses on disorders, looking for DNA markers linked or associated with disruptions of normal development. We are especially interested in identifying 'increasing' alleles that contribute to high ability. For this reason, the pattern of results we would be particularly interested to find is one in which the allelic frequency is similar for the low IQ and middle IQ groups but different for the high IQ group.

Conclusions

More is known about the origins of individual differences in cognitive abilities than any other behavioural dimension, although we are still closer to the beginning than to the end of the behavioural genetics story (Plomin & Neiderhiser 1991). It is clear that genetics plays a major role, and our DF analysis indicates that high ability is also strongly heritable.

Molecular genetics techniques are powerful tools for identifying differences in DNA among individuals without relying on familial resemblance. In addition to providing indisputable evidence of genetic influence, molecular genetics will revolutionize behavioural genetics by providing measured genotypes for investigating multivariate and longitudinal genetic issues, the links between the normal and abnormal, and interactions and correlations between genotype and environment. In a broader perspective, it will help to integrate genetic research in the increasingly fractionated biological and behavioural sciences at the universal level of DNA. The much-used phrase 'paradigm shift' seems no exaggeration for advances of this magnitude. As is the case with most important advances, it will raise new ethical issues as well (Wright 1990).

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DISCUSSION

Eysenck: Your work is tremendously exciting, and brings us into the realm of exact science. We used to think that the number of genes involved in *g* was around 40. Does your work enable you to give a more reasonable estimate of the number of genes involved, or is this a premature question?

Plomin: It's premature certainly for cognitive abilities. Geneticists can't say what a gene is now, let alone how many there are—the estimates for the genome vary widely. The concept of a gene is now more dynamic. For example, genes code for different things at different points in development. The best work has been done in plant genetics, where scientists have to deal not with simple traits, which is what the molecular geneticists want, but with commercially valuable traits that are complex, just like the things that we are studying. They have been applying these QTL approaches with large samples that make it possible to detect small effects. They find genes of varying effect size, but the largest effect sizes they ever find account for 15% of the variance. Current linkage approaches won't detect a gene that accounts for less than 40% of the variance. We need approaches that are powerful enough to detect small effects. It's not that we like small effects, but simply that they're the best that we are going to get. In the end, I'm convinced, we are not going to touch most of the genetic variance.

Howe: I may be just expressing my ignorance, but I have always assumed that if one wants to 'know' things, one hasn't just got to know what is the initial allele that's present, but what it is that it's actually doing. Presumably there's a long and indirect link between the physiological event and the test score you end up with. In this kind of work, is it inevitable, or is it likely, that one gets a more precise idea of what is happening through building up an account of the steps between the physiological event and the test score which ultimately reveals the difference?

Plomin: Geneticists would like to be able to study the developmental process and how it interacts with the environment. From my perspective, of quantitative genetics which estimates anonymous components of variance, we don't identify the environment and we don't identify the specific genes. I would be thrilled to get a handle on a few of those genes, even though I don't expect that we'll ever account for a substantial amount of genetic variance with specific identified genes. Even if we find just one gene that accounts for a small amount of genetic variance, at least we have pinned it down a bit. Then we can begin to study other processes such as interactions with the environment and we could find genes for developmental change. No doubt different genes come into play, for example, with symbolic reasoning in adolescence. I would love to find genes that account for such developmental changes.

Fowler: Do I understand correctly that you think ultimately we shall show not only that there are genes for change, but also that some genes can themselves change as a result of environmental influences? Or, do you mean simply that the expression of the phenotype will change?

Plomin: Most of the genetic change in molecular genetics involves transcription differences. There are dozens of transcription factors that work like a committee, voting on whether or not a gene will be transcribed. We used to think only about structural DNA, but that's a very small proportion of the DNA in the genome. The genes that are involved in regulating whether or not a structural gene will be transcribed are in a dialogue with the environment.

Gardner: How is what you have said about the heritability of intelligence and the distribution of intelligence in contradiction to what has been claimed earlier?

Plomin: I find when I talk about DF analysis, people think I am talking about individual differences in high ability. The data I presented don't speak at all to the question of why one child has an IQ of 140 and another an IQ of 150. DF analysis addresses the question of why children in the high IQ group, with an average IQ of 130, are different from the rest of the population. This approach is a group difference analysis, trying to explain the average difference between the high IQ group and the rest of the population.

Consider Doug Detterman's basketball players again. The individual differences in their heights are probably not good predictors of their ability to play basketball. The question is, why are they so much taller than the rest of the population? Doug Detterman presented some data on individual differences in heritability at the high IQ end and the low IQ end (p 27–29). During our discussion of his paper, it took us a long time to be clear that he was not talking about individual differences in high ability but about average differences between children of high ability and the rest of the population. Those are completely different questions, which could have completely different answers.

Hatano: Even if you find some genes contributing to *g*, your task will then be to break down the global notion of *g* into its various components. We know that the human mind consists of a number of modules. It will probably be easier to find correspondence between genes and modular abilities. I don't understand why you are so interested in examining *g*.

Plomin: I'm interested in *g* because it's the most heritable thing in the cognitive domain. As tests tap *g* more, the tests are more heritable. *g* is a reasonable place to start, but I didn't want to start with *g* alone. In our grant proposal our stated aim was to investigate specific cognitive abilities such as spatial ability and types of memory ability. The children in our study were given a three-day battery of tests, including Doug Detterman's wonderful touch-screen arcade game-like information-processing test. His test avoids the usual problem of boredom in children doing information-processing tests in which there is a high degree of repetition. The problem we have is getting the kids off the machine! Our initial proposal was to establish permanent cell lines at $250 from each of the 500 children. Then we could ask all these questions because we would have the whole distribution of all of the abilities. However, resources would not permit us to do this, and we had to select high and low groups for a single dimension. We chose *g*.

If we are able to identify any genes that account for even a little bit of the genetic variance, and that's all I hope for, this really would revolutionize the type of work we do, and would make it more relevant to people here.

With a few drops of blood or saliva, you will be able to amplify the DNA with polymerase chain reaction techniques, and then access several markers. These techniques will soon be available for everybody to use without them having to become molecular geneticists.

Sitruk-Ware: Although I am impressed, I'm a little bit worried about the consequences of this research. If you find the gene which is correlated to a part of intelligence, pregnant women may ask for injections of the 'gene for intelligence'. It is already possible to alter genes *in utero*.

Plomin: This issue is most severe at the moment for single gene molecular genetics. It is possible to identify a gene that will cause a severe illness later on. The issues about employment discrimination and insurance are with us now—they're not hypothetical. With single gene disorders, if you have that gene, you are going to get that disease.

People often seem more concerned about cognitive ability than about these single-gene diseases which are already important problems. People think that parents will want to select children on this basis, as they already do in some countries for sex. I take the old-fashioned view that we can make decisions better with knowledge than without it. We have an obligation to make sure our work is interpreted correctly by the media and the public. The bottom line, for me, lies in the inherent weakness of genetic analyses of behaviour. There are so many genes involved that we shall never reach a genetic prediction that exceeds the prediction we could already make on the basis of other family members' IQs.

Wright's (1990) article with the wonderful title *Achilles' helix* tried to address some of these issues. There are several books (e.g., Bishop & Waldholz 1990, Nelkin & Tancredi 1989) that deal with the implications of identifying genes, primarily those involved in single gene medical disorders, but which at least mention the problems that will come up when we turn to complex traits that involve many genes as well as many environmental influences.

I would like to stress that I'm not saying that cognitive ability is all genetic—IQ is as much due to non-genetic factors. Genetic data provide some of the best evidence we have for the importance of non-genetic influence. In addition, genetics provides the designs that allow us to look for environmental influences in a way that takes genetics into account rather than trying to ignore it, as happens in studies of regular families, whose members are of course genetically related. When we find that parents who read to their children more often have children who read better, we just can't assume that's a causal environmental association.

Ericsson: You elected to study groups differing in IQ. It would have been preferable to have chosen groups differing in performance on a well-defined task that would have been more amenable to expertise research. People have tried to decompose IQ and understand its mechanisms and components. IQ tests were designed to differentiate successful and unsuccessful students; IQ summarizes performance on a large number of very different tasks selected for their psychometric properties. In contrast to differences in expert performance, where we can clearly specify the tasks and mediating processes, differences in *g* cannot be explicated in specific tasks and the mediating processes cannot be directly studied. It's unclear to me what you would find, were you to find it, by looking at extreme variations on the IQ dimension.

Plomin: That's because you don't really believe in *g*, whereas I think *g* is the most heritable thing we have. I'm quite impressed by the studies showing a strong correlation between the heritability of a test score and its *g*-loading (Jensen 1987, Pedersen et al 1992). From a genetic point of view, which is a difficult perspective for you to take, it makes sense to begin this work with whatever shows the most genetic influence. We didn't study chess ability, but we administered extensive tests of cognitive ability, including tests of information processing. We are interested in looking at other abilities, but our money allowed us to take only one shot. It seems clear to me that *g* was the shot to take.

Lubinski: People have been talking about decomposing *g*. I think it's important to realize that *g* is what is common to multiple symbolic/representational problem-solving systems. There are a lot of symbolic/representational problem-solving systems, and we use different symbols to solve different problems. We use linguistic–verbal systems to solve verbal problems, numerical–quantitative systems to solve quantitative problems, and spatial–mechanical systems to solve pictorial problems. What's common to all those systems is *g*. To determine the specificity of those systems, which I believe in (which is why we study mathematical talent), you first have to get a purchase on what's common to them.

Atkinson: Dr Plomin, by the time this volume is published you will be pretty far along in your research. Could you give us a hint as to what you expect to find?

Plomin: At best, we are going to identify a DNA marker or two that account for a tiny amount of IQ variance in the population. What's important is to phrase this appropriately, to realize that many many genes are probably involved. We may identify a few of those genes that account for a small amount of the variance in IQ. I don't think this will cause the huge uproar you are expecting.

Atkinson: What's a 'small' amount of the variance?

Plomin: That's a good question. I can't say precisely. Selecting individuals three standard deviations above the mean, we could find a DNA marker that has a large allelic frequency difference, something like 60% in one group and 30% in another group. That looks like a huge difference, but in terms of variance in the population, it would account for only a small amount of variation. Roughly, such an effect for a group three standard deviations above the mean might represent an effect size of less than 1% of the variance in the population.

Bouchard: What follows, though, is that all you need is enough genes, because they will add up.

Plomin: Experience in plant genetics suggests that a lot of the genetic effects will be so small that even with huge samples we wouldn't be able to detect many of the effects.

Bouchard: Plant geneticists are explaining 10–20% of the colour and the pulp texture in tomatoes.

Plomin: Those studies involve back-crosses and other inbred crosses. Outbred populations such as our species are more difficult to study. Modesty is in order!

We need to find markers on the environmental side as well. We talk loosely about them, but we need to apply the same rigourous demands for science on the environmental side. As Camilla Benbow remarked earlier (p 65), the issues there are just as severe. There's danger in implying that we know that all parents have to do is x, y or z to make their kids talented. That's probably more dangerous for parents and their well-being than any evil we have to offer on the genetic side.

Atkinson: That's a very sane description of what you are doing, but it will be quickly picked up, and who knows what the political uproar will be. I think it's going to be monumental.

Stanley: When Camilla Benbow and I published our article on sex differences in 1980 (Benbow & Stanley 1980) *Newsweek* almost immediately had the headline 'Do males have a math gene?' (Williams & King 1980). This and other similar media commentary caused us enormous difficulties, some of which still persist.

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The early lives of child prodigies

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Abstract. Child prodigies raise interesting questions about the ways in which childhood experiences contribute to adult achievements. The likelihood of a highly able child being called a prodigy partly depends upon whether or not the individual's abilities are readily apparent to other people. By no means all outstanding adults were prodigies as children. Biographical accounts by prodigies themselves provide interesting insights. They show that most child prodigies devote a substantial amount of time to learning and studying, that some prodigies experience serious problems which appear to be related to their unusual early lives, and that very few prodigies emerge in families that do not provide good opportunities to learn. The fact that evidence from prodigies and other sources of information shows that all outstanding adults were at least fairly able in childhood raises the question of whether it is ever possible for an individual who displays no signs at all of above-average ability before adulthood to eventually become outstanding over a broad range of intellectual abilities.

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One reason why child prodigies are interesting is that they help us to articulate questions about the importance for the longer term of events that happen in childhood. To what extent does early progress help to determine a person's mature achievements? Do certain kinds of intellectual developments have to take place early in life if they are to occur at all? Is it possible that there are circumstances in which precocity actually impedes a child's subsequent development?

Of the various kinds of accounts of the early lives of child prodigies, those which are in many ways the most interesting are autobiographical reports by the prodigies themselves. The best known have been written in adulthood, typically towards the end of the individual's life. Among the most intriguing are the fairly detailed autobiographical accounts by John Stuart Mill, Norbert Wiener, H. G. Wells and John Ruskin. But we do have to be wary about some aspects of these reports. It would be unwise to assume that they are necessarily representative of child prodigies in general, and, as with all autobiographical material, we have to be aware that memories of childhood, especially early childhood, are sometimes far from accurate. Nevertheless, all these individuals have helped us to understand what it is like to be a child prodigy, and later I shall make a few comments on some of their insights.

The concept of a prodigy

There are some difficulties raised by the actual term 'prodigy'. Efforts to investigate high abilities and explain their origins are plagued by more than their fair share of terminological and conceptual problems. The word 'genius' raises plenty of difficulties, and terms like 'gifted' and 'talented' sometimes add to confusion because they are often introduced in ways that initially appear to be innocently descriptive but in fact sneak an explanation 'through the back door'. Someone who calls a child gifted is not just saying that the child is unusually able, but also that the child is able because of something he or she possesses, with that something being some kind of gift. A number of assumptions are being made there. The existence of the gift is wrongly taken as an explanation for the child being so able. Also, if you ask people to define a 'gift' in rigorous terms, or ask for independent evidence of it, you often get no more than a blank look.

The difficulties with the expression 'child prodigy' are subtly different. The term is familiar and meaningful enough ('a child who has achieved an appreciable measure of adult intellectual standing before he is out of the years usually devoted to a secondary school education' according to one definition), but as usually applied in practice the word prodigy does not define the kind of precise category that makes for rigorous analysis or scientific explanation. A child is likely to be called a child prodigy only if he or she is *seen* to be doing something that, in the eyes of most adults, is remarkable. If a young child is an exceptionally good violin player for his or her age, it is more than likely that others will be aware of that, partly because a performing skill is inevitably not entirely private, and partly because the grading system enables us to know when a given level of performance in a child is not merely impressive but exceptionally so in relation to age. For similar reasons, if the child happened to be a chess player, we could be equally confident that any exceptionality would be apparent to at least some adults. On the other hand, had that same child's main interest been in a more private activity, such as thinking about literary or philosophical issues, or reading nuclear physics, it is possible that he or she could be exceptionally able but that hardly anyone would know about it. Such a child, however capable, might never be regarded as a child prodigy. So far as I know, nobody called the nine-year-old Einstein a child prodigy, and few people at that time detected signs of unusual precocity in him. All the same, he must by then have possessed abilities that were exceptional. By the time Einstein was twelve, one family friend (Max Talmey; see Clark 1979) noted that he was reading serious books about the physical sciences and was already an enthusiastic and extremely precocious young mathematician.

The likelihood of children being described by others as prodigies depends not just on their actual exceptionality but also upon how *obvious* that exceptionality is to other people. When asking questions about possible relationships between prodigious development in childhood and achievement in maturity we have to remember that, and acknowledge that the group of children who have been described as being prodigies form only a sample—and not necessarily a representative one—of a larger group comprising those children who have remarkable abilities. So, if we were to ask whether it is necessary to be known as a prodigy in childhood to be exceptionally able as an adult, the negative answer that we could justify by referring to Einstein and others who were not identified as prodigies in childhood would not in fact tell us very much about the actual relationship between childhood precocity and mature achievement.

Keeping this in mind, and avoiding the actual word prodigy for the moment, we can still ask whether it is necessary to be exceptionally able or promising in childhood in order to be remarkable as an adult. That is less easy to answer than the question about whether it is necessary to have been identified as being a prodigy, because if when we ask the question the person is already an adult, but was not identified as a prodigy in childhood, we often cannot be at all sure about the person's actual abilities as a child.

Many, if not most, exceptionally high-achieving adults do appear to have shown clear signs of being unusually able when they were children. Of course, if we ask whether for a person to be an exceptionally able adult he or she *must have been* an exceptionally able child, only one example is needed to justify a negative answer—Charles Darwin is a particularly well-known one, and Wordsworth and Van Gogh are others. So, it does seem safe to say that the answer to this question is no. Bear in mind, however, that no one can seriously suggest that Darwin was not an intelligent and energetic child with a fairly serious interest in biological pursuits, and it is clear that the activities and experiences of his childhood did form an excellent grounding for his early adult life.

Although it is not essential to be a child prodigy in order to become an exceptionally able adult, this does not mean that childhood is unimportant. Childhood does not decide everything, though, as other kinds of information confirm. In Terman's investigations, for example, although it was undeniably the case that individuals identified as being intelligent in childhood continued to do well in later life, there was no clear tendency for the brightest children in his sample to have the most glittering careers (Oden 1968). The 150 most successful and the 150 least successful of the sample differed in personality and temperament, but not in their average measured intelligence scores.

A similar situation may even be found with performing musicians, despite the fact that the long training in technique means that becoming highly skilled in childhood is essential if a young person is to have any chance of eventually being considered to be outstanding. Lauren Sosniak (1990) studied a sample of exceptional young pianists in the USA who by the age of around thirty were on the brink of successful careers as concert soloists. During their childhoods there were few signs that these particular individuals would be amongst the very few pianists who reach that high level. Even by the age of around fifteen, by which time they would have been studying the piano for seven or eight years and would undoubtedly have been very impressive technically, her subjects were not obviously better than hundreds (if not thousands) of other diligent and promising young pianists. It will be interesting to see, in the research investigating the early progress of young musicians that John Sloboda, Jane Davidson and I are conducting in the Manchester area, whether those children in our British sample who are judged to be the most excellent in mid-childhood are the most successful as adult musicians. Lauren Sosniak's findings prompt me to predict that will not be the case.

Lessons from individual prodigies

Some of the points I have mentioned help explain why the kind of detailed evidence that is available about the early lives of individual child prodigies cannot, on its own, answer all the questions it raises. Nevertheless, these accounts are valuable for a number of reasons. One is the sheer richness and detail of the information they provide. Another is that they add a temporal dimension, allowing us to see movement and progress actually taking place. A third reason is that these detailed accounts, especially when they are autobiographical, give us all kinds of insights about the point of view of the individual concerned.

Here are three things we have learnt from relatively detailed reports of the early lives of individuals. First, we are made aware in autobiographies like those of John Stuart Mill and Norbert Wiener that the business of learning can take up a good part of a child prodigy's day, even when, possibly especially when, parents or other adults make a point of expressing how surprised and taken aback they were by the child's progress. There seems to be a disingenuous element in some of Leopold Mozart's remarks about his children. Similarly, although Yo-Yo Ma's teacher reports astonishment at seeing the cellist, at the age of only four, playing a Bach suite, the fact that the child could do so seems less astonishing when we learn about the intensive regime he was subjected to. According to one account, Ma's father 'had developed a method of teaching young children how to concentrate intensively. No more than a short assignment was given daily, but this was to be thoroughly assimilated. He proceeded systematically and patiently. Each day, Yo-Yo was expected to memorize two measures of Bach; the following day, two more measures' (Blum 1989, p 48).

Sometimes parents appear to decide that a child is to be exceptional almost before he or she is born, and they do everything they can to ensure that their expectation is fulfilled. One writer (Rolfe 1978) argues that both of Yehudi Menuhin's parents strongly believed that every now and then a brilliant child would be born into their family, and they never seem to have doubted that their son was destined to be outstandingly able. A biographer of Keynes (Skidelsky 1983) describes his subject, as a young child, as being surrounded by the conviction that he was bound to be clever. John Ruskin's parents seem to have decided at a very early stage that their son was going to be a great person (Burd 1973). Frank Lloyd Wright's mother decided before he was born that her son was going to be a great architect, and from his earlier months she arranged for him to be surrounded by architectural images.

A second thing we learn from reports of the early lives of individual prodigies is that in families in which children become prodigies the family pressures placed on the children can be intense. The problems can be serious even when they do not have such dire consequences as in the sad case of William Sidis (Wallace 1986), a remarkable prodigy who died early after an unhappy life in which his early promise was never realized. John Stuart Mill argues convincingly that much of the unhappiness he experienced, and the difficulty he had in finding a real sense of direction, stemmed from his unusual childhood. It seems more than likely that John Ruskin's later troubles were caused in part by the over-intense, somewhat claustrophobic circumstances of his family life. Norbert Wiener writes at length about the severe difficulty he experienced in trying to develop into an independent adult in the face of parents who seemed to find it almost impossible to accept his need to assert his independence from them. One of the few generalizations that can be made about people of outstanding achievement is that they have to be fiercely independent and self-directed. It is clear that there is a tendency for some families of child prodigies to be rather inward-looking, with parents and children possibly too dependent on each other, and with the parents sometimes investing in their children's lives too much of the energy and ambition that would otherwise have been directed to their own lives. We can see the possibility that, in some cases at least, the circumstances that make it likely that a child will be a prodigy contain elements that may not be ideal for that child to develop into an adult who makes the best use of his or her capabilities.

A third thing we learn from these accounts is that the majority of the better known prodigies have come from families in which at least one of the parents was both educated and enthusiastic about education. In some cases there seems to be a very strong drive to educate one's children. We see this in particular in Karl Witte's book on the education of his son (1975), and parents such as Leo Wiener and Boris Sidis were similarly keen to communicate their educational ideas. These centred around the idea that most children are prevented by lack of opportunities and encouragement from achieving more than a small proportion of the things that all children are born capable of mastering.

There is doubtless much truth in educational views of this kind. They make us wonder whether it is possible for a child growing up in a family that provides few opportunities to learn and little encouragement to become a prodigy.

That question is not easy to answer. Certainly, there *seem* to be cases of child prodigies growing up in unstimulating home backgrounds, but, on closer examination, we often find that we do not know enough about the child's early circumstances to be certain that they actually were particularly unfavourable. For example, in H. G. Wells' autobiography we read of him growing up in some poverty, with an unhappy mother and a somewhat bitter father, neither of whom had much formal education. However, his father was actually something of a local celebrity and read lots of books, and his mother regularly kept a diary and made big efforts to encourage young Bertie to read; by the standards of the day Wells' early background may not in fact have been as unsupportive or unstimulating as it initially appears.

A particularly interesting case of another child who was a prodigy despite growing up in family circumstances lacking intellectual stimulation is a man named George Bidder, who grew up in the early nineteenth century in Devon. Bidder drew attention to himself as a young child through his remarkable capacity for mental calculation. As a result, wealthy patrons ensured that he was provided with a proper school education and then went to Edinburgh University. There, he became friendly with Robert Stephenson and, like Stephenson, became one of the great engineers of an age when engineering transformed much of the world. Bidder writes of his family as being poor and not at all educated. This suggests he was a child prodigy despite coming from a family in which opportunities for learning were few (Howe 1990). But the information we have about his childhood is too sparse to be sure: there are hints that he received quite a lot of encouragement from an older brother, and it is possible that his family were better educated and more prosperous than his very brief account suggests. Not only in Bidder's case, but also in others, we know tantalizingly little about people's childhood years. If only we had a fuller picture of the childhoods of Shakespeare, say, or Newton!

Prodigies in reverse?

Before I finish, let me raise a different question that comes to mind when one is reading about child prodigies. Is it ever possible for a person to be a kind of reverse of a child prodigy? Is it conceivable that a person who displayed no signs at all in childhood of being intelligent, let alone exceptionally able, could become exceptionally accomplished in adulthood?

Consider the case of Frederick James Tardy. I should warn you, however, the case is entirely fictional. Fred was the sixth of eight children of poorly educated parents. As a child he always seemed happy enough, but never did well at anything. At school he seemed reasonably interested and attentive, but his performance was never better than average and on the several occasions when his IQ was tested he scored in the 90s. Outside school his abilities were similarly unimpressive. No one regarded him as at all sharp or clever or imaginative.

At no point in his childhood or adolescence did Fred ever display any abilities or attributes that were at all out of the ordinary.

At the age of twenty-five Fred was sent to prison. He remained there for fifteen years, convicted for a murder that he had not committed. His experiences of prison were unusual. By chance, he happened to be sent to a prison where the educational facilities were exceptionally good. Also by chance, he happened to share a cell with a prisoner who was a charismatic ex-teacher with a burning desire to educate others. Fred's cell-mate succeeded in converting Fred to a way of life in which the desire to learn and become educated was central and all-important. So by the end of Fred's first year in prison, he was enthusiastically devoting about 15 hours every day to reading, study and other intellectual activities, with the constant support and encouragement of his talented and persuasive cell-mate, and with the impressive backing available in the prison. For his 15-year period in prison, Fred was an enthusiastic, conscientious and well-organized student. Every day he worked hard and constantly as a learner, and he became confident and enjoyed what he was doing.

At the age of forty Fred left prison a highly educated and able man, determined to devote the remainder of his life to the scholarly research activities that had filled his later years in prison. His published work was highly regarded and he was immensely successful. The quality of his achievements was widely praised. On his 65th birthday he learned that he was to receive a Nobel Prize.

Fred Tardy is, of course, only a fictional character; but could he have existed? Are there any circumstances in which someone who during their first twenty years or so is not only poorly educated but genuinely unintelligent and displays no signs of above average ability or potential could subsequently become highly able? We do know of people whose abilities have been radically transformed in adulthood. For fairly obvious reasons, incarceration in prison often helps provide the conditions suitable for such a transformation. There must be a fair number of cases of individuals who have educated themselves and have gained impressive qualifications. In most cases, unlike that of Fred, it is clear such people were, even before their prison sentence, sharp and astute, intelligent in at least some respects.

We also know, thanks to the research of Ericsson and his colleagues (Ericsson et al 1990) of adults who have never previously shown any indication of being exceptional, but who have, after intensive training, reached levels of performance at specific tasks which are exceptional enough to convince others that they must possess inherently special gifts. In these cases the tasks have been fairly narrowly circumscribed, and the witnesses were so impressed partly because they did not know that if you give any motivated ordinary person as little as several hundred hours training on a task that very few people are trained at, the chances are that the individual will end up being able to perform the task at a quite exceptional level. Yet, some of Ericsson's cases are impressive by any standards, even if they fall short of Fred's achievements.

In practice, the Fred scenario may not even be feasible. By the time people reach adulthood their personality, feelings about themselves, interests, personal relationships, values, and attitudes to life are not easily changed. Is it realistic to expect that a person's whole way of life could change quite as much as Fred's would have had to do? I suspect not, but who knows?

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DISCUSSION

Sternberg: I have found the studies of childhood prodigies that you and others have done very interesting and helpful, but there's one concern I've had about them, which would also apply to the work of Benjamin Bloom and others on gifted achievers, and that is the absence of a control group. How many parents have tried to do for their children what John Stuart Mill's parents did for him, but didn't succeed? I suspect there are many parents who had great ambitions for their children but saw the children falter because of inability or lack of motivation.

Howe: I was afraid somebody would ask that question. It is a necessary question, and the short answer is that we don't have an answer. The work I am doing with John Sloboda won't answer all the questions overnight, but it will help.

It is interesting though, that although I am talking about tiny and perhaps unrepresentative samples, it does seem that the particular child who does well is the child who has been on the receiving end of the greatest amount of parental investment. Certainly, with both J. S. Mill and Norbert Wiener, the parent went on being interested in the education of all the children to some extent, but the everyday work of educating was in a way put onto the oldest child. Both had to educate their siblings, and both obviously loathed it and I suspect did a pretty bad job. You can look at such cases, albeit in a totally subjective way, and find things about their early lives that differ from those of their brothers and sisters which might lead you to predict that they would be the successful individuals, but that doesn't of course compensate for the lack of a rigorous control.

Freeman: Since 1974 I have been carrying out a three-way comparison follow-up study of children labelled as gifted, with non-labelled but equally able children, and a matched control group of children chosen randomly for ability (Freeman 1991). Some of these children, if not geniuses, were certainly highly accomplished; over 25% of the sample had Stanford-Binet IQ scores of 150 or more. Watching them grow up from five to 14 allows me to answer some of these questions.

I can give one case study as an example, of a child who was noticed by her schoolteacher. Her parents were poor Irish immigrants, apparently of not more than average intelligence. When she was about six years old, her schoolteacher sent her to Cheetham School of Music for an audition because she could sing sweetly. The school of music took her in, trained her, and kept her as a boarder until she was 18. Although they thought she was extremely good, they didn't think she would be successful. Her parents could give her nothing, musically, but they did manage to buy her a piano when she got into the school. She won the BBC Young Musician of the Year competition, which covers all instruments and is an extremely difficult competition to win. She has now become a concert pianist and is doing very well. Deep questioning of her parents revealed that they had a great-aunt who played the organ in church, and that she had a great-uncle who was a wall-of-death driver in a fairground; she had quite a wide background, and her parents were in fact the least prepossessing. If I hadn't looked back beyond her parents to the previous generation, I would have missed all this. Enormously deep questioning and perseverance is necessary in discovering the precursors of high ability.

Howe: One of the questions John Sloboda and I are asking in our study is whether there is a tradition of musicians in the family. Quite often it turns out that there was, which in a way just raises more questions about causality rather than answering them.

Stanley: Camilla Benbow and I have been interested for a long time in young people who reason extremely well mathematically. We have classified them in two general groups. One group are the products of 'creator' parents, parents who want to produce such children. We don't find many such parents or children. The second group are those who are surprises to their parents, because, for example, they multiply accurately in their heads at the age of three or four. Good parents will give them opportunities to do more and more mathematics and related topics.

Atkinson: What's the ratio between those two groups?

Stanley: We haven't really counted. We don't encounter many fanatically eager parents like John Stuart Mill's father.

We know of a number of 'failed' prodigies, most of whom had 'creator' parents. The most publicized is William James Sidis (Wallace 1986). Edith Stern's father wrote a book about his methods of rearing his bright daughter (Stern 1971). She later became a routine computer-programmer, and disappeared into virtual anonymity. Michael Grost (1970) took a PhD degree in mathematics when fairly young but seems to have disappeared from public view. David Feldman (Feldman & Goldsmith 1986) had six youths in his study, two of whom I knew quite well—one was a product of our study and the other we tested and interviewed—but Dr Feldman is not following up the six. One of the most disappointing cases of which I am aware is Michael Deakin's (1972) report. He was studying an almost fanatical 'creator' mother and her interactions with her children. I wrote to him a few years ago to ask him what had happened to these children. He replied that he wasn't privileged to tell me, that it was confidential. I would have predicted that the children would not succeed at a high level.

On a happier note, I would refer you to Norbert Wiener's (1953) autobiography and the biography of John Stuart Mill by Packe (1954).

Freeman: The children in the family Deakin was studying didn't come to anything. Their great problem was that they couldn't make relationships; they were extremely odd, because they weren't allowed to play with other children. Their exceptional advances seem to have just fizzled out.

Howe: Obviously, to be successful in this world one has to have a lot of things going for one in addition to precocious intellectual advancement. Often, in the kinds of families in which, for one reason or another, the parents are tremendously dedicated to the education of their child, some of the things that are needed for a person to be a self-directed individual who is good at getting on with other people and has a sense of direction are lacking. On the other hand, there are still cases such as Mill and Wiener where a lot of those negative influences were present, but the individuals nevertheless did thrive in one way or another, though they were not without problems.

Stanley: My hypothesis is that most 'creator' parents fail to produce Mills and Wieners. Most who try are never heard about, but a few write books; from the evidence we have it seems that most fail because they don't take the social and emotional side into account.

Howe: I would agree that most parents who set out to make their child a genius will fail, for those kinds of reasons. We would be wise not to extrapolate from that to say that parents shouldn't stimulate their children and provide encouragement and opportunities.

Stanley: The point of the chapter on mathematics in Bloom's book (Gustin 1985) about outstanding mathematicians under 39 was that they did seem to 'come out of the woodwork'. Most were born into bright, facilitative families. Their parents moved along with their precocity and talent and provided excellent, varied learning opportunities geared to their child's interests. Most such parents did not start out thinking that they were going to have an extremely bright, inquisitive child. An interesting thing described in that chapter was that most of the children did not specialize early. Most people, however well they reason mathematically, cannot do good, real mathematics until they're 18–20 years of age. Before adolescence, they were not interested primarily in mathematics. They were avid learners, learning a lot of things, especially science. From groups of eager young learners come a few mathematicians. Most others become something else. Gustin did not take cognitive abilities explicitly into account, but it is obvious from his interviews that he was studying persons who were highly able when young.

Howe: I have heard it suggested, but not being a mathematician I don't know if there is any truth in it, that to some extent in mathematics a young person can be less dependent on a mentor or teacher than a young musician, for example.

Stanley: It is certainly true that young mathematicians don't seem to practise mathematics to the extent that someone practises a musical instrument. Most don't practise much in early life, but when they get to the PhD level, many do mathematics nearly all the time.

Howe: Bidder drew attention to himself as a lightning calculator, and that's how he got the help and encouragement which allowed him to be educated. When he was young his mathematics was done mentally, and the methods by which you learn to do mental arithmetic play down the role of memory and minimize the amount of material that has to be stored in memory. Someone who is learning arithmetic through writing and books would not use those methods and would never develop the kind of mental calculating abilities that he had, and would not draw attention to themselves in the same way as he did.

Gruber: The family as the environment in which early growth takes place may be more complicated than we've suggested. We talk about the parent, or the parents, and one child is our target. In fact, the other children in the family can play an important role. For example, Darwin's older brother, Erasmus, who never amounted to anything himself, created the chemical laboratory in which Charles did his first boyish scientific work. They corresponded about it quite a bit, because Erasmus went to Edinburgh University while Charles was still in Shrewsbury. There are many examples of siblings not being rivals and mutually destructive, but cooperative and mutually supportive, with the older ones generally teaching younger ones.

The other point I wanted to make was that children who end up as creative people participate in making their own environment, as you indicated with the example of Bidder. The profound effect of the environment on form and function is not an anti-biological idea. At many biological levels, an organism makes the world in which it functions, not only the internal environment but also the external environment.

We should guard against viewing early starts as the only way in which later great creativity comes about. There are at least some examples of late starters who really became spectacular. Van Gogh, for example, committed himself to being a painter only at the age of 30. Before that he had been a lay preacher and had done various other things, and he had only 10 years to do his work as an artist before he died at the age of 40. George Bernard Shaw is another example of a somewhat different sort; he didn't write a play until he was 40, and then he wrote an enormous dramatic *oeuvre*, but he had been a writer and he had all the other assets we have talked about such as family support and an interesting family to grow up in. It is significant, if you are interested in pin-pointing the particular nature of the abilities that a person brings to bear on his or her career, that Shaw didn't write a play until he was 40.

Howe: Tolstoy didn't really get into the business of writing until he was well into adulthood, and William James took a long time to make up his mind about a career. Being from relatively wealthy families, they could afford to prevaricate.

We all talk about environment, but what is really important in a person's life is their actual experience. We tend to glibly equate environment and experience, as if they're the same thing. Environment is only, by definition, as seen from outside, whereas how a person is actually influenced from inside is dependent on all kinds of things which are not apparent to the external observer. Previous learning, knowledge and attitudes determine how the 'environment' is actually taken in or experienced by the person.

Fowler: Much of the information that we have comes from retrospective accounts such as these, with all their limitations. I would certainly agree that we cannot address the nature versus nurture question in this way, because we are taking essentially a collection of single cases, and we don't know about all the failures. Despite this, suggestive evidence does come through. If you find a pattern, for example, that in all cases where there's evidence of the early life there have been certain types of interactions, rich verbal and intellectual stimulation and exchanges, then that would seem to be a necessary condition. Such a finding doesn't prove anything. Ultimately, much more experimental evidence is required, which is one reason why I have been trying to do a prospective study.

It's certainly true that mathematicians, typically, are not identified early, but they do tend to come from rich verbal environments, as indicated in Bloom's (1985) studies. You don't find cases of great mathematicians, where you know about early life, where there wasn't good verbal exchange.

I did a retrospective analysis (Fowler 1981) of some case studies of Terman (1919). These were not his famous one thousand gifted children, but an earlier version of the same thing, children of IQ above 130. I found that there were two categories of parents; one you might call the 'pushers' or 'planners', and the other group were parents who disclaimed any such intention. What struck me was that the planners would say, 'oh yes, we set out to make a bright kid' and, according to standard criteria, they succeeded, whereas the other group said 'we just responded; this kid was so bright that we couldn't resist'. The system of values is quite different. The 'pushing' families believed the environment was important, whereas the others tended to believe heredity was important, but they nevertheless responded, and the two categories of parents used essentially the same methods, which in my opinion were good methods because they were highly interactive, informal and built around play and activities appropriate for children.

Colangelo: In my experience of precocious youngsters or near-prodigies, seldom does a parent set out to achieve a particular goal. I encountered the facilitative more often, but the way Julian Stanley used that term (p 95) is a little benign, because being facilitative can be expensive. Some families in Bloom's studies moved from where they were living to be near a particular coach, for example. Tremendous resources were mobilized and time spent, at the expense of the other siblings.

Professor Howe, you suggested that these prodigies were fiercely independent on the one hand, but fiercely dependent, on the other hand, on either the mother or father. This seems to be a contradiction. What do you mean by independence? They do seem to have been highly dependent on one parent.

Howe: I was trying to say that if you are going to be a high achiever, a genius, in a sense you have to be fiercely independent, strongly self-determined and inwardly directed. People who do achieve important things are almost always like that. Nevertheless, often, in families who tried to make the child into a genius, gaining that kind of independence, for one reason or another, was difficult, and sometimes it never happened. This might to some extent explain what happened to young people like Sidis, who obviously was very able but was never able to make use of his skills. Even when people established the degree of independence and self-determination necessary, as John Stuart Mill and Norbert Wiener did, it was a struggle for them to get to that position. They had all kinds of problems and were in many ways rather unhappy people.

Colangelo: The trend, then, seems to be fierce dependence on at least one person, coupled with independence from or obstinacy with others. I haven't always found this independence. In my experience, there is an almost total engulfment with a coach or a particular teacher.

As someone who directs an education centre, I get many calls from parents. Two come to mind in particular, one about a boy chess player, and one about a boy who played a musical instrument. Both these boys seemed to be heading towards high achievement. The chess player was at the end of elementary school, and looked destined for national championships. However, the two boys had decided by the time they were in junior high that they didn't want to do their 'activities' any more. The great fear expressed by both their mothers was that they perhaps had pushed too hard, and they wanted to know where they had gone wrong. The fear generally is that failure to realize potential results from parents putting too much pressure on their children. Is there evidence that at a certain age a child with exceptional talent can suddenly let go of it, not necessarily burning out, but forming other interests?

Howe: John Sloboda and I have encountered this problem in our work in Manchester. Young people have come to us for advice after hearing that there is a psychologist in the school. They seem to reach the age of 15, 16 or 17, and then go through a crisis about whether they are doing things for themselves or for their parents. Presumably there is a delicate balance between a parental environment that is encouraging and supportive, and one in which a young person ends up feeling that they're not doing something for their own reasons, and they're not motivated for their own sakes. When parents set out to turn their child into a genius, it often happens that somewhere in the middle of adolescence things go wrong for that kind of reason, and the parents are disappointed and become alienated from their children.

Fowler: The problem arises not so much from general interactions between parents and children built around basic verbal and exploratory and sensory motor processes, but when there is an early specialization, when something becomes linked to a long-term goal. Fields such as music, chess or athletics seem to raise this problem because you need to start early to reach a really high level of achievement, but at the same time the adults are building in a target for a child without the child having an opportunity to have a more open-ended autonomy in his or her development. Nowadays we are unlikely to encounter pressure-cooker children as often as we would have done in the 19th century and before.

Atkinson: You mentioned music, chess and athletics. It may be that early training is important for mathematics too, only we can't begin to specify the kind of training that would generate a creative mathematician. The training one might have done in the 1700s or 1800s might have been useful for people working in mathematics at that time, but mathematics is changing so rapidly that it may be impossible to analyse the kind of training that would be needed now.

I knew Wiener in his later years. In my view, mathematicians don't think of him as having been a great mathematician. He was identified with the notion of cybernetics, which became a popular idea after World War II, and he was on the mathematics faculty at MIT for many years, but I don't associate him with great contributions to mathematics. It might be interesting to enquire of mathematicians whether his work is viewed as significant.

Stanley: Perhaps he was essentially an electrical engineer. He was a specialist in partial differential equations and other things that were useful in the electrical field. But Wiener thought himself a mathematician, as the title of the second volume of his autobiography, *I am a mathematician*, clearly indicates (Wiener 1956).

Edith Stern (Stern 1971) is of great interest, because she is one of the few females who have been pushed hard. Her father, who was determined she should become great and famous, set out to make her into a physician along the lines of Albert Schweitzer. At some point when she was a teenager, she decided she would get even with him because of his hard pushing, and that she would become a mathematician because she was not highly able in mathematics. Her father was not able to keep her on his predetermined track. It might have been her bent, but she rebelled against it.

Detterman: There is a difference between retrospective and prospective studies. Most biographical studies are based on reports from people. I like to take credit for my accomplishments, and disavow my failures. Retrospectively, people may reinterpret causal effect. The direction of effect may be somewhat different from what actually occurred. When your son wins a Nobel Prize, you may want to claim you taught him everything he knows. I know I would! I have one of Julian Stanley's SMPY kids in one of my classes, and I have tried to convince him to go into psychology. If he does and ever produces something important, I will take full credit for it. Has anyone, in a prospective study, looked at the change in people's attitudes or perceptions about such children over time?

Howe: I suspect little has been done on this question. John Sloboda, Jane Davidson and I will be able to get some of that information. We are getting 10- and 11-year-olds to keep diaries on a day-to-day basis. There are parents who take the credit for their child's achievement, but there are others who say that the child received a gift from God and that they had nothing to do with it at all. As proof of this, they will say that on one day their child had 623 words in his vocabulary and five days later he had 678, but that they knew nothing about why the child did so well; their obsessive record-keeping belies their professed uninvolvement in the child's early education.

Detterman: The person from Julian Stanley's study in my class said his parents did nothing exceptional for him that they didn't do for his other siblings. The parents want to feel that they haven't singled out one child. Could everything in the biographical self-report literature be rationalization on the part of the respondents?

Gardner: In general, parents don't know what 'exceptional' means; they don't have enough comparative data.

Fowler: It's hard to treat siblings alike, in any case, particularly if they are close together in age. The experience with the second, third or fourth child will never be the same as with the first.

Lubinski: Just because a parent gives most attention to the most precocious child, that doesn't mean that the child didn't manifest something that motivated the parent to do so. There are active *and* reactive interactions between people and environment.

Csikszentmihalyi: We have completed a prospective study of high school children who are fairly talented in mathematics, science, music and art (Csikszentmihalyi et al 1993). Our question was, what is the difference between those students who develop their talents throughout their high school years and those who fail to and fall back to mediocrity? The family is implicated, but the most important finding is that the phenomenology of what it means to do mathematics or music is the key to understanding whether or not children will continue to do what they are good at. Some children really enjoy what they're doing, and others don't, even though they appear to have the same cognitive ability. The parents' high expectations and the pressure they put on, or the parents' indifference to the child's ability, moderate the way the child experiences these activities. If the child does not find what he is doing enjoyable, either because there's too much expected of him or because not enough is expected, by the age of 16 the talent will be atrophied because he will find more interesting things to do than something which is not itself rewarding. Of course, there are huge differences. Almost no child enjoys doing mathematics at the age of 13 or 14, whereas music and art are easy to enjoy at an early age. Fully fledged mathematicians and scientists love to do mathematics and science, but somehow the way we expose children to those domains means that they are not enjoyable and that they have to have other reasons for doing them initially. We can't expect young people to perfect a talent just because their parents want them to or because it will be good for them 20 years later. There has to be some reward at the right time.

Howe: Perhaps we underestimate other not exactly random influences, and not exactly chance ones, but ones which we can't specify. For example, take a child of 16 or 17, for whom life is beginning to move on a bit, who is going out with friends and getting drunk and is turned off everything, and getting on badly with the family. Imagine that this individual gets a good part-time job which has a lot of responsibility which he enjoys, passes the driving test or does well in a test at school. Suddenly the transition to adulthood will seem a lot easier, and this individual will start seeing himself in a slightly different light, become more responsible and see the future as a more positive thing. However, it is possible that identical events could have a totally different influence on a different individual. We tend to assume that certain kinds of influence will always have certain kinds of effects, whereas the outcome really depends on how a particular individual happens to experience particular things.

Mönks: I think several kinds of coincidences are necessary to provide the most beneficial surroundings for a child. Maria Montessori (1871–1950) was a true mathematical prodigy, but against the will of her father she studied to be a doctor and became the first female physician in Italy (Mönks & Mason 1993). This is an example of real intrinsic motivation. The environment, her father, was *against* her, though he became proud of course when she got a PhD. She had no support, except a little from her mother. Whatever the family pressure, some kind of intrinsic motivation is necessary.

Sternberg: Among these 'creator' parents, who try to create extrinsic or, they hope, intrinsic motivations, there are those who decide they want their child to be a doctor or a mathematician or an x or a y. That doesn't work, because the children do not conform to the parents' image. Then there are the parents who let go of their preconceptions, who really want their child to be outstanding in something, whether or not it's what they initially had in mind. Those parents are more likely to have success.

Gardner: I would like to take up two different themes that have come up today. Nic Colangelo raised the point about the apparent contradiction between a child being dependent upon someone and the assertion that he needs to be autonomous and independent (p 97). That, rather than being a paradox, is almost the actual problem. Initially, children are unlikely to achieve much unless they have a close relationship with a mentor. Ultimately, however, if they want to do anything except be mimetic, they absolutely have to break away. This is the nature of the problem. Even when you have to be autonomous and independent, you never actually lose that dependency, but it gets played out in a specific kind of way.

Michael Howe's Fred Tardy could exist, I think, but Fred's existence would be more likely if he were Freda. There are two important factors: observational learning and social sanctions. You can learn a tremendous amount about something by watching, without ever doing it, particularly if the role that you have doesn't sanction public performance. Occasionally, people learn a tremendous amount, thinking that they would never be allowed to perform, and then something happens—such as their brother being assassinated—something changes, so that they are allowed to actually do it. Obviously, there are some things that you can't learn simply through observation, but you can learn a lot more about certain things which would seem to require practice than an unreflective person might believe. There are many cases, which are as well documented as they could be, of women or slaves who lived in situations in which they weren't allowed to be taught to read learning to by observation. There are people who weren't allowed to play instruments, who watched, and then, when they were finally allowed to play, played surprisingly well. You could go through much of your life looking like not very much, until you are given the opportunity to surprise people.

Freeman: John McVicar is an example of a Fred Tardy who is well known in Britain. He was from a poor background, physically and culturally, and became a criminal. He didn't get a Nobel Prize, but as a prisoner took an Open University degree and has now written several books.

Howe: Although he was uneducated he was a pretty sharp person.

Sternberg: The other variable here is opportunity, as Howard Gardner's example about becoming president of the USA because your brother is assassinated illustrates; some people have more opportunity than others to become president of the USA! Who knows how many others could have been more outstanding? In concentrating on abilities and environment, the one thing we may have neglected is pure luck. If you want to be King of England, unless you were born in a certain family, your chances are low!

Sitruk-Ware: In my country, the teaching system is designed to bring the lowest and the highest to the middle range. Unless the family acts as a catalyst and provides opportunities, the precocious children have no chance. The teachers need to be made to understand the importance of not only helping the handicapped and those of low ability, but also those 'handicapped' by high ability.

Stanley: A development which began in the USA in 1972 was the instigation of special supplementary academic courses outside the school system, held during the summer usually, for talented youngsters. That system has grown enormously. Johns Hopkins alone instructs about 4500 three-week enrollees every summer. Each of these youngsters has to qualify on the university admissions College Board Scholastic Aptitude Test (SAT). If they want to take a mathematics or a science course, they must score in the upper 1% of their age group on SAT-Mathematical, a difficult test of mathematical reasoning ability. Likewise, to be permitted to enrol for a verbal course (writing skills, history, foreign language, etc.) they must score high on SAT-Verbal. A high score on the mathematical reasoning test, particularly for boys, is as good a predictor of interest in mathematics as it is of ability. The same would be true of a general science test which at the age of 12 is probably a better indicator of interest in science than a typical standardized interest test would be. What Dr Sitruk-Ware is seeing in Switzerland also happens in schools in the USA. Often, youngsters who are highly talented in mathematics or verbal subjects don't get a chance to do anything special in school and are bored to death; but youngsters in the USA can go to the summer programmes, if they can afford them, and get stimulation and acceleration. The typical course taken at 12 or 13 is a mathematics course, usually the first year of algebra. Students can learn a whole year of school algebra in three weeks. Or, they learn writing skills if they're verbally talented. They can even do two three-week sessions in one summer. Some do as many as eight different three-week sessions before they finish high school, which gives them the opportunity to accelerate in those subjects in school, but also provides some relief from boredom and frustration.

Sitruk-Ware: For that, someone has to identify the potential and provide the opportunity. Where the appropriate family environment is lacking, and the teachers tell the bright child that he has to help the other children, the able child will be completely discouraged.

Stanley: That's where the talent search comes in. We run large regional searches, covering every state in the USA; at least 100 000 children take the SAT test each January, and a number take another test, the ACT, provided by the American College Testing Programme. The ACT is similar to the SAT, but oriented more toward subject matter and the standard curriculum. We find the bright children, tell the students themselves, and tell the parents and the students' teachers who they are. No other country that I know of has any such systematic approach for finding youths who reason exceptionally well mathematically or verbally.

Freeman: The alternative to conducting a talent search is to improve facilities within the state system, for example, by providing enrichment centres and a variety of other procedures in the schools in which children can participate without having to come from wealthy or highly motivated families.

Stanley: Our approach is not an enrichment approach. It's an academic acceleration approach in which the children study formal school subjects such as algebra, creative writing, American history, biology, physics, chemistry, computer science and foreign languages. They can learn a whole year of high school biology well in three weeks and then move on in high school to the next level of biology, which we call the Advanced Placement Program (AP) level, and get university credit for it. It's crucial for these children to be identified and then given the choice of subject, rather than them following the parents' or the teachers' choice.

If they're interested enough and competent enough, the youngsters love these residential summer courses. If you select simply on the basis of IQ, however, they won't necessarily thrill to the subjects offered. One of the big fallacies is that youngsters with a high IQ are good at everything. Grouping according to IQ is one of the worst possible ways to group youngsters for special instruction. You should group for mathematics according to mathematical reasoning ability, or for verbal studies on verbal ability; otherwise, you won't reduce the variability very much.

Howe: Could one result be, though, that the children become more disenchanted with what they get at school?

Stanley: That could happen, but one shot in the arm seems to help; even one three-week session in the summer seems to buoy them up. They return to school more confident, better able to cope with the slow-paced system.

Benbow: They call it a booster shot, because it protects them against the next year. Once they know that a programme like this exists, where they can find others like themselves, and that they can come back, they become better equipped to deal with the regular school year.

Lubinski: We have found that by providing an optimal academic environment for these children you simultaneously provide an optimal social and emotional environment. They make friends more easily, their humour is more subtle and they get each other's jokes, they strike up great friendships and correspond with each other. At the end of every summer session these kids are in each other's arms crying and saying goodbye to each other.

Freeman: How do you know this is different from other summer camps?

Lubinski: That doesn't matter if it's an optimal environment.

Gruber: What this discussion brings out is a broad agreement on the importance of factors other than skill or abilities of the kind that are focused on in the psychometric approach.

Stanley: The difference between an enrichment approach and an acceleration approach is that in the enrichment approach the intellectually brilliant child goes back to a class for which he or she is vastly overqualified and is still bored to tears.

Benbow: The acceleration approach also makes it more difficult for the teachers to ignore the child's problems. It forces educators to serve specific talents by, for example, adjusting the mathematics curriculum for a mathematically talented child.

Stanley: The youngsters also tend to acquire coping skills. People ask us whether they get more and more arrogant—in fact, just the opposite happens. They meet their true intellectual peers for the first time and go away more confident but more humble, more realistic. One bright kid, one of the brightest in the USA, said to me after a special science programme that everyone there was better at something than he was; even though he was probably the brightest one there, some played chess better, others did more mathematics. He finished the programme a different person.

Sternberg: I'm hearing a lot of things I like, but in fact in the USA things are going the opposite way. Just as there was political pressure to mainstream slow learners into the major groups, now the political pressure is to mainstream gifted children into regular groups. I see this in my own children's school, which is supposed to be one of the best in the state, where honours classes are being dropped. The attitude is to put all the children together so that the gifted ones can help the others learn. That's fun for the others, but in the meantime the gifted children aren't getting good instruction. As psychologists, we have to remember that political forces, regardless of anything we may find, may result in exactly the opposite to what we wish being done.

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Musical ability

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Abstract. Musical ability is the ability to 'make sense' of music, and develops in most people over the first decade of life through normal enculturation. Whether this ability is developed to a high level usually depends on the decision to start learning a musical instrument, which forces high levels of focused cognitive engagement (practice) with musical materials. Performance ability has both technical and expressive aspects. These aspects are not always developed equally well. Factors contributing to the development of a well-balanced musical performer include (a) lengthy periods of engagement with music through practice and exploration, (b) high levels of material and emotional support from parents and other adults, (c) relationships with early teachers characterized by warmth and mutual liking, and (d) early experiences with music that promote, rather than inhibit, intense sensuous/affective experiences. It is argued that much formal education inhibits the development of musical ability through over-emphasis on assessment, creating performance anxiety, coupled with class and sex stereotyping of approved musical activities. Early free exploration of a medium is a necessity for the development of high levels of musicality.

1993 The origins and development of high ability. Wiley, Chichester (Ciba Foundation Symposium 178) p 106–118

What is musical ability?

The use of the term 'musical ability' may already seem to presuppose too much. Such a term suggests that there is some common factor, or set of factors, underlying all accomplishments in the sphere of music. How does this square with the fact that there are singers who cannot read music, pianists who cannot sing in tune, performers who cannot compose, and music critics who can neither play an instrument nor compose? Do all such people possess some common attribute in virtue of which they can be said to be musically able? Those who have applied the concepts and methods of contemporary cognitive psychology to music would answer 'yes' to this question. They would say that musical ability is a particular sort of acquired cognitive expertise, entailing at its core the ability to *make sense* of musical sequences, through the mental operations that are performed on sounds (whether real or imagined). The term 'make sense' is somewhat analogical. Musical idioms are not languages, and do not have referential meaning in the way that languages such as English do. They do, however, have complex multi-levelled structural features which resemble syntax or grammar (Lerdahl & Jackendoff 1983).

How do we know if and when a person is 'making sense' of some music? There are a number of ways in which psychologists have operationalized this ability. First, people who are 'making sense' of music should be able to remember music which conforms to a cultural 'language' better than music which does not. There are many demonstrations that this is so, even in fairly young children (e.g., Deutsch 1980, Zenatti 1969). This exactly parallels findings in other domains such as chess. Chess players recall meaningful (i.e., game-plausible) boards better than random boards (Chase & Simon 1973). Second, people who make sense of music tend to make plausible substitutions when asked to recall music they have just heard (Sloboda & Parker 1985, Sloboda et al 1985, Oura & Hatano 1988). This is similar to the well-established finding that people rarely remember verbal information word-for-word, but reconstruct in their own words something that *means* the same as what they heard. This kind of finding suggests that people generally store something more abstract than the actual words or notes.

A third criterion for making sense of music is the ability to correctly judge whether or not given sequences are acceptable according to cultural rules. There is strong evidence that most children can reject blatant violations, such as discords, by the age of seven, and more subtle ones, such as unfinished cadences, by the age of ten (Sloboda 1985). A final criterion is the ability to correctly identify the consensual mood or emotion of a musical passage. Again, we have rather strong evidence that the broad parameters of this ability are in place for most children by the age of five (Pinchot-Kastner & Crowder 1990).

Although people vary quite widely in the level of sophistication to which they have developed their ability to make sense of music, the available evidence points to the conclusion that the vast majority of the population have acquired a common receptive musical ability, clearly evident through experimental demonstration, by the end of the first decade of life, *regardless of accomplishment in any particular sphere of musical performance, and regardless of having been in receipt of any formal musical education or training.*

How is musical ability acquired?

What features of music and the human mental apparatus make this widespread ability possible? There is broad agreement between music theorists and psychologists (e.g., Bregman 1990, Deutsch 1992, Huron 1991, Lerdahl 1988, Meyer 1956, Narmour 1990) that the most prevalent musical idioms have structural and mathematical properties that make them easily analysable by universal pre-cultural mechanisms of auditory perceptual grouping. Connectionist models of learning applied to music (e.g., Bharucha 1987, Gjerdingen 1990) demonstrate one way in which complex mental representations might be built up from such simple groupings on the basis of repeated exposure to a variety of musical examples sharing similar structures. There is also the beginnings of an understanding of how the confirmation and violation of expectations built up within such a system may lead to the experience of music-induced emotion and mood (Jackendoff 1991, Narmour 1991, Sloboda 1991). We may, therefore, make the strong conjecture that exposure through enculturation to certain types of music can be a sufficient condition for the development of musical ability. What remains to be explained is why individuals develop at different rates and to different levels.

Cognitive psychologists who study expertise in general have come to a simple but far-reaching general solution to the problem of individual differences, which may be summed up in the old proverb 'practice makes perfect'. More precisely, level of expertise seems to be a monotonic function of the duration of relevant cognitive activity. Most computer-based models of expert systems, including connectionist models, function according to this principle, because the relevant learning takes place through the processing of a large number of examples. The more examples processed, the more elaborate are the knowledge structures. If exposure to music is at least *one* of the preconditions for relevant cognitive activity, it is clear that different developmental trajectories may start very early indeed. For example, pregnant mothers who sing may provide their fetus with a particularly rich early database. Lest it be thought that the neonatal brain does not have the capacity to analyse and store music, I should point to recent evidence that infants exposed to particular pieces of music before birth show distinct preferences for those same pieces after birth (Hepper 1991).

Perhaps, however, the most common way by which young people come to increase their degree of cognitive involvement with music is by starting to perform it, through singing, or by learning a musical instrument. Such involvement forces cognitive engagement in a way that mere exposure may not. For most observers, it is the ability of people to perform well which constitutes the evidence on which we judge their musical ability.

We need, however, to be quite clear that there are several distinct abilities involved in performing a musical instrument, and only some of them are 'musical' in the sense I have been discussing. The other abilities are what I would call 'technical'. For example, a pianist may be able to play a difficult passage very quickly, very evenly, and very accurately. This will be possible because of very highly developed control systems for execution of hand and finger movements. The development of such systems to high levels will have required much practice, and they are manifestations of expertise. It is, however, possible that a person could learn to play a piece of music 'technically' without having 'understood' it musically at all. Such a technically perfect performance could equally well be generated by mechanical means.

Expressive performance

It is well established that notationally perfect performances of music are experienced by most listeners as dull, mechanical and uninteresting. What makes any performance musically interesting are the slight fluctuations in duration, loudness, pitch and timbre which together constitute expressive performance. Such fluctuations are what distinguishes one performance from another, and their importance is what keeps professional performers in business. Were it not for this, we could get computers to generate once-and-for-all perfect performances of musical works, and close most of our symphony halls and conservatories!

Recent research has made it increasingly clear that the existence of expressive performance is the best evidence we can obtain that musicians *understand* the music they are playing. This is because expressive variations are by no means random or idiosyncratic. A wide range of studies (e.g., Clarke 1988, Gabrielsson 1988, Shaffer 1981, Sloboda 1983) has shown that microvariations are highly systematic, both within the same performer and across different performers. Many of such variations are designed to make important structural features of the music more prominent to the listener. Their systematicity therefore depends upon the performer having understood what *are* the important structures. The best test that this understanding is deeply rooted in a performer is to ask that performer to sight-read some music he or she has never seen before. If a performer can apply appropriate expression in such a situation, then his or her understanding must be fully internalized. Evidence of such ability does indeed exist (Sloboda 1983), and it is often so deeply internalized that performers are not fully aware of the details of their own expressive repertoires; they have become intuitive and semi-automatic. This should not surprise us, because it is another well-documented characteristic of all cognitive expertise. Many people mistakenly assume that intuitive behaviour must be innate. This is a major fallacy. Any well-practised habit eventually becomes automatic.

It may seem at first sight that the statement that expression is systematic conflicts with the existence of interesting differences between performers. The contradiction is, however, more apparent than real. Performers differ from one another not so much in the nature of expressive devices used, but in their distribution and intensity. So, for example, one performer may achieve by subtle dynamic fluctuations what another achieves by temporal fluctuations. Such differences between performers, or between the same performer at different times, can be characterized as differences in expressive 'style' (Sloboda 1985).

Developing expressive skills alongside technical skills

Because high level musical performance has this dual technical–expressive aspect, the conditions for the development of expert performers must allow development on both fronts. This is quite difficult to achieve. There are many music professionals who are technically adept but lack a high level of expressive skill. There are also many non-professionals who have a high level of expressive insight, but cannot realize their expressive intentions in music of any technical complexity. The master performer is that relatively rare person who has managed to develop both technical and expressive skills to a high level in tandem. How is it done?

We now have evidence from a number of biographically based research studies (Ericsson et al 1993, Sloboda & Howe 1991, Sosniak 1985) that confirms that music is no exception to the general rule that 'practice makes perfect'. The study of Ericsson et al shows that student violinists rated as excellent by their professors have, by the age of 21, accumulated on average around twice as many hours of practice over the lifespan (10 000 hours) as more average players (5000 hours). Sosniak, in a study of 24 top pianists in the USA, showed that none of them showed particular signs of exceptional ability at the outset of training. Exceptionality was something which developed gradually through the early years of formal training. Indeed, the notion that very early achievement is the normal precursor of adult excellence finds very little support in the documented research literature. The child prodigy may be the exception rather than the norm.

It is not very easy for a young person to accumulate 10 000 hours of practice between starting an instrument (typically around the age of six or seven at the earliest) and the age of 21. To get some idea of the workload that figure implies, one can calculate that the accumulation of 10 000 hours of practice would require two hours every day of the year for 14 years. In reality, the typical 'expert' practice pattern begins with 15–30 minutes per day, and increases to 4–6 hours per day by the age of 21. Practice activities are not always inherently rewarding to young children, and we (Sloboda & Howe 1991) found that most children in a sample of students at a specialist music school had not always enjoyed practice as young children. They often required parental support, even direct supervision, to accomplish regular practice.

Indeed, the quality of the child's relationship with significant adults, both parents and teachers, appeared crucial in predicting long-term involvement with musical performance. The parents in our sample (Sloboda & Howe 1991) were characterized by a very high level of involvement in their children's musical life. In addition, students tended to remember their first teachers, not so much for their technical adeptness as for the fact that they made lessons fun. They communicated both their love of music and their liking for their pupil. Personal warmth seemed an important characteristic. Critical, confrontational or achievement-oriented approaches seemed not to be successful, at least in the early stages of learning.

We (Sloboda & Howe 1991) also found some surprising differences between the best and the average students in our sample. It turned out that the best students had done *less* formal practice in their early years than had the average students, and that their parents were less accomplished musically than the parents of the average children. The rich qualitative data obtained from interviews with these students strongly suggests a social–motivational explanation for these findings. Children whose parents were not musically accomplished tended to receive a high level of praise and admiration from their families for objectively rather modest achievements. This, in its turn, encouraged the children to develop a strong sense of themselves as special, as the 'musician' in the family. Musical parents tended to have higher standards, which were reflected in a more rigid, achievement-oriented, family environment, with much less admiration for modest achievements.

There is some indication that the best students did not spend less time on musical activity than their less able peers, but that they simply spent less time on formal task-oriented practice and more time on free exploration of the musical medium (improvisation, and other activities often perjoratively described by both children and parents as 'messing about'). I can certainly remember from my own childhood that I would despatch my lesson tasks in 10 minutes or so, and then spend hours 'tinkering' on my own projects, with the forbearance of my long-suffering parents, who none the less were often driven to enquire 'what *is* that strange noise you are making: are you sure it is part of your practice?'

These initially unexpected results now make a lot of sense to me. One may suppose that, by and large, formal task-oriented practice encourages the development of technical rather than expressive skills, whereas exploratory and improvisatory activities encourage the individual's expressive development. Successful musicians are those who have been able to achieve a proper balance between these two types of activity.

There is a considerable body of evidence, much of it anecdotal, but some experimental (e.g., Sloboda 1989), that there are two types of motivation to engage with music. One motivation is what one might call 'intrinsic'. It develops from intense pleasurable experiences with music (of a sensual, aesthetic or emotional kind) which lead to a deep personal commitment to music. The other motivation is what one might call 'extrinsic', and is concerned with achievement. Here, the focus is not so much on the music itself as on achieving certain goals (e.g., approval of parents, identification with role models, winning competitions). Clearly, any one individual will have a mixture of the two types of motivation. There is some evidence, however, that a too early emphasis on achievement can inhibit intrinsic motivation. In simple terms, children become so concerned about what others may be thinking of their performance that they have little attention left to allow the potential of the music to engage their aesthetic and emotional sensibilities deeply. All music becomes a source of anxiety.

Research on people's experiences with music in school (Sloboda 1989) shows that many remember their earliest encounters with music as ones of anxiety or humiliation which left them with the sense that they were not musically able. Those people who survived such environments were often those who had already experienced music as intensely pleasurable in some other context.

It seems that our society—particularly our system of formal education—is set up to produce a large number of musical 'walking wounded'. What may be needed to remedy that is the rehabilitation of the notion that, in the sphere of music if nowhere else, deep emotional experiences and sensual enjoyment are as important and valid as hard work and technical achievement. One of the reasons why music seems to be seen by many children as an essentially female activity may be the strong male conditioning against emotional display, which is fully present by the age of six or seven in most cultures. One of the unexpected findings of our study was the huge sense of relief and safety felt by some boys when they were able to get to a specialist music school where music was at last seen as a quite normal activity for boys (Howe & Sloboda 1991).

Finally, there is considerable evidence that children are aware of the associations of different types of music with social group identity. Schools often present children with the notion that classical music is superior to the popular and folk idioms with which they more naturally identify. Children can reject classical music as too highbrow and also become intimidated by the apparent requirement to step outside what seems comfortable and familiar before they can produce 'acceptable' music. Most of us are aware of the child who presents as incompetent in a singing class, but can be found the same day in the school bus joining in an informal sing-along session with competence and enthusiasm. There are strong social pressures from peers to conform to the norm and hide a potential liking for music which is 'different' (Finnas 1987). This means that teachers need to introduce music through, rather than in opposition to, the cultural musical norms of their students.

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DISCUSSION

Dudai: I understand comparison of PET scans from expert and novice musicians reveals quite striking differences in the way they process information. Can you comment on this?

Sloboda: There is evidence suggesting that as people engage in formal music training, they move from a holistic mode of processing music to a rather more analytic mode of processing; this is therefore evidence for a hemispheric shift, from right to left (Peretz & Morais 1988).

Sternberg: Your work is interesting and modest, because a lot of what you said would apply to special talents in any area, and I hope that you decide to extend the work you are doing and look at other things such as interest in computers, or art or dance or whatever.

You suggested that the best predictor of musical ability was the time spent on the tasks, essentially the amount of practice. I am concerned about the causal inference there. Obviously, there's a correlation, but one could argue that the people who practise a lot are 'auto-reinforced' by the way the music sounds. Suppose you grow up playing the cello, but it doesn't sound particularly good, and eventually you find that there are other things you can do better; you might well then stop practising. One of your classmates whose playing sounds better would get more reinforcement, and might practise more. These are interactive processes rather than a one-way cause. It does somewhat of a disservice to those who try but fail to be stupendous to imply that anyone who just puts in the hours will end up being Yehudi Menuhin.

Sloboda: I agree with everything you said!

Fowler: Whether or not the parents are musical doesn't tell us whether the child has had any other exposure to musical experiences, through popular culture, other mentors or school activities.

The aspect of informality is interesting. My niece, whose mother was a modern dancer and dance teacher, had a tremendous amount of exposure to music, in a flexible, open kind of way. She became very musical. She started learning to play the piano when she was five, and her relationship with her teacher was good. She became so accomplished that her parents got the master teacher in the area to give her lessons. This teacher was blind, and he taught by mimicking his pupil's hand movements. This disturbed my niece, who was 11 by this time. On top of that, her grandmother, who was an accomplished pianist, guided her musical practice every day, but, her grandmother, although a delightful person, was an extraordinarily demanding teacher. These two factors, added to the growing pull of adolescent peer interests, caused my niece to burn out and give up.

Ericsson: It's very important with respect to *our* research to make clear that when we talk about deliberate practice, we are talking about something that, at least from our studies of expert musicians, is a distinct activity in which the level of difficulty is adjusted to maximize improvement. When people talk about practice they don't make the distinction between deliberate practice and other more playful, enjoyable activities in the domain. Let me give you an example. It is generally recognized that better runners run longer distances as part of daily practice, presumably because they enjoy it more. However, if you examine the kind of training in which elite runners engage during practice you find that they do interval training and extended runs. Both these types of training are rare among recreational runners, who find them exhausting and aversive. In music, similarly, recreational musicians would be likely to engage in a higher proportion of playful improvisation than expert musicians and would typically avoid tasks specifically set to maximize improvement. You are not optimizing your improvement if you pick a task that is not sufficiently difficult and which is not suited for specialized, focused practice.

In most cases, current level of practice is highly correlated with current level of performance, but there are many findings showing that the accumulated amount of past practice influences current performance. For example, the Menuhins, the really outstanding musicians on different instruments, tend to have started playing two or three years earlier than the kind of musicians that we have looked at who reach only the national level. The argument is that an early start allows those children to reach a much higher level of acquired performance than other children of the same age with later starting ages. Anyone who looks simply at children of the same age performing might conclude that the early starters are more talented, when the observed differences could be due to differences in acquired skill. Recent studies are seriously questioning the claim that ability influences the level of practice rather than vice versa.

Atkinson: How does that fit in with the finding that if your parents are professional musicians you are less likely to succeed? I assume professional parents would probably begin the children's formal training much earlier.

Sloboda: I wouldn't want to be too mechanistic about that. It's not what your parents *are* that is the problem, but what they *do* as a result of what they are. I am sure there are some musical parents who actually do the right thing.

Atkinson: My summary of what you described would be that the successful child walked away with the attitude that his or her musical talent was special, and this belief provided the impetus to excel.

Ericsson: Part of believing that one is talented is being made to feel special, and being treated in a way that emphasizes that. Ten thousand hours of practice is necessary to even have a chance of an outstanding career. A decade of preparation is a long road, on which there are going to be ups and downs. If you reach a down and start doubting that you are as good as some of the other individuals in the domain, you may not be willing to make the effort to come back up. You need to feel that you have talent, and that ultimately your talent will allow you to reach the highest levels of performance. Sometimes, bringing talented children together can be a little disturbing for them, because they realize they're not as special as they had thought. However, talented children are not brought together as six-year-olds or eight-year-olds; it's only when they are 10 or 12, when they are actually a way into their development, that they will see the other talented children. When we compared some of John Sloboda's data with ours, we found that our 'best' groups seemed to practise almost twice as much as his 'exceptional' group. Perhaps we are looking at a more select sub-sample than John Sloboda and Michael Howe. That might explain some of the difference between our results.

When people talk about practice they refer to the activity of standing with an instrument and mechanically reproducing assigned music, which would be of limited benefit, as opposed to making an intentional effort to produce one's best musical performance, where one is actually concentrating on it and using the feedback from one's performance to refine one's skills. That distinction is an important one which is typically not made.

Sloboda: I must emphasize that *we* are talking about practising at the very earliest levels; it is at ages below 10 where we find that exceptional musicians practise less than 'normals'. Anders Ericsson's data (Ericsson et al 1993) from that age band are so subject to noise, because they are gathered retrospectively, that one can't place much weight on them. I'm quite convinced that by the age of 16, where we are now getting data, our exceptional people are practising more than the merely able ones. There's a reversal.

Atkinson: Are the data good enough for you to believe there is a reversal?

Sloboda: I think so. It's not an artefact. The effect relates to the early years of learning where different factors operate.

Ericsson: Something that matters is what counts as practice. Obviously, with retrospective estimates, it's difficult to make the distinction between how much time the person had spent playing the instrument and how much was spent in supervised practice activities directed towards improvement. Perhaps in John Sloboda's group there are students who were pushed into music by their parents, without them providing the motivational background. There, one can easily imagine that pushing the children to practise would have the opposite of the desired effect. The best way to make someone burn out is to push them into practice in which they don't have the sense that they're improving, and in which they're engaging in a mechanical, aversive activity. For this type of mechanical practice the amount of practice may not be related to current performance as suggested by the results John Sloboda has reported.

Stanley: In the USA there is a tendency for Asian American children to become better musicians than other children. Groups entering the Peabody Conservatory Preparatory Department of Johns Hopkins University are mixed, but by the time of graduation the proportion who are Asian American has increased. Something in the Asian American culture seems to make the children keep practising. Most of my non-Asian friends' children find excuses not to practise, and they don't practise long or hard. The Asian Americans develop good skills that they exhibit at talent nights in our summer academic programmes.

Atkinson: Your remark would apply to anything in the USA, not just music!

Sloboda: Let's look at what their parents are doing. I am sure that family culture would give you most of the answers.

Gruber: You used the word connectionist. Does your use of this word carry any special meaning, or are you just responding to the latest usage?

Sloboda: The models of associationist learning of music which are around tend to be connectionist—that's all I'm saying.

Gruber: When we talk about giftedness we mean many different things, and different things in each field. There's no real possibility of 10 000 hours of practice for a neurosurgeon—what would he or she practise on? In Bloom's (1985) study of prodigies and precocity there was a group of neurologists. The time course of their development was obviously very different from that of the musicians in his study, as reported, but when you reach the final chapter, you find that he has lumped all the different forms of giftedness together with some stereotyped remarks about early exposure and prodigies and so on. We need to invent new ways of conceptualizing what constitutes practice. When we talk about the performing arts, we are not talking about anything that necessarily applies to politicians or neurosurgeons.

Sloboda: Bob Sternberg said that I was being modest (p 114). I prefer to be modest, because although these results may generalize to skills other than music, one needs to test each case.

Dudai: Are there late bloomers in music?

Sloboda: I would prefer not to answer that question, because I would be talking on the level of anecdote.

Detterman: Do children bloom musically past 13 years of age?

Sloboda: There are some children who didn't start formal musical instruction until around the age of 12 or 13 who have still made good professional careers.

Dudai: Had they practised a lot informally before that time?

Sloboda: I would guess they had listened to music a lot.

Ericsson: Manturzewska (1990) didn't find anybody who had begun formal musical training after the age of nine in her study of elite Polish performance musicians.

Sloboda: There are many examples of high-performing jazz musicians who didn't have *any* formal instruction at any age. Louis Armstrong began to practise the trumpet seriously only when he was about sixteen.

Gardner: I want to push you a little on your opinion of special talents. Are you dubious about the existence of special talents? Do you think that they exist, but that they're not very important, or that they exist and are important but are not enough; or, none of the above?

Sloboda: They exist, probably, and they are moderately important, but you can get a long way without special talent. There may be some kinds of activities which are more central to humanity than others. It seems to me that music is at the core of many cultures. John Blacking's (1976) work, for example, on the Venda tribes in South Africa showed that *everyone* seems to participate in the music of the culture. In that culture there are not the same huge disparities between people who are exceptionally good at music and other people who are poor. That makes me wonder whether it is something about our culture that determines the ability distribution, rather than something about genetics.

Gardner: You began rather provocatively, talking about critics who cannot play, and singers who cannot read music. It's important to stress that performance of classical music is one specific kind of musical competence. It may tell us little about other cultures, and little about composing, which people can begin relatively late in life, and which is a specific kind of performing competence.

Sloboda: Composing can begin late, but it is a *manifestation* which would not emerge unless the child had already achieved a certain level of musical *understanding* through enculturation. That is the key process from which other specialized branches may grow.

Hatano: How much can we generalize from music to other domains of expertise? The nature of the task or skills required seems critical. In music, as you pointed out, both technical and expressive components are important. There is no expressive component in abacus operation. It's simply a matter of technical training. In that area, performance is probably more strongly correlated with the total amount of practice. Music is a domain in which practice of skills is separated from other domains. We can't expect much progress in piano-playing from practice on a violin. Musical skills are in a sense closed, as are those of abacus operation. In contrast, in some domains practice can be done outside the domain itself; in surgery, for example, manual skills can be trained through other activities. The extent to which we can generalize about the relationship between amount of practice and skilled performance depends on the nature of the task or skills involved.

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Boys and girls who reason well mathematically

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Abstract. Since 1971 the Study of Mathematically Precocious Youth (SMPY) at Johns Hopkins University has pioneered in discovery of and provision of educational help for 12-year-old boys and girls who reason better mathematically than 99% of other 12-year-olds. SMPY originated widespread searches for such youths and special academic classes for them outside the regular school system. A regional talent search, verbal as well as mathematical, now covers all 50 states of the USA, and many varied residential summer programmes are offered across the country. These have provided educational facilitation for many thousands, and have encouraged greater curricular flexibility in schools and better articulation of in-school with out-of-school learning experiences. From the first talent search conducted by SMPY in 1972, it became obvious that boys tend to score considerably higher than girls on the College Board Scholastic Aptitude Test-Mathematical (SAT-M), a test intended mainly for college-bound 17- and 18-year-olds. This difference was reported in 1974 but attracted little attention until a controversial report in 1980 stimulated research on sex differences in various aspects of mathematics. Here I describe a study of sex differences over 10 years on 14 College Board high school achievement tests, which are taken (three usually) by bright 17- and 18-year-olds seeking admission to the USA's selective colleges and universities. Among the high scorers on the European history test the ratio of males to females was greatest, 6:1. The next most sex-differentiating test was physics, 2.9:1, followed by elementary-level mathematics (mainly algebra and geometry), 2.5:1. Other ratios favouring males were, in 1991, chemistry (2.4:1), American history (2.1:1), biology (1.8:1), precalculus mathematics (1.6:1), Latin (1.6:1), French (1.4:1), modern Hebrew (1.1:1) and German (1.02:1). Tests in which more females were high scorers were literature (1.26:1), English composition (1.05:1) and Spanish (1.01:1). The largest sex differences on other standardized tests, for mechanical reasoning and spatial rotation, favour males. There are even larger differences for self-reported evaluative attitudes, with the theoretical value high for boys and the aesthetic high for girls. Such value scores correlate strangely with scores on achievement and aptitude tests. By 12 or younger, bright boys and girls already show many of the cognitive sex differences found in 18-year-olds.

1993 The origins and development of high ability. Wiley, Chichester (Ciba Foundation Symposium 178) p 119–138

The title of this paper may seem to imply that there is a validated psychological construct called 'mathematical reasoning ability'. That term calls forth 26 entries from a computerized database of *Psychological Abstracts* published from 1980 until about the middle of 1992. 'Mathematics and reasoning' produces 193, 'arithmetic and reasoning' 61, 'aptitude and mathematics' 267, and 'mathematical ability' 924. For comparison, 'intelligence' yields 12 046, and 'general intelligence' 342. 'Fluid intelligence and mathematics' yields only two.

Thus, although a great deal of literature about various aspects of the topic is published (e.g., Gustin 1985, Skemp 1971, Krutetskii 1976), it seems difficult to nail down the construct itself. No nomological network (Cronbach & Meehl 1955, Campbell & Fiske 1959) comes even close to validating the construct of mathematical reasoning ability across methods of measuring it as thoroughly as general intelligence has been tested during most of this century (e.g., Jensen 1992). In fact, it is thought by many that various tests of individual mental abilities tend to measure mostly a general ability, making unnecessary a construct such as 'mathematical reasoning ability'.

Recent work by Detterman & Daniel (1989), Deary & Pagliari (1991), and Detterman (1991) lends support to the basic concept of the Study of Mathematically Precocious Youth (SMPY), which I started in 1971. Detterman & Daniel state that 'correlations of mental tests with each other and with cognitive variables are highest for low IQ groups'. We of SMPY have long known that extremely able boys and girls have many different profiles of mental abilities. This becomes especially noticeable at IQs of 200 or at a standard score of 700 or more on the mathematical part of the College Board Scholastic Aptitude Test (SAT-M) before the age of 13.* We have, for example, observed the different style and speed with which two 12-year-old boys, one with an SAT-M score of 760 but a score on the verbal part (SAT-V) of only 310 and the other with scores of 720 and 750, respectively, learnt mathematics. The former progressed much faster and took a Bachelor's degree in electrical engineering at an early age, but showed no interest in 'pure' mathematics. The latter's degree was in music. There are many other examples of discrepancies between scores on SAT-M and SAT-V. These and related aspects are being investigated by Drs Camilla P. Benbow and David Lubinski in their 50-year longitudinal study, which began in 1986 at Iowa State University, and by Dr Linda E. Brody in her Study of Exceptional Talent (SET) at Johns Hopkins University. I hope to produce a book of case studies about how those with extremely high scores on SAT-M fare as adults. Especially interesting are youths who reason extremely well both mathematically and verbally, because a number of them seem to have difficulty academically.

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*In 1991 the average college-bound 16–18-year-old male in the final (12th) grade of a senior high school in the USA scored 497 on SAT-M, with SD = 127. The average such female scored 453, with SD = 115 (College Board 1991).

The work of Horn (1980), Guilford (1967), Sternberg & Detterman (1986), Gardner (1983), Gustafsson & Undheim (1992), Jensen (1992) and others is relevant to the question of how many different important forms of intelligence there are, and whether one of these can be usefully conceptualized as mathematical reasoning ability. For the most mathematically able youngsters, how independent of 'fluid intelligence' is their mathematical reasoning ability? How important for its effective utilization as they develop is general intelligence, which (except perhaps for a general visualization factor) Gustafsson & Undheim (1992) essentially equate with fluid intelligence?

We of SMPY chose SAT-M as our initial test for identifying youths who reason exceptionally well mathematically, because it seems to measure much more than learned algorithms, to be difficult enough for all but the very ablest 12-year-old, and is available six times each school year at centres across the USA and is administered under tight security provisions. It is a 60-item 60-minute multiple-choice test on which the average college-bound male earns a *raw* score of about 30, which transforms into a score of about 500 on the 200–800 scale. Only 1% score 57 or more. Bright females average somewhat lower than males (Benbow 1988).

In our first (1972) talent search (Stanley et al 1974) we also tried mathematics achievement and science knowledge tests, but because of the resulting score patterns and intercorrelations decided to concentrate on SAT-M. SAT-M, augmented by SAT-V, seemed to provide us with the most powerful direct information that could be obtained readily. Although, from the start, we assumed that SAT-M measures some aspect of mathematical reasoning ability, we understood that SMPY was to be a long-term exploration of various concomitants and consequences of high scores on SAT-M.

We suspected that most of our 'protégés' would not become mathematicians, or even physicists, electrical engineers or computer scientists (cf., Gustin 1985); nor would all of them be superb students. Humans are too complex in their genetic compositions and environments to make accurate prediction possible within a group that is homogeneous with respect to SAT-M level but otherwise diverse. Although many of the boys stay in the mathematics–science domain, some take degrees elsewhere. One, on leave from a great university, is a nationally ranked racket-ball player. At age 19 another was the *summa cum laude* 'mathematics valedictorian' of a huge, renowned state university; he quickly headed for a brokerage house to become a financial analyst. In a sense, the world may have lost a fine potential mathematician, but his personal value structure militated against graduate study. He had considerable aptitude for pure mathematics but not the necessary interest in mathematical research.

Our goal was not, as Terman's had been (Oden 1968), to study the highly intelligent youth essentially undisturbed in his or her 'native habitat'. We saw ourselves as a type of educational engineer, trying to help our mathematically precocious youths obtain the special, supplemental, accelerative educational opportunities they needed for proper utilization of their great abilities. We thought that, without these opportunities, many of them would fail to utilize their full potential. We strove for 'cumulative educational facilitation', a concept well elucidated by Zuckerman (1977): each accomplishment makes the next more probable. (See Stanley & Benbow 1986 for the rationale of SMPY.)

Thus, from 1971 until the present we have created networks of support across the USA and elsewhere, especially the People's Republic of China (Stanley et al 1989). In 1972 we began our first fast-paced academic class, covering the four and one-half school years of pre-calculus mathematics, from beginning algebra through to analytical geometry, in about 120 hours of Saturdays outside the school system (Fox 1974). Over the years, this approach spread to other universities throughout the USA, so that nowadays bright seventh and some eighth graders (11–14 years old) in all 50 states are covered by regional and state talent searches. Also, these youngsters are told about many ways to supplement their school-based education; foremost among these are academic, accelerated summer courses.

Results have been spectacular. For example, during a recent year, five of the six members of the USA (high school) team competing in the International Mathematical Olympiad were members of SMPYs small '700–800 on SAT-M before age 13' group. From this and similar groups have come the highest-ranking students taking degrees in various subjects at Yale, Pennsylvania, Harvard, the Massachusetts Institute of Technology (MIT), Chicago, the University of California at Berkeley, and other highly selective universities. One 20-year-old graduated from MIT after a total of four years with four Bachelor's degrees. The list could go on and on.

Ten research generalizations

Central to the mission of this symposium are some of the conclusions that have come out of SMPY's research. Here are a few.

(1) About one in 100 male and one in 200 female 12-year-olds reason better mathematically than the average college-bound 12th grader (17–18-year-old) does. Quite a few of them are also highly precocious verbally, i.e., they score at least 430 on SAT-V before the age of 13 (College Board 1991, Stanley 1988, Benbow & Stanley 1983).

(2) Special, fast-paced academic classes during summers or at weekends promote learning well (Lynch 1992, Benbow & Stanley 1983) and save the mathematically talented much time and from boredom.

(3) Among able youths there are large differences in mathematical reasoning ability favouring males (Benbow 1988), but the differences between able college-bound males and females are even greater in other areas such as European history, physics and computer science (Stanley et al 1992). Differences tend to be greatest for evaluative attitudes at the college level (Allport et al 1970);

even at age 12 they are surprisingly large (J. C. Stanley, unpublished data; see below). The usual gender-'bias' causal hypotheses about such discrepancies have not been validated in systematic studies (Benbow 1988).

(4) Acceleration into and through college tends to work well for many academically highly qualified young men and women (Benbow & Stanley 1983, Brody & Stanley 1991).

(5) There are at least 15 different ways to accelerate the educational progress of an academically talented child. Only one of them is what the term 'acceleration' usually connotes, grade-skipping (Southern et al 1993).

(6) Different types of intellectual talent (i.e., mathematical versus verbal) appear to be associated with different working-memory characteristics and with differences in how digit and word stimuli are represented in memory (Dark & Benbow 1991).

(7) Parents of mathematically or verbally extremely precocious boys and girls tend to differentiate their support as a function of the talent domain involved, fathers being more involved with quantitative areas and mothers with verbal areas. These findings do not seem to explain the gap between males and females in mathematical precocity (Raymond & Benbow 1989).

(8) Predictors of educational achievement and educational and career aspirations of mathematically talented youths were found to be, in order of importance, quality of instruction, home environment, motivation, ability, attitudes and quantity of instruction. Even among such students, environmental interventions may enhance educational achievement, especially of females (Benbow et al 1991).

(9) Among the mathematically top 1% of students from age 13 to 23, those in the top quarter on SAT-M score outperformed (statistically significantly) those in the bottom quarter on 34 of 37 variables studied (Benbow 1992). Generally, SAT-M seems to have greater predictive value for students tested as seventh and eighth graders (11–14 years old) than for those tested near the end of high school (17–18 years old). Of course, it has a higher 'ceiling' for the younger children and requires a different type of mental approach because of their not yet having studied much mathematics.

(10) Considerable assortative mating seems to have occurred among the parents of intellectually highly precocious youths, but this alone does not reliably predict their children's extreme giftedness (Benbow et al 1983, Lykken et al 1992).

Differences between the sexes on selection and placement tests

In this section I shall discuss differences between able male and female students who, as applicants for admission to selective colleges and universities, take difficult standardized achievement tests in regular national administrations. Most of them are not SMPY youngsters. Most of the reviews and meta-analyses of sex differences on cognitive tests have dealt largely with representative age groups, rather than with aptitude and achievement tests used for college selection or placement within college. The SAT and its junior version, the Preliminary Scholastic Aptitude Test (PSAT), are exceptions to that generalization. For recent reviews, see Benbow (1988, 1990) Linn (1992) and Cleary (1992). Some of Cleary's conclusions seem worth quoting: 'Distributions of male and female scores are more similar than they are different. Although between-group differences are small when compared to differences within each group, girls are generally disadvantaged relative to boys. This disadvantage becomes greater as age increases, task complexity increases, and quantitativeness increases. It is greatest at the upper percentile levels. No consistent trends are evident over time. There is probably a biological component to the sources of gender differences on aptitude and achievement test scores, but there are also major social, psychological, and educational factors' (p 76).

Table 1 shows how scores on 14 of the College Board high school achievement tests, taken chiefly by 16–18-year old college-bound 11th and 12th graders, have changed from 1982 to 1991. Two different measures of sex differences are reported there. One is the mean of the males' scores minus the mean of the females' scores, divided by the square root of the average of their two variances. This is my version of the familiar 'effect size', being a standardized measure that makes comparisons among tests feasible. (The mean difference divided by the standard deviation of the females' scores is perhaps a better measure of discrepancies between the sexes. Anyone using this measure might, though, be accused of bias, because the usually lesser variability of the girls' scores would, with this method, tend to increase the effect size. This simpler version of the effect-size statistic should relate more closely to the upper-tail ratio discussed below.)

The other sex-difference statistic is the ratio of the percentage of males taking a given test who score 700 or more on the 200-to-800 standard-score scale, divided by the percentage of females taking the test who score that well. This is a non-parametric way of taking into account both the mean difference and the shape of each of the two distributions. The cut-off at 700 is arbitrary. Many admission officers of highly selective colleges and universities in the USA probably expect applicants to have at least one score of 700 or more. This type of 'upper-tail ratio' has been used little in research into differences between girls and boys except by Stanley et al (1992). It gives a more accurate estimate than the effect size of the influence sex may have on selection into college or on placement into college courses once the applicant is admitted.

The typical college applicant offers three achievement test scores. Two of these (English and either of two levels of mathematics) are usually specified by the college, leaving one to be chosen by the student from the 11 other tests available. Thus, apparently, the examinees believe their background and ability in that area are better than for any other available test.

French was preferred by far more females in both 1982 and 1991; only 29% and 28%, respectively, of those electing to take the French test were

TABLE 1 Differences between males (M) and females (F) (16–18 years old) on 14 difficult high school achievement tests

	1982				*1991*			
Test	*No. M*	*No. F*	*E*[a]	*Ratio*[b]	*No. M*	*No. F*	*E*	*Ratio*
European history	2081	1110	0.63	6.60	2734	1764	0.64	5.95
Physics	13024	2967	0.58	2.92	14252	4590	0.61	2.86
American history	31250	23917	0.43	2.78	26226	21005	0.27	2.07
Chemistry	22582	12306	0.42	2.48	19897	12260	0.44	2.40
Mathematics I	72546	72731	0.39	2.55	62244	72222	0.41	2.51
Biology	18312	21934	0.38	2.22	20481	22996	0.31	1.79
Mathematics II	24677	12926	0.37	1.60	35767	24734	0.43	1.65
Latin	1215	1332	0.18	1.49	1508	1620	0.25	1.60
Modern Hebrew	169	277	0.11	1.32	176	315	−0.06	1.09
Spanish	9396	16046	0.07	1.30	11225	19416	−0.01	−1.01
French	6696	16580	0.07	1.35	5853	14980	0.11	1.40
German	1772	2007	0.03	−1.04	1344	1566	−0.04	1.02
English composition	90887	89750	−0.10	−1.11	88154	95415	−0.04	−1.05
Literature	5629	9274	−0.11	−1.24	8166	16364	−0.06	−1.26
Overall	100239	96752	0.50	2.43	97537	103079	0.28	2.34

[a]E, Effect size: mean of males' scores minus mean of females' scores, divided by the positive square root of the mean of the two variances.
[b]Ratio: % males scoring 700–800, divided by % females scoring 700–800 if M% is larger than F%, or % females scoring 700–800 divided by % males, with minus sign.

male.* Although physics was much preferred by males (81% and 76%), the number of women taking it increased by 55% over the 10-year period, whereas the number of males increased by only 9%. Thus, although the effect size and the upper-tail ratio for physics remained approximately constant from 1982 to 1991 (0.58 vs. 0.61, 2.92 vs. 2.86), the *number* of women scoring 700 or more increased by 91.5%! This means that almost twice as many young women in 1991 demonstrated substantial physics preparation for college as in 1982. National efforts by feminists, teachers and parents to encourage girls to move towards science seem to have paid off.

*For the 14 tests, the correlation between the percentage of males taking the test and the effect size is 0.78. The larger the percentage of males, the better they score in relation to the females. This is opposite from what I had expected.

That encouragement appears to have had even more effect on pre-calculus (mathematics II). In 1991, 3714 more young women than in 1982 went to college certifiably well prepared in this important subject, even though the effect size and upper-tail ratio remained essentially constant.

The most sex-differentiating of the 14 tests is European history, where the percentage of males scoring 700 or more is six times greater than the percentage of females. Next comes physics, with a ratio of 2.9. Other sharp discriminators are mathematics I (chiefly algebra and plane geometry), chemistry, and American history. Only in the language usage area did girls outscore boys appreciably, in literature (1.26 ratio in 1991).

Only for American history is there some consistent evidence that females are catching up a bit with males. Graphing scores for each year reveals a slight downward trend for both indices of sex difference, as depicted in Fig. 1. It is not apparent why declines seem to occur just for that test.

The data in Table 1 help to answer the frequently asked questions (or assertions) as to whether or not differences between the sexes are large enough to be important and whether or not they are declining. As judged by upper-tail ratios in 1991, all of the tests except Hebrew, Spanish, German, English

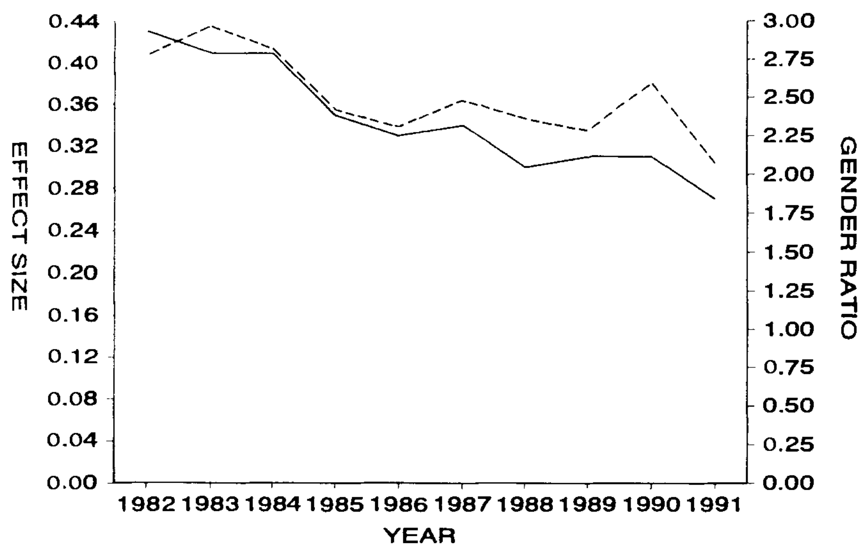

FIG. 1. Differences between bright male and female 16–18-year-olds on the College Board high school achievement test on American history 1982–1991. Effect size (——) is the mean of the males' scores minus the mean of the females' scores, divided by the square root of the average of the two variances. The gender ratio (----) is the percentage of males scoring 700–800 divided by the percentage of females scoring 700–800. The two scales, effect size and gender ratio, are not directly comparable. Each seems to be showing a moderate downward trend.

composition and literature rather strongly favour males. For example, if admissions officers used the information directly, for every 100 girls accepted on the basis of their French score, 140 boys would be; a seemingly inconsequential effect size of 0.11 translates into a ratio of 1.40. This illustrates why effect sizes may be misleading where selection at the upper (or lower) end of the distribution is involved.

The data in Table 1 do not agree with the conclusion by Feingold (1988) that 'cognitive gender differences are disappearing', but he was not analysing these types of tests. It may be that as the Educational Testing Service (ETS) focuses its meticulous attention about 'gender bias' onto these achievement tests, some of the differentiating items will be removed, thereby lessening the sex differentiation. Thus far, the ETS's 'differential item functioning' (DIF) searches seem to have been directed mainly toward SAT and PSAT. It will be interesting to see how considerations of 'equity' and 'political correctness' will eventually influence the content of achievement tests. For example, if the syllabus for a European history course includes Napoleon and the Battle of Waterloo, but girls are found to score lower than boys on items involving this content, should the items be discarded or reoriented? Should Florence Nightingale be substituted for Napoleon, Madame Curie for Einstein?

Advanced Placement Program Examinations

Results for 24 College Board Advanced Placement Program (AP) college-credit examinations for high school students from 1984 to 1991 are similar, but the magnitudes of effect sizes and upper-tail ratios tend to be smaller. (The pattern of sex differences in the AP tests is similar to that in the achievement tests, and the standardized regression slope of effect size on percentage male is about the same, 0.75.) This may be because each AP examination is based on a taught syllabus, and each (except for studio art) consists of half multiple-choice and half 'free-response' test items, whereas the College Board achievement tests are wholly multiple-choice. This is a complex issue that has not yet been investigated well (see Bridgeman 1989 and Bridgeman & Lewis 1991).

In 1991, the largest AP effect size (favouring males) was 0.57 for the first semester of college computer science (computer science A). The upper-tail ratio was 3.3 for the highest possible score, 5. For the two-semester computer science examination (AB), the respective figures were 0.53 and 2.8. Eighty-three per cent of the students taking computer science A and 86% of those taking computer science AB were male. Thus, on all three counts, there was a great imbalance in this important subject. Up to 1992, no systematic change seems to have occurred since the first year the examination was offered, 1984. Thorough, detailed, long-term study of these persistent sex discrepancies seems urgently needed.

The three AP physics examinations showed the next largest sex differences, with upper-tail ratios ranging from 2.4 to 1.7. Females excelled the males most on Spanish literature, 1.2.

Thus far, the greatest effect size we have found for an aptitude or achievement test is 0.89 for a large, representative sample of 12th graders on the mechanical reasoning test of the Differential Aptitude Test (DAT) battery (Stanley et al 1992). Nearly nine-tenths of a standard deviation at the mean implies that few females will be found to reason as well mechanically as most males do. This could be a serious handicap in fields such as electrical engineering and mechanics, especially if the student also does not perform well in mathematics, computer science and physics. Such discrepancies would seem to make it inadvisable to assert that there *should* be as many female as male electrical engineers.

Sex differences in evaluative attitudes and interests

Large as some of the differences between the sexes on cognitive tests are, they are dwarfed by the effect sizes on certain 'self-report' measures of values. Strictly speaking, these are not *tests* because one can fake a high score on them. An example of these sex differences is on the Study of Values (Allport et al 1970, p 12).* Effect sizes for college students in the 1960s were as follows: theoretical, 1.10; aesthetic, −0.90 (i.e., favouring females); political, 0.79; social, −0.70; economic, 0.64; and religious, −0.60. Effect sizes on only two of the 14 College Board achievement tests reached even the low 0.60s, and none of them did for the 28 AP tests in 1991.

In 1977, for 188 male and 90 female mathematically precocious seventh graders age 12 or 13 (selected by SMPY) the effect sizes were as follows (taken from an unpublished MA degree paper in psychology, *Toward a national talent search*, by S. J. Cohn): aesthetic, −1.13; theoretical, 1.01; economic, 0.95; social, −0.69; political, 0.56; and religious, −0.48. Recent data from Iowa (David Lubinski, personal communication July 1992) for bright 12- and 13-year-old boys and girls confirm the direction and pervasiveness of such sex differences and of the huge difference in mechanical reasoning ability (0.97) favouring males even at this young age.

Clearly, as judged by this unusual values inventory based on the philosophical system of Spranger (1966), boys and young men seem oriented towards the following three evaluative attitudes: theoretical ('The dominant interest of the theoretical man [or woman] is the discovery of *truth*' Allport et al 1970); political ('The political man is interested primarily in *power*'); and economic ('The economic man is characteristically interested in what is *useful*').

Girls and young women tend to be strongly aesthetic ('The aesthetic man [and woman!] sees his [and her] highest value in *form* and *harmony*'); social

*A typical type of item is, 'Whom do you admire more, Madame Curie or Florence Nightingale?' Choosing Curie gives a point to theoretical, whereas choosing Nightingale gives a point to social.

('The highest value for this type is *love* of people'); and religious ('The highest value of the religious man may be called *unity*. He is mystical, and seeks to comprehend the cosmos as a whole, to relate himself to its embracing totality').

The Study of Values is intrinsically ipsative, which means that across the six value scales each examinee receives the same total score as any other examinee; in principle, one can interpret only an individual's *profile* of such scores. Despite this theoretical restriction, the scales behave logically across individuals, differently by sex. Remarkably, too, scores on the Study of Values correlate appreciably with scores on non-ipsative cognitive tests, as shown in Tables 2 and 3. There it can be seen that the value most positively associated with the ability test scores is theoretical for the mathematically talented boys and aesthetic for the mathematically talented girls. The value most negatively associated with ability is political for the males and (less clearly) religious for the females. Apparently, trying to discover 'truth' fuels the mental engine of our typical bright male, whereas considerations of 'form' and 'harmony' fuel that of our females.

Or is it more complex than that? Behrens & Vernon (1978) found substantial correlations between ability and personality variables, with marked sex differences, but the personality variables did not appreciably or reliably improve prediction of achievement in mathematics and English beyond that provided by measures of intelligence. Does knowing a person's six evaluative attitudes according to Spranger's typology improve prediction in some ways? I suspect that an individual's long-term goals, such as whether or not to work toward a PhD degree and become a researcher versus choosing to enter the work world after college, may be associated fairly closely with his or her value orientation. Spranger emphasized that living is ipsative; one must continually make choices, borrow from Peter to pay Paul. An orientation such as theoretical must compete with other orientations and either lead the way or drop behind.*

A brief anecdote may illustrate this. Two of the girls found by SMPY to be rather bright and academically promising succeeded far beyond our expectations for them. Both became truly outstanding researchers at quite early ages. When I looked back at their records, an extremely high theoretical score stood out for each—high even for a male, but most unusually so for a female.

It seems to be true that even the most able youths are not likely to seek theoretical work if they are oriented primarily otherwise, such as towards utility

*The Holland (1973) Occupations Checklist (non-ipsative) yielded rather different effect sizes for Cohn's 188 male and 90 female seventh graders: −0.91 for social and −0.79 for artistic, but only 0.001 for enterprising, 0.10 for investigative (similar in concept to theoretical), 0.15 for conventional and 0.41 for realistic. Dr Cohn and I are ipsatizing the Holland scores [i.e., making each individual's six scores sum to 100%] to see how this affects sex differences. Unfortunately, there is no way we can de-ipsatize the Study of Values, because it was constructed in a counterbalanced fashion. Relevant to this discussion is Mills (1981), who 'emphasizes . . . that the relationship between cognitive and personality variables is a complex one' (p 110).

TABLE 2 Correlations of eight cognitive abilities with six evaluative attitudes[a] among 188 12–13-year-old mathematically precocious boys studied by SMPY[b]

Cognitive ability measures[c]	*T*	*A*	*E*	*R*	*S*	*P*
ACT-NS	0.29	0.09	0.06	−0.09	−0.18	−0.17
ACT-M	0.27	−0.05	0.09	−0.19	−0.01	−0.04
SAT-M	0.23	0.02	0.11	−0.24	0.02	−0.02
SAT-V	0.22	0.20	−0.11	−0.08	−0.05	−0.19
Alg. IB	0.18	−0.06	0.11	−0.19	0.07	−0.01
DAT-SR	0.14	0.05	0.02	0.11	−0.19	−0.21
DAT-MR	0.13	0.11	0.06	−0.02	−0.25	−0.07
DAT-AR	0.03	−0.01	0.00	0.09	−0.11	−0.05
Sums	1.49	0.35	0.33	−0.62	−0.70	−0.76

[a]Evaluative attitudes were assessed according to the Allport–Vernon–Lindzey Study of Values (Allport et al 1970), which breaks down into: T, theoretical; A, aesthetic; E, economic; R, religious; S, social; and P, political values.
[b]The columns are ordered according to the strength of relationship of the value with the eight ability tests. See the column sums. Theoretical dominates. Even though a number of the correlation coefficients are quite small, a clear pattern emerges. Ipsative scores create peculiarly constrained inter- and cross-correlations because of being forced to sum to a constant (Gleser 1972).
[c]The ability measures are as follows: American College Testing Program Natural Science Reading; ACT mathematics; Scholastic Aptitude Test–Mathematical; SAT–Verbal; Alg. IB, Cooperative Mathematics Test, first-year high school algebra, Form B; Differential Aptitude Test Spatial Relationships; DAT Mechanical Reasoning; and DAT Abstract (i.e., non-verbal) Reasoning.

TABLE 3 Correlations of eight cognitive abilities with six evaluative attitudes among 90 12–13-year-old mathematically precocious girls studied by SMPY[a]

Cognitive ability test	*A*	*T*	*E*	*P*	*S*	*R*
DAT-MR	0.27	0.08	−0.03	−0.04	−0.08	−0.21
SAT-V	0.23	−0.22	−0.13	−0.22	−0.09	0.30
Alg. IB	0.18	0.11	0.06	−0.08	−0.08	−0.18
DAT-SR	0.16	0.04	0.04	0.00	0.02	−0.22
ACT-NS	0.14	0.01	−0.07	−0.27	−0.10	0.18
DAT-AR	0.14	0.05	0.08	0.11	−0.10	−0.21
ACT-M	0.08	0.06	0.05	0.00	0.02	−0.19
SAT-M	−0.06	0.08	0.02	0.05	−0.09	−0.03
Sums	1.14	0.21	0.02	−0.44	−0.50	−0.55

[a]For names of the tests, see the footnotes to Table 2. Note that the order of the columns (according to the strength of correlation) is different from that of Table 2. In the girls, aesthetic dominates, even though there is only one negative *r* in the theoretical column.

and power. Because they are bright, they may be superb students, but at some point choices must be made. That may be where information from instruments such as the Study of Values becomes important. We know, however, far too little about how such values, perhaps especially the aesthetic one, change with age, experience and circumstances.

MacKinnon (1962) found aesthetic important, in conjunction with a high theoretical score, for creativity in several professions. Is a bright 12-year-old already about as well developed aesthetically, relative to Spranger's other evaluative attitudes, as he or she will be 10 or more years later? We suspect not.

Conclusion

Mathematical reasoning ability is an important predictor of academic achievement in mathematics and science. Particularly for boys, we have found it relates fairly closely to chosen career field. Mathematical aptitude provides an early basis for grouping children for fast-paced instruction in order to speed the precocious youth into more challenging levels of science and mathematics, thereby preventing or alleviating the frustration and boredom caused by the slow pace of the typical mathematics and science classroom. Scoring highly (500 or more) on SAT-M before the age of 13 is a good predictor of fast, high level achievement in algebra, geometry, calculus, linear alegbra and elementary differential equations, and success in mathematics, physics and computer science contests, but is not as good a predictor in 'pure' mathematics—analysis, higher algebra, mathematical logic, number theory and topology. A partial reason for this may be the greater mathematical ability of students enrolled in the higher-mathematics courses, but theoretical and other interests are probably more important; for example, the high scorer on SAT-M who keeps asking 'What are the applications of this mathematics?' is not likely to become a pure mathematician.

We fear that mathematical *reasoning* ability itself may be more difficult to improve than most current advocates of direct training of thinking skills and problem-solving abilities realize. The USA may be *en route* to returning to the overly abstract emphasis of the 1960s, when university-based mathematics educators tried unsuccessfully to get young average or below-average students to 'think like mathematicians'.

An incidental observation by Camilla P. Benbow (personal communication to me in 1985) should provoke thought. In attempting to compare, within the Johns Hopkins University talent search groups, boys and girls who scored high on SAT-M and low on SAT-V with those who scored low on SAT-M but high on SAT-V, she was able to find plenty of the former but almost none of the latter. It seems that a 12-year-old who scores high on SAT-V can somehow 'figure out' a considerable number of correct answers to the mathematical aptitude items, even without much formal background in mathematics.

They probably lack the ability to learn mathematics as fast as youths (of less-high IQ?) who earn equally high SAT-M scores 'despite' scoring low on SAT-V. The difference may lie largely in non-verbal reasoning ability, the ability to strip a mathematical problem or formula down to its basic symbolic elements and work directly with them, rather than using an inefficient verbal approach. This is highly conjectural, of course. Research is needed. Some is sure to come out of Dr Benbow's centre.

From our work we are convinced that an able child's SAT-M versus SAT-V balance is important in predicting his or her career. This M and V aspect is moderated, however, by the individual's other special abilities such as non-verbal reasoning, mechanical comprehension and spatial relationships, and by his or her value orientations. Human beings are complex combinations of genetic predispositions interacting with environmental opportunities and limitations, including good luck such as being the right person in the right place at the right time to take advantage of the *Zeitgeist*.

We of SMPY continue to advocate searching for students in the seventh or lower grades who before age 13 score highly ($\geqslant 500$) or *extremely* highly ($\geqslant 700$) on SAT-M. One can then assess their other abilities, evaluative attitudes and interests in order to help them obtain the special, supplemental, accelerative educational opportunities they sorely need and, for their personal and professional benefit and society's good, richly deserve.

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DISCUSSION

Lubinski: Could you say a little more about the importance of looking at differences in ratios between the sexes at the upper tail? A lot of attention is now devoted to meta-analysis, as there should be, because it's a wonderful tool for aggregating studies based on small samples. When you aggregate studies you often observe powerful effects. However, differences between the sexes in variances have been under-appreciated. Males are typically more variable, which is one of the reasons you get large male–female disparities using stringent selection criteria.

Stanley: In fact, an upper-tail ratio represents a non-parametric blend of the difference between means and the difference between variances. In a test such as SAT-M, the variance of the females' scores is often less than that of the males' scores. Probably the best thing to do when you have the data is to take a certain upper percentage—1%, for example—of the scores and look at the ratio of percentage males to percentage females. I used a fixed-score cut-off (700) instead, because of the nature of the data available to me.

Some people, even some high level professionals, somehow believe that because the variances are different there really aren't differences between the sexes. The difference in variances is in itself very much a sex difference. When the mean differences are combined with differences in variances there can be dramatic results. For example, Cohen (1977), who pioneered the notion of effect size, gives effect size levels—negligible, small, medium and large—which can be misleading if one is using a test for selection. For the Latin high school achievement test, the 0.18 effect size favouring males translated into a ratio advantage for males of nearly 1.5, even though the effect size is negligible by Cohen's standards. You probably need both kinds of effect size for the means and upper- or lower-tail ratios for selection. If you are selecting for, say, a remedial reading class, you need a lower-tail ratio; if you are selecting for admission to Harvard, you need an upper-tail ratio. If you just want to know whether boys and girls or young men and young women differ at the mean, you need an effect size.

Atkinson: The size of the differences between the sexes is quite striking. Can you make any international comparisons? I spent three weeks in Cuba recently, and learned that two-thirds of the students at the universities were women. In technical fields such as engineering the ratio was 50:50. The overwhelming number of students were women. Medical students were about 80% female. They have recently passed a law in Cuba that henceforth the number of men and women in medical school should be the same. People are admitted to universities in Cuba strictly on the basis of an examination, given, on the same day of the year, to high school students throughout the country. This is a written examination, with no multiple choice tests, and is highly analytical. In the Cuban equivalent of a business school that I visited, the Dean and the senior faculty were nearly all women—there were only two or three men.

Stanley: I don't have any direct information on Cuba, a highly politicized country whose dictator can equate by fiat if he wishes, but I can make a general point.

In the USA girls and young women achieve better grades than boys and men in the courses they take, all the way through kindergarten to the PhD level. They tend to score less well, however, on nationally standardized tests (except in languages) than the boys who achieved lower grades. In a class, you might find that the girls who got A grades didn't do any better on the test than the boys who got Bs. Also, girls do not differ from boys in mathematical knowledge. They learn facts in class just as well. If you use examinations that are based strictly on the curriculum of the school, the girls score as well as, if not better than, the boys. Where girls really fall down is on mechanical reasoning tests. The effect size for a large, random, representative sample of 12th grade girls (17–18 years old) in the USA is 0.89, nine-tenths of a standard deviation (Lupkowski 1992). Few girls in the USA are as able mechanically as the typical boy. It doesn't seem likely that this would be dramatically different in another country. People have said that we 'should' have as many female electrical engineers as male electrical engineers. In view of the data, which show that the difference in mechanical reasoning is dramatic, the difference in knowledge of physics large, and the difference in mathematical reasoning fairly strong, it just doesn't seem to make sense to suppose that parity is a feasible goal until we find ways to increase such abilities among females.

Sitruk-Ware: At the age of 12–13 when you apply the tests the girls are through puberty but the boys are not. Might that have an effect?

Stanley: I have the results of the Secondary School Admissions Test (SSAT) given to 7944 able fifth and sixth graders (10–11-year-olds). Effect sizes for both quantitative (0.4) and verbal (0.1) ability are about the same as for college-bound 12th graders, who are six or seven years older. Seven times as many boys as girls scored in the top 1% on SSAT-Quantitative. It is an article of faith in the USA that somehow, because of bias against them, girls, although they aren't different cognitively from boys when young, become somewhat different as they go through school. That doesn't seem to be true. They differ from boys in mathematical *reasoning* ability all the way down to at least fifth-grade level (CTY 1992).

Benbow: Carol Mills has demonstrated that this sex difference exists in the second grade (personal communication). It is basically specific to mathematical reasoning ability. The difference isn't simply due to puberty or adolescence, but to the type of questions you ask.

Freeman: Why do people impose percentage criteria on admissions? In my day, medical schools would admit only 12½% females, so that the girls had to stand aside while boys with much lower grades were accepted to study medicine. Why have there been quotas against girls, for example, or Jews, in universities? The only reason can be the fear that in fact these people will do better than the incumbents. In the UK, now that the doors are open are to girls, they represent 51–52% of medical students, and their numbers are rising.

I'm fascinated by these children who can do a whole year's course in three weeks. I wondered how much this has to do with American education. We have some very selective schools in the UK—Manchester Grammar School, for example, where the average IQ of over 1000 boys is about 144. Could they do a year's course, as provided by that school, in three weeks, or is there something in the nature of the course with which the American children were presented that made it possible for them to zip through it?

Stanley: Both ability and the nature of the course matter. Biology, for example, is a fairly elementary course in the ninth or 10th grade. It's difficult for the average student but for the superior students it's almost trivial; they can learn it much faster.

Gardner: Your presentation was a nice demonstration of how much one can find by playing around with numbers. You have found lots of interesting things, some of them, I think, important. However, there is a danger of what I would call test 'idolatry'. You suggested that for women who do well on academic tests, the bad news is that they're high on aesthetic attitudes and not on theoretical.

Stanley: I didn't mean to imply that is bad news, but simply that they're different from the males. That is a warning sign if strongly theoretical orientation is important for investigative work and research.

Gardner: That's a very important 'if'. One has to see what those girls actually do, whether they can be good scientists. Similarly, you said that females' scores on the mechanical reasoning test mean it will be hard to find female electrical engineers. We have to go to Cuba and see whether they can produce female electrical engineers—if they can, so much the worse for the test profile. You said women do well when the test is linked to the curriculum. It's imperative that we have good curricula with examinations, rather than relying on this more ethereal notion of an aptitude which might relate to ultimate performance in some way.

Stanley: Remember, though, that the good grades girls achieve are based not only on tests they have taken in class, but also often on homework, attendance, handwriting, language usage, good behaviour, etc.

Detterman: What proportion of students in the USA do you presently screen, and do you think this should be a national programme, not only in mathematics but also in other areas? Also, how much money, proportionally, should we devote to such students?

Stanley: We cover the whole country now through the four regional searches conducted by Johns Hopkins University, Duke University, Northwestern University and the University of Denver, plus more local searches such as Camilla Benbow's in Iowa. I do think the talent identification and facilitation programmes should be extended. Also, I wish we had a national mechanical comprehension search, to identify young students who have great technical talents.

Detterman: What about the arts?

Stanley: Yes, of course, we should have similar programmes for the arts, although a different approach might be required. The wonderful value of tests, of course, is that one can use them for hundreds of thousands of children. We simply tie into the Education Testing Service's SAT testing each January.

As to cost, the youngsters' parents, unless they are quite poor, pay the costs of entering the talent search and attending the summer programmes. It costs about $20 to enrol in a talent search, and about $20 for the SAT test. Three-week residential academic summer programmes cost about $1000–1800 each.

All four regional centres are run by private universities and must subsist on fees. It would be wonderful if the US Government did more for the gifted than it does.

Detterman: Do you think that will ever happen? There's a lot of talk, but an amazing mismatch between the talking and what actually gets done.

Stanley: We do achieve a lot through the private sector. Parents and teachers know about these summer programmes, but official educational policies have not yet been influenced much. It's difficult to get anything other than educational 'business as usual': the clamour is for more teachers, smaller class sizes, better pay, revised curricula for average or below-average students, etc. The special, supplemental, accelerative educational opportunities that intellectually highly talented boys and girls sorely need are largely lacking (Stanley 1990).

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Scientific ability

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Abstract. Following an introductory definition of scientific ability, product-oriented, personality and social psychological approaches to studying scientific ability are examined with reference to competence and performance. Studies in the psychometric versus cognitive psychological paradigms are dealt with in more detail. These two research strategies complement each other excellently in describing and explaining scientific ability and achievement or expertise in the field of science and technology. Whereas psychometric studies seem to be essential for diagnostic and prognostic purposes, cognitive psychological studies help to explain excellent performance. Finally, various possibilities for nurturing scientifically gifted adolescents are discussed, with sex-related problems being touched upon.

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Generally, the hypothetical construct 'scientific ability', or 'scientific giftedness', can be defined as scientific thinking potential or as a special talent for excellence in (natural) sciences. Both descriptive and explanatory terms are necessary for a theoretically *and* practically efficient definition. This further necessitates different research strategies. Below are described a minimum of research approaches which can be distinguished.

Product-oriented approaches

Exceptional performance in the sciences is used as an indicator of special scientific ability or competence. This approach is plausible and, of course, very practical, which is why it has long been the preferred method in creativity research (Sternberg 1988, Glover et al 1989). However, it does not answer the following questions. (1) Is exceptional scientific achievement primarily determined by cognitive problem-solving competence or are other factors—motivation, for example—also important for eminent achievement? (2) Are there scientific under-achievers, that is, individuals who do not turn their potential abilities into adequate scientific performance? If there are, the use of performance indicators to assess scientific abilities will be inadequate or even misleading.

This approach is also unsatisfactory from an educational point of view—for the nurturance of scientific talents in adolescence—and also neglects social and cultural influences on the development of giftedness.

Kim (1990) suggested that the *results* of scientific research should be classified according to the following criteria with reference to the (process) characteristic 'scientific discovery'.

Alignment. This refers to the isomorphy between the model and reality, that is, the validity of theories and their universality.

Possibility. 'A good deal of the theoretical work in the sciences is also one of construction. This relates to the development of general models, frameworks, or theories that can accommodate diverse empirical observations' (Kim 1990, p 91).

Impossibility. A 'negative' result, i.e., the proof that a hypothesis does not hold true, is just as important scientifically as the confirmation of a hypothesis. Einstein's Theory of Relativity or Heisenberg's Uncertainty Principle are famous examples of this.

Trade-offs. 'An important class of results relates to interdimensional trade-offs. These may relate to the relationships between performances and efficiency, or time versus space, among others' (Kim 1990, p 92).

Whereas trade-offs and possibility are relevant evaluation criteria for *technological* products, alignment and impossibility are central considerations for the importance of *scientific* results.

Personality-oriented approaches

One can differentiate at least three paradigms here: psychometric, cognitive psychological, and neuropsychological or neurobiological approaches.

The psychometric paradigm

In the psychometric paradigm, an attempt is made to identify or measure cognitive and non-cognitive (e.g., motivational) personality traits that could be the basis of scientific ability. The following characteristics, which include both intelligence and creativity aspects, are frequently mentioned: formal-logical thought processes, abstract thinking ability, systematic and theoretical thought processes, and individual potential for creativity—problem sensitivity, inventiveness and flow of ideas, the ability to restructure problems (flexibility) and originality of solving methods and of products. In addition, non-aptitude traits, such as intellectual curiosity and searching for knowledge, exploration and the desire to question, are considered important. Other frequently mentioned characteristics include clear interests, a need to seek information, intrinsic achievement motivation, goal orientation and persistence at tasks, tolerance of ambiguity, uncertainty and complexity, and non-conformity. After childhood, these characteristics and their configuration are considered to remain relatively stable, generating differences between individuals, and so can be used in diagnostic–prognostic models for predicting exceptional scientific ability. The problems involved in this approach are discussed in Hunt (1987), Benbow & Arjmand (1990), Trost (1993) and Gardner (1993, this volume). Despite the justified criticisms of psychometric paradigms, as yet we have no better alternatives by which to predict scientific excellence, as explained below.

In their meta-analysis of 50 international studies on the ability of personality characteristics to predict scientific and technical achievement, Funke et al (1987) calculated a mean (corrected) validity coefficient of 0.38 across all predictors studied. Of all the individual types of predictor, coefficients were highest for the biographical questionnaire, followed by subject-related ability and creativity tests. General intelligence and creativity tests had the lowest prognostic value.

Trost & Sieglen (1992) studied early biographical indicators of exceptional scientific and technological professional performance in West Germany in a combined prospective–retrospective study. During 1973, more than 9000 students from the senior year of the *Gymnasium* (13th-grade students, about 19 years old) were given a general test of studying ability. In addition, school grades, teachers' evaluations and data from questionnaires about the students' study and work habits, extracurricular interests and activities, their study and professional plans were obtained, as well as demographic and sociographic information. In 1990, 17 years later, 3554 subjects from the 1973 sample were questioned retrospectively. At this point it was possible to measure professional scientific success (the number and type of publications, patents, gross income over DM180 000 p.a., direct responsibility for more than 50 employees, etc.). In order to determine the predictive function of various indicators, Trost & Sieglen (1992) determined d scores (for interval scale α values) and ω scores (for nominal and rank order data) for the effect size of differences between the subgroup with higher professional performance and the representative comparison group (Table 1). According to Cohen (1977), d scores above 0.2 and ω scores above 0.1 indicate weak effects, d scores above 0.5 and ω scores above 0.3 intermediate effects, and d scores over 0.8 and ω scores above 0.5 strong effects.

The most powerful long-range predictors of professional success in science and technology are apparently domain-specific problem-solving abilities and motivational and social leadership abilities. These results correspond well with those from other studies, e.g., Benbow & Stanley (1983), Stanley & Benbow (1986), Rahn (1986), Swiatek & Benbow (1991), Facaoaru (1992) and Subotnik & Steiner (1993). Rahn (1986) studied all of the 1123 German winners of the

TABLE 1 Values for the effect size for various predictive characteristics of differences between a group with high professional achievements in science and technology and a group with average such achievements, according to Trost & Sieglen (1992, p 102)

	Effect size	
Predictive characteristic	*d value*	*ω value*
Motivation and ability to solve problems	0.71**	
Desire to influence, initiative and leadership success	0.62**	
Search for knowledge	0.43**	
Concentration ability and persistence	0.18*	
Self-evaluation of school performance during the last three years at school	0.35**	
Results of quantitative section of the test for study abilities	0.31**	
Average grade	0.29**	
Total score in test of study abilities	0.22**	
Early home upbringing directed towards active and independent coordination of one's life	0.42**	
Nurturance by teachers	0.31**	
Mother's educational level	0.26**	
Father's educational level	0.21*	
Value placed on education within the family	0.21*	
Parental support of the development of abilities and talents	0.20*	
Number of extracurricular activities named	0.26**	
Average time spent on extracurricular interests	0.23**	
Number of subject-related interests named		0.11**
Number of prizes won in school competitions		0.08**

*$P<0.05$, **$P<0.01$.

annual competition *Jugend forscht* (youth researches) at the state and national level from 1966 to 1984. The total number of participants was 23 945, 81.9% boys and 18.1% girls. Rahn studied the course of winners' school, university, professional and general lives, and came to the conclusion that interests and individual goals, as well as achievement motivation and action competencies, are more important than intelligence factors; cognitive abilities were, however, not tested in Rahn's study. Subotnik & Steiner (1993) analysed adult manifestations of adolescent talent in science in the USA. In their longitudinal study of 1983 winners in the Westinghouse Science Talent Search, Subotnik & Steiner (see also Subotnik et al 1993) got results quite similar to those described above. See also Zuckerman (1987, 1992), who stressed the mentor–apprentice relationship as well as sex-specific differences in science.

Recent research on the expertise paradigm from a lifespan perspective has proven that the development of expertise, that is, performance at high or the highest levels, is a function of an individual's developmental stage. Whereas motivation and interest in a subject or domain seem to be the determining factors at early stages, instructional methods and quality of teachers become more and more important as the difficulty level increases (Ericsson et al 1990). Hayes (1989, p 143) also remarks that 'the origin is in motivation not cognition'. Furthermore (and partly in contrast to Hayes' statement), differences between individuals in scientific problem-solving competence depend at the novice level more on cognitive abilities, but at the expert level more on learning experiences and domain-specific knowledge. (See also Weisberg 1986.)

The role of cognitive abilities is probably underestimated in studies using the expert–novice comparison paradigm and also in educational practice, because confounding variables such as the acquisition of knowledge and intellectual abilities, and restriction of range (which reduces the relationship [correlation coefficient] between intelligence and performance; see Detterman 1993, this volume), are not considered. During the evaluation of various enrichment courses for gifted students in Baden Württemberg, we found that the instructors did not select their students according to motivation, interests and achievements, as they had claimed, but according to intelligence; there was, however, in fact a strong consideration of (domain-specific) cognitive abilities (Hany & Heller 1990). This observation was recently confirmed in a study evaluating a scholastic acceleration programme (K. A. Heller, J. Brox & B. Sacher, unpublished work 1993). C. Facaoaru (unpublished final report on the Technical Creativity project to the Federal Minister of Education and Science, Bonn, 1992 [University of Munich]) also drew similar conclusions from her evaluation of five extra-curricular courses for technical creativity. She also examined various personality characteristics. Although the 11–19-year old students who participated in these extracurricular courses did so voluntarily, and intelligence test scores were not used as an admission criterion, the students demonstrated above average *domain-specific* cognitive abilities (Table 2).

TABLE 2 Means, standard deviations and minimum and maximum T-values[a] in ability tests given to 11–19-year-olds participating voluntarily in extracurricular courses for technical creativity

Ability characteristic	*Mean*	*SD*	*Min*	*Max*	*n*
AWI: spatial representation	64.54	11.17	42.00	80.00	67
APT: physical and technical comprehension	60.96	12.79	36.50	80.00	67
KFT Q-scales					
Arithmetic thought (Q1 + Q2)	61.43	12.25	35.00	80.00	28
Calculating ability (Q3 + Q4)	59.32	11.61	33.00	80.00	28

[a]$M_T = 50$, $s_T = 10$.

The cognitive psychological paradigm

Whereas psychometric theories cannot be replaced in the identification of scientifically gifted adolescents, or in the prediction of later professional or university success, they do not provide any explanatory information. In contrast, information-processing or thought process analyses in the cognitive psychological paradigm can answer questions about the conditions required for the development of scientific competence and expert performance. Examples of this include the cognitive component approach of Sternberg and colleagues (Sternberg & Davidson 1986) and the experimental diagnosis of giftedness of Klix (1983). Van der Meer's (1985) experiments on mathematical and scientific talents also exemplify this approach.

Process-oriented approaches to individual differences are directed to the identification of those psychological mechanisms that form the basis for individual differences at the level of performance of cognitive processes. According to Klix (1983), the ability to reduce complexity in problems through information processing and thus to reduce the cognitive demands for solving a problem is a characteristic essential for scientific giftedness. Task-related motivation plays a key role in this, primarily by generating and maintaining the activity level necessary for an effective search, introduction and processing of relevant information through to finding a solution (Van der Meer 1985, p 231).

In an approach similar to that used by Sternberg & Davidson (1986) in their analysis of components, Van der Meer gave subjects tasks requiring inductive and analogous thinking. Analogous conclusion processes are made up of the recognition and transfer of relationships between terms from one domain to another. Analogous terms in Van der Meer's experiments were chessboard-like patterns of varying complexity. The most important empirical finding was that mathematically/scientifically gifted adolescents (special students in mathematics at the Humboldt University in Berlin) showed above average ability to solve the analogy test items. The author viewed this as an essential feature of mathematical/scientific ability, and it can be demonstrated up to the 9th grade (15-year-old students). In addition, the mathematically talented process information in basal cognitive processes faster than average students, as well as showing less effort in finding solutions to complex tasks. It could be that they have more effective problem-solving strategies that are better adapted to the structure of the task. This means that mathematically/scientifically gifted students from the upper grades expend less effort than students of normal intelligence, and rely on minimal intermediate storage of partial results in memory, reflecting a higher quality of thinking. The superior manner in which basal operations are combined, and the increased simplicity and effectiveness of problem-solving, are, according to Van der Meer (1985, p 244), characteristic of mathematical/scientific talent. Because extraordinary interest and persistence in cognitive challenges play a role in solving difficult, complex problems, Van der Meer believes that reliable predictions of later excellent performance can be made on the basis of early high achievements in mathematics and natural sciences. One limitation on this idea is the fact that only a few aspects of scientific ability, central though they are, are measured here (see Benton & Kiewra 1987). In their monograph entitled *Scientific discovery*, Langley et al (1987) discussed another central aspect of scientific research which seems to be of general importance for generation of and decisions about hypotheses. In relation to this, Clement (1989) emphasized three different functions of analogies: (a) the heuristic function of indicating new observations or new explanatory characteristics that should be considered; (b) the role of a 'rough initial model of the target situation' that can be developed and refined later; and (c) the explanatory model which is to be linked through analogies to the target situation (p 361).

Further information about cognitive approaches in the context of creativity research can be found in Sternberg (1988, p 125–238). See also Siegler & Kotovsky (1986).

Neuropsychological and neurobiological approaches

Neuropsychological and neurobiological approaches are dealt with elsewhere in this volume, so I can limit myself to some literature citations: Obler & Fein (1988) and Eysenck & Barrett (1993); see also Plomin (1988) and Thompson & Plomin (1993).

System-oriented or environmentally oriented and social–psychological approaches

Most of the studies that follow such approaches were developed to prove that certain environments promote creative learning. Nurturant and non-nurturant socialization influences on the development of giftedness have been studied mainly in the social settings of the family, the school, in leisure time or in professional environments, e.g., Amabile (1983), Gruber & Davis (1988), Csikszentmihalyi (1988). According to these authors, not only stimulating learning environments and experimental opportunities are necessary, but information sources and community resources must also be available. Expert and 'creative' role models are particularly important. New science curricula which meet the special needs of gifted adolescents have been recognized to play a key role. Linn (1986) collected important information for a necessary revision of the science curriculum. The process of *discovery* in science learning seems to be especially appropriate for facilitating the development of competency in scientific problem-solving, together with *domain-specific knowledge* and *autonomous learning*. These principles are of general importance for the education of the gifted (cf., Zimmerman & Schunk 1989, Colangelo & Davis 1991). For a review of programmes and strategies for nurturing talent in science and technology, see Halpern (1992) and Pyryt et al (1993).

Future directions and a consideration of sex differences

Although my coverage of the various approaches has been brief, it is apparent that none of them can be ignored if one is trying to explain and describe the construct 'scientific ability'. The limitations of the individual paradigms have led to the recommendation of synthetic approaches (e.g., Gardner 1988; Sternberg & Lubart 1991). These synthetic approaches, and interdisciplinary exchange of information, should be important goals of this symposium. Other authors emphasize the role of coincidental factors or the importance of situational variables (Simonton 1988, 1991), which cannot be dealt with here in detail. I would like to summarize several considerations about the development and nurturance of talented adolescents in the field of science and technology in five points (for more details, see Heller 1992a).

(1) The interaction of scientifically talented youth with successful scientists is often recommended in the literature and seems, from experience, to be beneficial (Zuckerman 1992, Jacobi 1991). However, the role-model hypothesis cannot be proven to explain differences between the sexes in talent and performance in the areas of mathematics, science and technology (Beerman et al 1992). Independently of this, one expects that the master–pupil relationship will, as in the fine arts, have positive effects in science education. Studies at the Technical University of Dresden and at the University of Leipzig have documented this; see also Zuckerman (1992).

(2) If one compares proven stimulating institutions of higher education or research laboratories with those with little or no stimulatory effect, the following characteristics of the successful institutions become obvious: the requirement for a high degree of commitment to tasks and high demands, coupled with an open-mindedness for new ideas; and, a readiness to participate in open, critical but constructive discussions and a balance between solidarity and competition in dynamic interactions among group members (Amabile 1983, Weinert 1990).

(3) Creativity in science and technology can be seen primarily in original procedures and new methods, useful inventions and socially valuable products. The task of schools and universities is, therefore, to create an environment suitable for the acquisition of methodological and factual knowledge and abilities, and to show how these can be used in situations which are challenging to the individual. Creative variables and role models play an important role (Van Tassel-Baska & Kulieke 1987).

(4) When there is a basic consensus between the team members about research ideology, interdisciplinary or intradisciplinary research teams put together in a heterogenous fashion provide the best conditions for creative performance in the natural sciences (Weinert 1990). Such teams increase individuals' factual and methodological expertise, and offer a change in point of view which is a positive force in scientific production.

(5) Finally, one should take a look at the sex differences in scientific competence and performance, which have been receiving more attention recently. Sex differences are most evident in the hard sciences (physics, chemistry, astronomy) and in mathematics and technology. Space and quantitative factors are the areas of cognitive ability in which women and girls are usually weaker than men and boys. These effects tend to increase rather than decrease with increasing ability (Beerman et al 1992; see also, this volume, Benbow & Lubinski 1993, Stanley 1993). Inappropriate motivational patterns and causal attribution styles need to be eliminated from nurturance approaches for scientifically gifted girls, and their scientific problem-solving abilities need to be strengthened. In the early phases of intervention, the problem of eliminating deficits in prior knowledge, e.g., in the areas of physics or technology, should be given special attention. When such personality-oriented nurturance approaches are accompanied by supportive educational and classroom measures, we believe that feminine competence and performance in science and technology can be boosted, and we favour this approach over organizational alternatives or quotas (whose negative effect on the self-image of the gifted is frequently overlooked). A quasi-experimental study examining the central hypotheses of this model has been presented recently (Heller 1992b).

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DISCUSSION

Hatano: Your review was comprehensive, but you neglected one area which seems to me important, that is, the informal knowledge acquired by children in their everyday lives. You referred to the significance of analogy, but analogies need source domains, and source domains are often taken from everyday experience. Science and mathematics are different from learning a musical instrument. For science and mathematics, practice is done outside school, at least to some extent. Recent developmental theories suggest that children possess rich and fairly accurate knowledge in, for example, physics, psychology and biology. The good students in science and mathematics can use such informal knowledge more skillfully than other students.

Heller: I agree with you. Two years ago we began a study of leisure-related technical experiences of 13–15-year-olds (Heller & Hany 1991, Hany & Kommissari 1992). This is an important issue, but studies are rare. Our preliminary results suggest that youngsters, male and female, acquire subjective misconceptions in physics in their leisure time. It's not sufficient to provide adolescents with the opportunities to experience and learn—we must also ensure that the informal knowledge they acquire is correct, especially physical concepts. About 50% of boys' concepts analysed were incorrect, and 80% of the girls'.

Stanley: Camilla Benbow and I have long wondered why boys seem to learn more outside school than girls. If males are already geared more towards theoretical and investigative attitudes, it is logical that they would learn more incidentally outside school. However, if that is the case, girls should be learning more aesthetic and social things outside school. It would be interesting to test that. You could get the six evaluative attitude scores for various people and see what individuals high on each attitude know. It makes sense to suppose that in the scientific and mathematical areas the boys who are doing poorer school work than girls but getting better scores on the tests are actually learning more outside school classes.

Fowler: We should consider the origins of differences between the sexes. I taught in a nursery school while I was writing my dissertation. Being oriented already towards trying to encourage girls to participate more in the 'thing world', the mechanical–spatial construction activities in which boys are so involved and which apparently lay the foundations for science and mathematics, I ran up against two major problems. One was the fact that the teachers themselves were virtually all women, and were not interested in or cognizant of these orientations. The second problem was that the boy culture itself, particularly by the age of four, is firmly entrenched. If you try to get the girls and boys to play together with blocks or vehicles, the boys employ exclusionary tactics, and they are persistent and strong. You can do this more easily in a family. I have three daughters, and we set up a subculture combining the boy and girl worlds. I don't want to make causal inferences from such limited evidence, but all three of my daughters were strong in mathematics; two of them scored highly, 670 and 720, in SAT-Mathematical, as well as in verbal tests. The third didn't score quite so highly on the SAT-Mathematical test (570), but this may have been because she attended a bilingual school where even the mathematics was taught in French. According to the SAT manual, such experiences may depress SAT scores.

Mönks: Professor Heller said that the development of expertise is a function of the developmental stage. We have been talking about prodigies, and a prodigy is simply a person with precocious functioning. When we are talking about developmental stages, we have a kind of normative framework, an age-related framework; the developmental stage is, to a certain extent, related to age. I had thought that highly able children cannot be identified with reference to a developmental stage, because they do things earlier than developmental psychology text books tell us they should.

Ericsson: Micki Chi (1978) has done a lot of work in this area. She has studied young chess experts to see how they differ from adult experts in their knowledge structures. Young experts, even though they may be only 10 or 12, resemble adult experts of a corresponding performance level more than they do other children. They are given appropriate instruction and practice, which seems to encourage the development of more complex structures in their domain of expertise than develop naturally in other areas of everyday life.

There are strong relations, though, between age and the time at which an individual attains the highest levels of performance, such as when he or she is most likely to become world champion in chess or to break the world record in a sport. Any physical performance will obviously be constrained by size and other maturational factors. Eminent contributions to science, or the writing of classic novels, occur most frequently between the ages of 30 and 40, which may reflect the necessity for a combination of maturation and acquisition.

Mönks: Is it simply that highly gifted children are developmentally ahead of other children of the same age? Early maturation indicates age-independent development.

Ericsson: Normal development within a domain can be speeded up, but, if you take a comprehensive view, there may still be maturational factors that constrain achievement of the highest levels of performance. In music, for example, it's well known that a child may develop mechanical skills much faster than expressive skills.

Gruber: Professor Heller, what I particularly liked about your paper was that you made a real distinction between creativity and ability, or creativity and giftedness. These are two quite different concepts, two different fields of research, in which different factors are emphasized. You spoke of biographical analysis, domain-specific knowledge and motivation, all taken together as a package that in a way describes the task someone has in becoming a creative person. We were talking earlier about the need for practice. A field like natural history, where you can go out in the woods and collect insects or whatever, is one in which you can amass thousands of hours of experience as a child and as an adolescent. That was clear in Charles Darwin's case. I haven't really calculated the number of hours he accumulated, but two hours a day, day in and day out, for years and years, would not be an exorbitant guess. But, even being a natural historian like that, a collector at a high level, not just a kid messing around, didn't make a theoretical biologist of him. Darwin went hunting beetles in the woods with his pals, and they were all passionate about what they were doing, but the others did not become biologists; one became a minister, and another a judge. We need to link up the fields that we are dealing with here, which seem to be passing each other by as we talk about different things. One part of such an endeavour would be a critical examination of the nature of the task involved in becoming a creative person. I don't mean to imply that all creative people are the same—in fact, quite the opposite. To be creative in different fields requires different things, and even in one domain different things apply at different points in history. As Holmes (1989) pointed out, what Lavoisier needed to be a good chemist was quite different from what Hans Krebs needed to be a good chemist. I am not objecting to the use of testing, but it should be supplemented by a careful and considered analysis of the work involved in being creative. Starting from childhood and working forward in time is one approach. Starting with the genuine article, the creative person, and actually examining what he or she has achieved is another. This approach is not a collection of anecdotes, but careful historical and biographical research.

Heller: I tried to explain some different approaches to research in this field, but I also stressed my opinion that it is necessary to combine different approaches to solve complex problems. Let me give an example. In our research work over the last five or six years we have combined intellectual and creative factors to investigate problem-solving processes related to difficult, complex tasks. For a particularly challenging scientific problem, you at first need creative ability, for the generation of hypotheses and so on. You also need convergent thinking processes to prove these hypotheses, plus a flexible, available, domain-specific knowledge base. For many problems in life, both creativity *and* so-called intellectual competence are required.

Bouchard: I should like to make a comment on the prediction of creativity. I'm not terribly familiar with this literature, but in my experience, when people do research in the area of scientific creativity and giftedness, and they say they have measured IQ, in fact all they've done is administer a five-minute verbal ability test or an eight-minute vocabulary test. My own mentor, Donald MacKinnon, for example, didn't even bother to measure IQ in his studies of creative people because he thought it wasn't relevant. They went back years later and measured Wechsler adult inventory scale IQs for many of the participants. There's a fundamental bias against using IQ as a predictor. When you compare IQ tests or general ability tests with personality tests, you run against the problem that the personality measures, the motivation measures, are obtained concurrently rather than predictively. These people already know how they feel about what they're reporting. One wonders whether you would get the same results if you were working on a predictive basis. There's a bias towards emphasizing high correlations for these measures and it may be artifactual.

I should also like to repeat what I said earlier (p 42) about chance effects influencing outcomes. Howie Gruber brought up the example of Darwin, which is a nice example of how one can look back at the history of a case; but, again, you can be misled. It would be easy to conclude, for example, that Darwin was able to come up with the theory of evolution because he came from a wealthy family, which meant he was able to pay his way on The Beagle and had time to work with all the data he gathered. In Darwin's case, though, we have a control—Alfred Russel Wallace, who was a poor school teacher who migrated to Malaysia and had to go out and collect bird specimens and send them back to England to get paid to continue what he was doing. Wallace came up with the same theory at the same time. Unless you have built-in controls, you can be terribly misled.

Gruber: In fact, Darwin thought of it in 1838 and Wallace in 1858. This demonstrates the value of broad historical knowledge, not that you should ignore it and replace it with psychometric testing. You are perfectly right in almost everything you said about Darwin, but the way to do the work isn't to try to winnow out test-like data, but to use the biographical data, the notebooks, to reconstruct how Darwin actually did his work. I'm not trying to make a prediction about Darwin. We *know* that Darwin developed a theory of evolution. Making believe that you are predicting it by some kind of methodological legerdemain is foolish, and a waste of the opportunity to form a better picture of how creative people do their work. People should treat this as a respect-worthy analysis and then connect it up with the understanding of the abilities that go into that work, not treat one approach as kosher and the other one as tref—unclean.

Csikszentmihalyi: The advances in understanding high ability in the future will probably come if we take seriously the question of the difference between domains studied. What are the differences in adult outcomes, and how can we characterize the difference between domains? One way to describe domains is in terms of how enclosed they are, or how contextual. For example, a seven-year-old playing chess is tackling essentially the same task as a 50-year-old chess international grandmaster, not only in terms of the task itself, but also in terms of the social context. A chess tournament has the same arrangement throughout one's lifespan, and the same arrangement in different countries. Chess is a pure, self-contained domain. After chess, I would place high level mathematics or perhaps classical music; classical music is more or less the same across history, in terms of both time and culture. It's not surprising that these are the kinds of domains for which the predictions from childhood are the easiest to make. With other types of abilities the social context changes with age, and the performance expectations change, both culturally and historically, which makes prediction more difficult because the social context, the motivation and the particular ways of processing information that are required at different ages have to be taken into account. We are talking past each other because we are looking at different domains, and at different predictive tasks. I've been involved with the visual arts, where prediction is incredibly difficult because every 15 years the performance expectations change. At one point a successful artist will be one who is naturalistic, then the fashion changes to an expressionistic one or back to a geometric one, or back to pop art. Different types of young people are able to perform at high levels, depending on their motivation and skills. Perhaps you would then say we should focus on areas where we can make good predictions. If we did that, we would miss a lot of the richness about high ability. We need to have patience with the messier domains.

Sternberg: I would like to question an assumption that Julian Stanley and Camilla Benbow and perhaps others are making. Let's compare what we are talking about with what medical researchers do when they test the disease-fighting ability of various medicines. First, they try the medicine in a laboratory, out of the context of the body. If it works, they take that as a good sign and test it in the body. If it doesn't work, they may look for some other way to make it work, but if it only works in a test-tube, that is viewed as a failure. We seem to do the reverse. Instead of saying that what's really important is the disease-fighting ability in the body, we say that what really counts is what you show in isolation. We look at ability shown by tests, which after all are just a medium, like anything else is a medium, for measuring abilities. Then we find that on a lot of tests the boys do better, whereas in school the girls tend to do better. There seems to be an implicit assumption that the girls do better because they play a better social game, they behave better or they know better how to interact. The implication is that there's something shady about that, and that the boys really have more ability. If you consider my medical research analogy, you might say that the girls have more ability because they show it in context. What really matters is what you *achieve* with your abilities, not what you can do sitting for an hour in a testing centre.

Benbow: Girls show better performance in the classroom, as reflected in grades attained, but more boys earn degrees in the physical sciences. Many more boys make it through to the portals in the physical sciences, and from these they can go on to be creative. We can identify children at the age of 13 who are likely to get a PhD in a physical science. Whether the smile of good fortune, special educational opportunities, the field and the domain all come together in the right way will determine to a large extent whether the individual who has passed through all the portals will do something that will be remembered. We can't predict that. I don't understand the point you're trying to make. More boys get advanced degrees, and many more boys than girls have gone on to do great things throughout history.

Sternberg: But boys and girls throughout history have not had equal opportunities.

Benbow: You are the one who is telling me the girls are more successful. I didn't say that.

Sternberg: I'm saying that you should look in context. You use school achievement as a criterion. One could easily argue that the girls have more ability than the boys, because *in context*, they perform better. If you told me that until recent years more men than women made achievements in medicine, I would be less than impressed, because in the past women weren't admitted to medical school. It would be interesting to compare men and women actually in jobs now, male versus female psychologists, for example. Are males achieving at a much higher rate, if you control for other variables?

Benbow: Yes, they are. I agree that as doors are opened to women, things can and will change. For example, out of our first cohort of mathematically talented students, who were identified in the early 1970s, many more of the boys than the girls eventually went to medical school. Five years later, out of our second group of mathematically talented children who were at least as able as our first group, more of the girls than the boys eventually entered medical school. The difference between the sexes had been reversed.

The next question is, why aren't there as many female as male psychologists at high levels of academia? Females do not publish to the same extent as males. Within their domain, females tend to gravitate towards the teaching end of the academic role, not the scholarship and research end. Why is that? Why are these decisions being made? Females are choosing to focus their energies in different ways. You say that girls do better in terms of course grades than boys through school. That's probably true, although differences are small (Kimball 1989), but new evidence indicates that ability relates to course selections. Girls tend to enrol in college for courses in which aptitude is less strongly related to performance, and grades eventually achieved in these courses happen to be higher. In contrast, males tend to enrol in courses where aptitude relates more strongly to performance, yet course grades happen to be lower in those disciplines. The point I am trying to make is that even with an apparently simple factor such as course grades there are a lot of confounding variables that have to be accounted for before proper conclusions can be drawn. I'm suggesting that you look at your argument that girls are more successful than boys from a different perspective.

Stanley: Bob Sternberg's analogy seems to me incorrect. We don't administer psychometric tests to laboratory rats to determine whether or not the tests are applicable to humans.

Sternberg: The question is, what is the value of taking a test in a room for an hour?

Stanley: Ability testing utilizes a short but systematic and probing sample of behaviour in a carefully controlled, standardized situation meant to elicit maximum cooperation and effort.

Benbow: Ability test scores do predict future academic performance and do so well. That is the value of such tests.

Gardner: At the early levels in college science, you wouldn't be able to distinguish the women's dossiers from the men's. They have high test scores, good grades and career ambitions. However, there is a dramatic change from one year to the next. One could argue that women don't really have the aptitude, and when things get more difficult they drop out; but one could make an equally powerful, if not more powerful, sociological argument about role models, ways of studying together, and decisions between career and family. One has to be careful before assuming that the major determining factor, in some abstract sense, is that women students cannot be perfectly good scientists.

The area of psychology I know most about is developmental psychology. I would say that there's absolutely no difference in this field between the top males and females. You might say that developmental psychology, because it involves children, would interest women more, and that historically there have been fewer sanctions against women going in to that field. But I'm talking about people making contributions, people whose ideas have had real effects in the field.

Even in the current context, forgetting about the history, there are powerful signals which make it difficult for women to continue certain subjects in college. In certain fields, such as developmental psychology, where there have been fewer sanctions, there is no sex differential in scientific contributions.

Benbow: We are making the same general point, but are coming at it from different perspectives. I am suggesting that there are many more pulls on females than males which affect the types of choices they will make; gifted females are more broadly developed, with more competing interests than gifted males. Also, males in our sample of high ability students have been much more committed to a full-time career than such females, a finding that has remained stable for over 20 years. This certainly affects females' choices.

Many females go into psychology, but there are few female experimental psychologists. Even within a discipline, females, just as males do, gravitate towards those areas which better fit their preferences and needs. I don't think developmental psychology attracts women just because there are fewer sanctions. I believe part of the reason is that developmental psychology is more congruent with females' profiles of preferences and needs. Although ability is an important factor that affects your career choice, so do your preferences, commitment to family life, and many other things. More females than males are awarded PhDs in psychology, but most of the females go into clinical practice, rather than academia. It isn't that females aren't developing their talents, but that they're choosing to develop them in different areas.

You also mentioned role models. Role models are important, although I think that males can be good role models for females. But, consider the Asian Americans who are taking over science in the USA. Who were or are their role models?

Bouchard: You have just given the most powerful refutation I have ever heard of the most overplayed, non-empirically demonstrated explanation one can hear in psychology. The evidence for role models being causal factors is practically nil. Role models are repeatedly postulated as an *ad hoc* explanation.

Gardner: Do you mean gender-linked role models?

Bouchard: I mean role models as a general phenomenon.

Fowler: Would you accept the concept of mentors?

Bouchard: That's a different concept. A mentor is a person who provides a certain kind of training. The generalized notion of some kind of abstract role model is just a pseudo-explanation.

Fowler: In the history of the handful of great women mathematicians there was always some person who served as a special mentor, typically a male, because males were the ones available. These mentors were models of some sort.

Bouchard: That's a much more generalized explanation. As Camilla Benbow said, males can act as an exemplar and provide guidance. The idea of the role model most often carries with it the requirement that the model be of the same sex, race, etc.

Gardner: Nobody took that position except you!

Detterman: Zuckerman's (1967) study showed that many Nobel Laureates had studied with previous winners of Nobel Prizes.

Gardner: You would have to work with male Nobel Laureates whether you're male or female, because there aren't many female Laureates.

Bouchard: Now you are talking about experiences in adulthood, not developmental phenomena. The tremendous accomplishments made by groups for whom it's hard to pin down role models show that role models are certainly not a necessary condition. When role models are invoked there's usually no adequate control. People go through the data and find what they want. Each of us is in contact with large numbers of people, so you can always find a role model. We need controls.

Gardner: Some people at the top of their fields don't have contemporaneous role models. They have what Dean Simonton calls paragons and exemplars. Obviously, you can talk about this empirically if you have instances where it doesn't happen. The fact that Simonton was able to distinguish biographically between cases in which you can point to somebody the person knew, who was older than them, and those where you can point only to someone they knew from the historical record shows that it is possible to study this.

Freeman: Doctors' children become doctors, lawyers' children become lawyers. There is plenty of evidence there for the effects of role models who are close to the child, and plenty of controls, children of similar potential in differently oriented families who are more likely to follow the careers with which they are familiar.

Bouchard: That is not true in all cases. The correlation is much less than 1.00. You have to do adoption studies to get a proper answer to the question.

Gruber: If you were considering Darwin's life, it would be ridiculous not to talk about Henslow, his teacher at Cambridge, Humboldt, a person he greatly admired, and Lyell. Then you get to Wallace. Darwin was Wallace's role model.

Atkinson: Tom Bouchard was responding to a definition of a role model as someone of the same sex and the same socio-economic background.

Bouchard: The term role model is used in a highly specific way, but I would argue that this idea has not been carefully conceptualized at a scientific level. Of course there must be a teacher around, of course the context has to be there, of course you have to acquire the material. I would like to see somebody do a really careful scientific review.

Stanley: Would you advocate studying students who weren't Darwins, for example? Many studied with Henslow, but only one Darwin emerged.

Gruber: Darwin was known at Cambridge as 'the man who walks with Henslow', while the others were not. We need a careful study of how being a role model works, but specifically in the case of highly creative people. The relationship between Darwin and his role model was very warm—he was more than simply a teacher in a classroom who taught Darwin what he needed to know. Tom Bouchard said you have to have a teacher, but there's more to it than that—you have to have a teacher with whom you share something like a love relationship.

Hautamaki: Attachment learning (Minsley 1985) is the term I would use to explain why in a classroom situation some teachers are more capable than others of instilling long-term commitments in their students. A student who allows a mentor or a teacher to work with his values and goals, making sense of the world, is also ready to engage in long-term work. Teachers are not normally given such a possibility by the child, but sometimes the 'doors' open. Parents have that attachment relationship with their children all the time, but teachers seldom do. In Finnish schools, the relationship of pupils with the teacher is value- and goal-neutral, but sometimes attaching situations or teachers will encourage even normal children, not only the able, to engage in long-term commitments.

Freeman: Alice Miller, the Swiss psychoanalyst, uses the term 'witness' (Miller 1981). This is not quite the same as a role model, but somebody who stands up for the child, usually the mother, giving the child a sense of self and authority with which to set forth.

Bouchard: That's very different from a role model.

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Mechanical inventiveness: a three-phase study

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Abstract. This paper focuses on mechanical inventiveness, the conception and development of new devices which require use of mechanical principles. In Phase 1 of the three-phase investigation, we studied 34 inventors who received between three and 82 agricultural and industrial patents. These inventors formed the original criterion group of mechanical inventors. Phase 2 of the investigation was the development of an inventiveness measure. From the criterion group of adult mechanical inventors, the Iowa Inventiveness Inventory (III) was developed to measure attitudes and characteristics of inventors. Subjects for Phase 3 of the study were 90 young inventors (40 males, 50 females), students (grades five to eight) who won local and regional invention contests and reached the state convention of *Invent Iowa*. In Phase 3, *Invent Iowa* state finalists in grades five to eight ($n = 90$) were administered the III and the Mechanical Reasoning test of the Differential Aptitude Tests. Characteristics of the young inventors, as delineated by these assessments, are provided.

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A common perception of the inventor includes terms such as weird, individualistic, wild-eyed, odd, socially inept, and quixotic. Rossman (1964), in his book *Industrial creativity: the psychology of the inventor*, provided several conceptions and misconceptions about the personal characteristics of the inventor. There have been a number of books, papers and magazine articles on traits of the inventor.

Colangelo, Kerr, Hallowell, Huesman and Gaeth (Colangelo et al 1992) undertook an intensive biographical study of 34 adult inventors who received agricultural and industrial patents. Our interest was to understand mechanical inventiveness better. A person was deemed inventive if he (no females were identified for the initial criterion group) had obtained a patent. Mechanical inventiveness was operationally defined as obtaining an agricultural or industrial patent that included principles of mechanics.

Arnold Skromme, an engineer and inventor, provided the names of the 34 inventors (including himself) of agricultural and industrial inventions. The inventors were prominent and productive. The number of patents they had received ranged from three to 82, with an average of 20. All the inventors were males aged between 42 and 82, with a mean age of about 60.

There is evidence that the construct of creativity overlaps other constructs, such as intelligence, achievement and competence (Hocevar & Bachelor 1989). In addition, creativity seems to be tied closely to the level of skill in a particular field of endeavour. We viewed mechanical inventiveness as a domain-specific expression of creativity. Domain specificity is allied to Gardner's theory of multiple intelligences (Gardner 1983, 1988, Ramos-Ford & Gardner 1991). These intelligences are: linguistic, logical-mathematical, spatial, musical, bodily-kinaesthetic, interpersonal and intrapersonal intelligences. Gardner posited that these intelligences are independent of each other. Mechanical inventiveness, although related to creativity in general, comprises its own set of skills and abilities. Using Gardner's categories, we speculated that mechanical inventiveness combines spatial, logical-mathematical, and, to some extent, bodily-kinaesthetic domains or intelligences (Colangelo et al 1992). Furthermore, we speculated that mechanical reasoning ability may also play a role in mechanical inventiveness.

There are three phases to our study of mechanical inventiveness. Phase 1 was commissioned by the inventors themselves, and included an extensive gathering of biographical, vocational and personality data on the 34 inventors (N. Colangelo & B. Kerr, unpublished paper, Iowa Talent and Giftedness Conference, October 1987, and unpublished paper, College of Engineering Conference, Iowa State University, November 1987). Phase 2 was the development of an instrument which could be used to assess and identify young people who possess characteristics associated with mechanical inventiveness. This instrument, the Iowa Inventiveness Inventory (III), was based on themes underlying mechanical inventiveness established from the data collected in Phase 1. Phase 3 is an ongoing investigation of the development of the inventiveness construct in young inventors, defined as those whose inventions are selected for the state convention of *Invent Iowa*. These students (grades K [kindergarten] to eight, up to 13 years of age) are selected for the state convention by 'winning' local and regional invention contests.

Phase 1: interviews and biographical information on 34 inventors

The study of 34 inventors holding agricultural and/or industrial patents was headed by Nicholas Colangelo and Barbara Kerr. The inventors were interviewed either at their homes or at the University of Iowa. The collection of data included a lengthy structured individual interview for each of the 34, and group interviews with 13 of the inventors who were able to come to The University of Iowa for group discussions.

It is impossible to capture on paper the excitement our research team felt in meeting these men (and their wives). The inventors were enthusiastic about their participation in the study and revealed a tremendous amount in terms of their personalities and their work. Each inventor was interviewed by two members of the research team. (The team was made up of Colangelo, Kerr and several graduate assistants.) All interviews were tape-recorded and later transcribed. Also, the entire team had a discussion about the interviews with each inventor so that we could get 'impressions', as well as collect data.

Our goal was to find themes in the extensive 'pieces' of data that we had collected. In the end, we came up with a number of themes and we shall discuss what the team considered to be fundamental themes that apply to the majority of the inventors.

Biographical themes

Happy home life as children. Every inventor described his early home life as positive, warm and caring. Their recollections were that parents were supportive of them and their 'work'. They were given responsibilities and autonomy. As adults, they also reported very harmonious lives and marriages. There were no divorces in the group.

Love of work. Love of work and passion for work have been talked about as indicative of creative/inventive individuals. We found this to be extremely pervasive with our group. Most talked about what it means for them to be able to 'get back to their work'. In response to the question, 'what do you do for fun?', almost all responded, 'I work'.

Religious orientation. The inventors came from religious homes, although all reported a 'non-oppressive' religious orientation. No one claimed to be an atheist.

Small towns. The vast majority (over 90%) of the inventors came from rural or farming backgrounds. This is probably a result of Skromme's selection of inventors of agricultural and industrial patents.

A place to tinker. Every inventor mentioned that he had a place to tinker or a workshop of sorts. Often it was a father's or uncle's workshop to which they had easy access. As adults, all of them had a workshop which was where they went to 'do their work'.

No problems with alcohol or drugs. There were no problems related to alcohol or drugs among the inventors' parents. Also, none reported problems with alcohol or drugs as adults. Experimentation with drugs was simply not an issue.

Inventing at an early age. All inventors reported making some gadgets or modifying tools or toys by the age of eight. Several of them said that as children they were more interested in taking toys apart than in playing with them.

Humanitarian principles. In our interviews, all the inventors expressed a caring for humanity and their views could be considered 'liberal', in terms of acceptance of others. Overwhelmingly, the inventors cited 'helping others' or 'contributing to society' as a primary motive for their invention. The other major motive was 'seeing' that something could be made better or simpler and feeling a pressure to make the change. Very low on the impetus for invention was the desire to make money from it.

Although humanitarian principles were espoused, almost all the inventors stated they did not greatly enjoy socializing. They placed clear value on work (and usually working alone) rather than on spending social time with family and friends.

Perseverance. Perseverance has been attributed to creative individuals and inventors. This was a striking feature with our sample. All related stories of 'failures' and obstacles to their successes. They all felt that the willingness to not be defeated by the attitudes of others or by failures was one of their distinguishing features.

Work habits. We received extensive information on the work habits of our inventors, from interviews with them and their wives. There were a number of idiosyncrasies about how they went about their work, but three themes pervaded their work habits.

(a) The inventors unanimously said that when an idea or problem 'captured' them, they could not put off working on it. They could not let something lie, tackling the problem immediately, in their shops, at their jobs, or on paper. There was no sense of taking care of other responsibilities before getting down to the new idea. No time elapsed between the conception of an idea and its tangible application.

(b) Keeping notes or journals was a characteristic common to all the inventors. They would write bits and pieces down as they thought of them. Most wrote on whatever was handy, rather than keeping formal journals, but they 'never misplaced these notes'.

(c) Although all the inventors said that they worked whenever an idea hit them, they also reported that there were times when they felt most 'inventive', that good ideas tended to come to them late at night or early in the morning. (They all claimed to be early risers.)

Workers, not spectators. The inventors disliked being 'spectators'. The vast majority disliked watching sports events and especially television. They had a very strong preference for working on something, rather than watching or attending events.

Academic themes

We were interested in learning about our inventors' school lives and attitudes, because one of our goals was to understand how schools can foster or hamper inventiveness in young people. The following themes emerged from interviews about schools and schooling.

Attended small schools. Almost all came from small rural schools and several from one-room schoolhouses. Again, this is a result of the process by which our group was selected.

Liked school but did not excel. Not one inventor considered himself a strong academic student. Over 50% considered themselves 'low achievers' and over 60% failed at least one subject in school. Three did not go to high school and only 50% had some type of post-high school training.

They reported that their weakest areas in school were English and reading classes, and that they were not strong in writing or verbal skills. All reported mathematics as an area of strength.

In their interviews, the inventors held that they would not do well on IQ tests or tests that measured academic abilities. We did not find a single inventor who claimed he would do well on standardized measures of academic ability.

Got along but were not social leaders. The inventors all reported good experiences with school. They got along with teachers and did not describe themselves as difficult or as trouble-makers. They had got along with other children, but none claimed to be social leaders or exceptionally popular.

School was not their primary place of learning. The inventors found school pleasant, but not the primary source for their knowledge of mechanics. They reported that they learned most of what they needed to know on their own, by reading books and magazines on areas of interest. For the most part, they learned by 'doing and observing'. All, except one, claimed that school had not helped in any significant way with their inventiveness.

Lastly, we asked the inventors to tell us what they thought schools could do to help inventive students. We could not get a clear answer on this. Again, our inventors were positive about school as a socialization institution and a place to learn academic skills, but they were not sure how schools could help young inventors. Some felt that schools could not do anything, that it was up to the inventor to do what was needed. Others maintained that schools over-emphasized conformist thinking and did not encourage or recognize creative or inventive students. The vast majority thought that schools needed to do more to recognize and encourage inventive students, but they did not have clear ideas on how this could be done. In reflecting on the interviews, our summary would be that inventors just didn't think schools could break their conforming patterns enough to really help inventive students.

A last comment we wish to add was a piece of advice that a group of the inventors had for young students who had an idea for an invention. Their advice was to keep one's idea to onself, nurture it, and work on it. They believed that 'others' are quick to criticize new ideas and show why they can't work and that new ideas are squashed before they have a chance to take hold.

Phase 2: the Iowa Inventiveness Inventory

From the interviews of the inventors in Phase 1, it was obvious to us that inventiveness was different from academic ability or achievement. Because of the strong feeling on the part of our inventors that inventive youngsters were not to be found by looking at standardized test scores and school grades, we developed an instrument on the basis of characteristics revealed in our group of 34 inventors.

The Iowa Inventiveness Inventory was developed from a review of the transcribed recorded interviews with the 34 inventors. From these transcripts were generated a pool of items which were eventual'y put together as the Iowa Inventiveness Inventory (III). The original III consisted of 80 items on a 1–5 scale (1 = strongly agree to 5 = strongly disagree).

A complete description of the III has been published recently (Colangelo et al 1992). Here we present an abbreviated version.

Instrument description

An item analysis was carried out on the original 80 items from the III, using data collected from five groups of subjects ($n = 447$). The revised III consisted of items which were found to be interrelated (correlations of 0.70 or higher), as well as items which had an appropriate range of responses (i.e., 1–5). The III can be used from grade five (age 10–11) to adult.

Procedures

To estalish the validity of the III, we administered it to the following five groups:

(1) Adult non-inventors, teachers and the inventors' spouses or friends who volunteered to participate. Total $n = 214$; 133 females, 79 males and two individuals who did not report sex.

(2) Industrial technology students from a community college in Iowa. Total $n = 164$; 18 females, 142 males and four individuals who did not report sex.

(3) Inventors: the inventors from our Phase 1 study served as the criterion group. Of the 34 men in the original group, 29 completed the III.
(4) Child IGI non-inventors, gifted adolescents (ages 13–15) who participated in the Iowa Governor's Institute (IGI) at The University of Iowa. These IGI students were selected for this group on the basis of their academic and artistic talents ($n = 67$; 35 females, 32 males).
(5) Child IGI inventors, IGI students selected into our group on the basis of their mechanical inventiveness, from plans they submitted for an invention and from teachers' recommendations. Standardized test scores and grade-point averages were not considered in the selection procedures for this group ($n = 11$; all males).

Validity

The items that constitute the III were derived by carefully analysing reoccurring themes from the interviews with our Phase 1 inventors. The fact that items were based on statements made by the criterion group is perhaps the best basis for this instrument's construct validity.

Table 1 contains the Cronbach's α coefficients and other summary information for the five groups given the III. The α coefficient provides an estimate of reliability for measures composed of items with varying scale values (e.g., strongly agree to strongly disagree). The α coefficient is a measure of how the items in the III correlate with the total score, and therefore is essentially a measure of the homogeneity of the items in the inventory. The α coefficients indicate that for each group, the III measured a common trait.

To examine further the construct validity of the III, we compared mean scores on the III for adult non-inventors, industrial technology students, young inventors enrolled in the Iowa Governor's Institute, young non-inventors enrolled in the Iowa Governor's Institute, and our original inventors who had received patents. The overall analysis of variance reveals significant differences between groups (F [4480 df] $= 13.79$, $P < 0.0001$).

TABLE 1 Summary statistics for each of the five groups given the Iowa Inventiveness Inventory

Group (No. in text)	*n*	*Mean*	*SD*	*α Coefficient*[a]
IGI non-inventors (4)	67	208.01	14.21	0.78
Adult non-inventors (1)	214	215.33	14.21	0.76
Industrial technology students (2)	164	217.77	13.60	0.74
IGI inventors (5)	11	223.26	14.58	0.76
Inventors (3)	29	231.80	16.17	0.79
Total	485	216.55	14.64	0.77

[a]Cronbach's α coefficient, a measure of reliability (see text).

TABLE 2 Comparisons between inventors (3) and the four other groups given the III

Group compared[a]	*t*	*df*
Adult non-inventors (1)	5.20*	241
Industrial technology students (2)	4.23*	191
IGI non-inventors (4)	6.59*	94
IGI inventors (5)	1.25	38

[a]Equal variance was assumed for all tests.
*$P<0.0001$.

The inventors and the IGI inventors scored higher on the III than the other three groups. Table 2 contains comparisons (*t*-tests) of the inventors with the other four groups.

Reliability

The stability and test–re-test reliability of the III were assessed using responses from a group of 104 undergraduate students on a career development course at the University of Iowa, 30 males and 74 females between the ages of 18 and 22. Students took the III as a group in their class, and again three weeks later in the same class.

Internal consistency was computed to provide an estimate of the reliability of the III. The correlation between the results obtained from the two administrations of the test was 0.72 for the total scale and 0.66 for items constituting the inventiveness scale, indicating moderate reliability (see Colangelo et al 1992).

Phase 3: *Invent Iowa*

Invent Iowa is a state-wide programme providing a curriculum for schools on inventiveness, and opportunities for students to compete in local and regional invention contests. *Invent Iowa* is a programme for grades K to eight which has been widely participated in by students. In 1990–91, over 13 000 Iowa students took part and in 1991–92, nearly 15 000 students participated. Students who enter and win local and regional contests can be selected for the *Invent Iowa* state convention, which is held in April in Des Moines, Iowa, and includes the two hundred local and regional winning projects. (Students may enter as a team on a project and thus more than 200 students reach the state convention.) Table 3 gives a breakdown of the students who participated in the *Invent Iowa* state convention in 1991 and 1992.

One obvious limitation of the inventor group from our Phase 1 study is that they were all males. In Phase 2 the IGI inventor group was also all-male.

TABLE 3 Participants of the *Invent Iowa* state convention

	1991			*1992*		
Grade	*Male*	*Female*	*Total*	*Male*	*Female*	*Total*
K	3	1	4	2	4	6
1	8	9	17	3	4	7
2	10	9	19	4	10	14
3	14	12	26	16	20	36
4	23	23	46	30	30	60
5	19	31	50	29	29	58
6	28	18	46	30	26	56
7	13	14	27	10	12	22
8	9	7	16	7	4	11
Total	127	124	251	131	139	270

Invent Iowa has had a balanced representation of the sexes at the state convention.

As part of our on-going study of inventiveness, we gave the III and the Mechanical Reasoning test of the Differential Aptitude Tests (DAT) to a group of 90 students (40 males, 50 females) in grades five to eight from the *Invent Iowa* 1992 state convention. The students took the Level 1 (Form C) of the Mechanical Reasoning test, which is geared for students in grades seven to nine. The Mechanical Reasoning test, as are all tests in the DAT, is designed to measure aptitude: 'Aptitude is the capacity to learn given appropriate training and environmental input. In other words, aptitudes are not inherited, rather they are considered to be developed abilities' (DAT 1991, p 20).

The Mechanical Reasoning test is a 60-item test to be completed within 25 minutes. 'The Mechanical Reasoning Test measures the ability to understand basic mechanical principles of machinery, tools and motion. Each item consists of a pictorially presented mechanical situation and a simply worded question. Items represent simple principles that involve reasoning rather than special knowledge' (DAT 1990, p 10).

Table 4 contains the 1992 *Invent Iowa* students' results on the mechanical reasoning test. These students appear to reason well mechanically.

It is important to look at how the students who make the *Invent Iowa* state convention perform on academic measures. This analysis is in progress. Our hypothesis, based on what we learned in Phase 1, is that these students will not have high standardized achievement test scores. Also, we would hypothesize that their verbal achievement scores would be below their mathematics achievement scores.

TABLE 4 Results of the Iowa Inventiveness Inventory (III) and the Differential Aptitude Tests Mechanical Reasoning test (Level 1, Form C) for 1992 *Invent Iowa* participants

		III			*Mechanical Reasoning test*		
Sex	*Grade*	*n*	*Mean*	*SD*	*Mean*	*SD*	*Percentile*
Male	5	16	223.52	15.36	40.50	7.12	65[a]
Male	6	15	229.97	23.68	45.20	7.08	82[a]
Male	7	5	214.53	16.00	46.40	6.11	78[b]
Male	8	4	232.80	10.88	50.25	3.77	80[c]
	Total	40	225.74	18.84	43.98	7.26	
Female	5	18	214.54	16.00	35.50	7.37	74[a]
Female	6	22	215.19	14.72	37.45	6.12	79[a]
Female	7	8	223.28	11.52	38.88	8.63	76[b]
Female	8	2	231.04	5.12	38.00	5.66	59[c]
	Total	50	216.88	14.90	37.00	6.90	
	Totals	90	220.82	17.25	40.10	7.84	

[a]Seventh grade (1991) fall norms.
[b]Seventh grade (1991) spring norms.
[c]Eighth grade (1991) spring norms.

Future

At The Connie Belin National Center for Gifted Education we are presently giving the III and the DAT Mechanical Reasoning test to students who are identified for pre-college programmes on the basis of their academic abilities and plan to compare them with *Invent Iowa* students. We will pay particular attention to item responses on the III and sex comparisons.

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DISCUSSION

Gardner: One important element about these people which didn't come through is their political and social conservatism. Of the 34, how many do you think would have been Reagan/Bush supporters? Also, what is their genuine relationship with their children? Growing up in the 1980s and 1990s is not like growing up in the 1940s. Do they think the world is going to hell, and want to go back to the old days, or are they pretty realistic about their children and what's happening in the larger scene?

Colangelo: If clothes have anything to say about conservatism, these men are conservative. You are probably not too far off the mark as regards the way they would vote, although we didn't actually ask about this. They seemed to have a sense of liberalism about humanity in general. I would speculate that the majority would vote on a conservative ticket. No significant problems about their relationship with their children came up, but we didn't really pursue that.

Gardner: You need to be aware of a Pollyanna-type picture which comes through. It might be worth re-visiting some of them. Who they vote for is really unimportant, but it would be important if you found that they were having problems with their children.

Colangelo: Can I defend myself against your use of the word 'Pollyanna'? I didn't think that anybody had the right to be so happy about life! I looked through our case materials closely. I appreciate that there are things we could have missed, but we spent many hours with them and with their spouses, and the consistency of their positive outlook is pretty impressive.

Freeman: You made home visits. What were the homes like? Were they visually rich? Did they have mechanical things in them?

Colangelo: We worked in teams, so I didn't make all the visits. They were very comfortable homes. There was nothing sterile about them. The three millionaires out of our sample of 34 came to the university, so we didn't get to visit their homes. Outside the house, they would show us their work areas. I don't think you could have walked in and said, 'this is an inventor's home'.

Howe: I love this kind of descriptive material. This kind of work builds up a temporal picture. In a sense, these people seem to be filling an environmental niche. If something else had happened to them, they would have been siphoned off into higher education where they wouldn't have been so close to farmers and their concerns. I, and I suspect a lot of us, have been tending to feel that if you want to know about high ability you have to be interested in people who win Nobel Prizes, and people who get to the top, that the higher someone's achievement is the more relevant they are to what we are interested in. From your study, I get the sense that by looking at people who certainly are creative, though not quite the same as Nobel Laureates, we learn a lot of things that we don't learn from Nobel Laureates which are just as valuable and just as relevant to understanding what we can do to help ordinary people.

Colangelo: One thing I have learned is that it's not worth my trying to do a study to find the next Einstein. These men have many patents. That doesn't put them at the pinnacle of their field; I wouldn't say it's ordinary, but it is a considerable step down from an inventor such as Edison. Some of their names would be familiar to Iowans, but they would not be world renowned.

Gruber: Naturally I applaud the idea of taking a restricted group and asking what these people have in common. This is a much more productive question than asking whether *all* creative people are this or that. The literature is full of a confusion of different levels and different types, treating all creative people as though they must be alike.

What you have described in your results are essentially correlates of inventiveness. Did you do any work on the actual process of invention? That too could be done retrospectively.

Colangelo: We tried to get an idea of when they were inventive, asking whether there were particular times during the day, for example, that were better than others. For the most part they said they had ideas at any time, although they ended up saying that they probably did their best work early in the morning. A few said that at night they spent time thinking about their inventions. We didn't address this formally. They did say they could easily visualize what they wanted done, that they could see things, and could see how something ought to look if they made a modification. They used the word 'see', some even 'visualize'.

Gruber: Did any of them report working on more than one stream of activity simultaneously? While they were experiencing difficulty with one project, were they developing something else?

Colangelo: We didn't ask that specifically.

Gruber: There's a rich mine of information there about the actual process of invention.

Atkinson: Is it your hypothesis that people are focused on just one invention at a time?

Gruber: The process of invention has been badly slighted by people studying creativity. A couple of books have been published on this subject recently (Weber 1992, Weber & Perkins 1992). It would be interesting, and fun, to find out how inventors actually go about their work. How do they visualize things, what triggers off an idea, are there sudden insights or a slow build up, do they have guiding metaphors and does the same metaphor repeat itself in their other inventions? In Edison's case, certain metaphors crop up over and over again. I don't have a hypothesis about what these people are like, because they haven't been studied in sufficient depth.

Colangelo: They talked about putting something aside when they'd taken it as far as they could, but, like a pit bull terrier, they would keep at it.

Fowler: Your description suggests that mid-west, small-town USA is an ideal ecology for the generation of creative inventiveness, something like the New Harmony Indiana Utopia of 19th century American lore. I wonder whether you would be able to find such a self-selected sample in an urban area, or whether it is the closeness to farm machinery, and the availability of tools all around you in everyday life in an informal way, that makes the difference. A lot of boys tinker, and they apparently have plenty of opportunity to do so in small-town USA. I'm interested in what made the tinkerers turn into people who were curious about transforming things. That must have happened secondarily. Have you any information on that? Also, did they tend to collect things?

Colangelo: Some had collected stamps or rocks, but that didn't appear to be a major, obsessive characteristic. They did say that even before the age of eight they modified things, that they would do things to reduce the amount of time that they had to spend on chores, but none got a patent before adulthood.

Fowler: The important questions is, why did *some* of the tinkerers start to reorganize things?

Colangelo: We don't have a control group who tinkered a lot and had pretty good mechanical abilities but who have never received any patents.

Csikszentmihalyi: It's interesting to compare your farm machinery inventors with automobile appliance inventors, who are apparently a very different breed. The man who invented the intermittent windscreen wiper has just been awarded huge damages in a court judgement from Ford and Chrysler who apparently stole his patent. When I heard about this man I started reading about some other inventors in Detroit who work for motor vehicle manufacturers. There, inventors have to work with armies of lawyers in an atmosphere very different from your inventors of farm machinery. This is probably a general domain difference, and I am glad that there are people like those you described still working.

I have studied young artists who at age 20 all described their early lives as harmonious and happy. Then at age 40, when we interviewed them again, those who had been fairly successful still said in retrospect that they had had a harmonious home life, but those who had gone through a hard time and had become alcoholics or drug addicts all blamed their parents. Most of these people had also been in therapy, so the question remains whether they actually had a bad childhood which was repressed until the therapist uncovered it, or whether it was something they invented to justify their failure. Such retrospective reconstruction is problematic, but that doesn't detract from the fact that in the particular domain you have studied the individuals may actually be happy.

Lubinski: This study is fascinating, and it actually mirrors a study of spatially talented students I have done (Humphreys et al 1993). Of the three major symbolic/representational systems of intellectual functioning—verbal, numerical and spatial—we neglect the spatial abilities in our culture. I analysed the entire project talent databank, a databank compiled by John Flanagan in the 1960s consisting of a stratified random sample of USA high schools. It has good measures of spatial, quantitative and verbal ability on 400 000 subjects. It also has longitudinal tracking of these students 11 years after their graduation from high school. Spatially gifted students tend to have a rather inconspicuous personological profile, and are more likely to come from lower socio-economic levels. This mirrors C. P. Snow's two intellectual worlds quite nicely. In the USA, we over-emphasize the literary and humanistic culture, and neglect the scientific culture which is composed primarily of spatially and quantitatively gifted people, and we lose a lot of talent that way. If you arbitrarily take the top 1% of spatially gifted students, that cut-off score will give you a profile of cognitive attributes quantitatively in the 93rd percentile and verbally in the 90th percentile. That would disqualify over half of the spatially gifted students from the most select schools of engineering and physical sciences. I would think your inventors' responses to education are due to the way their academic products are assessed, by paper-and-pencil tests. If you could get them to build things, create things in workshops and laboratories, and get several experts to grade their products, they would probably be more responsive to education. These people appear inconspicuous; they don't look like college material and they don't present themselves in culturally refined ways. I believe spatially gifted people represent the greatest loss of intellectual talent in our culture.

Benbow: My question is perhaps a slightly personal one, but it might illuminate an aspect of Profesor Colangelo's study we haven't yet touched on. My neighbour is an inventor of agricultural machinery, who could have been in your study. One of his most distinctive aspects is his self-image. I was wondering, how do these individuals view themselves? How do they view their own creativity, their own skills?

Colangelo: Again, we didn't measure this formally. They would say they were not particularly intelligent, but that they worked hard and knew how to solve problems and how to ask the right questions. They were confident in themselves, that they knew how to do what they had to do, despite a lack of formal education. They might say that even though they weren't good students they felt intelligent and capable when they were working on a problem. They don't have tremendous interpersonal skills, but in meeting them one got no strong sense that they were odd socially.

Bouchard: As I have said before to others, your study would be greatly enriched by the appropriate controls. An appropriate control group could include a brother, or a near neighbour. I suspect with a control group many of your findings would disappear, because you do have a sample of mid-west, small-town farm boys. We don't know which factors are causal to inventiveness and which sample artefacts.

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The relationship between early giftedness and later achievement

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Abstract. Although some prodigies grow up to become creative masters as adults, there is no necessary link between early signs of talent and ultimate achievement. Four possible relations between early and late achievement are explored here. The analysis draws upon two lines of evidence: (1) a new theoretical approach that posits the existence of multiple intelligences and examines the important role of the domains and fields in which individuals work; (2) case studies of seven highly creative individuals who lived at the turn of the century. A strong contrast emerges between the adult creator, who must discover the domain in which he or she can excel and the child prodigy, who must invent a creative personality.

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Four relations

The French critic Guillaume Apollinaire once reflected on the artistic development of his close friend Pablo Picasso. As Apollinaire saw it, there are two kinds of artist: the virtuoso who is 'all put together' at the start, and the emerging, reflective, deliberate self-constructer who must mediate his or her own development. As a prodigy, Apollinaire claimed, Picasso epitomized the first type, but was able to convert himself into the second kind of artist: 'Never has there been so fantastic a spectacle as the metamorphosis he underwent in becoming an artist of the second type' (Apollinaire 1949, p 22).

With this suggestive analysis, Apollinaire introduces the problem with which I am concerned here. Four relations are possible between the abilities displayed by a young practitioner within a domain and the abilities of an accomplished master of that domain.

(1) Of least interest to us here is the most common case, an individual of normal talent during youth who becomes a proficient adult practitioner of the domain. The habitual may indeed be the flywheel of civilization, but it elicits little interest precisely on that account.

(2) A poignant state of affairs results when an individual of high talent and promise ends up failing to achieve that potential. There are famous examples, such as that of William James Sidis (Montour 1977), a scholastic child prodigy who ended up as a loner, as well as countless anonymous instances of talented young musicians or athletes who never achieved mastery.

(3) In retrospective studies of people who have made remarkable advances in a domain, these individuals are rarely found to have been prodigious during youth; rather, they were individuals of clear talent and considerable promise whose ultimate destiny could not readily have been anticipated (Bloom 1985).

(4) Picasso epitomizes the final, quite rare, category. Like John Stuart Mill, Carl Gauss and Yehudi Menuhin, he was an individual distinguished both as a remarkable youth and as an accomplished, creative master. Just how such occasional individuals succeed in negotiating this treacherous path is a major theme of this paper.

The classic view and a challenge to it

Although the problem I have outlined is a classic one, the stance that I shall take is not. The standard approach dates back to the time of Francis Galton, continues through the studies of Lewis Terman, and is realized today in the core tenets of the London School. Under this approach, individuals are considered to be born with a certain degree of talent or intellectual potential. This talent is generally assumed to be of a quite general sort—true genius, as Samuel Johnson declared, is 'a mind of large general powers, accidentally determined to some particular direction' (Bate 1975, p 252). Individuals who are blessed with general intelligence or creativity are expected to do well, whereas others with a lesser degree of innate endowment are unlikely to make any mark. On this account, the Mills and Gausses should represent the norm of talent; Mozart, who was considered by Terman's colleague Catherine Cox to have an IQ of a mere 135, probably squeaked through by virtue of the possession of a specially distinctive talent.

In a contemporary critique of these notions of intelligence and creativity, I take issue with all of the classical assertions (Gardner 1983, 1993a). I do not believe that there is a single general talent, whether it be called intelligence, creativity or '*g*'. I do not locate talents completely within the human skull, preferring to construe all accomplishment as an interaction between cognitive potentials on the one hand, and the resources and opportunities provided by the surrounding culture on the other. Finally, I embrace a developmental perspective, which posits quite different needs and opportunities at different points in the life cycle and which recognizes that the trajectory of the development or dissolution of talent follows a vexed path within and across cultures.

In a paper of this brevity, it is not possible to review the findings on which this heterodox perspective has been based. I can say briefly that it builds not only on our increasing understanding of the highly differentiated nature of the human brain—an understanding that recognizes the different processes and operations involved in dealing with diverse contents in the physical and social worlds—but also on a consideration of the various kinds of roles that are valued in different cultures and the routes through which the desired mastery can be achieved. This combination of biological and cultural lines of evidence suggests the existence in human beings of at least seven different intellectual competences, each of which clearly has genetic origins, but each of which is also developed—or not developed—because of decisions made within the cultural envelope in which individuals find themselves.

Elements of the giftedness matrix

This 'multiple intelligences view' has clear consequences for a study of extraordinary promise and achievement. In work carried out in conjunction with David Feldman (Feldman & Goldsmith 1986) and Mihaly Csikszentmihalyi (1988), I make the following distinctions. All intellectual and creative work takes place within some kind of social discipline, craft, or organized activity, termed a *domain*. Accordingly, there is no sense in which one can speak about a person as being intelligent, or creative, in general. An individual is considered *gifted* if he or she develops intelligence in a domain more rapidly than is usual. If such development occurs with rare rapidity, so that the youngster is performing at the level of the adult, one can speak of that individual as being *prodigious*. And if an individual comes to perform at the highest level within a domain, he or she merits the term *expert* or *master*.

The family of giftedness, prodigiousness and expertise all presuppose performance in a domain as it is usually constituted—challenges are out of order. A different state of affairs exists when an individual challenges the domain as it is customarily structured and practised; those who do so successfully are called *creative*. Creativity involves at least two aspects: the capacity and desire to be innovative; and the acceptance of the innovation by a group of knowledgeable individuals (dubbed by Csikszentmihalyi [1988] as the *field*). In the absence of the motivation to be innovative, an individual is restricted to the achievement of expertise. In the absense of the acceptance of knowledgeable peers, the would-be innovator is judged as eccentric but not creative.

It should be stressed that no limitations need to be invoked in judgments about creativity; a field may exercise its will immediately or, as in the case of Johann Sebastian Bach, Gregor Mendel or Emily Dickinson, many years later. An individual who is not (yet) judged to be creative need not be considered *un*creative; rather, one simply cannot judge whether or not that person is creative.

In the interest of completeness, let me indicate two other nodes in what I have elsewhere called the 'giftedness matrix' (Gardner 1994). A *successful* person is one who is rewarded by the contemporary field, irrespective of whether he or she is judged then, or in the future, to be creative. Both Picasso and Norman Rockwell were successful, but only Picasso is thought to have been creative. A *genius* is an individual whose creativity comes to be thought of as addressing the deepest issues while resonating across a global audience.

Seven case studies

In an effort to gain a deeper understanding of those individuals who attain the heights of creativity, I recently conducted case studies of seven individuals who lived around the turn of the century (Gardner 1993b). These seven were deliberately chosen to represent a range of human intelligence: T. S. Eliot (linguistic intelligence); Albert Einstein (logical and mathematical intelligence); Pablo Picasso (spatial intelligence); Igor Stravinsky (musical intelligence); Martha Graham (bodily and kinaesthetic intelligence); Mahatma Gandhi (interpersonal intelligence); and Sigmund Freud (intrapersonal intelligence).

This study produced a number of surprising findings. Although these individuals differed (by my design) in the type of intelligence that they exhibited, they were strikingly similar in personality. All were hard-driving, extremely ambitious individuals, who sacrificed all for their work and who caused considerable damage to others close to them. They forged a Faustian bargain in which they sacrificed material or psychological comforts in order to pursue their projects. It took at least 10 years for each individual to achieve an initial breakthrough, and subsequent breakthroughs occurred also at intervals of about 10 years. (An individual who gets an early start, such as Picasso, can achieve a significant number of breakthroughs over the course of a long life.) At the time of their most significant breakthrough, they had the need of support, both cognitive support (someone who could understand the new symbol system that they were forging) and affective support (someone who could assure them that they were all right and not mad). In a way reminiscent of a mother teaching her child a new language, these creators were teaching a symbol system that they had just created to someone who has the potential to understand it, at least in part.

Two sets of findings are particularly revelant here. First of all, in contrast to what I had thought at the outset (cf., Langley et al 1987), not all creative activity can be thought of comfortably as problem-solving. Indeed, although all of my chosen creators engaged in problem-solving activities, the cohort is better thought of as having been involved in four other pursuits: (1) creation of a broad encompassing theory, such as the theory of the unconscious or the theory of relativity; (2) creation of a permanent work as an instance of a genre—the poems of Eliot, the compositions of Stravinsky, the paintings of Picasso; (3) creation of a performance that is ritualized, such as a dance by Graham; (4) creation of a performance that is 'high stake'—the confrontations and fasts-to-the-death in which Gandhi engaged. Any consideration of the relationship between early and mature accomplishments must take into account the kind of creative activity in which the individual is engaged. The fact that most 'classical' studies of creativity examine only problem-solving (and not even problem-finding) underscores the limits of those investigations.

The second group of findings concerns the relationship betwen the early pursuits and talents of these redoubtable creators and their subsequent achievement. Among the seven, only Picasso emerged as talented in his domain, painting, at an early age and continued in this domain until his death. Even though I have chosen to include Picasso as a prodigy, some critics, such as his biographer John Richardson (1991), claim that he was not prodigious, and Picasso himself belittled his own youthful work.

Consider briefly the other six. Stravinsky trained to be a lawyer and did not begin to compose seriously until he was about twenty. Only in his late twenties did he attract attention with his compositions. Gandhi was an unremarkable youth who did not get into his stride as a lawyer and adjudicator until he moved to South Africa in his early thirties. Martha Graham did not even start to dance until she was twenty and became well known at an age at which many dancers were almost ready to retire. Einstein showed an early interest in scientific matters but was an inconsistent student who did not gain entrance initially to the Zurich Polytechnic and could not find an academic job after the receipt of his doctorate. At the age of 20, it was *completely unclear* what would happen to these individuals.

Unlike the five creators mentioned so far, both Eliot and Freud were good students and seemed destined for academic careers; but, as is the case with the others, there were few early markers of their ultimate callings. Eliot pursued a doctoral degree in philosophy and made the decisive move to poetry when he was in his mid-twenties, despite the protests of his family. Freud oscillated from one professional niche to another throughout his teens, twenties, and well into his thirties. Only as he neared the age of 40 did he discover psychology, and found psychoanalysis, the domain in which he was to make his important contributions.

If, then, these creators did not begin as prodigies in a chosen domain, do any patterns of regularity emerge, at least across most of them? First, contrary to legend, most of them did not grow up under conditions of adversity. They came from homes that were intact and reasonably comfortable, bourgeois in a positive sense, yet not close to the seats of power and influence of their society. Although they were not always close to their families, the creators were encouraged to follow their own curiosity, at least until it came to the choice of a career. What characterized the households was high moral demands and the insistence on meeting standards of excellence in one's work. The areas of talent were evident from an early age but, excepting Picasso, there were no strong pressures to follow these lines.

Intriguingly, by the time they reached their twenties, all of these individuals were drawn as if by magnetic force to the major cities of Europe—London, Paris and Zurich. There, with amazing speed, they ferreted out their peers and made common cause with them to lay out a revolutionary line of thought or practice. Even though later on these individuals became increasingly private and increasingly difficult, they were characterized during early adulthood by a sense of excitement, engagement and collaboration.

Towards a model of the four relations between early and mature achievements

In the light of earlier research about human talent, and my recently completed study of seven remarkable creators, it is possible to flesh out the four relations between early and adult achievement that I introduced at the beginning.

Least problematic, as noted, is the individual whose early and adult accomplishments are unremarkable. Some of these individuals will show a strong proclivity in the early years, while others will be seen merely as more or less competent across a range of domains. In either case, however, there is a lack of the native talent, the drive and motivation, and the investment of social resources that lead to ultimate stunning achievement. The most that can be expected is routine expertise; in a sense, these individuals therefore constitute our control group.

Our second group is composed of individuals who do demonstrate unusual accomplishment in their early years—the classically gifted or prodigious children. Sometimes these individuals are scholastically talented, populating our 'gifted' and 'talented' classrooms, while others have a strong gift in a specific domain, be it dance, chess or mathematics. They will be recognized in the event of a 'coincidence of factors' (Feldman & Goldsmith 1986), namely native talent, yoked to parental support, and opportunities for accomplishment within a culturally recognized domain.

Some of this group will go on to become highly accomplished adults; we might think of them as 'effortless experts' or 'natural masters'. They are good citizens and perhaps good teachers but they do not leave a mark on the domain. Others encounter a less happy fate. As chronicled by Jeanne Bamberger (1982), they may undergo a temporary or permanent 'mid-life crisis' which leads them to stop their activity altogether. This 'disengagement from talent' (Csikszentmihalyi 1993) can occur because the society ceases to provide support, because the nature of accomplishment in the domain has changed, because the youths themselves come to have a different view of their own lives, or for other reasons and combinations of reasons.

The third pattern is the one that I encountered repeatedly in my recently completed case studies. An individual who has been given latitude to develop, in a home of high standards, comes to seek the company of others who are similarly motivated and ambitious. In no case could the future creator have chosen a domain randomly. There is no way that Eliot could have become a scientist or Einstein a painter. Rather, there is a kind of mutual adjustment.

An individual searches for a domain (science, poetry, statesmanship) and a kind of creative activity (theory building, accomplishment of a work, a ritualized performance) which is most congenial to his or her gifts and aspirations. Sometimes this moment of crystallization occurs quickly, whereas for others, as with Freud, it requires decades rather than days. In the end, however, the would-be creators find a *métier* that they can embrace passionately and pursue productively, until their powers begin to wane.

The least common, and most enigmatic case, is the one described in Apollinaire's words in my opening paragraph. Here, one begins with an almost pre-ordained match between an individual's powers and a domain that exists in his or her culture. Providing that the individuals stick to their pursuits, there is little question that they can become experts in relatively short order. If, however, the individuals wish to make creative contributions, they can no longer simply accommodate to the domain as it currently exists. Rather, they must come increasingly to challenge the domain, to avoid the easy victories, and to blend personal statement and mission to the existing languages of the domain, in the process forging a new kind of system of symbols.

Speaking of the French composer Camille Saint-Saëns, who had been an unrivalled prodigy, Hector Berlioz quipped, 'he knows everything but he lacks inexperience' (quoted in Schonberg 1969). The challenge faced by young gifted creators is clear. They must somehow distance themselves from the easiest, most ready lines of development, and instead discover areas which challenge them and the domain in which they work. This set of moves requires knowledge of oneself, a sense of will and purpose and the willingness to forego the easy victory in search of the uncertain future. Having been made by the Gods—and no less by their parents and teachers—into a prodigy, they must now make themselves into creative artists, scientists or leaders.

Here, we encounter the constructive contrast between our latter groups of masters. 'Normal gifted' individuals need not create their domains or themselves; both of these creations are taken care of by external factors. 'Normal creator's are formed as personalities by their families, but must discover their domains, their own form of creativity, and the stance that they will take toward both. 'Prodigy-turned-creators' are given their domains by their birthright, but must construct their own creative personalities.

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DISCUSSION

Atkinson: Could you make the distinction between field and domain a little more clear?

Gardner: They are quite different things. 'Domain' is simply a word which we use to describe any discipline or craft which exists in a culture in which you can lay out different levels of expertise. Any scientific discipline would be a domain, and so would chess or gymnastics, anything where there can be competition, mastery or innovation. The example I like to give is Bobby Fischer, possibly the greatest chess player in history. If he had lived in a society without chess he might well have been a nerd, because he couldn't have invented the domain. He was lucky enough to have an intelligence that matched an existing domain perfectly.

'Field' is a social construction. The field consists of people who know a lot about the domain, who are the gatekeepers—the people who give awards, who make selections, who publish your work or give you tenure. The field becomes interesting when someone invents a new domain, as Freud invented psychoanalysis. In effect, the inventor and his or her associates create the field. People often say that there's no place for women in a domain. The solution is to create a field which is composed of at least some women and which will recognize women. The domain is essentially an impersonal notion. You could abstract the structure of a domain without reference to sociology. The field, on the other hand, is a quintessential human collaborative process.

Detterman: You make a distinction between expertise and the sort of creativity shown by these seven individuals. Could you rank, or give a percentage, of how important these people were in terms of society's progress? Are these people landmarks, or milestones for a movement, or are they actually heavy contributors? Are they movers and shakers, or do they epitomize trends in history?

Gardner: I have picked the extreme in the continuum of human history, people who essentially got away with being radical without getting killed in the process. These people are anomalies in the big picture of human history. Most creativity has not been revolutionary but rather evolutionary, carried out by experts within a culture who make small, gradual changes. I want you to recognize that I'm dealing with a special kind of human behaviour which would not be permitted normally. People like those I studied are usually ignored or are got rid of. These seven happened to live in Western Europe, which in 1900, like Florence in the 15th century or Athens in the 5th century BC, was somewhere where experimentation was tolerated.

I also wanted to raise the issue of the relationship between expertise and creativity. One could assume that one would have to be an expert before becoming creative. However, it's also possible—and my assumption is that this is usually what happens—that people who are ultimately going to make the breakthroughs, or at least try to, begin the *decomposing* fairly early in life. Out of 100 children who play the piano, a small number will begin to try and change things and do things in their own distinctive way. There are many people who become great pianists who never even think about doing that; for them, the task is to be a great performer. They might be somewhat innovative in the way they perform, but that's obviously different from turning your back on the performing stage and writing in your room every night. It would be interesting to know, developmentally and biographically, whether the future expert and the future creator could be discriminated from one another early on in life, or whether it is more usual that expertise is acquired first.

Bouchard: You said *g* wouldn't explain everything. You picked seven very different people. Let me make the assertion that none of them would have accomplished what they did unless they were pretty bright. I would argue that each of these people accomplished what they did because of the special configuration of their traits. If you put Gandhi in Einstein's place and Einstein in Gandhi's place, by no stretch of the imagination could you envisage the same things happening. You like to do thought experiments, so let's put Einstein's reared-apart identical twin in India, and Gandhi's in Germany. What would you predict the outcome would be?

Gardner: All seven would probably have a fair amount of *g*, whatever it is, though it might well not have turned up in most measures. Some of them were severely anti-academic. Gandhi certainly was. Picasso was a disaster who probably wouldn't have finished elementary grade if he hadn't been given the answers! Some of them had bad scholastic experiences. You might have had to use a Jensen button-press kind of measure to find out about their psychometric '*g*'.

Bouchard: You have read their biographies. Imagine you had the opportunity to have a conversation with each of them for five or six hours, and popped in a few IQ questions here and there, and graded them at the end of the interview; what kind of IQ score do you think they would have got?

Gardner: Most of them, though not all, would have struck us as bright children, less in terms of answers to test questions, but more in terms of being energetic and curious and seeking experiences. Some of them were simply not interested in the sort of things you have to be interested in to do well scholastically.

I am impressed by the twin studies, as you know. I believe that Gandhi's and Einstein's identical twins would have searched within their culture for a niche which would allow them to realize something that was consonant not only with their own intellectual profile, but also with the kind of activities (theory construction or high-stake performances) that they liked. Some people like to tinker and solve problems, some people are more keyed in theoretically and some people like to perform. Their success depends largely on domain and field, whether there is a domain in that culture which teases out that particular configuration of talents and inclinations, and, if there is such a domain, whether the way they work in that domain is something that is recognized by the field. The fascinating thing about these seven individuals is that initially most of them did not receive a good response from the field, but their persistence was so powerful that it ultimately changed the way in which the field worked, in Einstein's and Picasso's cases quite quickly. Most of Graham's early reviews ridiculed her, and we shouldn't underestimate the fortitude it took for her to continue working.

Sternberg: One thing that has struck me about many of the talks we have heard is the need for us to specify the universe of generalization, whether we are talking about intelligence, creativity or whatever. It's difficult to know how far we can generalize from what's been found. If you leave open what the generalization is, the results may be interpreted in unfortunate ways. What I'm thinking about here is the Faustian bargain you referred to, giving one's all for the maintenance of a creative life. What are the implications of that? The people in psychology who have influenced me or have been mentors don't fit that pattern. People such as Endel Tuluing, Gordon Bower and Tex Garner have had positive effects on people around them. They've certainly been successful, being National Academy of Science members and winning APA distinguished career awards, but have had well-adjusted children and students who have gone on to make achievements. Perhaps they're not at the level of an Einstein, but the danger is that people will think that to be creative you have to sock it to the other guy to get ahead.

Gardner: That's a valid point, but I do think, with all due respect to your mentors, that they would not be recognized even by the people in this room as titanic figures in science.

Sternberg: I agree. My question is, what's the universe of generalization?

Gardner: The last thing I am ever going to be known for is being a methodologist. None the less, I feel that I have developed a method that can be used to study highly creative people. It would be possible to study people of the sort you described, who are at the second level, one below the Freud level, as well as people like Darwin, who may not have had to undertake a Faustian bargain. Just as I pay tribute to Howard Gruber, I pay tribute to Dean Simonton, who has opened up an area of study of large populations of individuals. We need to make the bridge between idiographic and nomothetic methods, to see whether, if we can find measures of traits such as sadism and masochism or perseverance or marginality, these are necessary conditions. What has struck me about these seven people is that even though I consider myself to be a hard worker (most people think I'm a workaholic), I can't hold a candle to these people. I have never known anyone like them.

Bouchard: Frank Barron, Donald MacKinnon and Harrison Gough will tell you that the highly creative people they studied were unpleasant people who burned those around them.

Detterman: Through neglect or on purpose?

Bouchard: Both. Some of them were downright mean.

Gardner: My sample is heavily weighted towards artists.

Bouchard: The creative architects and writers in their studies were artists in the more general sense of the term.

Gardner: It may be that in a science area you would find that people are not particularly hostile, but that remains to be probed systematically. It was funny to hear from Nicholas Colangelo about the inventors (p 160–174). They love people, but basically want to be left alone; if the rest of the world leaves you alone life is easy and you don't have to go out of your way to harm others.

Gruber: In this kind of discussion you have to constantly broaden the hermeneutic circle, or broaden the knowledge base on which you are making your statements. I have three inventors in mind. One of them, Edison, fits Nicholas Colangelo's picture reasonably well. Tesla, whose field of invention was pretty similar, is wildly different as a character and also in his origins. The third is Einstein, who had a few patents, although inventing wasn't his main line of activity. He was interested not only in the world of ideas but also in the world of things. It is possible to create a picture of inventors in a certain domain, in a certain geographical region or certain cultural space, but that doesn't mean that to do the same job of work in another world you would have to be the same kind of person. It's a shame that it's so complicated, but that's how it is!

There is one point on which Howard Gardner and I really agree. Other work had to be done at other levels for him to do the kind of work he reported. He couldn't have made all those comparisons and the rich and interesting schematizations if he hadn't known a lot about each of these individuals. He did some of that work himself, but all seven people have also been studied in detail by others. We need to work at the level of the detailed study of the individual, we need comparative studies of the kind that Howard Gardner reported on today, and we have to do the other kinds of work, which includes studying expertise. Instead of trying to prove which of us is right, which one of these approaches is the correct one, and which is really scientific, we would be better advised to build bridges between groups.

I want to make a final remark about the relation between expertise and creativity. There is one group of experts who don't want to be creative—artistic forgers. They can do anything that the people they're stealing from can. Sometimes they're not stealing, but serving an 'apprenticeship' to a great master, but the activity is the same, doing what somebody else has done. There is a reasonably clear distinction between expertise and creativity, and we ought to work out the details of that difference.

Gardner: Forgers can be creative in method—they just don't want to be creative in result. Also, because they are unlikely to have had a mentor, they have to train themselves, so forgery is probably not a job for someone sheep-like.

Howe: You seem to have identified a number of non-intellectual personality variables that might be crucial. These people hurt others, and they were on the whole daunting, powerful personalities. I wondered whether those factors might to some extent have entered into people's appraisal of them because of the way we now regard them. Had Freud, and Picasso too, been less bold, less confident, less outgoing, would we now see them, in comparison with another artist of the same period, as having the dominant status which we attribute to them?

Gardner: There is information about most of these people when they were young, so we are not forced into baseless speculation. Gandhi and Eliot, it's quite clear to me, were extremely confident from an early age, though you would not have thought so if you had met them. Eliot made a virtue of appearing diffident, because he was in a strange society and didn't want to appear brash and aggressive, but his letters to his brother reveal exactly how calculating he was and how he engineered things. The contempt he had for everybody else from the time he entered Harvard at the age of 18 makes it quite clear that his parents gave him that most wonderful gift of thinking he could do no wrong.

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Family influences on the development of giftedness

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Abstract. The relationship between early family environment and later creative achievement is rather ambiguous. On the one hand, a context of optimal support and stimulation seems necessary. On the other hand, the lives of some of the greatest creative geniuses contradict this notion, being full of early trauma and tragedy. On the basis of longitudinal studies of young artists and talented adolescents, as well as a retrospective study of mature creative individuals, we explore the outcomes of various family environments. It seems that the two extremes of optimal and pathological experience are both represented disproportionately in the backgrounds of creative individuals. However, creative persons whose childhood was more traumatic appear less satisfied with themselves and their work. So, although a difficult childhood might be more conducive to creative achievement, it does not seem to lead to a serene adulthood. Our study of talented teenagers showed that students who came from a 'complex' family environment that provided them with both support and stimulation were more likely to take on new challenges in their area of talent and to enjoy working on and developing their skills. Such students reported feeling happy more often than those from other family types, and were significantly happier when spending time alone or in productive work.

1993 The origins and development of high ability. Wiley, Chichester (Ciba Foundation Symposium 178) p 187–206

In this paper we summarize many years of research on gifted individuals and on the creative process. The focus is on the role of motivation in supporting the development of talent, and on how families facilitate the development of creative motivation. The conclusions are based primarily on three studies: (a) a longitudinal study of 290 artists begun in 1963 and continued to the present, which used tests, interviews, naturalistic observations and content analysis of creative work (Getzels & Csikszentmihalyi 1976); (b) a five-year (1985–1990) longitudinal study of 210 talented teenagers which used questionnaires, interviews and the experience sampling method (Csikszentmihalyi & Larson 1984, 1987, Csikszentmihalyi et al 1993); and (c) an ongoing study of 75 elderly creative individuals—scientists, artists and leading business and political figures, some of them Nobel Prize winners, who provided videotaped interviews which have not yet been fully transcribed and analysed.

Motivation and creativity

From the earliest studies of creativity, researchers have noted that despite innate talents, a person without the right motivation is unlikely to make creative contributions. Thus Cox (1926, p 187) concluded: 'High, but not the highest intelligence, combined with the greatest degree of persistence, will achieve greater eminence than the highest degree of intelligence with somewhat less persistence'. Although cognitive scientists have recently claimed that computers can achieve creative solutions by replicating normal rational problem-solving processes (Simon 1988), we have argued that because the motivation to solve as yet unformulated problems is essential to the creative process, creativity remains outside the range of what computers can simulate (Csikszentmihalyi 1988).

What kind of motivation drives people to pursue unformulated problems? Generally, creative individuals describe their work in terms of a deep enjoyment they experience when they work in their domain (Schlick 1934). Artists become fascinated by painting, musicians by music, and scientists by the pursuit of elusive relationships in Nature, and the rewards intrinsic to the activity are what accounts for the perseverance that is necessary for achieving new breakthroughs. As Thomas Kuhn (1962, p 36) noted in his book about the nature of scientific revolutions: 'The fascination [of research is that even though its outcome can be anticipated] . . . the way to achieve that outcome remains very much in doubt . . . The man who succeeds proves himself to be an expert puzzle-solver, and the challenge of the puzzle is an important part of what usually drives him on.'

Paul Adrien Maurice Dirac, who shared the Nobel Prize for Physics in 1933, described his work as follows: 'It was a game, a very interesting game one could play' (Dirac 1978, p 7). Albert Michelson, the first American to get a Nobel Prize in physics, when asked why he had spent all his life making increasingly precise measurements of the speed of light, replied: 'It was so much fun' (Chandrasekhar 1987, p 25). There seems to be no question that being intrinsically rewarded by one's work is necessary for creativity. Those who don't enjoy their work rarely drive themselves to go beyond the boundaries of what is already known (Csikszentmihalyi 1990a).

The ability to enjoy work for its own sake can be further split into two seemingly opposite personality traits. The first of these is the persistence, endurance, or 'driving absorption' (Roe 1952, Simonton 1988) that is perhaps one of the most often mentioned motivational prerequisites of creativity. One important difference between geniuses and more normal artists and scientists seems to be that the former are able to continue working in the face of failure and adversity, partly because they enjoy the day-to-day struggle and are thus less dependent on external recognition and success. The second main trait which distinguishes the creative genius is a quality variously called 'curiosity', 'openness', 'intense interest' (Mach 1896, Simonton 1988) or 'intrinsic motivation' (Amabile 1983, 1990). Although the majority of people are interested primarily in stimuli for which we are genetically programmed (such as sex), or culturally conditioned (such as money), creative persons preserve a childish, unprejudiced wonder in whatever is new and mysterious.

It seems that for a person to make creative contributions in any domain, a combination of these two complementary motivations is necessary: a great curiosity that leads to recognizing new *challenges*, and a great perseverance that leads to the development of new *skills* (Csikszentmihalyi 1990b, Rathunde 1989).

The role of the family

How does a person acquire these somewhat contradictory responses, perseverance joined with openness and wonder? It is possible that inborn neurological differences will one day explain why some people have these traits while others do not, but as yet we have almost no clues as to what these genetic factors might be. However, there is evidence that the early environment of gifted persons, especially their relationship with their families, has unique characteristics that may account in part for their unusual intrinsic motivation.

Although much has been written about how the family milieu influences the future accomplishments of children of high ability (e.g. Albert 1971, 1980, 1990, Albert & Runco 1986, Pressey 1955, McCurdy 1960, Goertzel & Goertzel 1962, Goertzel et al 1978, Bloom & Sosniak 1981, Bloom 1985, Colangelo 1988), the conclusions are far from unanimous. Colangelo & Dettman (1983, p 25) wrote, concerning 'the home environment and family environment of high-ability youngsters', that 'there is still considerable confusion in terms of what the major family influences are'; and Tannenbaum (1986, p 46) wrote 'All that can be said about children destined for greatness is that they vary widely in their relationship with parents'. Is it possible that the confusion is the result of two quite distinct and opposite trends, which seem to cancel each other out unless they are perceived as such? We shall try to distinguish these trends, and in the process bring some greater clarity to the issue of how early experience is implicated in the development of talent.

Positive outcomes of early family trauma

It has been said that there is a distinction between *creative* children—those who suffer high rates of parental loss and disruption (Albert 1971, 1980, Simonton 1987)—and *effective* children—highly able, successful, but not necessarily creative children who have more normal family relationships. This distinction is in agreement with findings reported by Getzels & Jackson (1962) in their study of highly creative and highly intelligent children.

There is also ample historical evidence to suggest that the early environment of highly creative people is often disrupted. Leonardo da Vinci was illegitimate and grew up scarcely knowing his mother. Michelangelo's father was a failure, and he had to be apprenticed in the shop of the artist Ghirlandaio at the age of 13. Several of the respondents in our current study of creative individuals lost their fathers before they reached puberty. There seems to be some justice to the saying attributed to J. P. Sartre to the effect that the best favour a father can do a son is to die early (Sartre 1964).

There are good reasons why an unusually difficult early environment should be associated with later creativity. Children growing up in atypical and adverse circumstances tend to develop feelings of marginality, which results in unconventional thinking, and, if the child has the talent and the opportunity to use it, originality. Children growing up in difficult circumstances will try to escape from the painful situation by submerging themselves in some unusual, often solitary interest. This motivation in turn leads to a full investment of psychic energy in the area of talent, often accompanied by a strong desire to succeed. As Einstein noted, science and art are the highest forms of escape from reality.

Two case studies from our current research show how one form of childhood trauma, the early loss of one's father, can be overcome by very different means. Linus Pauling, winner of Nobel Prizes for Chemistry and Peace, lost his father when he was seven years old. He had been allowed to help in the back of his father's pharmacy, grinding and mixing the various chemical substances for making prescription drugs. When he became an orphan, the other pharmacists in his town helped the son of their former colleague and let him work in their shops. Pauling remembers that, from the earliest days, he was fascinated by how two compounds, when combined, could yield an entirely different third substance. This curiosity is what steered Pauling into applying quantum mechanical principles to chemical bonds, and it remains lively even now, when he is in his nineties.

Wayne Booth, an eminent literary critic and philosopher, also lost his father very early, when he was six years old. In the Mormon church, of which he was a member, the eldest male has an almost divine status. Wayne Booth, as the eldest of his siblings, was to become the centre of the family of whom everyone expected great things. The experience left Booth with deep doubts about the faith and the culture in which he was raised. If his father had been the centre of the universe, why did he have to die? He came to feel that he had to live the life his father had been prevented from completing. In school, he idolized teachers who temporarily substituted for his loss; his first book was dedicated to 11 teachers who had been particularly influential. Although his early religious faith was transformed to a faith in learning, the early doubts continued to inform his critical intellectual approach.

It would seem, then, that creative achievements often result from the process of overcoming an early tragedy. The motivation to create, as well as original thinking, might be helped more by hardships than by positive facilitatory efforts. This conclusion is consistent with Riegel's (1973) notion of *dialectical* *development*, which postulates that psychological growth is the result of conflict rather than smooth maturation; with Maddi's (1965, 1989) concept of *hardiness*, or the tendency of creative persons to thrive on challenge; with Gardner's (1988, 1993) concept of *asynchrony*, which points to discontinuities in the development of creative individuals; and with Csikszentmihalyi & Beattie's (1979) concept of *discovered life themes*, which almost invariably start with a compelling existential problem that the subject must resolve.

Yet such early trauma often leaves even the most successful creative people with deep emotional scars. This is eloquently expressed at the end of a chapter entitled The Fatherless, in a recent book by one of our respondents, the eminent cancer biologist George Klein (1992, p 184), whose father died before he was born, and who ascribes to his orphaned childhood his 'power of initiative' as well as his 'notorious self-assurance or arrogance'.

> Father, little brother, my son, my creator, you who will never allow me to know you, come, oppress me, crush me, mold me into whatever you want—into someone I never was, never will be, if only I could tell you that . . . What would I really want to tell you? Perhaps only this: It is wonderful to live—thank you for making that possible for me. I probably would have killed you if you had lived, but I was never truly able to live while you were dead.

Positive outcomes of a normal childhood

Looking at the lives of creative writers, artists and scientists, one is almost driven to the conclusion that early trauma is a necessary condition for the full flowering of genius. Reassuringly, there are also examples of persons who were not only creative, but also seem to have had exceptionally supportive childhoods, and have lived to a serene and happy old age. One might think of Raphael among artists, J. S. Bach and Verdi among composers, and Goethe or Manzoni among great writers. In our current study one example is Manfred Eigen, winner of the 1967 Nobel Prize for Chemistry, who was the son of a cellist in the Bochum Symphony Orchestra. Eigen started playing the piano at six years of age, but although he was exceptionally good at it, he became tired of constant practice three years later. At that point his father insisted that unless Manfred was to practise seriously, he should stop playing altogether, but, in that case, that he should find another interest to which to devote himself seriously. Manfred agreed, and started a chemical laboratory in the basement; at the same time, unbeknown to his father, he kept practising the piano regularly at a friend's house. Some time later, for his father's birthday, he suggested they should play a Schubert sonata together, and played so well that his father engaged an excellent tutor for him. Now in his mid-sixties, Eigen directs one of the most exciting Max Planck institutes in Germany, where he replicates the evolution of inorganic molecules, and plays the piano at a semi-professional level.

Another typical example of a warm and stimulating childhood is that of the historian John Hope Franklin. He credits his parents with enormous influence on his intellectual and personal development. Both parents were educated, and he learned the value of study and reading from them, as well as the honesty and integrity which he feels have been strong aspects of the way he approaches his teaching, research and writing. Franklin considers his father the most disciplined man he has ever known. As a lawyer, Franklin's father spent his time studying when not busy with a client, and he often read or wrote at night, all part of a life-long learning effort. This is what John Hope Franklin has always done also. He grew up thinking this is what you are *supposed* to do. Franklin also credits his mother with great courage and intelligence. Her encouragement and expectations are well expressed by a favourite admonition to her son: 'Just do your best—even angels can't do any better than that'. The characteristics shown by Franklin during his prolific career as a teacher, writer and reinterpreter and elucidator of Afro-American history, a community for whom he was a role model, seem to follow quite clearly from the parental influence on his childhood and adolescence. His 55-year career as a university professor reflects the ability to tackle new problems and themes with the faith, discipline and persistence necessary to produce ground-breaking historical books and articles, while taking great enjoyment and pride in the teaching of thousands of students. Although the support and encouragement of his parents shines through Franklin's description of his childhood, their achievements did not come easily. For example, Franklin mentions with pride the fact that his father, a graduate of the all-black Morehouse University, came second in his state bar examination, behind a white graduate of the University of Michigan, in a time long before the civil rights movement and equal rights legislation.

In cases such as these, early childhood trauma, if present at all, was mitigated by a close relationship with supportive parents. Both Eigen and Franklin had their share of difficulties: Eigen was drafted to serve as a gunner on a Luftwaffe anti-aircraft battery at the age of 15 and did not finish secondary school; and Franklin was always painfully aware of the obstacles he had to confront as a member of a racial minority. Yet, both remember their early childhood as being both emotionally warm and intellectually stimulating.

Negative outcomes of early family trauma

Although difficulties in childhood may motivate a talented person to excel, creative lives that start from disrupted childhoods are often unhappy. In such cases the motivation to create may acquire an obsessive character. Instead of enjoying the work that leads to understanding or discovery, the genius whose early wounds have been too deep keeps searching for a cure that cannot be obtained. It is for this reason, perhaps, that Martindale (1990, p 7) attributes pessimism and melancholia to creative individuals in the arts, while S. Chandrasekhar, the recent physics Nobel Laureate, concludes his biography with the generalization that the pursuit of science rarely leads to peace and contentment (Wali 1991, p 305).

Unfortunately it is impossible to prevent tragedy from blighting the lives of many of our children. Death, illness, war, financial setbacks and irresponsible parental conduct will presumably continue. Most children exposed to adverse circumstances will break down. A few fortunate ones endowed with special talents will confront adversity and use it as a spur for exceptional accomplishment, but all too often this effort will have high emotional costs.

A model of optimal family environment

What, then, is a positive family environment like, one which will promote both creative motivation and lasting personal fulfilment? Two main dimensions are suggested by theoretical considerations and empirical results. The first is parental *stimulation*, which should result in differentiation, individuation, curiosity, interest and willingness to take on challenges. Take Manfred Eigen, for example; his father's high standards and clear expectations seem to have shaped the son's own motivation to excel. The other dimension is parental *support*, a warm emotional acceptance, which is expected to result in integration, self-confidence, inner harmony, endurance and the development of skills, so well exemplified by the case of John Hope Franklin.

To study the effects of family stimulation and support on the course of giftedness, Kevin Rathunde, a former student of the first author, developed a questionnaire based on these two dimensions. This complex family questionnaire, CFQ (see Table 1) was used to assess young people's perception of their family environment in a recently completed longitudinal study of teenagers talented in mathematics, science, music, art or athletics, who were followed from age 13 to age 17 to determine why some developed their talents while others did not (Rathunde 1989, Rathunde & Csikszentmihalyi 1991).

The sample was divided into four groups. 'Complex' families were those perceived by the children in them as being above average on both dimensions,

TABLE 1 Breakdown of categories on the complex family questionnaire

	Support		*Stimulation*	
	Harmony	*Help*	*Involvement*	*Freedom*
No. items	5	8	7	4
Reliability (α)	0.72	0.78	0.50	0.62
Example of question	Are there clear rules that keep the house running smoothly?	Do other family members modify their plans on your behalf?	Are family members proud, do they work hard and have high ideals and values?	Is it hard to find privacy at home when you need to?

stimulation and support. 'Differentiated' families were high on stimulation but low on the support dimension. 'Integrated' families were the opposite, low on stimulation but high on support. Finally 'simple' families were low on both dimensions. It was found that the children's perception of their family environment matched reasonably well their parents' perceptions, which were independently measured (Rathunde & Csikszentmihalyi 1991, Csikszentmihalyi et al 1993).

We expected that children from complex families would have the easiest time developing their talent during their school years. Being able to experience both support and stimulation, they would be the most likely to develop creative motivation—openness and curiosity on the one hand, and endurance and persistence on the other.

In fact, several suggestive findings linked family type to the development of talent. For example, when asked to report their moods eight times each day for a week when signals were sent to their electronic pagers, children from complex families reported being the happiest no matter what they were doing, followed by children from integrated, simple, and then differentiated families (see Fig. 1). Students from the four family groups were not significantly different from each other when involved in interaction and leisure, but students from

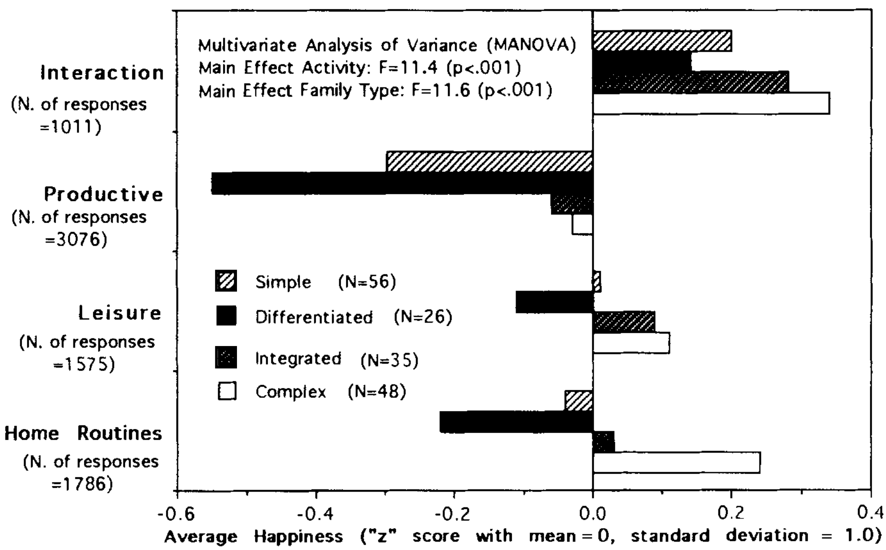

FIG. 1. Mean level of happiness during different activities, interactive, productive, leisure and routine, in a sample of talented teenagers. The sample was divided into four groups according to family type, simple, differentiated, integrated and complex, on the basis of the children's responses to the complex family questionnaire (see Table 1). The teenagers were asked to record their mood, on a scale of one to seven, eight times a day each week when signals were sent to electronic pagers they carried around.

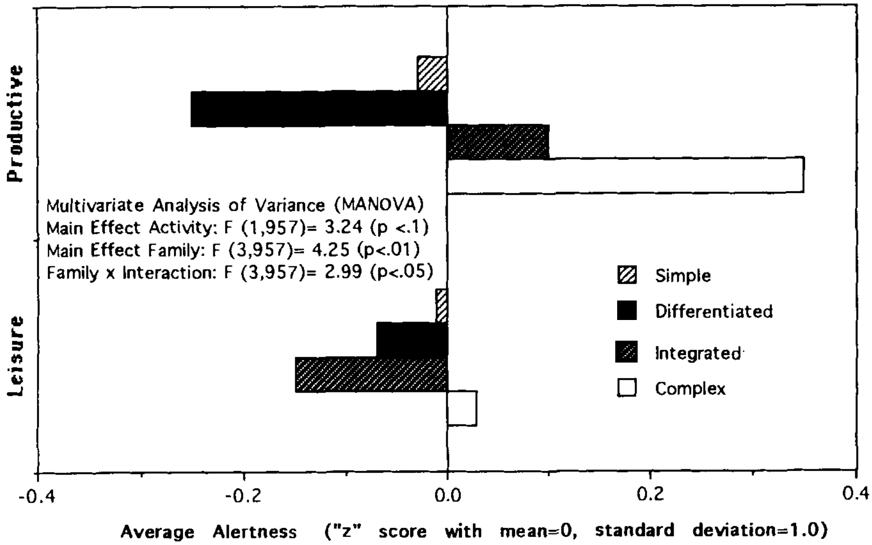

FIG. 2. Mean level of alertness of talented teenagers during productive and leisure activities at home. Teenagers were asked to rate their alertness on a scale of one to seven as in Fig. 1.

complex families were significantly happier than those from the other three groups when studying and when doing household chores. Clearly, family support and harmony make a difference to how happy talented teenagers feel, especially when involved in a basically unpleasant but necessary activity, such as studying.

A similar pattern is shown in Fig. 2. Here the question is, does family context make a difference to how alert talented children are when involved in different activities? Again, children from complex families report being significantly more alert when studying, but not when engaged in leisure activities, than children from the other three groups.

Does the difference in the quality of experience translate into greater motivation and achievement? Figure 3 shows the class ranking of children from the four family types in the year they were initially interviewed and tested with the experience sampling method and in the two following years. At each point, talented children from complex families had the highest class rank (around the 12th percentile), and their peers from simple families the lowest (around the 25th percentile).

On most measures of talent development in high school (for example, teachers' ratings of living up to one's potential, grades in talent area) the students from complex families performed significantly better than the other groups. Having both support and stimulation in the family is obviously a powerful help in realizing one's gifts.

Interviews with these talented teenagers confirm the results pointing to the effects of family background on motivation and achievement. Table 2 provides some

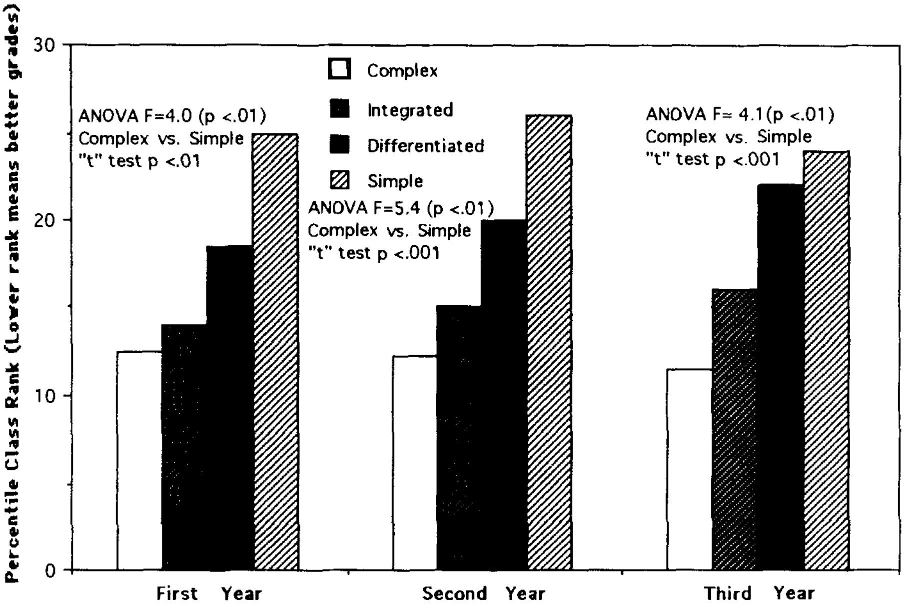

FIG. 3. Average class rank of talented teenagers according to family type in the year they were initially interviewed and tested (First Year) and in the following two years.

TABLE 2 Examples of how talented teenagers perceive their families

Committed teenagers (developed talent through high school)	*Non-committed teenagers (failed to develop talent through high school)*
'As far as grades go, they always tell me to do my best, but they are not gonna shoot me if I don't make some quota. They always encourage me that I can do better, or should always push myself to do better . . . I see my parents as happy and successful in what they are doing.' (227, male)	'They let me do what I want. I don't know if they have something they want me to be but they never say anything. I like that. I don't know if I'd be able to handle it if they wanted me to be something.' (34, female)
'I can talk to my parents about anything, and whatever I do, they say they'll never be disappointed . . . They're proud of me. They think I'm responsible and that I'll go somewhere in life.' (29, female)	'My parents believe that if you like something, then you should strive until you're very good at it . . . My parents have a certain idea of what they want my life to be and they recommend things and try to give me advice . . . your parents pressure you and you know you have to get it done.' (83, male)
'The main thing to them is academics, doing the best you can—don't have to be the best in class, but have to do as well as we can . . . my parents are gung-ho about me being anything I want to be.' (315, male)	'My dad constantly says "If you don't get good grades, how do you expect to be anything later? You always have to work hard to get what you want. Nothing comes free".' (36, female)

TABLE 3 Examples of how talented teenagers perceive their motivations

Committed teenagers (developed talent through school)	*Non-committed teenagers (failed to develop talent through high school)*
'I always wish I could be involved in more musical things, but . . . I'm happy with the level I'm at right now. It's a pretty high level and challenging.' (227, male)	'You're always taught to do well in school—that's why it's there . . . You have to go to class, you might as well learn something while you're there.' (27, female)
'I get a lot of satisfaction out of solving problems. If I could figure out something really interesting, then I'd be really happy. To solve a big problem in the universe . . . physics gives me a lot of opportunities to do that.' (53, male)	'I want to do something in the medical field, probably a doctor. I want to be rich—not too rich. A nice car and apartment. Stay single forever—no kids.' (120, female)
'History's something that's interesting that you sort of have to know . . . It's required, but I hate to think about it that way. I'd say, hey, you enjoy history.' (226, female)	'I'd like to do well in life . . . not rich or poor, upper-middle class and not have to worry about money and be able to travel and have money and nice clothes.' (410, male)

examples of how talented teenagers who do develop their talent through their school years view their families differently from those equally talented peers who fail to develop their talents. Table 3 describes some of the differences in the kinds of motivations that students in the two groups mentioned.

Generally, it can be seen that those teenagers who live up to their potential at school see their parents as having high expectations, but allowing them a great amount of freedom. Teenagers who give up developing their talent see their parents as either too intrusive, or too disinterested. In terms of motivation, the first group shows curiosity and intrinsic motivation, the second is generally more motivated by extrinsic rewards such as financial success, comfort or status.

Discussion

We mentioned at the beginning that the literature contains confusing results concerning the relationship between childhood and creativity. Some authors stress the fact that creative individuals suffered parental loss and trauma in the early years, while others describe extremely warm and supportive early family environments. It is probable that both accounts are true, and that the quality of early life and creativity are related by a U-shaped function. Highly creative individuals are likely to have had either very disrupted childhoods which they succeeded in overcoming, or very good early environments that provided stimulation and support. An average or normal childhood, on the other hand, may result in effective development, but is unlikely to lead to creative accomplishment. However, when the early childhood years involve tragedy or unusual difficulty, the creative person may be left with emotional scars that will result in an unhappy and unfulfilled adult life.

Current social trends point to the eventual obsolescence of the traditional bourgeois Western family. At present, it is claimed that only 10% of children in the USA will grow up in traditional two-parent families with father working and mother at home. By the end of the decade it is expected that half our youth will grow up in one-parent families (Csikszentmihalyi 1993). Under such conditions it is difficult to see how the support and stimulation necessary for the development of talented *and* adjusted adults will continue to be provided. It has been noted that alternatives to the family, such as the Israeli kibbutzim, appear to be detrimental to creativity. Yet, society can ill afford to lose the creative potential of our gifted children, and it would be cruel indeed if the fulfilment of that potential had to be purchased at the expense of a serene adulthood. Given the choices, it would seem wise to learn more about how a child's environment can provide the stimulation and the emotional support that are required for the cultivation of both happiness and creativity.

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DISCUSSION

Lubinski: How many subjects were in the study shown in Fig. 3?

Csikszentmihalyi: There were about 50 individuals in each of these groups, who produced about 1000 observations. Each individual responded several times. For an ANOVA we used each individual only once, but this analysis shows all the responses, and $F = 957$, because that's how often the 200 individuals divided into four groups of 50 responded.

Lubinski: Is that the appropriate degree of freedom, or should those four responses by each subject be aggregated into one?

Csikszentmihalyi: We did that too, and it came out the same way.

Hautamaki: In Finland there have been similar studies in which these four types of family support and family demand were related to each other (Hautamaki 1982). The aim was to predict school achievement and verbal reasoning and numerical skills, and also stages of Piagetian thinking. The model worked well for school achievement and for verbal, numerical and reasoning ability, but could not explain the variation of Piagetian stages. The idea was to analyse family mediation and social class differences from a Vygotskian perspective, because it was supposed that the zone of potential development is also created at home by these two factors—demand and support. This demand and support model was a more powerful predictor of success in school than social class.

Csikszentmihalyi: We found the same. These talented children were preselected, in a sense, because their families were more like those that Nicholas Colangelo described than the others in their community. Their families had fewer divorces and separations than the community in general, were of higher social class and were better educated. The children were followed for five years, but these demographic factors did not account for any of the variance; what was important was the way the family dealt with the children.

Hautamaki: The four types of demand and support relationships did exist within different social classes. The problem of continuing their educational career was greatest for the working-class children, who had to fight against their families' low demands and low support. A different type of personality is needed to make achievements in the face of low family expectations.

Fowler: Professor Csikszentmihalyi, I'm interested in your measures of stimulation. Could you give us more examples? One you mentioned, involvement, doesn't seem to suggest that there was any necessary interaction with the child. Are there other items that address the kind of learning resources and modes of adult interaction that would influence the child's development?

Csikszentmihalyi: We tried to develop items that would not be specific to one domain. Stimulation was measured by two factors. The first was 'freedom', and included items such as, is it hard to find privacy at home when you need it? The second was 'involvement', with items such as, how high are your parents' expectations of you in what you do, and, how much time do you spend doing things together with your parents?

Fowler: Does that mean doing domain-related things together?

Csikszentmihalyi: Not specifically, but the implication was how much time do the parents spend with them doing what they are good at.

Freeman: I too have found that the family nuance makes all the difference, but that chance factors also need to be accounted for in individual cases. There were a couple of boys whose fathers left home a few weeks before their university entrance exams. The mothers said this was due to jealousy of the talented child and that the fathers were doing as much as they could to make the boys fail. There are other chance factors, such as a teacher tearing up a boy's work in front of his classmates. So much seems to depend on the fortitude the children had to surmount these chance factors. Did you take chance factors into account?

Csikszentmihalyi: With young people, it's difficult to measure chance factors. I was surprised that almost all of the people of Nobel Prize-winning calibre we interviewed tried to credit chance for their achievements. This is partly humility, but there is at least circumstantial evidence that chance plays a tremendous role. For example, almost everybody in the sciences in our sample grew up in the age in which quantum mechanics moved from Europe to the USA, and one of them applied it to biology, one to chemistry and one to astronomy. Essentially, they were the first to have this new conceptual framework at their fingertips, brought from Europe by their teachers. Obviously, they had to have talent as well, because a lot of other undergraduates were exposed to these ideas at the same time, but chance did give this cohort the opportunity to apply this new perspective in a variety of fields. Chance is involved, but the interesting thing is that some people know what to do with it.

Gruber: Some clarification about the relation between intrinsic and extrinsic motivation would be helpful. There are good studies suggesting that during the creative work itself, intrinsic motivation is far more important. On the other hand, creative people, like everybody else, grow up in a world surrounded by inducements such as prizes and rewards and money and recognition. Your stress on the family as a support system is also indicative of extrinsic motivation, extrinsic to the actual work involved. The creative person has to somehow manage his or her own motivational system, in some way dealing with the complexities of intrinsic and extrinsic motivation.

Csikszentmihalyi: One of the central findings of our study is that artistically and musically talented children in general are tremendously rewarded by practice in their domain, whereas mathematically and scientifically talented children are not; their motivation drops when they are doing science and mathematics. Only those science and mathematics students who are rewarded in the early grades by mathematics and science continue to develop their talent. In other words, the scientist has to discover intrinsic rewards in his or her domain during high school, or will probably stop. For the artists and musicians, the opposite is true. They have intrinsic rewards, but if they don't discover a way in which they can make a sensible plan to use their ability in music or art in a life-long profession or career, they will drop out. By the end of high school, those who continue to develop their talents have both intrinsic and extrinsic motivation, but the scientists have to make up for the lack of intrinsic rewards.

Atkinson: The lack of intrinsic rewards for young scientists and mathematicians is in part due to the type of curriculum that was introduced after the Soviets launched sputnik. Before then, schoolchildren could be involved in practical projects such as building radios. Those scientists who made great contributions around the time of World War II often attribute their interest in the field to these early experiences. Once the USA responded to sputnik with a whole new curriculum that was abstract and theoretical, students had little intrinsic motivation to take such ideas back into their homes and environment. More practical issues should be built into the science and mathematics curricula.

Csikszentmihalyi: Our mathematically talented children enjoyed mathematics and were motivated mostly when they were working with computers. When they were reading or solving problems their motivation level was way below average.

Atkinson: After sputnik there was a dramatic reform in science and mathematics education in the USA. I don't know if it's unfortunate or not, but this was driven by scientists and mathematicians who tended to approach the matter in an abstract way, and the curriculum was abstract. This often left the teachers dumbfounded as to what to do, and it also drove out lots of students who just couldn't grasp the ideas. I'm very much in favour of going back to a curriculum in the early grades that is more focused on applications.

Stanley: You are referring to the School Mathematics Study Group (SMSG) curriculum revision in school mathematics after 1957, and perhaps also similar efforts in physics. These were abstract and seemed to hinder the average student. The top 10% may have benefited, especially if they were in tune with what the goal was. It seemed to me a strange goal, to get youngsters to think like mathematicians. Few people are ever likely to think like mathematicians, nor indeed should they. They need more practical training. Also, Physical Science Study Committee (PSSC) high school physics was alleged to have cut the number of physics students sharply for a while. Under pressure from the National Council of Teachers of Mathematics the mathematics curriculum from kindergarten through to the 12th grade appears to be becoming more abstract again. I don't know what the effect will be. Few youngsters will become pure mathematicians; even among those who score highly on SAT-Mathematical at the age of 12, very few will have all the other abilities and characteristics necessary to get a PhD in mathematics.

Atkinson: Even if I wanted to create pure mathematicians of the most abstract variety, I'm not sure I would want that type of curriculum.

Stanley: Also, we need to be sure that youths who reason exceptionally well mathematically move ahead at the right rate and don't get bored.

Gardner: I want to ask about a type of motivation which Professor Csikszentmihalyi didn't mention with respect to the older creative people. I like to encourage other people to do the kind of studies that I have been doing, so each year I ask the 50 students I teach to criticize current theories of creativity. I brain-wash them with your ideas and my ideas, and those of other theorists, and then, happily, they attack them in their papers. This year, two students attacked the notion of intrinsic motivation, claiming that the motivation for their subjects was very different. Their subjects were Spike Lee, the black film-maker, and Sister Kenny, a nurse who had an early cure for polio. Both of these students, independently, argued that their subjects were motivated by moral considerations. Because the word 'moral' makes me nervous, I told the students that I would accept that these two subjects had 'missions'. Spike Lee clearly states that his purpose is to show that blacks can make good films. Sister Kenny's explicit motivation was obviously to help society by curing a disease, but she was also motivated by the fact that as a woman she was ignored by the medical establishment. She wanted to show that a woman could make a contribution. Howie Gruber has also talked in some of his studies about the sense of mission that individuals have. Do you encounter such feelings of mission in your subjects, and, if so, is a mission more likely to be encountered in women and minorities?

Csikszentmihalyi: Most had initially extrinsic goals when they began their careers. However, I think those goals were simply the way to get involved in something. If after you have become involved you don't enjoy the process, you will probably either drop out or reach only a level of mediocrity, or at best expertise, but you won't want to do it all the time. Why do mountain climbers climb Everest? We all say they do it to get to the top, and this is how we explain things to ourselves and organize our activities, by saying that we want to get to the top. But nobody climbs a mountain to get to the top, because there are so many much easier ways to it—you could do it in a helicopter. Most climbers climb by the hardest route, because it's the climb itself that provides the motivation. The top enables you to know that you have achieved your aim.

Gardner: Are you implying that you did not find your subjects talking about a mission?

Csikszentmihalyi: Having a mission is one way in which some people first become motivated. Spike Lee wanted to prove that blacks can make good films; I would bet that eventually he got to love what he's doing.

Gardner: My student thought that when he was actually into the filming that he was on a high.

Csikszentmihalyi: That's necessary to break out of mediocrity, but the original motivation may be completely different.

Heller: Have you differentiated between self-initiated and other activities? Self-initiated activities, such as leisure activities, are more reliable and valid predictors of achievement in adulthood in vocational areas than the predictors related to the school curriculum that are usually used.

Csikszentmihalyi: You mean that if a student decides to practice in his free time, that's a better predictor than achievement in school. I would think that would be true.

Bouchard: I don't want to sound like a record stuck in a groove, but we still don't have a control group. All your correlations between family activities and outcomes in the children are completely confounded. One can't make causal inferences without doing the experiment with an adoption sample. That doesn't mean you shouldn't have done the study, but it does mean you must condition your conclusions absolutely. Bob Plomin has shown that self reports about family characteristics are themselves heritable. What you are interpreting as causal family conditions may in fact reflect the genetics of the parents.

Freeman: My similar work with control groups produced similar results (Freeman 1991), though my sample was admittedly relatively small, only 210 children.

Bouchard: Control groups don't control for genetics unless you do an adoption study. I shall give you an example, which I'm sure will make some of you laugh. My colleagues at Minnesota have done a massive adoption study, and have shown that divorce is largely genetically determined (McGue & Lykken 1992). In a population where divorce is allowed, where the phenomenon is allowed to express itself, most of the variance can be explained by genetic factors, not interactive factors, but simply additive factors. Hundreds upon hundreds of articles in the literature in the USA use divorce as an environmental variable to predict some kind of outcome, and that's a wrong inference.

Gardner: Mihaly Csikszentmihalyi's picture still holds, but he cannot talk about the origins of creativity or motivation with impunity unless he does an adoption study. Heritability was probably not something in which he was particularly interested. It is only important if he wants to tell us how we should raise children differently.

Bouchard: The implication from his results is that certain kinds of families have certain kinds of outcomes on children. I'm saying you can't *know* that unless you do an adoption study. You could do the same study with adoptees, with the children reporting on the behaviour of their adoptive parents. Take Fig. 2, for example. There, one could argue that the common underlying factor in the 'differentiated' group is a tendency to depression in the parents and in the child.

Csikszentmihalyi: Why wouldn't they also be more depressed when they are interacting with friends?

Bouchard: They would be more depressed when they were being pushed, when they were in a context that brought it out. Neuroticism and depression both tend to come out under conditions of stress. The productive setting will initiate a set of responses for which the individual is predisposed.

Csikszentmihalyi: Everybody is sadder in productive activities in Fig. 1 than in any other condition.

Bouchard: Sadness is specific to a family that's differentiated, a family that doesn't provide support, that probably has characteristics of depression. This may not be the explanation, but it's a plausible genetic alternative that you need to test.

Atkinson: How would doing the study with adoptees answer your question? There would be all sorts of confounding variables there as well. Perhaps we are at a point where the questions are not answerable.

Bouchard: I would do the adoption study and then I would look at these patterns with respect to there being dependent variables in the twin study. If I found no relationship with respect to these variables in an adoption study, and I showed the effects were heritable in a twin study, I would say Mihaly Csikszentmihalyi's data must be interpreted genetically.

Csikszentmihalyi: What you are saying may explain the fact that these family environmental variables are of genetic origin, but are you also saying that the children's response is irrelevant to what they experience in different types of family contexts?

Bouchard: That's what I'm saying. You would see the same characteristics in children without the family characteristics.

Csikszentmihalyi: Do you think that even if the 'differentiated' children were adopted by a 'complex' family that they would be unhappy when engaged in productive activities?

Bouchard: That's a possibility. In my twin studies, the twins are largely adopted. In the adoptees, there's no correlation between the socio-economic status of the adoptive families and the children's IQs. In biological families these correlations are about 0.33. Those correlations are constantly interpreted as environmental. The claim is that the families' higher socio-economic status causes them to have brighter children. That's not the case—it's three-quarters genetic.

Lubinski: If there are confounding variables, we can make them a parameter and measure them. For example, some identical twins reared apart have some contact. Some live together for two or three months with a relative. Some live with each other for a year, others for two years. Independent raters could rate similarity to see if that moderates heritability estimates. You can refine the experiment even when there are confounds.

It isn't necessary to do elaborate twin studies of identical and non-identical twins reared together and apart to assess genetic effects. You can do adoption studies. That needs to be stressed.

Plomin: Family studies are useful too, as long as we realize that these are *familial* associations, not necessarily environmental ones. As Howard Gardner remarked, problems arise if you take the next step and dictate what parents ought to do with their children, which would imply that you have interpreted the results as environmental results.

I'm surprised that there haven't been behavioural genetic studies of what is now a common family type, the broken and mended family. Many families now contain half-siblings, whose genetic relatedness is 0.25. Studies of these families are not as good as a newborn adoption study, but their great value is numbers—there are so many of such families. The confounds—such as how long the children have been with the 'parents'—are all empirical and actually add to the design because you can ask whether they matter. In many family studies, researchers probably don't even know if the children are genetically related to the parents or not!

Atkinson: The constraints of doing such elaborate studies are heavy, but the new developments in communications open up huge possibilities. You might never even know who your subjects are; you could contact them and ask questions over the telephone and the response could be fed back in by a voice-analyser.

Bouchard: These studies are complicated, but they can be done. Some of the designs have been outlined. I think psychologists are the best scientists in the social sciences. We know how to create a control group, and how to analyse data, but we don't have access to the resources. If a physicist came up with an experiment for which he knew all the design parameters, it would be a 10 million dollar study. Mihaly Csikszentmihalyi's study is a tremendous study, and I know how much work went into it; because under current circumstances we don't have the funding that is necessary to do the right study, we don't do the right study, even though we do know how to.

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Accelerating language acquisition

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Abstract. How much can the development of language and other skills be accelerated in the general population? High correlations between early verbal and mental competencies and parent and teacher language socialization practices suggest enormous potential for widespread improvement. Here we report follow-up research in progress in studies of late adolescent children from diverse ethnic and educational backgrounds who participated in a language enrichment programme during infancy in the home or day-care. In 39 of 44 home-stimulated children located to date (nearly all from college-educated families) 62–93% were: in gifted or advanced programmes, obtaining high grades, avid readers and skilled in writing (over half read before school and wrote creative material independently) and generally highly skilled in verbal, mathematical and other academic domains. They also excelled socially and in sports, and showed intellectual independence. Additional subjects and data (on competence, later experiences and Scholastic Aptitude Test [SAT] scores) are currently being collected. Preliminary data analyses suggest that although early language enrichment can in the short term easily increase competence in all groups well beyond norms generated by current socialization practices, long-term outcomes are a complex function of developmental dynamics between the early, complex, foundation of high skills and motivation for learning, and the interaction with facilitative parental resources.

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Can the development of language be accelerated in children? If it can, by how much, under what circumstances, in what populations, at what ages, for how long, and with what effects on other skills? What constraints do biological processes place on acceleration? Does acceleration necessarily imply some form of pressure, pushing children through some form of external stimulation to learn and develop beyond their 'natural' maturational capacities? And, why single out language in the first place? Does it enjoy special properties not contained in other mental abilities and skills, such as problem solving and other forms of cognitive processing of ideas about the world that are processed in other ways as well as through language?

A review of research on the role of early language stimulation in development has revealed the high potential of children to respond to heightened early stimulation in language development, and also that current developmental test norms may grossly underestimate children's biological potential to acquire language and other cognitive competencies in complex forms (Fowler et al 1994). Firstly, young children are highly responsive to language stimulation in various components of language, ranging from phonological inputs (Ervin & Miller 1963), through vocabulary (Hamilton 1977, Strayer 1930) to syntactical complexity (Cazden 1972, Nelson 1977). Secondly, both early verbal and general cognitive competencies are highly correlated with the quality of language stimulation observed in current cultural practices in both the home and day-care. This quality varies enormously in day-care centres (McCartney 1984) and even among highly educated families (Hart & Risley 1992, Huttenlocher et al 1991). Thirdly, many early intervention studies, in which language stimulation was a major component, have regularly produced substantial language and cognitive gains in children from poor communities over norms and controls. The fact that gains are largely lost after the termination of the programme (Lazar & Darlington 1982, Consortium for Longitudinal Studies 1983) simply suggests that a good early foundation cannot inoculate children against later debilitating circumstances. There is also a great deal of information available from biographical material, and many case studies implicate early language stimulation as a major ingredient in the development of great intellectual achievers, as discussed at length elsewhere (Fowler 1981, 1983, 1986, 1990a). Exceptional attention during infancy, centring on verbal communication and early reading, has been the hallmark of the early experiences of the historically highly talented.

Thus it seems inescapable that language development can easily be accelerated, at least in a child's early years. It also appears that the main constraint on the development of competence is the quality of current socialization practices, rather than any biological limitation. The problem appears to be less one of a need for 'acceleration', in the sense of pressuring children to excel beyond their 'natural' capacities, as the concept of acceleration is often interpreted by its critics (Howe 1990), than one of arrangng circumstances so as to optimize learning and development.

Our studies on early language stimulation

In the early 1970s, impressed by the apparent potency of the language component in a research-designed day-care project (Fowler 1972), we began a series of early educational projects involving guiding parents, in which language stimulation was a major if not always the exclusive focus. The core process, first presented to parents in demonstrations and a guide (Fowler 1974) and recently described in a book (Fowler 1990b), was cognitively oriented language labelling activities conducted by parents through social interaction in play and daily infant-care routines. The approach thus combined both the referential and social strategies which have been identified as alternative courses of development among different children (Nelson 1973). First-born infants were usually selected, to optimize parental motivation and child-rearing circumstances.

After successful pilot studies with 15 infants (Fowler & Swenson 1979), Ogston (1983) and Swenson (1983) undertook research projects using the same method of guiding parents in language stimulation over periods of 6–12 months with randomly selected experimental and control groups. Swenson investigated the effect of the age of starting (three versus seven months), whereas Ogston compared the effects of intensive language stimulation with those of gross motor stimulation in an exercise programme (Levy 1973), both groups starting at about three months of age. As will be seen, however, language turned out to be a serendipitous component of the motor stimulation as well.

Several types of developmental measures were used, ranging from standardized mental tests, one of which provided a multi-competence profile including language (Griffiths 1970), to language assessment scales (Bzoch & League 1970), tape recordings and daily parental records of the infant's progress in sound, word and sentence acquisitions. Follow-up measures (at age 24–60 months) consisted of interviews with parents and the subject. Data were pooled for analysis across projects.

Early development

In both the pilot study and in Ogston's and Swenson's studies, every child given language stimulation gained substantially in comparison with norms, and the rates of acceleration increased with development. Stimulated children were 2–6 months ahead of norms in producing their first words, and 4–11 months ahead of norms in their first use of phrases. In contrast, in Swenson's control group, parents of only two of the six children reported them using any phrases as early as 16–18 months (at post-testing, i.e., immediately after the termination of the programme). In Ogston's groups, mean levels of language attained (number of phrases [a] and percentage using 7–10 different parts of speech [b] at follow-up [from both parental records and audiotaping]) were highest for the language-stimulated group ($\bar{x}$[a] = 4.1, $\bar{x}$[b] = 67), next highest in the motor-stimulated group ($\bar{x}$[a] = 3.1, $\bar{x}$[b] = 17) and lowest in the controls ($\bar{x}$[a] = 1.3, $\bar{x}$[b] = 0).

Mean Griffiths' quotient scores in language (LQ) and IQ (Griffiths GQ) did not favour the group subjected to language stimulation as consistently, and the differences were significant less often, because these mental tests do not provide good assessments of the language processes summarized above. Mean Griffiths' score differences at programme termination were significant in Swenson's study but not in Ogston's. Mean differences in language scores favoured the language groups over controls on REEL scales (Bzoch & League 1970) in Ogston's study, however.

As expected, Ogston's motor-stimulated group surpassed all groups in mean motor score gains, but, unexpectedly, they gained enormously in language as well, reaching a mean LQ of 150 (compared with 135 in the language-stimulated group and 133 in controls) at post-testing (at termination of the programme). It turned out that parents had been using focused language extensively when guiding the exercises.

Short-term follow-up assessments of children aged 24–60 months confirmed the high levels of language competence attained in all language-stimulated groups. Mean lengths of utterance at 24 and 42 months in Swenson's stimulated group and the three children in the pilot study were 1.4–2.8 morphemes longer than those for equivalent socio-economically middle-class samples of Miller & Chapman (1981). All three of Ogston's groups—including controls—had by 30 months attained mean LQs of about 150. LQ and IQ scores ranged from 124 to 181 in Ogston's and case study children assessed at 42 and 60 months.

It seems that early language enrichment can promote high language and cognitive competencies in children. A strong complex foundation of competencies was established in every stimulated child, and this advanced system of skills was maintained throughout pre-school years. The unexpected advance shown by Ogston's control group at the follow-up stage may have resulted from control parents having increased language stimulation after the post-programme testing stage, using the programme guidance (including a written guide) supplied to control parents at this point.

Long-term follow-up

If excellence in language can be readily established in the early years, even when enrichment begins later and with less professional guidance, as in Ogston's controls, does this strong foundation hold any advantages for later development? Table 1 shows preliminary follow-up data derived from interviews with family members on 39 of 44 children stimulated at an early age followed up between the ages of 13 and 18 years. Note that Ogston's controls are now included as a stimulated group, because of evident parental intensification of language stimulation at 16 months. No data are yet available on Swenson's controls.

As evident in Table 1, 24 of the 39 children (62%) are in special programmes, and 30–32 of them (77–82%) (two now in university) have consistently obtained A and B grades in high school, are highly skilled and generally avid readers, or have competent writing skills. Over half (22, 56%) learned to read with some fluency during their pre-school years (before the age of six) and the same proportion engage in some form of creative writing (stories, poetry or scripts).

The ease with which many (33, 85%) learn second (and in several cases third and fourth) languages is striking. Even given Canadian practice of French immersion, their language-learning skills are outstanding, as are their verbal memories. Especially interesting is the high proportion (36, 92%) who

ompetence patterns (number of children[a] rated highly in different categories) at follow-up assessment among childr articipated in early language stimulation programmes

	Swenson (1983) study			Ogston (1983) study				Case studies[c]
	Young	*Old*	*Total*	*Language*	*Motor*	*Control*[b]	*Total*	
ng e (months)	2–4	6–8	–	2–5	3	16	–	3–8
cts followed l no.)	6 (6)	6 (6)	12 (12)	5 (6)	12 (12)	5 (6)	22 (24)	5 (8)
gramme[d]	6	4	10	3	6	2	11	3
s	6	5	11	5	10	2	17	4
tly motivated	6	6	12	5	12	3	20	4
	6	6	12	5	11	3	19	4
chool	3	4	7	2	9	1	12	3
ll	5	6	11	5	11	1	17	4
eatively	4	6	10	1	8	1	10	2
guage	4	6	10	5	10	4	19	4
	2	4	6	2	4	1	7	3
cial science	3	0	3	3	3	1	7	5
	6	5	11	5	5	2	12	3
	6	5	11	2	6	0	8	3
	3	3	6	3	6	1	10	3
	2	4	6	3	4	1	8	0
	0	2	2	0	4	0	4	0
	5	5	10	4	10	1	15	1
	6	6	12	4	12	5	21	5
	6	5	11	5	9	1	15	5
s	5	6	11	5	8	2	15	5
	2	5	7	4	9	2	15	5

e largely from at least partly college-educated families; a few with one or both parents with high school education or less ar
gston's original control group whose parents were guided on early language stimulation at project termination.
e subjects from the first pilot study, four from student seminar projects and one additional case study (bilingual) of Swe
ses (18), highly academic schools (2) or advanced in grade (4).

demonstrate high motivation for intellectual activity in such activities as reading, writing, mathematics and science projects, computers, drama and debating. The relatively high proportion skilled in acting (16, 41%), given this domain's strong verbal and memory components, is not surprising. Many also display advanced skills in mathematics (26, 67%) and science (22, 56%), underscoring how skill in the basic language code seems to transfer easily to mathematics and other abstract domains of activity, as earlier biographical studies have shown (Fowler 1983, 1986). One girl scored in the 97th percentile on the Scholastic Aptitude Tests (SATs) in grade 7 (aged 13) and was placed on the Johns Hopkins University Mailing list. The showing in the verbally loaded areas of social science and history (15, 38%) is relatively low, partly because our information is still incomplete.

Most students also have a diverse range of interests, encompassing drama (16), music (19) and the visual arts (14), and 26 (67%) are strongly involved in sports of all kinds, both team and individual. Note that these figures (Table 1) include only those who are definitely skilled in the areas in question. Equally important is the apparent psychological balance in their development; 31 (80%) are skilled in relations with both peers and adults and 27 (69%) have demonstrated leadership skills. Nearly all enjoy good health, with only occasional illnesses. Three individuals have experienced learning disabilities, but one of these is in gifted classes and two are skilled in writing (one in writing stories). One student who abused drugs (now recovered) nevertheless writes poetry.

Across the different studies, what stands out is the especially high proportion of high ability and high-achieving students in the Swenson samples—all of whom have been located. Almost all are in special programmes, have excellent grades, are excellent readers, are independently motivated and have good writing skills, 10 of them writing creative material independently. They are consistently highly skilled in learning second languages and in mathematics, science, sports and social relations.

Although a smaller proportion of Ogston's group and the case study group (40–60%) are enrolled in special programmes or are highly skilled in mathematics and science (36–60%), high ratings in the critical verbal domains are not far below those in the Swenson groups. Percentages average around 80–90 for Ogston's and the case study groups in grades and skills in reading, writing and learning second languages, and in motivational independence. They are less diversified in the arts than Swenson's subjects, but generally skilled in social relations and in sports.

It is evident that Ogston's original control group, whose stimulation began 16 months later and whose guidance continued for a shorter time, were less often highly rated than the 'language' and 'motor' groups in almost every area. From enrolment in special programmes, grades and motivation, to verbal, mathematical and science skills, the arts, social skills and even sports, only 10–60% of this group were highly rated in comparison with percentages of 40 to over 90 in the other groups. Only in ease of acquiring languages do they match the others. The combined case study groups were comparable to Ogston's 'language' and 'motor' groups, however, except in sports where only one child was skilled.

Discussion

In evaluating these promising findings, we must proceed with considerable caution. Samples are small, data are incomplete, and we shall have no true controls until Swenson gains access to the files which will enable her to trace her controls. For now, we must rely on comparisons with norms and between expected and actual developmental outcomes.

There is little difficulty in claiming some validity for the positive effects of language enrichment on early development. Almost every infant greatly surpassed norms for language development during the programme. Moreover, their advanced competencies appeared to continue over much of the pre-school period beween 30 and 60 months, when both language and general IQ levels consistently exceeded levels reported for samples of equivalent socio-economic class. This includes Ogston's original control group whose parents were offered limited guidance in language stimulation when the children were 16 months. The early gains in the original stimulated groups not only surpassed norms but also exceeded those of both Swenson's and Ogston's control groups up to termination of the programme at 16–18 months of age.

How valid would it be to claim that a portion of the outstanding abilities and intellectual achievements in late adolescence could be attributed to 6–12 months of early enrichment in infancy? Of those subjects located, 62% were in special programmes. In the Ontario school systems, into which these students were enrolled, entry to gifted classes requires a WISC (Wechsler intelligence scale for children) IQ score of at least 130 on both the total scale and one component (verbal or performance). (The IQ criterion for entry as early as first grade is 140.) These are high requirements: 130 IQ falls at the 98th percentile and 140 IQ at the 99.6th percentile.

However, we must also ask what percentage of children from families with a largely college level educational background would be expected to attain these levels. In a study cited by Humphreys (1985) from Project Talent on the relationship between intelligence and socio-economic status (SES), of a sample of more than 40 000 ninth grade boys, 28.63% were rated as SES level 5, and only 4.8% of these (i.e., 1.36% of the total sample of 40 000) scored at intelligence level 9, the highest level. Level 5 SES, from which the highest proportions of high IQ students are drawn, is probably the category into which the mainly professional and semi-professional families in our studies would fall. We would thus expect only about 4.8% of our sample to be at this level of intelligence, if the above results can be generalized to both sexes, all high school grades, current conditions (which Humphreys indicates is reasonable) and the Canadian population. In any case, our figure would not be expected to differ by more than a few percentage points. The intelligence measure used in the study cited by Humphreys (1985) was a composite of tests of reading comprehension, arithmetical reasoning and abstract reasoning, considered to correlate highly with the total Wechsler IQ.

The proportion of our total sample, 62%, enrolled and performing at high levels in many academic domains in special programmes, which may be considered as evidence of high ability, is far greater than the 4.8% one would expect in students from their familial background. Another indication of our samples' high ability is that 56% read fluently during pre-school years, in comparison with the rate of less than 1% of early readers reported in a study of over 5000 first grade children by Durkin (1966).

If, as seems clear, the high levels of language and cognitive competencies appearing in the later development of the children who took part in our early language enrichment programmes greatly exceeds levels expected for this population, what role, if any, has early enrichment played in their total, especially their later, development? Because we have not yet collected systematic data on the intervening developmental histories of these children, we can only offer some speculative answers and a suggested model of how they may have developed. It is noteworthy, however, that quite a few parents have commented that the early enrichment programme contributed much to their child's development.

The dynamics of development tentatively identified in our studies appear to conform to a model of development of giftedness earlier identified by Fowler (1981) in an analysis of the pattern of development evident in a series of case studies on children with an IQ above 130 reported by Terman (1919). In both Terman's cases and ours, early verbal stimulation was associated with intelligence, though in his cases the stimulation was a matter of chance practices by parents, whereas in ours it was planned. These practices during infancy generated high verbal and related cognitive competencies that include, on the one hand, high curiosity, motivation and advanced skills which facilitate further learning in the child, and, on the other, heightened parental responsiveness that in many cases encouraged early reading skills in the child or ease and keen interest in learning to read on entering school. This early established interactive combination of the child's self-motivation for learning with the parents (and sometimes teachers) acting as facilitative resource persons and mentors continues throughout the school years, the child being well armed with verbal, reading and reasoning skills that provide a strong basis for cognitive autonomy in learning.

The high independent motivation for cognitive learning in 36 (92%) of our high school students supports this interpretation in our own studies. This intense motivation, combined with diversity of parent and teacher resources and the generative powers of language, open opportunities to many alternative pathways to cognitive competence. The high proportion of high-achieving students in mathematics and science in our studies illustrates this possibility, and is in agreement with the evidence for the role of early intensive language stimulation in historically eminent mathematicians (Fowler 1986) and in modern mathematicians (Bloom 1985). The wide diversity of superior competencies, high motivation and productivity in other areas—from creative writing to drama, music and even the visual arts—to which the early generated motivational-skill-parent resource dynamics contribute further illustrates this developmental pattern. Even gross motor skills are well represented in our subjects, by the 26 (67%) excelling in sports of all kinds, though Ogston's early motor exercise programme contributed more than its share in dance: not only did four students from this group excel in dance, but also a total of nine (75%) in this group had strong interests in dance.

Not by any means the least important of the adolescent outcomes are the well-developed social skills in 79% of our students: the diversity of high verbal and cognitive competencies seems to facilitate development in the social arena also, as past surveys have generally shown (Janos & Robinson 1985), in spite of the special difficulties the extremely gifted face. The combination of cognitive–referential use of language in the early stimulation with social interactive play is considered to be a major factor in initiating the developmental course that will lead to these balanced outcomes of high verbal–cognitive and social competencies.

From the evidence collected in our studies so far, it would appear that children's potentials for developing competence in language and many other spheres are indeed greatly unfilled, at least in college-educated families. Our studies also suggest that early enrichment may be a key agent in launching a developmental process that greatly increases the possibilities of a child realizing his or her potential. Early language stimulation, particularly when oriented in cognitive and socially interactive ways, may play a vital mediating role in advancing the development of many forms of competence.

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DISCUSSION

Sloboda: You measured the degree of performance above norm at the end of the intervention. Did you also check whether the children were at norm at the beginning of the intervention?

Fowler: Yes. Some were ahead, and some were below norm at the beginning. Experimental–control differences on a variety of language measures and some IQ means were significant at post-testing, after controlling for pre-test covariances.

Atkinson: The sort of intervention that you were doing, three or four minutes of talking to the children three or four times a day, seems to me what one might find in a fairly normal home environment.

Fowler: It actually isn't normal. That's the myth about how well-educated parents rear their children. Huttenlocher et al (1991) showed there is enormous variation in the amount of time and attention such parents give to language development. The amount of time the parents spend using language with their children differs 10-fold between the extremes, and the vocabulary gains in children with the so-called good or competent parents are 10 times higher than the gains of children of the least verbal parents. One of our researchers visited the homes once a week, and would guide the parents, through demonstrations, on how to interact productively with babies to stimulate language. Quantity of intervention does make a difference, but it's less important than the quality, the *kind* of interaction. Ogston's (1983) assessments have shown that the children who develop most well are those whose parents interacted with them best as babies. The best way is to take turns. The parent labels an object when the baby's eye focuses on it. When the baby reaches for a cup, the parent says 'this is a cup'. Many parents use language in the abstract, and do not tune the language into the physical reality of the baby's world. This is very important.

Stanley: 'Head Start', a pre-school compensatory education programme in the USA, has been reported to be improving school and life adjustment of the children participating in it, but not their intellect *per se*. Large amounts of money have been spent on this programme, and the President is committed to allocating even more. I am concerned because there appear to be no 'blind' studies of the programme's effectiveness. They are difficult to do. Many investigators who report benefits are those who gain by reporting good results because they need continued governmental or private funding for their programme. I wonder whether this is really where we should put increasingly large amounts of scarce resources.

Atkinson: What is your view of the research on early childhood intervention and Head Start programmes?

Stanley: I haven't done a systematic study of this in recent years (Stanley 1972, 1973), but I have scanned *Psychological Abstracts* to get a feel for recent research. This is an extremely complex, politically sensitive area. Between 1980 and 1992 there were 261 abstracts involving the subject 'head start', almost all dealing with some aspect of Head Start. Strong advocates include David P. Weikart, long-term head of the Perry Preschool Project in Michigan (see Weikart 1972, 1989) and Edward Zigler of York University (e.g., Hale et al 1990). There is much controversy in the literature on Head Start (Zigler 1975, Bentler & Woodward 1978, Cicirelli 1984, Bereiter 1986, Gamble & Zigler 1989, Schweinhart & Weikart 1991).

My impression is that the research base is not yet firm enough or the goals well enough defined to justify adding billions of dollars to the current Head Start funding. The original largely compensatory educational nature of the programme has given way to presumed social and welfare benefits only tangential to facilitating learning of subject matter in schools. Rather quickly, Head Start (which began in 1965) was found not to raise IQ except temporarily nor to increase educational achievement enough to justify its cost (e.g., Bereiter 1972, Beilin 1972, Karnes 1973).

Fowler: 'Head Start' is a generic term for all early intervention, which includes a variety of pre-school programmes designed to give poor children a head start. There was a lot of research on it. A consortium of investigators did a follow-up evaluation of the best controlled blind studies. They found stable functional gains, such as the children staying at grade and not being put into special classes, but not in terms of IQ scores or test scores.

Stanley: My point is that so much money is going into this area that it's crucial that careful, independent studies be done.

Fowler: The main point we should take from those early intervention studies is that an early start is not a panacea. You cannot take kids from poor families, help them for a year or so then throw them back to their original environment with no support systems in place. Mihaly Csikszentmihalyi's work shows that family support is important. This wasn't generally available to these children. They are poor kids from difficult environments. All you can show is that an early start will not work without later follow through. In the studies I have been talking about there has been continued family support and stimulation throughout the child's development.

Gardner: You suggested earlier that SAT scores are lowered by students being taught in French immersion classes (p 151). How does this Canadian French immersion system work?

Fowler: The classes are three-quarters or seven-eights French. My daughter's mathematics was even taught in French.

Gardner: So it's almost like going to a school that teaches in a language that is different from your mother tongue. It would be interesting to see whether the scores improved if you gave children the French translation of the test.

Dudai: Is there any information on the development of language ability and verbal reasoning in children without a mother tongue, children born to mute parents?

Hautamaki: The family will communicate by signing.

Fowler: The norms for language development for signing families are more advanced than ordinary speaking families, but this is a selected population; because their parents are mute the children get special attention so they're more involved. The advance might be because of this.

Dudai: The attention in an enrichment programme would have to be not a linguistic attention, but a communicative attention. Is it the case that any attention will do?

Fowler: You could call signing a linguistic form.

Hautamaki: In a recent unpublished pilot project in Finland, children with Down's syndrome have been taught sign language from the age of four months for one or two years. The children seem to have been able to reach the normal level of development. They have real difficulties in speaking but they can communicate and they learn gross motor skills, cognitive skills and social coping skills better than children with Down's syndrome in the control group.

Fowler: My programme is a cognitively oriented, socially interactive communication programme which uses language as a tool for communicating as well as representing concepts about the world.

Dudai: Must it be human communication? Would interactive communication with a computer or something mechanical do as well?

Fowler: Perhaps a young child could be induced to interact with a talking computer, but the representation could only be a moving visual image. This method would lose the perceptual motor and concrete referential basis of activity, which is almost essential, I believe, to infant learning of both language and spatial concepts.

Sternberg: The results of French immersion and what Howard Gardner was talking about point out the need to be specific and clear as to what outcomes you value in terms of identification, teaching and assessment. If the immersion course were in Serbo-Croatian, a language which presumably has almost no value in this country, at least for most people, and then gave the SAT in that language and selected for college or graduate school on the basis of the Serbo-Croatian SAT, no one would be interested. Yet, many of us can see value in French or Spanish immersion because they are useful languages for us. My point is that we really need to clarify what are the outcomes we value. Do we care what the language is? That's one of the things we are trying to do in our summer programme, identifying children with analytical, synthetic and practical abilities. However you identify, if you don't clear up these value issues in advance, you end up with ambiguity about what kinds of results matter to you.

Fowler: There are lots of issues, and they're not easy to sort out in a programme. My daughter became a creative writer, but she often consulted me about certain points of English grammar. At school, her writing skills in French were better than her English writing skills. Some of the children in our project write creatively in French as well as in English. There is a general problem. How can you develop high competence in both languages? That apparently hasn't been thought through politically in Canada.

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Can we create gifted people?

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Abstract. Only in the light of specific theoretical frameworks for the development of superior performance can we productively ask to what extent that performance is due to controllable external factors and thus could potentially be engineered or 'created'. The popular view of talent acknowledges that instruction and practice are necessary but not sufficient for the attainment of élite performance. With extensive practice individuals are assumed to achieve all possible modification through learning, so that the ultimate level of performance is a function of the components that cannot be modified and are thus presumably innate. However, recent research shows that improvements in performance are possible even after extensive experience in a domain, and that performance at an international level requires over ten years of intense preparation. Furthermore, research has failed to specify and measure talent factors that predict performance. An alternative framework has been proposed on the basis of the amount of deliberate activities aimed at improving performance. The amount of deliberate practice accumulated during many years of preparation is found to be related closely to performance, even at the highest levels. This framework accounts for expert performance in terms of acquired characteristics and identifies new and different constraints on its attainment.

1993 The origins and development of high ability. Wiley, Chichester (Ciba Foundation Symposium 178) p 222–249

In nearly all human endeavours there appear to be some people who perform at a higher level than others, people who for some reason stand out from the crowd. At different points in history and in different activities, such individuals have been labelled exceptional, superior, gifted, talented, specialist, expert, or even lucky. Only in the light of specific theoretical frameworks for the development of superior performance can we productively ask to what extent that performance is due to controllable external factors and thus could potentially be engineered or 'created'.

Throughout history, attributions of exceptional performance and achievements as the reflection of acquired skill have been contrasted with unique endowments of eminent individuals. The belief that very high levels of performance can be attained through deliberate efforts was proposed by Hesiod as early as 700 BC (in Lattimore 1959, p 45).

> Inferiority can be got in droves, easily: the road is smooth, and she lives very near. But in front of Superiority the immortal gods set sweat; it is a long and steep path to her, and rough at first. But when one reaches the top, then it is easy, for all the difficulty.

However, opportunities to pursue excellence in freely selected domains were severely restricted at this time. During the medieval age it was believed that God had a plan for each individual corresponding to a vocation or occupation consistent with a society of fixed social classes. After the French revolution, all individuals were considered to be created as equals, and thus to have the same opportunities for success in any selected domain.

The character ethic movement

An early account of observed differences in performance that did not assume innate differences in ability was offered by the character ethic movement. According to this movement, which drew on the heritage of Benjamin Franklin and Cotton Mather, the major dictum for success, not only in business, was that 'industry, honesty, perseverance, sticking to one thing invariably leads to success in any reputable calling' (Huber 1987, p 95). The mainstream of this movement rejected the influence of chance, contacts with influential people, environment and heredity, and even suggested that being born poor and having to work hard during childhood was an advantage. The character ethic movement offers an explanation of success and superior performance in terms of self-discipline (character) and full dedication to a goal. This emphasis on the individual was consistent with the demands of industrialization in the USA. Self-discipline and self-education implies that the individuals themselves create their success—the emergence of the 'self-made man'. Empirical evidence for their claims is primarily anecdotal and referring to specific successful individuals, such as Thomas Edison. More systematic analyses have found little or no evidence for the myth of rags to riches (Wyllie 1954).

Sir Francis Galton was the first scientist to investigate empirically the possibility that excellence in diverse fields and domains has a common set of causes. On the basis of an analysis of eminent men in a wide range of domains and their relatives, Galton (1869) argued that three factors had to be present, namely, innate ability and capacity, zeal and eagerness to work, and 'an adequate power of doing a great deal of very laborious work' (p 37). The last two factors were essentially in agreement with the character ethic movement's emphasis on effort and motivation, so the primary focus of later investigators has been to show the necessity and even sufficiency of innate abilities and capacities for élite performance. Galton's view acknowledges a necessary but not sufficient role of instruction and practice for the attainment of élite performance. According to this view, quality of performance increases monotonically as a function of practice, towards an asymptote which represents a fixed upper limit on performance. Similarly, researchers generally assume that some of the components mediating performance can be modified while others cannot. If performance achieved after extensive training is limited by components that cannot be modified, it is reasonable to assume that the ultimate level of performance is determined by genetic factors. This argument logically implies that élite performance must reflect innate talent and natural abilities.

The talent view

The assumption that innate abilities determine the ultimate level of performance in a domain provides a parsimonious explanation for the scarcity of exceptional performance, for the tendency for certain families to produce eminent people, and for the observation that expert levels of performance appear to be qualitatively different from lower levels of performance in a particular domain. The talent view is so popular that superior and eminent performers are normally referred to as 'talented' and 'gifted'. At the same time, the talent view projects a rather gloomy picture for anyone who wants to 'create' or promote the development of superior performance. Teachers and coaches are left with the primary task of identifying 'gifted' individuals and providing them with the training and resources necessary for them to reach their exceptional potential. The major weakness of this view is the vagueness of the specification of what constitutes talent in a given domain. Efforts to measure talent with objective tests for basic cognitive and perceptual motor abilities have been remarkably unsuccessful in predicting final performance in specific domains (see Ericsson et al 1993 for a review). Performance during and immediately after training is better predicted, but the correlations between ability test results and later performance in the domain is reduced (even after corrections for restriction of range) to such low values that their practical usefulness and validity are questionable (Hulin et al 1990).

Better evidence for specific talent factors has been obtained by comparing élite and regular performers, especially in sports. Differences in height, in the size and structure of hearts, volume of lungs and types of muscle fibres have been found to reliably differentiate these groups of highly experienced performers.

Recent research has accumulated evidence seriously questioning the assumption that individuals reach their stable maximal performance after sufficient, albeit limited, amounts of practice and experience. Even workers and professionals with extensive experience in a domain can dramatically improve their performance when they make deliberate efforts to do so. Furthermore, international levels of performance in many domains are attained only after a minimum of around ten years of prior intense preparation (Ericsson & Crutcher 1990, Simon & Chase 1973). Attaining élite performance involves far greater changes over more time than is commonly believed.

The skill acquisition view

It is relatively uncontroversial to say that attaining an expert level of performance in a domain requires mastery of all of the relevant knowledge and prerequisite skills. Those who hold the skill acquisition view make a more controversial claim, that the acquisition of knowledge, skill and characteristics is the primary challenge in attaining expert performance, and that ten years of preparation are necessary to attain mastery of these prerequisites, whether the preparation is to optimize physical performance or to organize knowledge and skills.

When the problem of reaching expert performance levels is framed as one of acquiring the prerequisite knowledge skills and characteristics, the key issue becomes that of how the acquisition process can be maximized. In all major domains an accumulation of knowledge about the domain and about skills and techniques mediating superior performance is necessary. This accumulated experience is documented and regularly updated in books, encyclopaedias and instructional material written by masters and professional teachers in the domain. Hence, the most effective procedure by which to acquire knowledge and skills in a domain would be supervised instruction by a qualified teacher who designs practice activities tailored to the individual with intermittent evaluation. Ericsson et al (1993) refer to such activities designed to improve the performance of an individual as *deliberate practice*.

When one surveys the kind of activities individuals engage in for the popular domains, it becomes clear that the vast majority of active individuals spend very little, if any, time on deliberate practice. Most of the time is spent on *playful interaction*, in which the primary goal is inherent enjoyment of the activity. Another type of activity, *work*, refers to public performances, competitions and other performances motivated by external social and monetary rewards. In work activities the focus is to generate a quality product reliably. For example, an expert computer programmer designs a program to meet a specific request. To give their best performance, in work activities, individuals rely on previously well-entrenched methods rather than exploring new methods of unknown reliability. Although work activities offer some opportunities for learning, they are far from optimal (Ericsson et al 1993).

Deliberate practice is an effortful activity motivated by the goal of improving performance, which, unlike play, is not inherently motivating, and, unlike work, does not lead to immediate social and monetary rewards.

According to the framework of Ericsson et al (1993) the primary mechanism responsible for expert performance in a domain is deliberate practice. It is interesting to inquire why individuals begin to engage in deliberate practice, when it is not inherently enjoyable. From many interviews, Bloom (1985) found that international-level performers in several domains engaged in playful activities in the domain as children (see Phase I in Fig. 1). After a period of playful and enjoyable experience they reveal 'talent' or promise. At this point, parents

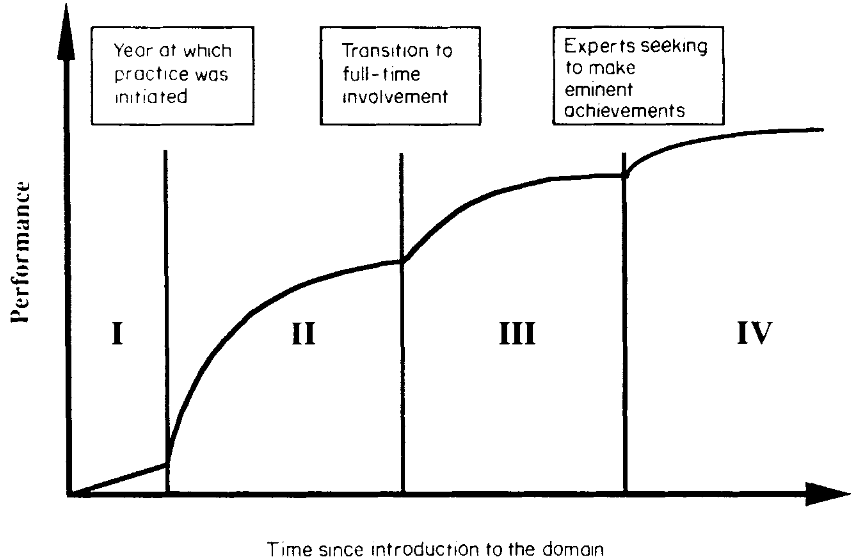

FIG. 1. The three phases in the attainment of expert performance, followed by the fourth phase in which experts attempt to reach the level of eminent achievement.

typically suggest the start of instruction by a teacher and limited amounts of deliberate practice. The parents support their children to encourage them to acquire regular habits of practice and teach them about the instrumental value of deliberate practice by remarking on improvements in performance. Phase II is an extended period of preparation ending with the individual's commitment to pursue activities in the domain on a full-time basis. Phase III is full-time commitment to improving performance, which ends when the individual either can make a living as a professional performer in the domain or terminates full-time engagement in the activity.

One reason why it has been difficult to predict adult performance from early performance is that the criteria used to evaluate performance change as higher levels of performance are attained. Throughout a child's development towards adult expert performance, parents and teachers focus on the current level of performance. At first, the most important thing is motivating the child to engage in deliberate practice and inducing the parents to provide optimal training resources. Later, the focus shifts to quality of performance, which is essential for winning competitions and scholarships and gaining access to master teachers, coaches, and training facilities. The first three phases involve mastering the available knowledge and skills that master teachers and coaches know how to train. For the highest level of achievement (eminent performance) individuals have to go beyond the available knowledge in a domain to produce a unique contribution to the domain (Phase IV). Eminent performance is, by definition, not directly instructable. At the same time, we believe that mastering all the current knowledge of the domain is advantageous, perhaps even necessary, if an individual is to go beyond the available knowledge in the domain. Our framework only predicts that the probability of making eminent contributions is related to the amount of deliberate efforts directed towards that goal.

Individual differences in expert performance

A description of the life of an international-level performer shows the necessity of a long period of supervised practice at a sustained high level. The simple assumption that these levels of deliberate practice are necessary accounts for the fact that the vast majority of active individuals, who stop practising prematurely, never reach the highest levels. However, in most major domains there are a relatively large number of individuals who continue deliberate practice, yet among this select group of individuals striking individual differences in adult performance still remain, as would be predicted by the talent view discussed above.

Ericsson et al's (1993) theoretical framework hypothesized that even the individual differences within such a select group could be accounted for in terms of differences in the amount of deliberate practice. The main assumption (the

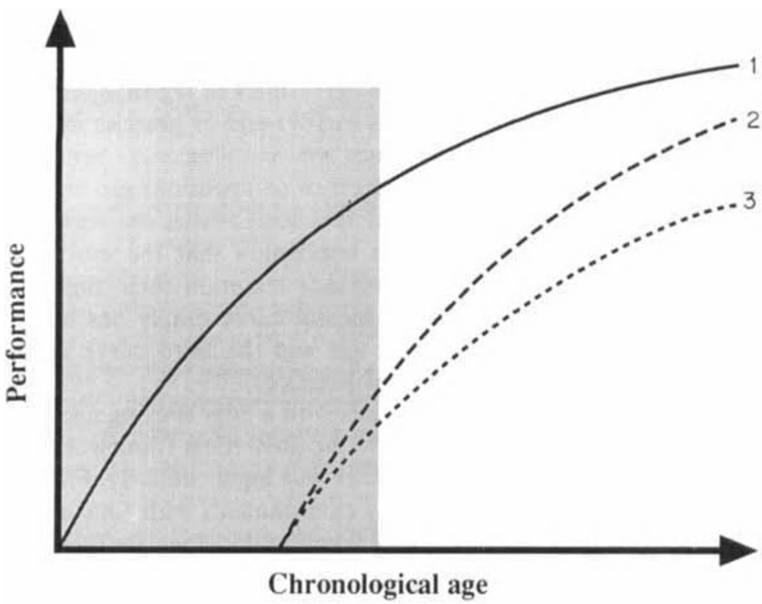

FIG. 2. Three schematic relations between chronological age and performance, where the early, less observable, portion has been shaded. The solid line (1) shows performance associated with an early starting age and a high level of practice. Line 2 shows performance attained with an equally high level of practice but with a later starting age. Line 3 shows the performance associated with the same late starting age and a lower amount of practice.

'monotonic benefits assumption') is that individuals' performances are a monotonic function of the amount of deliberate practice accumulated since their start of deliberate practice in a domain, as illustrated in Fig. 2. The accumulated amount of deliberate practice and the associated level of performance of which an individual of a given age is capable is therefore a function of the age at which practice began and the weekly amount of practice during the intervening years.

In two new studies (Ericsson et al 1993), musicians kept diaries of their activities during a week and gave retrospective estimates of the amount of deliberate practice per week they had engaged in since the start of instruction. In the first study, it was found that three groups of expert violinists of different current performance level had accumulated different amounts of practice. For the two top groups in performance quality, the difference reflected differences in weekly practice during early adolescence; the current weekly amount of practice did not differ between the two groups. The third group had uniformly lower levels of current and past amounts of practice. A second study of expert and amateur pianists showed that the amount of deliberate practice accumulated could predict performance differences between skill levels as well as inter-individual differences within groups for a series of tasks requiring bi-manual coordination in execution of rapid movements.

In a comprehensive review of other studies comparing the starting ages and weekly amount of practice of international, national and regional-level performers, Ericsson et al (1993) found performers at higher levels tended to start practising earlier (often 2–5 years earlier) and to practise more.

Everyone recognizes the importance of maturational factors; hence comparisons of performance in the context of competitions are nearly always made within particular age groups. If the first comparisons are made at around the age of 10–12, one would get the impression that the most 'talented' individuals with the best early performance maintain their superiority, as illustrated in Fig. 2, even though the second curve simply has been moved horizontally to reflect a later starting age and the third curve additionally incorporates a lower weekly amount of practice.

Would it not be possible for individuals with a later starting age or a lower initial weekly practice rate to catch up? Our theoretical framework identifies two reasons why this is not possible, or is at least highly unlikely. Firstly, access to master teachers and the best training environments with financial support for further study are quite limited, and selection decisions are typically based on performance evident at the age of 18–20. Secondly, those individuals with the highest quality early performance appear to be practising at the highest level which can be sustained without exhaustion. Any attempt by an individual to increase the amount of practice beyond that level is likely to be ineffective in improving performance or to lead to over-use injuries or 'burn-out' (Ericsson et al 1993). Overall, the skill-acquisition framework can provide a plausible basis to explain the individual differences in performance which are traditionally believed to reflect differences in talent.

Alternative explanations of other findings traditionally attributed to talent

In our earlier discussion three findings were cited in support of the talent view: familial relations between expert performers, early signs of talent, and physical characteristics differentiating élite adult performers. With a few exceptions, these findings can be better accounted for in terms of the skill-acquisition view.

Expertise, particularly in music, appears to run in families. This has been interpreted on a genetic basis, but the importance of access to equipment and instruction at ages as young as 3–4 years old makes it plausible that a shared *environment* may be the relevant factor. In fact, Coon & Carey (1989) found in their twin study of musical ability that shared environments were generally more important than genetic relationships.

The early detection of signs of talent plays a central role in the talent view. Because children begin activities in some domains at early ages, it is unclear what kind of behaviour they could actually have shown prior to instruction. Scheinfeld's (1939) descriptions suggest that 'early talent' means promise rather than objective evidence of unusual capacity. These accounts are consistent with Bloom's (1985) interviews with parents and teachers of international-level performers; Bloom found that the level of talent exhibited by these individuals was unusual only in comparison with that shown by other children of a similar age in the immediate environment. We find this evidence more consistent with demonstrated interest and enjoyment of a domain than with any superior, innate advantage involving fixed capacities.

Finally, recent research has shown that many of the physical characteristics differentiating performers, especially élite athletes, are physiological adaptations to intense practice over extended periods, in particular during adolescence when the body is growing rapidly (see Ericsson 1990 and Ericsson et al 1993 for reviews). Only for height is it possible to definitely rule out the effects of practice as an important influence. Recent research has also shown that expert performers acquire skills that allow them to perform tasks in a qualitatively different way from beginners. Experts can dramatically increase the capacity of their working memory for use in planning and evaluation by acquired domain-specific memory skills relying on long-term memory (Ericsson & Smith 1991), or circumvent the limits of rapid sequential processing by anticipatory mechanisms in typing (Salthouse 1991) or sports (Abernethy 1991). There appears to be only a small, if any, overlap in the mediating cognitive mechanisms involved in early and in late performance, which is consistent with the reported failure to predict individual differences in final performance after extensive practice and experience.

According to our review (Ericsson et al 1993) of the evidence, innate capacities and abilities (talent) appear to play a minor, even possibly negligible, role in the attainment of expert performance among normal children and adults.

Summary and conclusions

All three views on expert performance are consistent with the fact that after a long period of preparation only a small fraction of individuals attain the highest level of performance and generate truly great achievements. We believe that the primary merit of the skill acquisition view is that it focuses on the most effective methods for improving the individual's performance (deliberate practice) throughout his or her development. The relative neglect of systematic research on deliberate practice is probably due to the widespread acceptance of the alternative views that the ultimate level of performance is determined primarily by sustained effort and dedication (character ethic movement) or inborn capacities (talent view).

The emphasis of maximal effort in the character ethic movement appears to disregard the necessity of seeking out teachers and sustaining optimal levels of practice. In our review of élite performers and their teachers (Ericsson et al 1993) we found that deliberate practice requires full concentration and can be maintained effectively for only about 3–4 hours per day with scheduled periods of rest and sleep if exhaustion and burn out are to be avoided. Without careful monitoring of one's learning processes and motivational and physiological state, practice may become ineffective such that the amount of practice becomes unrelated to improvement.

A positive attribute of the talent view is that 'talented' children are treated as if they are special. In many cases parents may need to hold this belief if they are to spend the necessary time, money and effort on their child. Bloom (1985) found that only one child in a family is treated as special. Attributed talent may thus serve as a self-fulfilling prophecy (see Ericsson et al 1993 for supporting evidence). Potentially more harmful is the view that talent and associated creativity are innate and would be revealed effortlessly even before the individual has mastered all the relevant knowledge and skills within the domain. A premature diversion of time and energy away from supervised learning towards unsuccessful efforts to produce unique eminent contributions might at best be wasteful and at worst discouraging and lead to termination of commitment.

Some people feel that the acceptance of the skill-acquisition view is dangerous because it might encourage greedy parents to push young children too hard toward becoming experts in some lucrative domain. It is interesting to note that some of these people would have fewer problems with the same treatment of a 'talented' child, maintaining that the parents feel a responsibility to help their child realize his or her unfilled promise. We believe that motivation is a necessary *prerequisite* for effective practice, because when the goal to improve is given up, individuals cease deliberate practice. At the same time, we recognize that remarkably little is known about the development and maintenance of the motivation to practise over the long preparational period. None the less, an analysis of motivation will be an integral part of the on-going effort to understand fully the attainment of expert performance.

For a long time the study of exceptional and expert performance has been viewed as distinct from general psychology owing to the unique characteristics of these individuals. The skill-acquisition view instead proposes that these individuals can and should be seen as having adapted, extremely, to restricted domains through life-long efforts. An analysis of the acquired characteristics and skills of these individuals as well as their developmental history and training methods will provide us with general insights into the structure and limits of human adaptations.

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DISCUSSION

Hatano: Your model can explain only some types of skills well. John Sloboda distinguished two aspects of skilled musical performance—the technical and the expressive. Your model is good for the technical aspect, but it is a little difficult to apply it to the expressive aspect. Learners may not know the best way to improve their expressive skills. Consider other skills such as gardening or carpentry. Gardeners and carpenters do not spend much time on deliberate practice. They engage in authentic activities, using their skills in a socially meaningful context. That is very important for the development of those kinds of skills. To generalize your example to all forms of expertise is not without danger.

Ericsson: In the classic domains of expertise teachers instruct their students in optimal practice activities. We have been doing some research on domains such as chess, jazz music and science, where the direct influence of teachers is much less. We have speculated about what kind of things would constitute deliberate practice in such domains. Interviews suggest that one of the problems that potential chess masters have is spending enough time working with chess masters. However, there are activities which may help. You can study published games between two chess masters and try to predict the next move for each of the intermediate positions of the game. If you are unable to predict the next move correctly, you have done something wrong and you need to go back and analyse why you did not match the move made by the master. This activity does not need an instructor. Some of the chess masters we interviewed spent three or four hours a day in this particular kind of activity. Most jazz musicians do not have teachers, but, at around 12–13, when they start getting interested in jazz, they tend to do a lot of 'training' in which they imitate recordings of performances of the masters. This is a constrained activity, with available feedback and the means for successive correction of errors. Biographies of scientists suggest that the most treasured activity is writing on their most important research. We would argue that writing is an externalization of thinking that provides opportunities for feedback; the scientists can go back to their written text and revise it and update it, or show it to colleagues who find problems and suggest changes. Many scientists try to set aside at least a couple of hours in the morning to do this type of demanding activity.

If you study what experts are doing, you can identify activities that seem to be much more beneficial for ultimate success than others. Imitating famous musicians playing the same instruments as themselves may be one method by which young children can improve their expressive skills. One should be able to uncover activities in which students of music experiment with their instruments to produce distinct musical experiences, such as specific sounds or images. It should be possible to teach many of these to students and aspiring experts.

Hatano: Jazz musicians may practice in the way you described, but they also play jazz music on the stage. In science, graduate students actually submit their own papers to journals in addition to studying how their supervisors write a paper. They are engaging in authentic activities.

Ericsson: Mihaly Csikszentmihalyi pointed to the inherent enjoyment people get from playful interactions. Experts in any domain love sitting around talking about what they experience and getting other people's opinions. What I'm arguing is that in trying to achieve a performance goal, there are practice activities in which people engage, even though they do not rate these activities as enjoyable. When we talked to musicians about inherent enjoyment, we have told them to disregard the result of the activity, to think only about the process of engaging in it. A lot of people would say that the result of cleaning up is enjoyable, but you find few people who say that it is an enjoyable activity in itself. Having the practice activities embedded in a social support structure, where other activities and interactions provide the individual with motivation and encouragement, is critical. But, from our analysis, when it comes to attaining the performance goals, the most important thing is deliberate practice.

Howe: In a solitary, effortful kind of activity there will be enormous differences in people's attentiveness and happiness while they are doing it. Almost all the evidence we have on practice in children is retrospective. We need better evidence about exactly what happened and how children felt about it. When I was 11 I spent a disastrous year learning the violin. In my periods of practising I was very much going through the motions, and a lot of it was a total waste of time. If we had some sort of way of sampling when children of the age of five, six or seven are actually practising, we might end up with more meaningful statements and relationships. In my work with John Sloboda, even though we are only going back a year or two, we haven't found the kind of clear relationships and correlations with practice that I think we were hoping for and expecting. There are enormous differences in the amount of time the children in our study practised, but no clear picture emerges. In your study, the data tend to be retrospective, and global, and there are probably a lot of things that we are missing out on.

Ericsson: I couldn't agree more. We have actually done some studies using a slightly different technique, in which we ask for concurrent reports of the practice activity. From learning theory you can make predictions about how you ought to structure activity to make it optimal. Master teachers constantly argue for the importance of being completely attentive. They uniformly say that when you feel that your attention is lapsing, you are basically wasting your time and should stop and take a rest. We find that the average length of the practice is about an hour, followed by a 15–30 minute break before a return to practice. An appreciation of the necessity of mental clearness and full attentiveness, and the necessity of specifying specific goals for improvement, allows you to optimize training. It should be possible to track cognitive processes during deliberate practice through concurrent and retrospective verbal reports.

The more inexperienced performers are, the greater are their problems. If there is a locus of a genetic, biological, origin for individual differences, the ability or the propensity to engage in deliberate practice activities would be a much more plausible locus than this idea that you have an inate configuration of neurones that nobody else has.

Detterman: Are you saying that with the prescribed amount of practice I or anyone else can become as expert as the people you are studying?

Ericsson: Yes, if you have the prerequisite motivation, and are willing to invest the energy. We believe there is an incredible metabolic cost involved in sustaining practice at these high levels. My answer to your question, on the basis of the available data, would be that I don't see any reason why not; but, on the other hand, I wouldn't bet my new house in Tallahassee, because I don't have evidence to show that all possible rebuttals to this argument have been met.

Bouchard: I would be willing to bet my house that you're wrong!

Detterman: A fundamental principle of learning is that people profit differentially from experience.

Hautamaki: Dr Ericsson is perhaps saying that the learning curve for experts is also a power curve, therefore it's possible for everyone with a certain amount of practice to reach the asymptotic level (see Lane 1987).

Ericsson: Some of the research findings on the effects of practice on the acquisition of perceptual skills (Ericsson & Faivre 1988) and memory skills (Ericsson 1988) are relevant. Even when people come to a situation with a lot of relevant background knowledge, and acquired skills, they do not always spontaneously adopt the best strategies for performing the task. Many of the people we studied used inferior strategies; only when subjects are instructed in the use of the best strategies can we realistically expect improvements toward expert-level performance.

Detterman: I agree that you can teach people an awful lot of things, but it will take longer to teach a group of mentally retarded people music than a group of college students. That's fundamental.

Ericsson: Mental retardation is problematic and in our current work we consider only normal and healthy individuals. However, the theoretically relevant question is whether mentally retarded subjects would be able to sustain the kind of attention and focus that is required for deliberate practice. If they're not able to, the preconditions for deliberate practice have not been met.

Detterman: Innate ability is what you are talking about when you are talking about talent.

Atkinson: This is an incredibly interesting analysis, but I don't see why one can't equate the results without coming to the conclusion that talent is not a factor. You are saying you don't think talent is much of a factor, but I can't believe that these asymptotes are not affected by the age at which the student begins the instructional process. You implied that they all reached the same asymptote under ideal conditions of attention, deliberate practice and so forth.

Ericsson: Perhaps our difference is one of usage. When I refer to talent, I mean the unique, inborn capacities that some people have from birth which can never be attained by other people. That's not the same as inheritable factors that would correlate with the acquisition of expert performance.

Atkinson: Let's take tennis as an example. I am not even sure if the question of whether all people with ideal histories of deliberate practice would reach the same asymptote is an answerable one. I don't know how one could answer that question. Who can say what the ideal deliberate practice sequence is for a given subject?

Ericsson: There is some interesting longitudinal research on élite German tennis players. Schneider et al (1993) did not find anything related to basic capacities that predicted tennis performance at the age of 17. The best predictors were measures of tennis-specific skills and motivation.

Atkinson: Tennis may be one domain where only a minimal talent is necessary. What about the high jump, or the 100-yard sprint; there's just no question that special abilities are required.

Ericsson: If you control for the effects of individual differences in height, it's still an open issue whether you need additional genetic factors to account for the differences in performance.

Atkinson: Those may be answerable questions, but I'm not sure your model provides an answer.

Ericsson: I have nothing in principle against accepting the role of basic talent factors, but, from my reading of the literature, there is no conclusive evidence that they are related to the acquisition of expert performance. I could restate this as an invitation to others to tell me about research findings that we may have overlooked.

Bouchard: Such a study is experimentally feasible and can be done with animals. All you would need to do is to take a heterogeneous, genetically different, strain of rats, choose your performance criteria and train them in whatever way you want. If you treat each one alike, I can guarantee that you will not eliminate individual differences. I'm ready to bet my house on that, again!

Ericsson: There is some really interesting work on maze-learning in rats of various strains (McClearn 1962), and also a lot of interesting work measuring performance of dogs of different breeds (Scott & Fuller 1965).

Bouchard: This work shows that you can breed for the character, which means there are fundamental genetic differences between organisms.

Ericsson: For general capacities, such as learning capacity, the evidence does not support that. Although it is possible to breed rats that will show superior performance on a specific learning task, this superior learning ability does not transfer when the drive is manipulated.

Dudai: That is absolutely not correct! I bet *my* house on that.

Ericsson: I can only refer to the review by McClearn (1962). We have been unable to find any recent contradictory findings in texts on behavioural genetics (e.g., Plomin et al 1990).

Fowler: I am prepared to agree with Tom Bouchard that there are innate factors, but there's another whole dimension, the informal experiences in the family, especially the early ones, that serve as a whole basis for ease in later more formal learning situations. For example, encouraging informal motor skill experiences by providing opportunities to climb and jump in a child's early years will make a difference to how well the individual can take advantage of any later formal practice system. Age is bound to be important, as are the type of attitudinal, cognitive and skill experiences that a person has had.

You mentioned physiological changes that occur with practice. Are the skills that develop, planning skills and other cognitive skills, specific to the domain?

Ericsson: They are specific to the domain. There is no increase in general working memory capacity. Experts acquire memory skills using long-term memory for storage of domain-specific information which can be retrieved rapidly with cues in working memory. Their acquired memory skills are tailored to the specific demands on storage and retrieval access in their domain of expertise.

Research has shown that after about the age of 20, physiological characteristics are essentially declining. Obviously that would be a factor. Consider a thought experiment. A 25-year-old man wants to be a master violinist. The performance of expert musicians tends to peak at around 35. Even if he had the normal learning acquisition curve he might not reach his highest level before the age of peak performance in music. Who would be willing to give him a salary and support him for the 10–20 years it would take to try it out? Considerable resources have to be made available just to give individuals an equal chance with the best.

Fowler: So you would put more money on duration, provided that you could duplicate the right attitude and approach to the problem, than on an early start. Aren't these correlated, or synergistic, because one has to have the advantage of early informal preparatory experiences?

Ericsson: There are some abilities, such as absolute pitch, that seem to be easier to acquire at younger ages. There's good evidence that unless ballet dancers start training before 11 their joints will never be as flexible as they need to be.

Gardner: The issue of whether you can achieve extremely high level performance through practice in something like playing a musical instrument is a different issue from that of whether there are important inborn differences in talent. I would think that teachers in what I might call the prodigious domains, such as music, chess and mathematics, could discern in very young children huge differences not only in speed but also in the heuristics that they bring to bear on patterns and on problems. Although we can't be sure that these approaches are innate, my own experience as a music teacher and as an observer of other piano teachers tells me that there is an enormous difference between children who come in with absolute pitch, children who can pick out pieces on an instrument even though they have never been formally taught, children who can hear a piece once and then reproduce it, and children who can play pieces in different keys without being shown how. That doesn't mean that if you spend 10 000 hours practising you can't be a good musician even if you lack all of these abilties; but, if you have them, not only does it mean that you can approach lessons in a different way, but also that master teachers are much more likely to work with you. The very teachers who deny that there is such a thing as talent, when you ask them how they select the children with whom they are going to work, fall back on these kinds of factors and markers. It may be that having the qualities that Tom Bouchard would bet his house on determines both whether you are willing to put in the 10 000 hours of practice when you can see other children playing far better than you, and whether you can ultimately go beyond level three to get to level four. As a researcher, you need to work with the tennis teachers, the chess teachers and the music teachers who deal with five-year-old children, and let them tell you about the differences they see before you conclude that everybody starts at the same level and goes through the same kinds of practice.

Ericsson: Many of the things you have referred to as talent factors could be viewed as abilities that one would acquire through experience. If you engage in certain kinds of activities, you are even more likely to acquire absolute pitch before the age of five, because the normal acquisition of relative pitch may interfere with the ability to acquire absolute pitch perception. Some music savants have been shown to be able to reproduce a piece of music after a single hearing (Sloboda et al 1985, Charness et al 1988). They cannot sight-read, so they can only do this through listening. To memorize music efficiently after a single hearing, they need to acquire the memory skill. We know from a wide range of domains that domain-specific memory skills can be acquired, but motivation is needed. I'm not aware of research on individual differences in motivation and their relation to perceived talent. The problem is that some people believe in talent so strongly that they don't even see a need to put forward objective evidence that would refute alternative views.

Gardner: I agree, but there is a difference between children picking up skills or understanding from the ambience and doing so because somebody has structured the environment for them carefully.

Ericsson: The family environment and the family's attentiveness to musical properties may be one of the factors that would induce children to be interested in music and to listen to it and mimic it.

Atkinson: What I think you are saying is that if I reject the notion of talent I shall look more deeply at these problems in more sophisticated analyses, whereas if I accept the idea of talent I shall explain everything away at too early a stage. You would argue that by rejecting the notion of talent you have uncovered some complicated processes that could explain performance. In a hypothetical sense you are saying what Watson said; 'Give me a dozen healthy infants, well-formed, and my own specified world to bring them up in, and I'll guarantee to take any one at random and train him to be any type of specialist I might select—doctor, lawyer, artist, merchant-chief, and, yes, even beggar-man and thief, regardless of his talents, penchants, tendencies, abilities, vocations, and race of his ancestors' (Watson 1930, p 104).

Lubinski: It has to be said that on the same page, Watson said he was going beyond the facts.

Atkinson: I like Anders' argument that it's wise to not accept the talent idea too early, but I think he does his work a disservice by trying to conclude from it that talent is not important.

Ericsson: If you read my written work you will find that I have not actually made that claim. I'm saying that I don't know of any affirmative evidence for the talent view. My colleagues and I are proposing an alternative theoretical framework that provides a sufficient and in some respects superior account of the available data.

Sitruk-Ware: A gift is something a child has at birth, and the role of the adult is to detect the gift and provide an environment favourable to the attainment of achievement at the highest level. However, adults want to create certain talents and intervene in a particular way at an early stage before there is time to detect any other potential talents.

Ericsson: Providing a child with opportunities is not very different from allowing children to develop into whatever they can develop into. What is it that convinces you that a particular child has a certain ability? I would be interested in getting real evidence about early signs of specific talents that do not also occur in control groups. If the behaviour that is supposed to reveal talent is also shown by other children whose parents are not able to see it or are not looking for it, the early signs of talent will reflect the perceptions of the parents rather than unique characteristics of the children. Early signs of talent shouldn't be necessary for parents to help their children to develop as much as possible.

Sitruk-Ware: How do you make the diagnosis and decide whether you will develop them verbally or musically or whatever?

Ericsson: You would have to look back and see whether there was compelling evidence that the child was talented in mathematics as opposed to something else. If you are locked into believing that your child has verbal talent when he actually wants to do mathematics, you are making a mistake. Bloom (1985) argued that you should work hard and try to reach your potential, but the particular area in which you reach your potential is not important. If it is necessary for children to start learning music at three years of age if they are to be competitive as solo musicians, music would not be a good domain to try to direct your child into, because if you detect the child's interest at age seven, he or she will be four years behind all the other children who starts at three. That would be a direct disadvantage. There are other activities, such as science, for which the starting age is difficult to determine. The prerequisite development for scientists is hard to trace to a specific starting date, and choices about specific scientific disciplines are made around 18–20.

Sloboda: There is a considerable body of literature now about low IQ experts (Howe 1989). I have studied a musician with an IQ of 65 who has a memory which is probably greater than that Mozart had at a comparable age (Sloboda et al 1985). The only thing that differentiates this particular expert from anybody else is the large number of hours of relevant practice he has put in on that task, in his case self-motivated and without a tutor. There doesn't seem to be anything else to explain how someone with a very low IQ achieves such incredible levels of expertise.

Detterman: It may be possible to teach anybody anything, but it takes longer to teach people of lower IQ. There are incredible amounts of data showing that persons of low IQ take longer to learn the same amount as persons of high IQ. This is true of every kind of learning that has been studied.

Gruber: Professor Ericsson, it seems to me you have chosen the hardest area in which to make your point. You have chosen an extreme problem, musical performance. Darwin, for example, didn't have to be at the high level of expertise that you are talking about. What he had to do was to organize other people who were experts. In processing the data collected on the Beagle voyage, he published five books, each of which was co-edited with an expert in a particular area, herpetology, ichthyology, mammalogy, ornithology or fossil mammalogy. Another type of greatness comes about through the synthesis of a variety of skills and knowledge domains. If you don't have to be quite as expert in any one domain as a performance musician, more room is left for varying the role of practice. The question becomes one not of the amount of practice but of how the practice is distributed.

Ericsson: Once we get away from the individual performance domains, to management, for example, different kinds of skills will be relevant. Even the social system for supporting further skill development is different. In these non-traditional domains there are typically a lack of systems by which masters and teachers guide individuals toward activities that would improve their performance. It would be at least interesting to try to apply our idea of deliberate practice to the non-traditional domains. Many successful people in these domains appear to engage in similar kinds of activities, and make similar kinds of priorities among alternative activities. This suggests that some activities are more relevant to improvement of performance and success than others.

Obviously, we need to go beyond this simple experiential view where you simply count the number of hours somebody has worked in a job, because that doesn't have a relationship with performance. When you identify deliberate practice, you see clear relationships. In some domains it will be difficult to identify such activities to improve, but we should be willing to think about which activities might be the most relevant and important. My reading of biographies suggests that there are many people who are concerned about these issues; most experts seem to be aware of how they can further improve themselves and their performance.

Heller: This discussion demonstrates that we need different approaches for different questions. Your approach provides us with useful information about the development and nurturing of giftedness and talent. But, we must consider its constraints, and use other approaches for other questions and preconditions.

Ericsson: I couldn't agree more. The more people can at least consider the plausibility of alternative accounts, and begin to accumulate evidence that will either support or rule out different theories, the closer we shall come to integrating data from different research traditions. People seem to think that talent is so obvious that they don't take the care to accumulate scientific evidence in its favour.

Benbow: I don't think that anybody is doing that here, except you; you are turning this into a black and white issue, ignoring the grey area. No one in this room disagrees with you that practice is important. You are the only one saying that talent isn't important. You seem to feel you cannot believe in both talent and practice. Why can't we just agree that there is room for both?

Ericsson: I've been trying to describe evidence that I think makes the case that practice is important to individual differences in performance.

Bouchard: I don't disagree with a thing you said, but you came to the wrong conclusion! The empirical facts are fine. This is great work, no one would dispute that, but you cannot conclude from it that talent is unimportant.

Ericsson: As I see it, the evidence for the importance of talent is not available. That's why I am asking you all to point out empirical evidence demonstrating its relevance for expert performance.

Detterman: What kind of evidence would satisfy you that talent really is a factor?

Ericsson: We have looked for specific proposals for innate talent, such as the ability to identify absolute pitch, certain capacities of muscles resulting from different muscle fibre types, and any kind of well-specified function that one could claimed could be performed only by individuals who have the proposed talent.

Dudai: Can you improve your vision through practice?

Ericsson: Virtually all of the improvements in perceptual performance are specific to the conditions of practice. For example, absolute identification of colour can be greatly improved with practice, and analysis of the improvement shows it to be specific to the range of colours in the set of practice stimuli. The idea that general basic processes are being modified by practice does not seem to be true in the skills I have looked at.

Detterman: What you are saying is that I have to show something that *doesn't* work, that *can't* be improved. That's an almost impossible argument to make. How could I convince you that something couldn't be improved?

Gardner: It is being 'off promise' which those of us who believe in talent think is important. If you give 1000 people the same experience, as far as you can, after 50 or 100 trials they will distribute widely. That's what most of us mean by talent. We don't feel that there is something inborn that nobody else could have.

Lubinski: Talent is a continuum.

Atkinson: In philosophy there's a notion called the doctrine of conventionalism. This is simply the idea that any theory is correct if you are free enough in the interpretation of the rules of correspondence. I suspect you will always be correct in rejecting any notion of talent if you reconfigure what you mean by ideal deliberate practice and how that practice has failed.

Ericsson: The question I was called on to address was: can we create gifted people? There is at the moment no unanimous answer to that question. All we can hope to do is to improve the inventory of available relevant information. The more scientists can understand alternative ways of conceiving information, the more likely they are to collect data relevant to different theoretical perspectives. With regard to early signs of talent, there may be data out there that would be convincing, but all the sources I have seen have bungled the job of collecting all the relevant information.

Howe: People keep throwing in this word, 'talent', without a precise definition, without saying what they mean by it except that in the broadest possible way that there is something present from the beginning which accounts for a person becoming exceptionally able. That seems a sloppy, vague, unscientific way of doing things. Anders Ericsson is trying to encourage us to look at things in terms of what we can measure and what we can define. We may not be able to go all the way, but let's try, rather than assuming unscientifically that this indefinable, vague thing called talent, which we haven't begun to think about, somehow accounts for everything.

Gruber: Seventy-five years of research on learning came to a cramped and limited conclusion about what people in general could do. Then with work such as Harlow's (1949) on learning sets, and the re-emergence of research on mnemonic processing, the conception of what everyone could achieve with just a modicum of training shot up. We don't actually know whether the rank order of individual differences changes when the process of remembering changes, or whether the good memorizer in the stereotyped slogging-it-out type of memory is also the good learner when mnemonic processing and the use of the imagination are encouraged. That change in our conception of cognitive limitations was a real revolution in cognitive psychology. Miller et al (1960; see also Luria 1968) in their book *Plans and the structure of behavior* exploited that kind of work, asking: here are the nails, how do we build a house? The work

Anders Ericsson and his colleagues have done is potentially another revolution that will provide a completely different idea of human potential. I agree with Tom Bouchard that when all is said and done there will still be individual differences; but, they may not be the same individual differences as we observe now with the present distribution of cognitive strategies in the populations studied. The rank order of ability may be radically different.

Sternberg: There's something to be said for converging operations. I get a little nervous with the kinds of statements Anders Ericsson and Tom Bouchard have made that imply that there's one kind of experiment you can do that tells us something and they don't want to be bothered by 800 studies of other kinds. There's no experiment that will finally answer the question for a particular person for which there will be no alternative interpretation of the data. Although the idea of looking at practice and taking it to its limits is interesting, I hesitate a little when you seem to discount any other kind of study. You seem to be discarding an awfully large literature, which is why you are getting a negative affective reaction here. It's up to you to say why these other studies are useless in terms of their providing converging operations, and suggesting that talent at least matters. If you don't do that, you end up rediscovering history. Dick Atkinson's reference to John Watson (p 238) was interesting, because, from one point of view, this is a re-run of the behaviouristic philosophy that one can make anyone into anybody. People lost interest in that idea because of a lot of converging operations suggesting there were questions that behaviourism didn't answer. We will simply cycle back and forth unless we acknowledge that there are different kinds of research designs that tell us different things about a given phenomenon. The perfect design or critical experiment that you seem to be looking for doesn't exist.

Ericsson: I do not mean to give the impression that I don't think that other research is interesting. However, I have often encountered research that has not collected data on the variables that I would consider important. As Robert Plomin suggested (p 84), if we could have the same kind of detailed analysis of the environment with its critical activities as we have of genetic factors, we should be able to bridge the communication gap and within the same studies have relevant information on relevant activities in the environment and genetic indicators. In some of the psychometric literature there is little information about what kind of subjects are being dealt with and how performance on tasks relates to pre-existing knowledge and experience. It is quite rare for people to study extended practice. Most laboratory research on learning is limited to performance that can be observed after a couple of hours of practice. Can we really extend the results attained after two hours of practice to those attainable after months and years of sustained practice? The processes involved in making the commitment to practise for four hours per day for 10 years are fundamentally different from the commitment to invest in a total of 5–10 hours of practice. If we want to understand that life-long commitment process, we may need to look at much longer periods. Longitudinal designs are needed to address such issues.

Sternberg: Do you think that the difference between the more eminent and the less eminent scientists is simply attributable to time of practice, that people who are more well known put more time into their work, or make better use of their time?

Ericsson: I don't know of any systematic studies of that question. I believe that predicting eminent performance is inherently impossible, because we don't know the deterministic process by which eminent performance is produced. From reading biographies of extraordinarily successful people, I'm struck by how committed they are to their work.

Sternberg: What about the thousands of others who were committed you have never heard of because they didn't make it?

Ericsson: I am making a probability argument. The more time someone spends working on making a contribution, the more likely they are to produce a major achievement. I would have an easier time picking eminent people who dedicated their lives to their work than eminent people who spent little time on the activities critical in their domain.

Sternberg: Thousands of people have been trying for years to get that first grant or their article published, and no one has written a biography about them! The people in the biographies worked hard, but you're not doing justice to all the frustrated people who have striven throughout their lives to achieve heights.

Gruber: This is where you need the case study method to make sense out of a life, rather than correlating a variable with a variable. I'm not denigrating that style of research; it has it's place, but it will not reconstruct a life for you, any more than an anatomist could correlate one bone in the body with another bone in the body to find out what makes a skeleton hang together.

Sternberg: We need the lives of the people who didn't make it. That's the whole problem.

Fang: According to Professor Ericsson's theory, we can create gifted people. I agree with most of those who have argued with you. I would answer yes to the question in your title if you changed it to, can we create people of high achievement? Then there would be no argument. Of course, practice is important for achievement, but talent should be a precondition, so that the person can be trained more economically. The talented people may achieve more than normal people who go through the same amount of practice. That is the point.

Ericsson: I admit that I can't answer the question posed to me by the organizer of this meeting, but once you start trying to pin down what some people call talent, you find a lot of diversity. Often what master teachers see in 'talented' individuals is an enthusiasm, a motivation, a commitment to the task, a basically spontaneous enjoyment of the domain. Assessments of talent are known to differ among teachers and to change over time (Kingsbury 1988). People who are interested in talent need to be more precise about what they're actually talking about, to allow others to review specific empirical evidence and integrate that into their theoretical perspectives. As long as talent is taken as given, no scientific progress will be made.

Benbow: Julian Stanley and I have an objective way of operationalizing what we mean by mathematical talent—a high SAT-Mathematical score at an early age. If you took a 13-year-old child who has a SAT-M score of 700 (among the top 1 in 10 000) and one who has a score of 300 (more than four standard deviations lower) and guided them both through massive practice, I would bet there would still be differences between the two children at the end which might even be larger than initially.

Ericsson: You have put your finger on what I think is the issue. You essentially said that performance reflects talent. One could just as well view performance as a reflection of acquired knowledge and skill.

Benbow: There's no evidence that these mathematically talented children have spent enormous amounts of time practising mathematics to get high scores. There's no evidence that their parents have pushed them; some do not even know about their talents. These individuals are in no way 'produced', and I wouldn't even know *how* one might produce them.

Ericsson: Get them to keep diaries to provide a good estimate of how they spend their time. Then I would have something to work with.

Benbow: They are typical children. I am not talking about prodigies.

Ericsson: Would it be possible for me to get more detailed information, to show that they are typical? You are saying only that you don't notice differences.

Benbow: We have some retrospective information from our questionnaires. We ask the parents, as well as the children, to reflect upon what they have done. Their answers clearly reveal that these are not parent-produced gifted children. For example, if a child gets 700 on SAT-M, he or she can get into a programme which will provide many advantages. A child who gets 690 won't get in. Unfortunately, we have to draw the line somewhere. There are children who try anything and everything to get over that line, but they can't do it. It isn't as easy as you suggest. Three weeks of intensive study of the mathematical content tapped by SAT-M produces little or no improvement in test score (Brody & Benbow 1990).

Have you read Mumford & Gustafson's (1988) review? They differentiated between major and minor contributions, and seemed to think that acquiring a huge knowledge base, mastering your domain, is useful for producing what they called minor contributions, but in some ways having too much knowledge can get in the way of the major paradigm-shifting contributions. From their review, they concluded that major contributions tend to be made while the individuals are still young, before they have too much knowledge and are too set in a particular way of thinking. I wonder if this extensive practice that you are talking about, which we *all* agree is important, may affect these different types of contributions differentially.

Ericsson: I have read that paper, but some time ago. It is important to ask what are the kinds of activities that we should promote in scientists and graduate students, what knowledge and skills they need, how they should allocate their time. As I remember that article, the importance of creativity was inferred from the different distributions of ages at which scientists made major and minor contributions. If we could describe the lives of successful scientists, we would probably find that they work on selecting important problems relatively early in their careers and then refine their insights about these problems though their research and accumulation of knowledge for the rest of their lives. Hence, successful selection of general, soluble problems is critical to making a major contribution, which is likely to occur between 30 and 40. There are obviously incorrect ways in which you can select problems and accrue knowledge. If you try to store as many small pieces of knowledge as possible, you will not get the kind of perspective that would allow you to survey a field and find a particularly promising problem on which to work.

Benbow: What Mumford & Gustafson (1988) argued was that in a way the individuals didn't know any better; they made major contributions because they started to ask questions that others could not because they were used to facing the facts in set ways, and did not question how the facts were structured because they had been trained to see and think along certain lines without considering the ways that current thinking was in error. Only someone who was not set in their ways of thinking could reorganize the facts. How would extensive practice affect the mind of those capable of making major contributions?

Ericsson: If we could have more detailed analysis of the early development and careers of unsuccessful people, we would at least have a starting point from which to address these issues.

Sternberg: I teach a year-long multivariate statistics course, and several years ago I decided to give the students a multiple regression exercise involving prediction of final grades. I included mathematics Graduate Record Exam score, but also asked the students the number of hours they spent per week working for the course. Mathematics GRE score was of course positively correlated with grade on the multivariate analysis course. The surprising finding, which made me decide never to do this exercise again, was that the correlation between the number of hours per week the students worked and their final grade was -0.84. When they began the course none of them knew any multivariate analysis, though they may have had different mathematics backgrounds. Anders Ericsson's message to someone who doesn't have the ability to do mathematics, who could be doing something else really well, is, keep working at the mathematics and eventually you can be big time too. Those who don't have the talent but wish they did might be better off deciding what their strengths and weaknesses are and pursuing something else for which they do have a talent. That's my concern.

Ericsson: In the 1930s there were a lot of diary studies of the relationship between how much people studied in college and their grades. The most negative correlations were in Bible studies. Those who didn't know anything about the Bible worked extremely hard, whereas those who had studied the Bible all their life needed to spend little time preparing for this class; obviously, there would be a negative correlation.

Sternberg: None of the students I taught knew about multivariate analysis before the course.

Ericsson: You didn't give them a test of all the mathematical knowledge and skills that are necessary to acquire mastery of multivariate statistics. It is possible that the students with the least background knowledge spent a lot of extra time trying to acquire the necessary background knowledge or finding ways of mastering the course without it.

Sternberg: There's nothing that will disprove your position. It's frustrating. The reason we have spent so much time on this is that you have set up an extreme cognitive system, and people pay attention to extreme points of view. We try to convince you that you are wrong and you intermittently reinforce for us that the next argument may be the one that convinces you, but it won't!

Freeman: Anders is offering us something enormously valuable. He is trying to make us pin-point what we think talent is, and *why* we are looking at what talent is, and whether or not it is acquired through practice. We are all making considerable efforts to understand the development of talent so as to make better provision for its promotion. If we, through the stimulation of such provocative arguments, can be more explicit about what talent is, we shall be better placed to deal with it productively.

Gardner: The 10 000 hours of practice doesn't help us distinguish between those people who are going to make a difference, whether in music or science, and those who won't. Let me just toss out two words—one is 'taste', the other is 'stretch'. I would not claim that spending time working on the achievement of those two virtues wouldn't help in the end, but I would claim that spending 10 000 hours practising may produce a musical drudge or a scientific drudge who works well enough in the traditional domain practices but shows neither taste in what he goes on to work on, nor stretch when something new comes along. Ultimately, the elements of taste and stretch may be worth many many hours of practice.

Ericsson: When one defines the qualities one wants to promote, one can find activities that will help one to improve. Obviously, there are many qualities that will not necessarily follow from skill-related training. If you want to acquire superior taste in musical expression, you might want to listen to superb performances by master performers, and try to represent what it is that these performers do to communicate musical experiences successfully.

Detterman: Do you think IQ itself is the result of practice?

Ericsson: Few people believe that someone is born with all the elements. The adult mind is essentially the result of an extended acquisition process. Looking at IQ from a practice perspective might be useful and interesting. I myself would rather study expertise than general IQ because most forms of expertise have a well-defined goal and a lot is known about important practice activities. There is an understanding of the role of instruction and teachers. IQ, in contrast, seems to have been introduced empirically without a theoretical conception of what it is that one is really trying to measure. Not being precise about what it is that is measured from a theoretical point of view makes IQ similar to other related concepts of talent.

Howe: We are confusing two kinds of question, and inferring that a negative answer to the first one implies a negative answer to the second. Question one is, if you give someone their 10 000 hours, will you manufacture a genius? We would all agree that the answer to that is no. The second question, a more realistic one, is whether it is largely true that when we put together the various circumstances that make up an individual's experience over the course of his life—not just his abilities, not just his preferences, not just his tastes, not just the amount he practises, not just the lucky breaks, not only whether what he is doing happens to be in tune with the climate of the time, but all these things together—we can then get a long way towards being able to predict how that life ends up. Bringing in the idea of talent to explain everything as if we are scientists arguing about the creation of the universe, and every now and again saying God did this or God did that, is perhaps not a precise enough way of proceeding. Yes, there are going to be differences between people at the time they are born, and yes, these differences may affect them in ways which influence their experience of life and their learning and so on and so forth. But we have got to be rigorous about the way we think about this. Much of the objection to the concept of talent is that analysis and definition are absent. The word 'talent' is introduced as if it will end the argument by knocking down some alternative explanation.

Gruber: We are all fascinated by how seemingly magical abilities come about. Consider Robert Burns Woodward, who was arguably the greatest organic chemist of the 20th century. He won a Nobel Prize and probably would have won a second had he lived longer. He is a good example of somebody who started young. He was given a chemistry set when he was 12 and he did remarkable things with it. That would not, of course, have won him the Nobel Prize, and we don't know about all the other kids who were given chemistry sets. We only know about him because he went on to do greater things. However, the greater things he did required the 10 000 hours of practice. When his co-workers went home to their families, he would go back to the laboratory and draw chemical configurations all night long (see Woodward 1989). One of the key questions that underlies this discussion is not whether or not there's a variable called talent, but something quite different, whether a person can transform himself or herself through activity.

Stanley: Getting through schooling early so that one can plunge fully into research also seems to be important. Woodward was only 20 when he obtained his PhD (Montour 1979). Norbert Wiener was only 18 when he received his (Wiener 1953). Even many prominent psychologists finished their doctorates early, for example, Leon Festinger and Robert R. Sears at 23, and William K. Estes and Robert L. Thorndike at 24; but none of these majored in psychology. It seems that extensive early 'practice' in psychology is not the mode even for the most renowned figures in the field. There are counter examples; as undergraduates, B.F. Skinner, Louis Thurstone and E.L. Thorndike majored in psychology.

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Closing remarks

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The quality of the discussions that we have had here on these issues is quite different from the level of analysis and theory that could have been brought to bear 25 years ago. In some sense we have the same unanswerable questions, but the improvement in the quality of the analysis is significant. Interesting new techniques have been mentioned here, for example, new genetic techniques and new methods for analysing the effects combinations of genes have on complex traits. I was intrigued also by Camilla Benbow's EEG work and its relationship to test scores, and with Mihaly Csikzsentmihalyi's random sampling of activities via telecommunication. These new techniques promise a greater understanding; the sorts of analyses that we can now do are much more detailed and sophisticated.

I'm pleased that we ended with Anders Ericsson's paper. His conception of problems is one that will lead to important research. I could repeat my earlier remarks (p 237–241), but it may be that it takes the drive and orientation that he has to pursue some of these issues in the effective way he is pursuing them.

This meeting has been very rewarding for me. I've been out of the field of psychology for about 17 years, and have found the discussions exciting. I had not met some of you before, but felt I knew you from reading your work. It's been a great pleasure.

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Edited by Gregory R. Bock, Kate Ackrill

Index of contributors

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Subject index