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How to actualize potential: a bioecological approach to talent development

Stephen J. Ceci, Sterling Williams-Ceci, and Wendy M. Williams
Department of Human Development, College of Human Ecology, Cornell University, Ithaca, New York

Address for correspondence: Stephen J. Ceci, Department of Human Development, College of Human Ecology, MVR Hall, Cornell University, Ithaca, NY 14853. sjc9@cornell.edu

Bioecological theory posits three interacting principles to explain developmental outcomes such as fluctuating achievement levels and changing heritability coefficients. Here, we apply the theory to the domain of talent development, by reviewing short-term and long-term cognitive interventions. We argue that macro-level analyses of cultural practices (e.g., matrilineal inheritance and property ownership) and national systems of education are consistent with the bioecological theory; when the findings from these analyses are unpacked, the engines that drive them are so-called *proximal processes*. This finding has implications for the design and delivery of instruction and the development of talent. We argue that talent is fostered by the same three bioecological mechanisms that explain the actualization of genetic potential. We conclude by discussing several self-descriptions and personal narratives by gifted students in which they spontaneously refer to these bioecological mechanisms in their own talent-development processes. Similar testimonials have been documented by historic talent researchers such as Benjamin Bloom, noting the importance of continual adjustments in feedback.

Keywords: bioecological; context; prediction; proximal processes

Remarking on his lifelong effort to develop a model of the theoretical threshold for manifestation of a phenotype, Grawemeyer prize winner Irving Gottesman cautioned readers that: "No one has ever been as bold or uninformed as to believe that understanding why one human differs from another across behaviors would be easy."[1] Although he was referring specifically to his 50-year effort to understand genetic and environmental factors in schizophrenia, Gottesman's caution is just as relevant for those studying the development of extreme talent. A full account of when and for whom talent will emerge would include understanding of the roles of (1) specific versus general processes, (2) genetic versus environmental factors, and (3) assets versus liabilities, within each combination of these causal mechanisms. However, in this article, we have a far more modest goal. We describe the bioecological theory of development and show how it sheds light on why individuals—despite sharing what is ostensibly the same environment—differ in their phenotypes, and what this difference implies about talent and its relationship to factors such as general intelligence.

In an authoritative monograph-length article that mapped the empirical and theoretical landscape of giftedness, Subotnik and her colleagues noted that, for nearly a century, scholars have clashed over conceptualizations of giftedness and talent development.[2] One of the central disagreements relates to the proposed mechanisms involved in the development of giftedness, which they define as the manifestation of performance at the upper end of the distribution in a specific talent domain, which is developmental in its trajectory, with potential being key at the earliest stage. As Subotnik *et al.* point out, most models of giftedness depict gifts as being based in some genetic potential in some specific domain that is actualized by learning and practice. In the literature, the mechanisms of learning and practice are usually undefined or assumed to evoke talents, but with little specificity regarding precisely how they do so. In this article, we attempt to add richness and depth to the understanding of

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an important mechanism in the development of talent: *proximal processes*. We do this both deductively (top-down from bioecological theory's tenets) and inductively (from studies that provide tests of the theory's predictions). We first consider the inductive approach, starting with a study that provides an unusual insight into extreme talent development.

What racetrack geniuses reveal about the components of extreme talent

In an experimental study of everyday thinking and reasoning,[3] 30 years ago, Ceci and Liker studied men who were highly experienced at handicapping races at harness racetracks in the Northeast United States. All of the men in the study had been attending races on a nearly daily basis for 15 years, on average, but they were not equally talented at handicapping races; some were documented experts and others, although very knowledgeable, were nonexperts. The researchers asked both expert and nonexpert handicappers to pick winners in actual races as well as in 50 hypothetical races. In the latter, seven variables were systematically varied to assess the extent to which each one contributed to handicappers' reasoning. Both experts and nonexperts had huge reservoirs of racing knowledge. But the experts were demonstrably better at predicting winners and, more importantly, at estimating post-time odds from past performance data. The latter skill is important because it is possible to pick a large number of winners and yet lose money if the winning payoffs do not justify the true odds of winning; conversely, it is possible to pick only a few winners and yet make money if the payoffs exceed the true odds of winning.

The individual quoted below was one of the experts in this study. He was interviewed a day before the race and asked to explain his handicapping, pointing to lines of data in the early form of the racing program, which contained past performance data (e.g., speeds at each quarter mile of each race for each horse for the past several months, its purse size, turf conditions, and position in terms of other horses at each quarter mile). This compilation of data did not contain expected odds, which are published on the actual day of racing, but experts are adept at predicting actual post-time odds.

Interviewer: Which horse do you think will win the next race?

Expert: The 4-horse should win easy; he should go off 3-to-5 or shorter, or there's something wrong.

Interviewer: What exactly is it about the 4-horse that makes him your odds-on favorite?

Expert: He's the fastest, plain and simple!

Interviewer: But it looks to me like other horses are even faster. For instance, both the 2-horse and the 6-horse have recorded faster times than the 4-horse, haven't they?

Expert: Yeah, but you can't go by that. The 2-horse didn't win that outing, he just sucked up.

Interviewer: Sucked up?

Expert: You gotta' read between the lines if you want to be good at this. The 2-horse just sat on the rail and didn't fight a lick. He just kept on the rail and sucked up lengths when horses in front of him came off the rail to fight with the front runner.

Interviewer: Why does that make his speed any slower? I don't get it.

Expert: Now listen, if he came out and fought with other horses, do you think for one minute he'd have run that fast? Let me explain something to you that will help you understand. See the race on June 6? (*He points to the relevant line of the racing program.*) Well, if the 2-horse had to do all of this fighting, he'd run 3 seconds slower. It's that simple. There ain't no comparison between the 2-horse and the 4-horse. The 4 is tons better!

Interviewer: And the longer you're on the outside, the longer the race you have to run, right? In other words, the shortest route around the track is along the rail and the farther off of it you are, the longer the perimeter you have to run.

Expert: Exactly. But there's another horse in this race that you have to watch. I'm talking about the 8-horse. He don't mind the outside post because he lays back early. Christ, he ran a monster of a race on June 20th! He worries me because if he repeats here, he's unbeatable.

Interviewer: Do you like him better than the 4-horse?

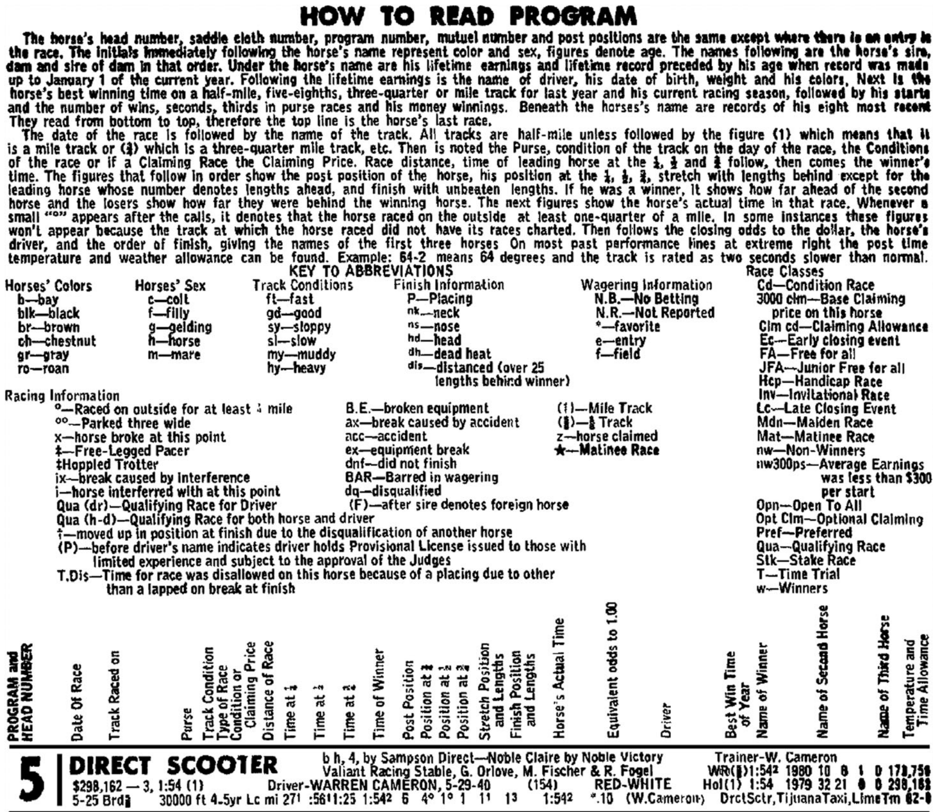
Expert: Not for the price. He'll go off even money. He isn't that steady to be even money. If he's geared up, there's no stopping him, but you can't bet on him being geared up. If he were 3-to-1, I'd bet him in a minute because he'll return a profit over the long run. But not at even money.

The above expert worked as a crane operator during the day, and he attended the races nearly every night for well over a decade. He was one of the top 16 experts in the study. What does his reasoning tell us about his cognitive complexity? In the interview, he demonstrates an impressive ability to think in a sophisticated fashion; he bases his choices on multiple interacting variables. This can be seen most clearly in the statistical modeling of his choices, but it can also be glimpsed in the above interview by the way he qualifies a horse's winning speed by the number of energetic moves it made during the race in question—indicated in the racing program by superscripts at each quarter mile time during the race that denote the number of lengths away from the inner rail at that point. A winning speed that involves three energetic moves is more impressive than the same speed achieved with fewer moves.

Not obvious in this interview is that the expert also qualifies his evaluation of these variables by the level of other variables, such as the circumference of the track for the race in question: some harness tracks are 0.5 mi in circumference and the horse must traverse the track twice in a 1-mi race, while other track circumferences are 0.67, 0.75, 1, and 1.25 mi. Experts will add weight to a horse's speed if, all other things held constant, it was clocked on a small-circumference track, because the increased curvature of a small track means a horse is likely to be further away from the rail than if the track was longer in circumference. Hence, racing on a small-circumference track means running more than 1 mile when traversing a half-mile track twice, rather than, say, traversing a 1-mi track once. The expert also considers the horse's breeding, which can be seen in the above dialogue when he argues that a horse's attempts to overtake the front-running horses (denoted in the program by a symbol at each point in the race) would have resulted in slower closing speed if the competition was better bred (indexed by factors such as claiming price and purse size), because each attempt to overtake better-bred horses in front of him would have led them to increase their speed and thus would have kept him off the rail for a longer portion of the race than the relatively weaker-bred horses were able to do in the race in question. Therefore, in a race with better-bred horses, he would have run a longer distance than he ran in the race in question, because cheaper horses could not keep him off the rail when he tried to overtake front-running horses. The expert considers all of these variables (and others) in arriving at a prediction of closing speed and post-time odds. The experts were able to complete this task with impressive accuracy. Note the assertion about the 8-horse: "He'll go off even money." Experts were able to estimate odds and closing speed far better than nonexperts, and this ability was causally related to their complex reasoning and prediction of winners. However, the complexity of their reasoning was unrelated to standardized measures of intelligence, including Wechsler Adult Intelligence Scale scores.

Figure 1 shows one line from the early form of the racing program for one horse named Direct Scooter. He ran this particular race at a track that was 5/8 mile in circumference in a $30,000 prize race. The turf conditions were fast (based on moisture content). The last quarter mile in the race on May 25 was run by Direct Scooter in 29 2/5 s (1:54 and 2/5 minus 1:25), and he ran this fast despite some early fighting to overtake front-runners. Experts will process several months of race data for each horse entered in the race, and most of the calculations are more complex than the example here. It is working memory intensive to hold all of the data in consciousness and qualify each analysis by myriad factors.

Notwithstanding its cognitive complexity, handicapping races is perhaps not a talent we would encourage in our children. But this ability provides an interesting window through which to study talent. As is true of other forms of talent, among a group of individuals with similar experience, only a subset develops true expertise. They are the ones whose passion and intuition prompt them to create complex mental models of racing that they continuously refine until they capture the empirical reality. Much of talent is like this; those who acquire it may have special gifts to begin with (excellent working memory capacity and analytic ability), but these gifts will be unactualized in the absence of years of practice and motivation—practice that involves the reciprocal interactions between predictions and reality, progressively more complicated, and enduring over time, for years. Nonexperts were satisfied with models they developed early in their racetrack experience, even though these models were incomplete—they did not generate the same impressive predictions that were made by experts' models, although nonexperts were far better than novices. The researchers found that the reasoning of expert handicappers was implicitly based on a



HOW TO READ PROGRAM

The horse's head number, saddle cloth number, program number, mutuel number and post positions are the same except where there is an entry in the race. The initials immediately following the horse's name represent color and sex, figures denote age. The names following are the horse's sire, dam and sire of dam in that order. Under the horse's name are his lifetime earnings and lifetime record preceded by his age when record was made up to January 1 of the current year. Following the lifetime earnings is the name of driver, his date of birth, weight and his colors, Next is the horse's best winning time on a half-mile, five-eighths, three-quarter or mile track for last year and his current racing season, followed by his starts and the number of wins, seconds, thirds in purse races and his money winnings. Beneath the horses's name are records of his eight most recent They read from bottom to top, therefore the top line is the horse's last race.

The date of the race is followed by the name of the track. All tracks are half-mile unless followed by the figure (1) which means that it is a mile track or (¾) which is a three-quarter mile track, etc. Then is noted the Purse, condition of the track on the day of the race, the Conditions of the race or if a Claiming Race the Claiming Price. Race distance, time of leading horse at the ¼, ½ and ¾ follow, then comes the winner's time. The figures that follow in order show the post position of the horse, his position at the ¼, ½, ¾, stretch with lengths behind except for the leading horse whose number denotes lengths ahead, and finish with unbeaten lengths. If he was a winner, it shows how far ahead of the second horse and the losers show how far they were behind the winning horse. The next figures show the horse's actual time in that race. Whenever a small "°" appears after the calls, it denotes that the horse raced on the outside at least one-quarter of a mile. In some instances these figures won't appear because the track at which the horse raced did not have its races charted. Then follows the closing odds to the dollar, the horse's driver, and the order of finish, giving the names of the first three horses On most past performance lines at extreme right the post time temperature and weather allowance can be found. Example: 64-2 means 64 degrees and the track is rated as two seconds slower than normal.

KEY TO ABBREVIATIONS

Horses' Colors
b—bay
blk—black
br—brown
ch—chestnut
gr—gray
ro—roan

Horses' Sex
c—colt
f—filly
g—gelding
h—horse
m—mare

Track Conditions
ft—fast
gd—good
sy—sloppy
sl—slow
my—muddy
hy—heavy

Finish Information
P—Placing
nk—neck
ns—nose
hd—head
dh—dead heat
dis—distanced (over 25 lengths behind winner)

Wagering Information
N.B.—No Betting
N.R.—Not Reported
*—favorite
e—entry
f—field

Race Classes
Cd—Condition Race
3000 clm—Base Claiming price on this horse
Clm cd—Claiming Allowance
Ec—Early closing event
FA—Free for all
JFA—Junior Free for all
Hcp—Handicap Race
Inv—Invitational Race
Lc—Late Closing Event
Mdn—Maiden Race
Mat—Matinee Race
nw—Non-Winners
nw300ps—Average Earnings was less than $300 per start
Opn—Open To All
Opt Clm—Optional Claiming
Pref—Preferred
Qua—Qualifying Race
Stk—Stake Race
T—Time Trial
w—Winners

Racing Information
°—Raced on outside for at least ¼ mile
°°—Parked three wide
x—horse broke at this point
‡—Free-Legged Pacer
‡Hoppled Trotter
ix—break caused by interference
i—horse interferred with at this point
Qua (dr)—Qualifying Race for Driver
Qua (h-d)—Qualifying Race for both horse and driver
†—moved up in position at finish due to the disqualification of another horse
(P)—before driver's name indicates driver holds Provisional License issued to those with limited experience and subject to the approval of the Judges
T.Dis—Time for race was disallowed on this horse because of a placing due to other than a lapped on break at finish

B.E.—broken equipment
ax—break caused by accident
acc—accident
ex—equipment break
dnf—did not finish
BAR—Barred in wagering
dq—disqualified
(F)—after sire denotes foreign horse

(1)—Mile Track
(⅝)—⅝ Track
z—horse claimed
★—Matinee Race

PROGRAM and HEAD NUMBER | Date Of Race | Track Raced on | Purse | Track Condition | Type of Race Condition or Claiming Price | Distance of Race | Time at ¼ | Time at ½ | Time at ¾ | Time of Winner | Post Position | Position at ¼ | Position at ½ | Position at ¾ | Stretch Position and Lengths | Finish Position and Lengths | Horse's Actual Time | Equivalent odds to 1.00 | Driver | Best Win Time of Year | Name of Winner | Name of Second Horse | Name of Third Horse | Temperature and Time Allowance

5 DIRECT SCOOTER b h, 4, by Sampson Direct—Noble Claire by Noble Victory Trainer-W. Cameron
Valiant Racing Stable, G. Orlove, M. Fischer & R. Fogel WR(⅝)1:54² 1980 10 8 1 0 178,758
$298,162 — 3, 1:54 (1) Driver-WARREN CAMERON, 5-29-40 (154) RED-WHITE Hol(1) 1:54 1979 32 21 0 0 298,162
5-25 Brd⅝ 30000 ft 4-5yr Lc mi 27¹ :56¹1:25 1:54² 6 4° 1° 1 1¹ 1³ 1:54² *.10 (W.Cameron) DrctSctr,TijuanaTaxi,LimeTm 82-0

Figure 1. The early form of the racing program for one horse named Direct Scooter.

complex interactive model involving as many as seven variables. As noted, individual handicappers' levels of performance at picking winners and predicting odds were uncorrelated with both their educational accomplishments and their IQ scores ($r = -0.07$ between IQ and the β coefficient for interactive thinking), leading the authors to conclude that "the assessment of the experts' intelligence on a standard IQ test was irrelevant in predicting the complexity of their thinking at the racetrack."[4]

In the next section, we shift to deductive analysis; we describe one theory's explanation of the developmental determinants of acquiring talent. Can anyone with some threshold level of innate potential become talented if they engage in sufficient practice and thinking? What roles do the environment and genetics play? The bioecological theory of development provides a set of principles that address these questions while sidestepping the fractious nature–nurture debate over the proportion of variance each explains. As will be seen, sheer mass practice and stimulation is insufficient in fostering talent. Instead, what is required is practice that embodies so-called proximal processes.

What the bioecological theory predicts about extreme talent

In an oft-quoted article written nearly 60 years ago, Anastasi[5] urged intelligence researchers that instead of seeking "to discover how much of the variance was attributable to heredity and how much to environment . . . a more fruitful approach is to be found in the question 'How?' . . . There is still much to be learned about the specific modus operandi of hereditary and environmental factors in the development of behavioral differences" (Ref. 5, p. 197). In making this argument, Anastasi argued that, rather than the assignment of variance to each source, a scientifically more fruitful approach to the heredity–environment problem is to address the question of how these sources interact "in place of focusing on which source and how much it contributes." It would be decades before researchers fully embraced her position.

Today, nearly 60 years later, her enjoinder continues to be current. The bioecological theory was formulated to explain how genotypes are translated into phenotypic talent. In what follows, we introduce evidence from different domains (sex differences in cognition, schooling effects on IQ) in support of this theory. We begin with the finding that changes in the environment can result in changes in a wide variety of both cognitive and non-cognitive outcomes, including academic achievement, basic cognitive processes (episodic memory), and IQ. However, we go beyond these observations to provide a theory of the mechanisms that produce such change. Specifically, we draw on Bronfenbrenner and Ceci's bioecological theory of how genotypes for cognitive outcomes are translated into phenotypes.[6] Some of the support for this theory has been known for many decades, while other evidence comes from recent research.[7]

The bioecological theory posits explicit measures of the environment, conceptualized in systems terms, which allow for nonadditive, synergistic effects in gene–environment interaction, and empirically assessable mechanisms, called *proximal processes*, through which genetic potentials for competence are actualized. The theory is built on three connected principles, each of which finds empirical support.

Principle 1: Especially in its early phases, and to a great extent throughout the life course, human development takes place through processes of progressively more complex reciprocal interaction between an active, evolving biopsychological human organism and the persons, objects, and symbols in its immediate environment. To be effective, the interaction must occur on a fairly regular basis over extended periods of time. Such enduring forms of interaction in the immediate environment are referred to henceforth as proximal processes.

Bronfenbrenner and Ceci described examples of proximal processes in parent–child, child–child, and child–object activities—group as well as solitary play, reading, learning new skills, problem solving, performing complex tasks, and acquiring new knowledge and know-how. They found support for each prong of this principle (e.g., the interactions had to be reciprocal, extend over fairly long periods, and become progressively more complex). Activities that were unidirectional or short-term or not progressive were often ineffective.

Principle 2: The form, power, content, and direction of the proximal processes driving development vary systematically as a joint function of the characteristics of the developing person, of the environment—both immediate and more remote—in which the processes are taking place, and of the nature of the developmental outcomes under consideration.

Characteristics of the person include genetic endowment as it plays out in various environments. Again, empirical support was summoned for each of the prongs in this principle. Finally, although many experiences facilitate talent development, proximal processes are the most effective "engines" driving the acquisition of skill.

Principle 3: Proximal processes serve as a mechanism for actualizing genetic potential for effective cognitive and social development, but their efficacy is also differentiated systematically as a joint function of the same three factors stipulated in principle 2.

Bronfenbrenner and Ceci hypothesized that proximal processes raise levels of cognitive and social functioning, and thus increase the proportion of individual differences attributable to actualized genetic potential for such outcomes. Importantly, they demonstrated that heritability is higher when proximal processes are strong and lower when they are weak. If a child has the genetic potential to speak Russian, write computer code, or paint but attends schools that do not expose her to progressively reciprocal processes in these realms, she will not actualize her potential. Heritability for these traits will thus be low. Others have shown that, across the 20th century, heritability has been lower in times of scarcity and famine because genetic potential is less likely to be actualized owing to lack of resources.[8]

In short, as the level of proximal process is increased, indices of competence will rise and those of dysfunction will fall, and the power of proximal processes to actualize genetic potentials for competence (as assessed by an increase in h^2) will be greater in advantaged and stable environments than in disadvantaged and disorganized ones.

In 1994, when Bronfenbrenner and Ceci theorized about the power and direction of proximal processes, there was only limited evidence to work with, so they based many predictions on pure theory supported by a literature review. Critical empirical tests were not available at that time. Thus, their main hypothesis was anticipated but not demonstrated when they opined that, while heritability increases in good environments because it reflects latent potential becoming manifest, the actual gap between advantaged and disadvantaged youth diminishes because much of the gap is caused by environments that lack proximal processes: "If persons are exposed over extended periods of time to settings that provide developmental resources and encourage engagement in proximal processes to a degree not experienced in other settings in their lives, then the power of proximal processes to actualize genetic potentials for developmental competence will be greater for those living in more disadvantaged and disorganized environments."

An early illustration of the power of proximal processes was provided by a Dutch researcher, Riksen-Walraven.[9] She assigned 100 infants and their caregivers to one of four conditions. Caregivers assigned to the "responsiveness" condition were told that infants learn best from the effects of their own behavior rather than from unidirectional instruction from others. Caregivers in this condition were instructed not to direct the infant's activities too much, "but give the child opportunity to find out things for himself, and to respond to his initiations of interaction" (p. 113). This condition captured much of what is meant by proximal processes—reciprocity between caregiver and infant, progressively more complex and enduring (in this case for 3 months). Caregivers assigned to the other conditions varied in these regards. In the "stimulation" condition, caregivers were told of the importance of providing a variety of experiences, such as "to point to and name objects and persons and speak a lot to their infants" (p. 112). There was little that was reciprocal or increasingly complex in this. A third condition combined these first two instructions, and the final condition was an untreated control group.

Riksen-Walraven confirmed that the caregivers' behaviors 3 months later conformed to the instructions they had been provided; they differed markedly in the way they interacted with their infants. As anticipated by bioecological theory, by the end of 3 months of caregiver–infant interaction, the infants assigned to the responsiveness condition exhibited a higher level of cognitive competence (they learned a contingency task more quickly). Thus, this early experiment contained the principal ingredients described above: the proximal process was caregiver responsiveness to the infant's initiations; the responses were progressively complex and reciprocal, unlike the stimulation group; and these proximal processes occurred over relatively long periods of time. The absence of any ingredient reduces the likelihood of the positive outcome.

Although we have no scientific documentation of the role of proximal processes in the development of expertise at the racetrack, there is some anecdotal information indicating that handicappers engaged in a long-term reciprocal process that was increasingly complex. Immediately following each race, experts, but not nonexperts, would review their predictions by studying the instant replay on the monitor and challenging their beliefs. Often they would exclaim that their reasoning was correct in spite of failing to correctly predict the outcome, pointing to a variable that intervened; at other times they would recognize they failed to consider a variable, which led to their mistaken prediction. Nonexperts rarely reviewed their predictions after the race ended, preferring instead to move to the next race in the program. It suggests that those with high levels of talent do not rest on their laurels, but continuously self-challenge, refine, and update their expertise in a reciprocal back-and-forth process between their thoughts and the race that is unfolding on the monitor. In a similar manner, researchers studying forecasting tournaments (elections, wars, economic crises) documented that successful forecasters engage in a continual, progressive reevaluation of their mental models, and it is this enduring, progressive reevaluation rather than their intelligence that is critical.[10] Superforecasters' intelligence scores are around the 80th percentile, whereas professional forecasters, whom they routinely outperform, have higher intelligence, but it is the continual reappraisal of their mental models in response to feedback that is predictive of superforecasters' success in making predictions.

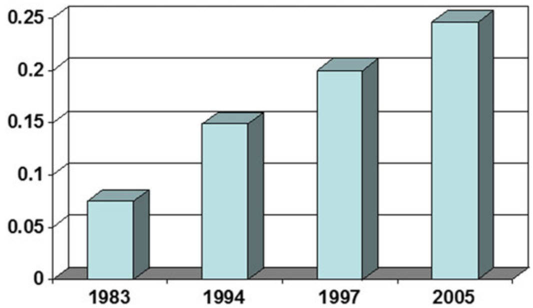


Figure 2. The changing percentage of female students at the extreme right tail in mathematics ability at age 13. From Ref. 13.

Domains of talent development

Schooling as a proxy for proximal processes

The most enduring interventions are associated with schooling, although the elements of reciprocity and progressive complexity cannot be guaranteed for most students. Notwithstanding this very real limitation, there is evidence that systematic variations in schooling are associated with substantial changes in expertise. At the level of sheer school attendance, we know that students who attend school less (e.g., due to travel, longer summer vacations, illness), start school late (e.g., due to regional cutoff dates that vary), or drop out of school early experience substantial IQ decrements. We have reviewed this evidence elsewhere.[11] For example, using Scandinavian data, it has been shown that two 14-year-olds with identical IQs will drift apart after one drops out of school, by on average 1.8 IQ points for each year. In some studies this decrement ranged between 2 and 4 IQ points per year of missed schooling.[12]

In the domain of mathematics, it is well documented that changes among elite students can occur as a result of increasing the number and level of math courses they take during their high school years. As recently as 1983, it was rare to find girls scoring in the extreme right tail of the mathematics score distribution. As seen in Figure 2, there were 13 male students for every female adolescent who scored in the top 0.01% (top 1 in 10,000). However, by 2005, this had improved to a 3-to-1 to 4-to-1 ratio of males to females in this elite range,[13] a result some scholars have attributed to increased number and level of mathematics courses taken by girls—although much of girls' advances occurred by the mid-1990s, and no further advance at the right tail of math achievement has occurred since then.[14] This suggests that interventions that led to girls making choices to take more math courses and more advanced math courses resulted in a significant start-up boost for girls, but that other factors are responsible for the remaining gender gap.

In the realm of spatial reasoning, the situation is similar, though less dramatic. A very large number of studies (and a half dozen meta-analyses of them) have amply documented large sex differences in mental rotation, especially 3D rotations.[15,16] This sex difference has been reported all over the world and in all age groups. The high female drop-out rate from engineering programs has been linked to poorer 3D mental rotation ability; freshmen graphics courses in engineering rely on 3D spatial rotation skills, and Sorby and Bartmaans[17] found that the mental rotation skills tapped by the Differential Aptitude Test are the single best predictor of freshmen engineering performance in a visual graphics course. Sorby[18] demonstrated that a freshmen course she designed to promote spatial reasoning was successful not only in increasing female spatial skills but also in stemming the drop-out rate from engineering and increasing female students' GPAs. Numerous researchers have demonstrated that an intervention involving playing spatially loaded videogames for 3 months nearly closed the gender gap in mental rotation ability scores.[19] In line with the bioecological theory, these interventions were reciprocal and enduring (3 months or longer) and they led to progressively increasing complexity as each new attainment led to an even more complex challenge. However, the epitome of an enduring intervention is one that lasts years or even epochs, such as childhood or school years. A number of studies of schooling and child-rearing practices fit this profile of enduring interventions.

On a broader scale of educational analysis, James Flynn has charted the steady, systematic gains in IQs over time to which his name is attached, the "Flynn effect."[20] These IQ gains are generally associated with increases in formal education but are obscured by periodic re-norming. Were IQ tests not re-normed, the cumulative growth in intelligence test scores would be dramatically obvious. Consider: of those persons born in 1877 who were part of the cohort that took the first IQ tests in the early 1900s, mean IQ would have been just below 70 if they were scored using contemporary IQ norms. This finding has led Flynn to conclude that, "Only the worst of the 2,200 school children used to norm the WISC-IV (in 2003) would have performed as low as the average child of 1900" (Ref. 21, p. 23). The flip side of this finding is that nearly all students born in recent decades would have been scored in the talented/gifted range of IQ if they were scored using norms developed from their great-grandparents' cohort! Such steady, cumulative gains in IQ performance are, as already noted, masked by periodic re-norming to reset the mean at 100. But as far as the actual cognitive performance is concerned, today's students are showing the benefits of the enduring intervention of increased schooling, especially in the post–World War II era in which activities shifted from a focus on practical goals to more abstract ones, which are tapped by some of the IQ subtests (e.g., detecting similarities between objects or concepts).

Rindermann and his associates have repeatedly shown the power of schooling (age of onset, type of school, class size, amount of schooling, etc.) in large-scale transnational analyses.[22] He has demonstrated that a positive schooling effect extends to talented students who attend programs in which teachers adapt teaching to individual and classroom ability levels and students are stimulated by other talented students.[23] Along these lines, Weber and her colleagues found that the magnitude of gender differences in three separate cognitive domains (episodic memory, mathematics, and fluency) fluctuates systematically with changes in living conditions and cognitive stimulation occurring in these places over time.[7] In line with bioecological principles, these researchers found that women benefit cognitively from these societal improvements more than men do, leading to greater sex differences in episodic memory favoring women, decreased gender differences in math, and elimination of gender differences in fluency.

Culture as a context

In an examination of the role of culture in spatial ability, researchers assessed nearly 1300 participants in two adjacent rural Indian villages (Karbi and Khasi, close kin) who were involved in the same form of subsistence rice farming and shared their genetic background on the basis of genetic analysis of six polymorphic loci.[24] None of the participants had prior exposure to puzzles. The Karbi are a patrilineal tribe whereas the neighboring Khasi are matrilineal.

The most obvious difference between the tribes is that the Karbi are a patrilineal tribe (e.g., women are not supposed to own land, and the oldest son inherits the property), whereas the Khasi are a matrilineal tribe (property is inherited by the youngest daughter, men are not allowed to own land, and any earnings of the male are supposed to be handed over to his wife or sister). The different societies are described in greater details elsewhere.[24]

Participants were given the equivalent of 25% of daily wages to solve a four-piece jigsaw puzzle that they had never seen before. The researchers found that spatial puzzle-solving ability was influenced by the interaction of education and culture. In the patrilineal tribe there is a gender gap, with males better educated than females; in the matrilineal tribe there is no gap. Each year of education was associated with a 4% reduction in time to solve the puzzle. However, controlling for education, there was a gender × culture interaction, indicating that substantial variance was explained by factors other than education. Among those living in homes owned by women or jointly owned by men and women, the gender gap in spatial ability was only one-third as large as in homes owned by men. In the matrilineal society, there was no gender gap.

Although none of the studies described has to do with the cultivation of special gifts, the same bioecological principles would seem to be relevant when it comes to fostering extreme talent. Numerous anecdotal reports exist in support of this claim. The best known is that of Antonio Vivaldi's legendary protégées at a Venice *ospedale* attached to a church. This was a combination hospital–orphanage–sanitarium where girls (and a few boys) were sent and lived in cloistered surroundings until they left to be apprentices or marry, or took vows and remained for life. Vivaldi was the music master at one such *ospedale* and the girls under his tutelage became renowned throughout Europe as musicians and singers. This is a particularly apt illustration of the three bioecological principles because the intervention (Vivaldi's instruction) was enduring for many years in the girls' lives, and it was increasingly complex (the girls moved along a laddered program from novices to teachers themselves as their skills increased), and Vivaldi's methods were continuously reciprocal, scaffolding the girls' efforts in an upward spiral. Royalty, popes, and musicians visited the *ospedale* to attend its concerts, including

J. S. Bach, who lauded their performances as being of the highest caliber. That a group of young girls who were not selected for their musical ability could be honed into world-class musicians suggests the power of proximal processes in the development of talent. None of this means that a genetic basis was unimportant, but it illustrates the germ of the bioecological theory, which states that heritability is maximized under conditions in which proximal processes flourish; it is highly unlikely that any of Vivaldi's girls would have crystallized their potential to become musicians without long-term exposure to proximal processes.

In sum, research shows that gene × environment effects vary depending on the social conditions of students and their families, with higher genetic contributions manifesting in higher–socioeconomic status (SES) families and their accompanying proximal processes, as postulated by the bioecological theory.[25] Lower-SES homes are typically those with lower levels of proximal processes, and consequently they exhibit attenuated genetic effects on talent, whether the latter is indexed by high IQ scores or achievement scores. This is in line with micro-level demonstrations of the power of proximal processes to drive cognitive outcomes,[9] which are also consistent with large-scale trends[20] and macro-level analyses of regular and gifted education across nations.[23] Merely increasing stimulation, massing practice, and providing rewards are not sufficient to produce high levels of talent. Instead, it is necessary to guide the learner from her or his current state by building on it with progressively small but increasingly complex steps, over long periods of time. Short-term interventions are less likely to actualize potential talent. When an infant at the beginning stage of language expression and comprehension points to an object and utters a sound, an effective proximal process entails elaboration and progressively complex utterances, each of which builds on the child's utterance, rather than mass practice; for example, responding to a child's utterance of "ball" by saying, "Yes, it is a ball, a red ball, and it is bouncy." In this way, proximal processes scaffold a child, taking the child's starting point and progressively elongating and embellishing it through a process of reciprocal interaction. Programs predicated on increasing stimulation through repetitive exercises are unlikely to elicit potential for talent.

If parents, schools, and cultures are the vehicles that drive student competence, proximal processes are the engines that propel these vehicles and point them in the right direction. This central mechanism in the development of giftedness is illustrated by the responses of gifted students themselves when asked about the roots of their high level of talent. We asked high-ability high school students in our local school district to think back on the beginnings of their talent and how it emerged, especially with regard to the types of intervention and training these students received. As can be seen in their responses, these students frequently described proximal processes in which their parent, teacher, or coach took them through progressively more complex levels of attainment, rather than assigning rote repetition and drill. This reliance on proximal processes was even apparent for medalists in sports, a domain in which one might imagine that sheer repetition of strengthening exercises is the prime driver. The diversity of talents developed by these youth illustrate the many environments in which proximal processes can work to further exceptional talent.

In their own words: what gifted high school students say about how they developed their talent

All this discussion about the importance of proximal processes in development of exceptional talent leaves us wondering how the landscape appears from the eyes of gifted and talented youth themselves. So we asked an ethnically and gender-diverse group of gifted/talented high school students to describe their special talents, and to comment on the precise steps involved in developing their talent. As can be seen, these gifted students usually indicated that the domain of their special talent was discovered on by themselves (e.g., realizing at age 5 that they loved the sound of a certain instrument or that they were drawn to the use of language to describe events), not by their parents or teachers. But once each alighted on a domain that excited her (music, mathematics, creative writing, athletics), they gravitated toward resources in their environment that pushed them progressively further along the path of developing expertise. Although they did this without any awareness of the concept of proximal processes, most of these students described a process that comprised reciprocal, increasingly progressive interactions with persons or objects in their environment that endured over long periods.

Chance: My very best talent is something that I've always been very skilled at: creative writing. From a young age, I have produced works of complexity on varying topics. As early as kindergarten, teachers noticed this talent of mine, and repeatedly notified my parents of it. Since then, I have worked with the aid of my parents and some teachers to hone this skill, to the point at which I have become a masterful creative writer. The process began with my parents reading my drafts. They would constantly spot improvements I could make to logistical and technical aspects of my use of language, such as grammatical constructions. However, after I became old enough to recognize the technicalities of language use, and after I routinely began incorporating them into my creative writing, my parents would point out more complex layers of insight. For example, they would point out ways for me to make my plots more complex, or my characters more multidimensional. As my competence grew, my parents started to give me more and more complex advice, until my writing got to the point at which I began winning local contests, tri-county writing competitions, and placing in regional and national competitions. This culminated in my recent gold medal award in a national writing competition.

Alicia: Two weeks ago I performed in my violin teacher's studio recital; I played the *Gavotte en Rondeau* and *Gigue* from the Bach sonatas and partitas for unaccompanied violin. I have been playing violin since I was 5 years old, and of course I can't remember, but my mom says that I chose myself to play violin because I liked the sound of the instrument. Because I started learning at the Suzuki program, my mom was very involved, taking notes on my lessons and helping me practice; however, I wanted to be more independent, and by the time I was 8 or 9, I had kicked my mom almost completely out of my practicing and was trying to get her out of my lessons as well. When I was 12, with my mom's support, I left this program and found another teacher. From then on, my solo violin playing has been interactive pretty much only with my teacher. I have weekly lessons, and she gives me considerable choice in what pieces I play and in how I musically interpret those pieces.

James Yoon: I think most of the talents that I've developed were results of my own initiative more so than they were results of my parents' guidance. I'm a pretty independent person, but my accomplishments, as insignificant as most of them are, developed only through asking for feedback, receiving criticism, gradually improving, and so on.

Ruth: One of my major accomplishments was making it on the junior dance team after only dancing for a few years. Dancing is something that I originally enjoyed doing, but I mostly improved because my teacher saw potential and helped to motivate me. My experience was interactive. I worked on dancing a lot at home, but I got corrections from my teachers at the studio a few times a week to develop my technique even further.

James Park: One of my major accomplishments would probably be swimming a 5K back in the summer before 8th grade. This took a lot of preparation and effort, but it definitely wasn't something that I could've managed on my own. I received help from almost everyone that knew about my endeavor: my coach, parents, friends. They were all so eager and willing to help out that, thinking back on it now, without them I almost certainly would have given up long before. As a result, the experience I had was very interactive, as I constantly learned at each step how to improve.

Isabel Comella: One of my proudest moments was in spring of 2015, when my friend and I raced our double (sculling boat, two people with two oars each) and won. We were the youngest competitors and yet we won. This double was put together by one of our coaches, but my friend and I were very enthusiastic about it. We came to many extra practices on our own without coaches needing to nudge us. We had some mentoring from coaches and encouraging words from parents, but because no one really expected us to win, a lot of the preparation came from us pushing ourselves, mentally and physically. One of my strengths as a rower is that I have good form. The area that my coaches have pushed me in is getting stronger. We lifted weights. Our coaches only told us we needed to get stronger, not to do anything specific to reach that goal. However, after each practice, a coach would tell us our strengths and weaknesses for that day, and the next day we would work on correcting them, getting progressively better as a double.

Inbal: This ability was something that I worked on because I was encouraged to do it by another person. I developed this talent partly working independently but mostly collaborating with someone else and getting feedback from them.

Alexei Aceto: In October 2015 I participated in the Ithaca College (IC) High School Piano Concerto Competition. This competition involved me learning a movement of a Mozart piano concerto, and later rehearsing it with an accompanist (who played a piano reduction of the orchestra's part). The competition required a finalized performance of this movement with the accompanist, and the winner would actually perform their movement with the Ithaca College orchestra. This was a very important experience for me; since my childhood I had seen a number of concertos performed by pianists whom I greatly admired. I guess I always knew that I wanted to be a pianist (I had been raised with the instrument and had lessons since I was 5). And being a concert pianist meant having these great performing opportunities, not to mention gaining all kinds of experience from playing with a conductor/orchestra. I had actually been working on my concerto movement for over a year before the competition came up... Preparing with the accompanist was so much fun for me. Finally there was someone to play the part of the music that I had listened to in my head for so long while playing on my own... I'm constantly listening to recordings of the concerto, in particular one by my favorite pianist, Piotr Anderszewski. And by now I'd say that I know the piece well enough to go through it all in my head, so that's another reference point—thinking about how I have played the piece in the past and ways I can change my overall performance. Music is a never-ending process, and I have to keep telling myself that in any amount of time I could discover an entirely new approach to the Mozart! I did not have any lessons on "the music" of the concerto—learning to play with continuity and lyricism, etc. I had actually been given lessons from my teacher on learning the notes and paying attention to the markings (dynamics, phrasing), but even these were very few and took place when I was first learning the piece. Recently I've been getting lessons with my teacher on the "music," and I feel like the piece has really taken some strides since October. As for the competition, it was pretty exciting and I really enjoyed it! And I think this outlook, which I unknowingly developed at the time, was what helped through the performance. As it turned out I won the competition, so I'm happy about how it ended. I'm greatly looking forward to playing the entire concerto soon. Of all the Mozart piano concertos, this has been my favorite for a long time. (A video of my performance can be found at https://youtu.be/dNz9CAA6u0U.)

These anecdotes are supported by the extensive reporting of Benjamin Bloom and his associates from their multi-decade project on talent development. For example, in describing students who achieved international acclaim by age 12, Bloom and Sosniak[26] pointed to the role of "a continual adjustment to the child learning the talent" (p. 89). The bioecological theory provides a theoretical basis to explain why progressive adjustments are necessary in talent development, and in predicting when and how biological potentials for talent will become actualized, with the key component being the concept of proximal processes. Each of the students' reports illustrates the importance of proximal processes, such as Chance's testimonial that "As my competence grew, my parents started to give me more and more complex advice," or Ruth's teacher's interactions that were progressively complex. In their words, we see the power of proximal processes to bring latent potential to fruition. Absent reciprocal, increasingly complex interactions, it is doubtful these students' talent would have reached their impressive levels.

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interviewed gifted high school students, compiled and edited these interviews, did follow-up interviews to expand on relevant concepts, and wrote up this portion of the manuscript. S.W.-C. also contributed to the section of the paper that discusses talent development.

Conflicts of interest

The authors declare no conflicts of interest.

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