REVIEW SUMMARY

SCIENCE OF SCIENCE

Recent discoveries on the acquisition of the highest levels of human performance

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BACKGROUND: Exceptional performers push the boundaries of human capability, drive innovation, and help solve the world's most pressing problems. For decades, research on the acquisition of human performance across domains (e.g., science, academia, music, sports, and chess) has primarily been conducted with young and sub-elite performers. This research suggested that, within these populations, higher early performance and larger amounts of discipline-specific practice generally are predictors of better later performance. Correspondingly, many elite schools, universities, conservatories, and youth sport academies around the world typically aim to select the top-performing young people and then seek to further accelerate their performance through intensified discipline-specific practice. Given that previous expertise research largely focused on young performers and that many elite training programs aim to select the top-performing young people, two critical questions arise: (i) Are exceptional performers at young ages and at later peak performance age largely the same individuals? And (ii) do predictors of young exceptional performance also predict later exceptional peak performance? Until recently, these questions were not systematically investigated among the world's best performers across domains.

ADVANCES: In recent years, research on the acquisition of exceptional performance has progressed. Several large datasets from adult world-class performers have become available to review and synthesize. The present literature review synthesizes findings on the development of more than 34,000 adult international top performers in different domains, including Nobel laureates, the most renowned classical music composers, Olympic champions, and the world's best chess players. The available evidence suggests a common pattern across domains with three major features. (i) Early exceptional performers and later exceptional performers within a domain are rarely the same individuals but are largely discrete populations over time. For example, world top-10 youth chess players and later world top-10 adult chess players are nearly 90% different individuals across time. Top secondary students and later top university students are also nearly 90% different people. Likewise, international-level youth athletes and later international-level adult athletes are nearly 90% different individuals. (ii) Most top achievers (Nobel laureates and world-class musicians, athletes, and chess players) demonstrated lower performance than many peers during their early years. Across the highest adult performance levels, peak performance is negatively correlated with early performance. (iii) The pattern of predictors that distinguishes among the highest levels of adult performance is different from the pattern of predictors of early performance. Higher early performance in a domain is associated with larger amounts of discipline-specific practice, smaller amounts of multidisciplinary practice, and faster early discipline-specific performance progress. By contrast, across high levels of adult performance, world-class performance in a domain is associated with smaller amounts of discipline-specific practice, larger amounts of early multidisciplinary practice, and more gradual early discipline-specific performance progress. These predictor effects are closely correlated with one another, suggesting a robust pattern.

OUTLOOK: The new evidence enhances our understanding of how world-class performance develops. The similar developmental pattern of world-class performers across different domains suggests widespread, if not universal, principles underlying the acquisition of exceptional human performance. Assumptions suggested by the evidence from young and sub-elite performers, along with other approaches discussed in the literature, cannot adequately explain the recent evidence. New explanations may further advance scientific understanding. As a starting point, we suggest three explanatory hypotheses: the search-and-match hypothesis, the enhanced-learning-capital hypothesis, and the limited-risks hypothesis. On the basis of the recent evidence, scientists can enhance theories, program managers can promote evidence-based practices, and policy-makers can better allocate funding. Such efforts may foster opportunities to enhance world-class performance across science, sports, music, and other fields. □

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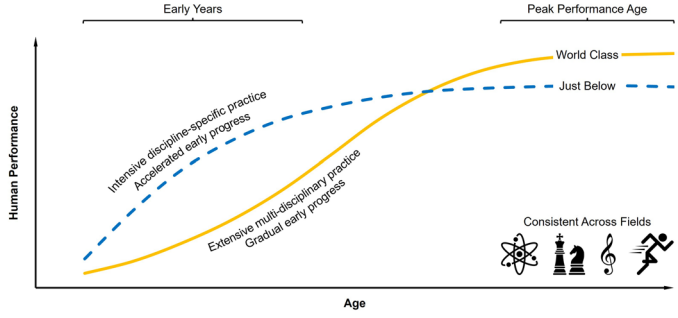

The development of the highest levels of human achievement. Across domains, world-class performers, compared with peers performing just below this level, engaged in more multidisciplinary practice and showed more gradual performance progress through their early years.

REVIEW

SCIENCE OF SCIENCE

Recent discoveries on the acquisition of the highest levels of human performance

Arne Güllich[1]*, Michael Barth[2], David Z. Hambrick[3], Brooke N. Macnamara[4]

Scientists have long debated the origins of exceptional human achievements. This literature review summarizes recent evidence from multiple domains on the acquisition of world-class performance. We review published papers and synthesize developmental patterns of international top scientists, musicians, athletes, and chess players. The available evidence is highly consistent across domains: (i) Young exceptional performers and later adult world-class performers are largely two discrete populations over time. (ii) Early (e.g., youth) exceptional performance is associated with extensive discipline-specific practice, little or no multidisciplinary practice, and fast early progress. (iii) By contrast, adult world-class performance is associated with limited discipline-specific practice, increased multidisciplinary practice, and gradual early progress. These discoveries advance understanding of the development of the highest echelons of human achievement.

Exceptional performers at the highest levels push the boundaries of human capability, drive innovation, and help solve the world's most pressing problems. What distinguishes these individuals from others? What makes Albert Einstein, Ludwig van Beethoven, and Simone Biles different from virtually every other person in history who has taken up physics, composing music, and artistic gymnastics? This question has been a topic of intensive research in a wide range of natural and behavioral sciences for well over a century (*1*, *2*). Nevertheless, the answer has remained elusive.

Until recently, research on the acquisition of expertise typically relied on studies conducted among the general population or among young and sub-elite performers within domains, such as secondary and college students, youth athletes, young chess players, or conservatory students [e.g., (*3*–*40*)]. Some of this previous research focused on the idea that performers' cumulative amount of discipline-specific practice is the major predictor of performance, regardless of early signs of potential (*3*–*6*, *41*–*43*). A performer's practice amount may be moderated by constraints of available resources (e.g., facilities, instruments, transportation), effort, and motivation (*3*, *43*). According to this view, across performers, larger amounts of discipline-specific practice predict higher performance. This view also suggests that, across domains, someone who begins early and maximizes discipline-specific practice will have a performance advantage throughout their career compared with someone who starts later (*3*).

Some other research on young people has taken more nuanced approaches. This research suggests that, across different domains, exceptional performance emerges from an interplay of multiple factors [see (*44*–*49*) for reviews]. These factors include characteristics of the person—early performance and corresponding early abilities, interest, task commitment, motivation, perseverance—and of the environment—long-term discipline-specific practice, opportunities, teaching or coaching, material provisions, and social support. When young people demonstrate exceptional early performance in a discipline (e.g., a school subject, basketball, concerts) and/or in corresponding abilities (e.g., intelligence, ball-handling, musicality), this is often considered an indicator of long-term potential (*7*–*12*, *44*, *50*–*58*).

Research has provided ample empirical support for the importance of early performance and discipline-specific practice among young and sub-elite performers: Consistent across domains, higher early performance and larger amounts of discipline-specific practice generally are predictors of better later performance [e.g., (*3*–*40*, *57*, *59*, *60*); these studies involved 5923 samples including N = 1,142,248 total participants]. This implies that, compared with less accomplished peers, young people with higher early performance and larger amounts of discipline-specific practice have better odds of developing higher later performance.

Correspondingly, many elite training programs typically aim to select the top-performing young people and then seek to further accelerate their performance through intensified discipline-specific practice. Examples include highly selective elite schools, universities, and conservatories, as well as elite youth orchestras, youth sport academies, and sport and chess federations' youth squads (*3*, *8*, *9*, *11*, *12*, *56*–*58*, *61*–*63*).

Investigations into the acquisition of the highest levels of human performance at peak performance age (*45*, *64*) have traditionally been limited. However, several large relevant datasets have recently become available. In addition, a number of studies that focused on different research aims included datasets on the development of exceptional performers. In this literature review, we synthesize the evidence on developmental patterns of international top performers across multiple domains.

Given that previous expertise research largely focused on young performers and that many elite training programs aim to select the top-performing young people, a critical question arises: Are young exceptional performers and later adult exceptional performers largely the same individuals across time? Supposing this is the case would imply that predictors of young outstanding performance also predict eventual adult outstanding performance. Notably, these assumptions have not been systematically investigated among the highest levels of peak performance [in creativity performance terms (*65*), "Big C" performers] across different domains.

Recent findings from world-class athletes (*57*, *59*, *60*, *66*) challenge these assumptions. This evidence has raised new questions that are critical to understand the acquisition of the highest levels of human capability across domains:

1) To what extent are early and later exceptional performers the same individuals or different individuals across time?

2) Relatedly, did the world's best performers already outperform their peers in their early years? If early and later exceptional performers are not the same people across time, but are largely discrete populations, and if the world's best performers did not outperform their peers at young ages, then predictor effects on early exceptional performance and on later exceptional peak performance are likely different. Thus, the first two questions are related to the next question:

3) Do predictors of early exceptional performance also predict later exceptional peak performance? Finally, the ultimate question for understanding the highest levels of human performance:

4) What factors predict the world's best performers?

These questions have not been systematically investigated in domains other than sports and are the subject of this Review. The synthesis of the available evidence from thousands of adult international top performers suggests that early and later exceptional performers are rarely the same individuals; that, when comparing performers across the highest levels, peak performance is negatively associated

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with early performance; and that predictor effects on early exceptional performance and on later exceptional peak performance are different. Notably, early multidisciplinary practice is associated with eventual world-class performance. We discuss the evidence from studies and meta-analyses demonstrating commonalities among world-class athletes, Nobel laureates in the sciences, the world's best chess players, and the most renowned classical music composers.

Criteria to investigate the highest levels of human performance

Some domains are better suited than others for investigating the upper boundaries of human performance. To investigate the open questions above, a domain should ideally meet four criteria: (i) There are objective, internationally standardized performance measures. (ii) The performance standards enable reliable distinction of performance levels, including the world's best performers versus those performing just below this level. (iii) There are large numbers of people who endeavor, over a period of many years, to improve their performance. (iv) There are available data on potential predictors across performers' entire careers.

The domain of sports meets each of these criteria, thereby offering an excellent empirical testbed to investigate the highest levels of human performance. Sports is also the first domain where the critical questions about the acquisition of exceptional performance have recently been comprehensively investigated (*57*, *59*, *60*, *66*). Investigation of world-class performers in other domains is more limited. Yet, the evidence that is available is highly consistent across domains. In each of the following sections, we first review findings from world-class athletes and then describe the evidence from outstanding performers in science, chess, music, and other professions (see Table 1 for characteristics of reviewed studies of exceptional peak performance).

These domains differ in several ways, including critical skill sets (e.g., cognitive, artistic-aesthetic, sensorimotor) and the age structure of careers [ages of entry and of peak performance (*45*, *64*)]. The different domains are also characterized by critical commonalities. Notably, each domain includes discipline-specific tasks on which participants in a domain endeavor to develop their performance and on which the performers can be compared. Only a small number of people reach the highest echelons of performance on those tasks. Further, they are all societally valued domains where large numbers of people seek to improve their performance.

We review studies that were each conducted within a given domain and then we synthesize central findings across domains. We searched for studies and datasets that allowed us to answer our critical questions for the highest levels of performance (the required types of datasets and the study search and screening are described in supplementary fig. S1). In many cases, studies included data that met our criteria even though the studies themselves focused on different research aims and did not include analyses of these data that addressed our research questions.

Many studies included data from all individuals in a population such as all Nobel laureates, Olympians, or world top-10 chess players from a given cohort (*57*, *66*–*72*) or some of the largest datasets of their kind (*60*, *73*–*76*). The Review comprises 19 datasets including 34,839 adult international top performers in different domains (Table 1). In addition, to reflect previous expertise research, we also review data from 66 representative studies conducted among young and sub-elite performers and contrast these results with the evidence from adult world-class performers.

The recent evidence

Early and later exceptional performers are largely discrete populations

Previous descriptive studies prospectively followed gifted young people into adulthood or retrospectively examined eminent adults' early years (*15*, *66*, *77*–*81*). The prospective studies suggested that, indeed, a fraction of gifted youth later become exceptional adults, whereas many others do not. Likewise, in retrospective studies, some eminent adults showed exceptional performance in their youth, whereas others appeared less remarkable in their early years. Famous examples of the first pattern include composer Wolfgang Amadeus Mozart, golfer Tiger Woods, chess player Gukesh Dommaraju, and mathematician Terence Tao. Famous examples of the second pattern include composer Ludwig van Beethoven, basketball player Michael Jordan, chess player Viswanathan Anand, and scientist Charles Darwin. This discrepancy in apparent patterns raises the question of which pattern is the rule and which is the exception.

The descriptive evidence from prospective and retrospective analyses further raises the question of the extent to which early exceptional performers and later exceptional performers at peak age are the same individuals or different individuals across time. Recently, a large-scale meta-analysis synthesized longitudinal prospective and retrospective studies (*66*). The aim was to quantify the extent to which exceptional youth athletes and later exceptional adult athletes at peak performance age are one identical population or two discrete populations over time. The findings revealed that elite youth athletes and later elite adult athletes are rarely the same individuals at both time points—that is, they are largely two discrete populations.

The meta-analysis examined longitudinal performance data from >50,000 athletes, including 3375 international medalists, across every sport played at the Olympic Games (*66*). The datasets included prospective studies, where researchers identified the championship levels of junior athletes (i.e., in their teens) and then determined how many of those athletes reached an equivalent championship level at senior age [i.e., in the highest, open-age category, typically in their 20s to 30s (*64*, *82*, *83*)]. The datasets also included retrospective studies, where researchers identified the championship levels of senior athletes and then determined how many of those athletes had previously reached an equivalent championship level as juniors (*66*).

Most successful junior athletes do not achieve an equivalent championship level later as a senior athlete. In addition, most successful senior athletes did not previously achieve an equivalent championship level as juniors. For example, 82% of international-level junior athletes do not later reach the international stage as a senior athlete, and 72% of international-level senior athletes did not previously achieve the international junior level (*66*).

By combining prospective and retrospective analyses, the degree to which early junior and later senior exceptional performers are the same or different people at both times can be quantified with the equation shown in the legend of Fig. 1. The vast majority—nearly 90%—of junior and later senior international-level performers are different athletes (Fig. 1A). Likewise, when examining the top performers within this already elite group, junior and senior international medalists are also nearly 90% different athletes (Fig. 1A).

Applying the same approach to chess reveals that the world's top 10 at under-14 age and later senior top 10 (i.e., in the highest, open-age category), across time, are nearly 90% different players (Fig. 1B). When examining the top performers within this already elite group, under-14 top 3 and senior top 3 are also nearly 90% different players (Fig. 1B). Similarly, about 90% of the top secondary and later top university students are different people across time (Fig. 1C).

These investigations are more difficult in many other professions. For numerous occupations, professional performance cannot be authentically measured during youth, because there are no youth fighter pilots, brain surgeons, stock market traders, and so on. Thus, when examining early performance and later professional success, proxies such as youth top cognitive and academic performance and later adult top earnings have been analyzed. This approach was established in the seminal Terman Study of the Gifted [e.g., (*77*, *79*)] and later used in the Study of Mathematically Precocious Youth (SMPY) [e.g., (*15*, *73*)]. Even using proxies, combining longitudinal prospective and retrospective analyses demonstrates that early and later exceptional performers are largely discrete populations (Fig. 1D): The top 1% of childhood cognitive performers and later top 5% of earners are 99% different people (*67*, *73*); the top graduates from highly selective elite schools

Table 1. Characteristics of reviewed studies of exceptional performers at peak age. *N*, sample size; *k*, number of studies.

Study	Sample	Variables
Early and later exceptional performers are largely discrete populations		
(*66*)	Meta-analysis Prospective analysis $N = 29{,}690$, $k = 112$ Retrospective analysis $N = 20{,}696$, $k = 100$	Athletes participating and winning medals at international junior (in their teens) and senior championships (in the highest, open-age category, typically in their 20s and 30s)
(*69*)	Prospective analysis $N = 77$ Retrospective analysis $N = 26$	International top 10 and top 3 chess ranking at under-14 and at senior age (the highest, open-age category, typically in players' 20s and 30s)
(*74*)	Prospective analysis $N = 6{,}136$ Retrospective analysis $N = 6{,}136$	Top 6.7% secondary school graduation and graduation from elite university (Russell group, about 5% of the UK population)
(*73*)	Prospective analysis $N = 2{,}329$	Top 1% cognitive ability at 12 years and later top 5% salary in mid-30s
(*67*)	Retrospective analysis $N = 3{,}876{,}267$	Top 5% salary in mid-30s and earlier top 1% cognitive ability at 12 years
(*74*)	Prospective analysis $N = 6{,}136$ Retrospective analysis $N = 6{,}136$	Graduation from elite school (Tatler group, about 1% of the UK population) and top 5% salary at age 42 years
(*75*)	Prospective analysis $N = 7{,}499$	Graduation from elite (1st tier) university (about 5% of the US population) and top 5% salary in late 20s
(*67*)	Retrospective analysis $N = 4{,}373{,}400$	Top 5% salary in late 20s and earlier graduation from elite (1st tier) university
World-class performers do not stand out early and take longer to peak		
(*60*)	Meta-analysis 508 senior world-class and 420 national-class athletes	Performance trajectory (placing at championships at international, national, regional, and below levels) from age 14 to 22 years
(*68*)	330 Nobel laureates and 1,595 Nobel nominees, but not winners, in physics and chemistry	Performance trajectory (citation ranking within their discipline) through 28 years before the award or nomination
(*70*)	15 senior international 1st- to 3rd-ranked and 9 4th- to 10th-ranked chess players	Performance (Elo points) (*87*) by age 14 years and senior peak performance
Predictor effects on early performance and later peak performance are different		
(*60*)	Meta-analysis $N = 7{,}365$, $k = 260$; including 812 senior world-class and 1,496 senior national-class athletes	Age to start organized practice in one's main sport; age to reach performance milestones (e.g., first national and international championships); cumulative amount (sessions, hours) of organized practice in one's main sport through one's career; cumulative amount (sessions, hours) of organized practice in other sports through one's career
(*57*)	Meta-analysis $N = 6{,}233$, $k = 23$; including 1,361 senior world-class and 1,633 senior national-class athletes	Age to begin involvement in institutional talent promotion programs (elite youth academy and federation's under-age selection team or squad)
(*70*)	15 senior international 1st- to 3rd-ranked and 9 4th- to 10th-ranked chess players	Age to earn the International Chess Federation's (FIDE) grandmaster title
(*71*)	45 German Nobel laureates in the sciences and 307 winners of the highest national German science award, but not Nobel Prize	Obtaining a scholarship as a student; age to earn first full professorship; practice in other scientific disciplines and other professions outside of science
(*72*)	510 Nobel laureates in the sciences and 2,900 awardees of the Royal Society and the National Academy of Sciences, but not Nobel laureates	Practice in other professions and avocations outside of science
(*76*)	911 operas of the 59 most renowned classical opera composers	Success of each opera composed* and previous experience with composition within the same genre and in other genres
(*90*)	20,040 scientists with 20 or more papers, 4,377 film directors with 15 or more films, and 2,016 artists with 15 or more artworks, all with 10-year or longer careers	Variation of disciplines, genres, subjects, and artistic styles or intensified focus on a single discipline, genre, subject, and artistic style in the years before and during a hot streak

*As defined by performances at the 10 major international opera houses in the 20th century; entries as major work in standard opera encyclopedias, dictionaries, and histories of opera; and noted recordings in standard recordings guides and catalogs.

(*74*) and later top 5% of earners are 92% different people; and the top graduates from highly selective elite universities (*75*) and later top 5% of earners are 85% different people (Fig. 1D).

In the domain of classical music, there are no equivalent datasets to combine prospective and retrospective analyses. Nonetheless, prospective studies have reported that many child prodigies do not become adult top musicians, and retrospective studies have shown that many adult top musicians were not child prodigies (*80*, *81*, *84*–*86*).

In sum, the available evidence from diverse domains consistently suggests that the populations of early exceptional performers and later exceptional performers at peak age are largely discrete populations: Most early top performers do not become top performers at peak age and, perhaps more notably, most top performers at peak age were not early top performers.

Next, we report the available evidence on the performance trajectories of elite performers: the world's best performers and their peers achieving peak performance just below this level.

World-class performers do not stand out early and take longer to peak

Given that many adult top performers were not among the best performers of their age when they were young (Fig. 1), it is critical to understand how their performance developed over time. Here, we examine the performance trajectories of the world's best performers relative to peers

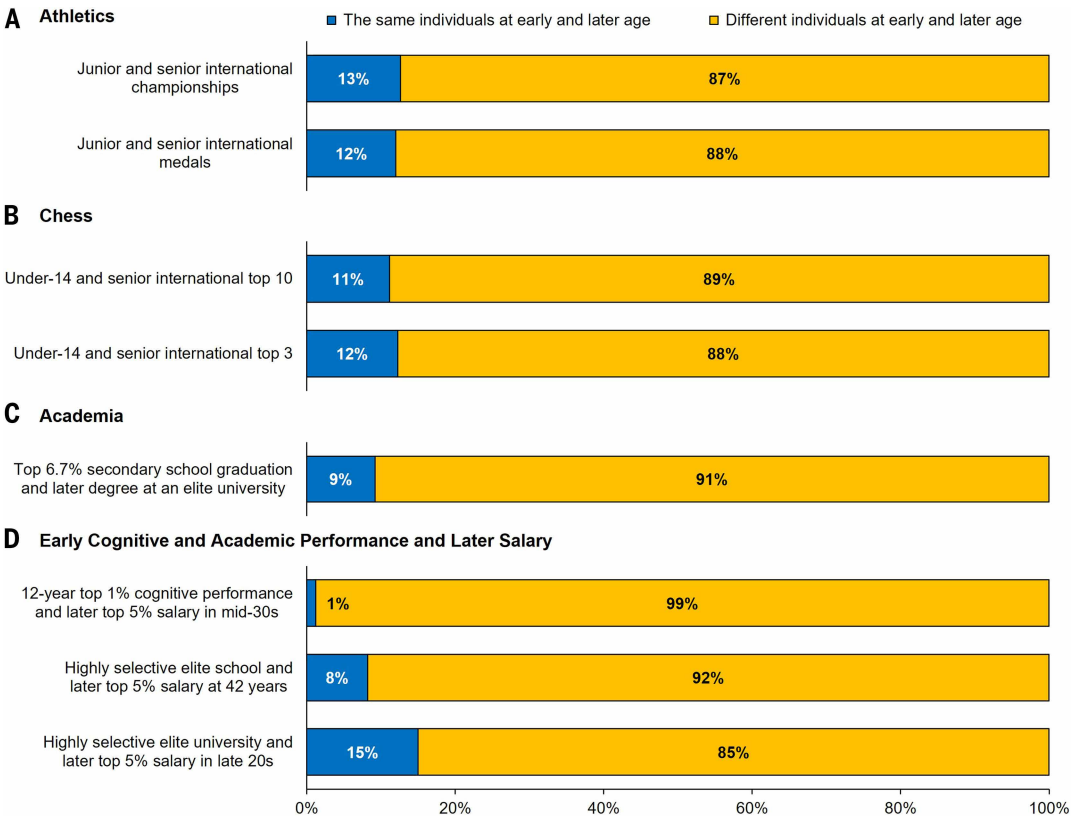

Fig. 1. The extent to which early and later exceptional performers are one identical population or two discrete populations across time. (**A**) Meta-analysis of studies involving athletes competing at international championships and athletes winning international medals during junior and later senior age. Based on data from (*66*). Prospective studies $k = 112$, $N = 29{,}690$; retrospective studies $k = 100$, $N = 20{,}696$. Junior athletes, individuals in their teens; senior athletes, individuals competing in the highest, open-age category, typically in their 20s and 30s. (**B**) International top 10 and top 3 chess ranking at under-14 age and at later senior level. Public rankings from the International Chess Federation (*69*); also see (*87*,*88*). Prospective analysis: All under-14 players ranked top 10 from 2001 to 2006, $N = 77$, follow-up until age 32 years. Retrospective analysis: All players ranked top 10 at senior level from April 2015 to March 2024, $N = 26$, follow-back of their earlier under-14 ranking. (**C**) Highest-achieving secondary school graduates and graduates from elite universities in the UK. Prospective and retrospective analyses $N = 6136$, respectively (*74*). (**D**) Early exceptional (top 1 to 5%) cognitive and academic performance and later exceptional (top 5%) salary (*67*,*73*–*75*). Prospective analyses $2328 < N < 7500$, retrospective analyses $6135 < N < 4{,}373{,}401$. See Table1 for study characteristics. In all panels (A) to (D), estimates of the proportions of identicality and discreteness across populations of early and later exceptional performers were computed by combining prospective and retrospective analyses based on equation $\%_{\text{identical}} = \frac{\%\text{identical}_{\text{prospective}}}{1+(1-\%\text{identical}_{\text{retrospective}})\,/\,\%\text{identical}_{\text{retrospective}} \times \%\text{identical}_{\text{prospective}}}$. Differences between domains in the extent to which early and later exceptional performers are two discrete populations are generally trivial ($\varphi < 0.10$). There are two exceptions with small effects: the 1% overlap between top 1% in childhood cognitive performance and those later earning top 5% salary is smaller than (i) the 13% overlap between junior and senior international-level athletes ($\varphi = 0.129$) and (ii) the 15% overlap between top university graduates and those later earning top 5% salary ($\varphi = 0.169$).

who achieved peak performance just below the highest level. Figure 2 illustrates the performance development through the careers of 508 senior world-class versus 420 national-class athletes (*60*) (panel A) and 330 Nobel laureates versus 1595 nominees who did not earn the Nobel prize (*68*) (panel B).

In both domains, the best performers at peak performance age, compared with their counterparts, demonstrated lower performance in their early years. Similarly, the senior chess players who ranked world top 3 through the last 10 years [April 2015 to March 2024 (*69*)], compared with those ranked 4th through 10th, scored, on average, 48 Elo points (*87*, *88*) higher at peak age, but had scored 62 points lower than their counterparts at age 14 (*70*).

In summary, when comparing performers across the highest levels of achievement, the evidence suggests that eventual peak performance is negatively associated with early performance. This evidence, along with the finding that early and later exceptional performers are largely different people, implies that predictor effects on early exceptional performance and on later exceptional peak performance are likely different.

Predictor effects on early performance and later peak performance are different

In sports, several predictor effects on early junior performance and on later senior world-class performance are not only different but are opposite (Fig. 3) (*57*, *59*, *60*). Higher-performing junior athletes, compared with age-matched lower-performing peers in the same sports, started their respective main sport at younger ages, entered institutional talent promotion programs at younger ages, and reached performance "milestones" (e.g., first national and international championships) at younger ages (Fig. 3). By contrast, senior world-class athletes, compared with age-matched lower-performing senior national-class athletes in the same sports, started their main sport at older ages, entered talent promotion programs at older ages, and reached performance "milestones" at older ages (Fig. 3).

Likewise, predictor effects of the types and amounts of practice also follow opposite patterns for elite junior and elite senior athletes. Higher-performing junior athletes, compared with lower-performing junior athletes, accumulated greater amounts of practice in their

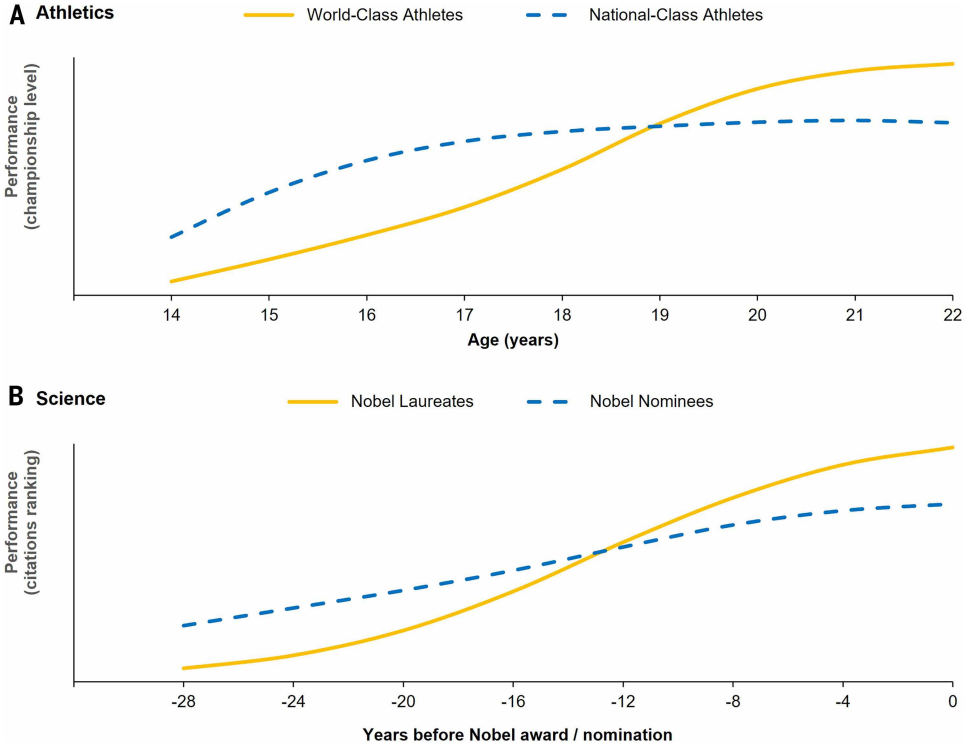

Fig. 2. Performance trajectories of the world's best athletes and scientists versus peers performing just below this level. Schematic illustration with smoothed (weighted moving average) normalized means and arbitrary units, respectively. (**A**) Performance level of 508 world-class versus 420 national-class athletes from age 14 to 22 years. Based on data from (*60*). (**B**) Performance level of 330 physics and chemistry Nobel laureates versus 1595 physics and chemistry nominees who have not earned the Nobel Prize; citation ranking through 28 years before the Nobel award or nomination. Based on data from (*68*) [extracted with Dagra software (*115*)]. See Table 1 for study characteristics.

main sport, but less practice in other sports (Fig. 3). By contrast, senior world-class athletes, compared with lower-performing senior national-class athletes, accumulated smaller amounts of practice in their main sport, but greater amounts of practice in other sports (Fig. 3). On average (sample-weighted means), senior world-class athletes engaged in two other sports over 9 years during childhood and adolescence. The findings are consistent across all types of Olympic sports (*57*, *59*, *60*).

There is corresponding evidence to junior athletes in other domains such as chess, academia, and music. At young ages, higher performance is associated with higher previous performance at earlier ages [e.g., (*7*, *9*, *10*, *12*–*14*, *16*–*23*, *26*, *29*, *30*, *32*, *34*, *35*, *37*, *39*); these studies involved 5005 samples including $N = 967{,}762$ total participants]. Likewise, higher performance at young ages is also associated with greater amounts of discipline-specific practice [e.g., (*3*, *4*, *6*, *11*, *18*, *24*, *26*, *30*, *36*, *38*); 78 samples, total $N = 19{,}411$].

The different pattern of predictor effects observed among adult world-class athletes is also evident in other domains. For example, consistent with world-class athletes' slower performance progress during their early years (Figs. 2 and 3), Nobel laureates in the sciences had slower progress in terms of publication impact during their early years than Nobel nominees (Fig. 2). Nobel laureates were also less likely to obtain a scholarship and took longer to earn their first professorship than the highest national-level awardees (*71*). Similarly, senior world top-3 chess players had slower performance progress during their early years than 4th- to 10th-ranked senior players (see previous section), and fewer world top-3 than 4th- to 10th-ranked senior chess players earned the grandmaster title of the International Chess Federation (FIDE) by age 14 years (*70*).

Furthermore, consistent with world-class athletes' greater multisport engagement, Nobel laureates in the sciences, compared with national-level awardees, engaged in more multidisciplinary activities in terms of study, practice, and working experiences, both within science (different disciplines) and outside of science (e.g., other professions, arts, music, and artisanship) (*71*, *72*). Similar to the additional two other sports played by world-class athletes, the Nobel laureates, on average, engaged in two additional avocations (*89*) (see Table 1 for study characteristics).

As another illustration, Simonton (*76*) investigated correlates of lasting success among 911 operas from the 59 most renowned composers of all time. Similar to the negative correlation between adult top athletes' performance and their amount of sport-specific practice, the success of composers' operas was negatively correlated with the number of genre-specific operas they had previously composed. Likewise, similar to the positive association between top athletes' performance and their amount of practice in other sports, the success of composers' operas was positively associated with the number of previous compositions across all genres. The findings imply that composers' previous experiences with diverse genres rather than specializing within a single genre predicted success (see Table 1 for study characteristics).

Relatedly, Liu and colleagues (*90*) investigated predictors of multiyear "hot streaks"—bursts of particularly high-impact works clustered together in close succession—among scientists, artists, and film directors. Hot streaks were consistently preceded by a multiyear period of work in other disciplines, genres, or artistic styles.

Table 2 provides an overview of the pooled effect sizes of multidisciplinary practice and gradual early performance progress on adult world-class performance across domains. All effect sizes are in the same direction and have a similar magnitude (Cohen's $d = 0.39$ to 0.58). Notably, effect sizes do not significantly differ across domains (Table 2).

Finally, meta-analytic evidence from athletics (*60*) shows that the performance-related effects of early performance progress, discipline-specific practice, and multidisciplinary practice are closely correlated with one another, implying a robust, coherent pattern of mutually connected predictors. This evidence suggests that world-class performers' greater multidisciplinary practice, reduced discipline-specific practice, and slower discipline-specific performance progress during their early years are not independent from one another. Rather, their slower early progress is associated both with their greater multidisciplinary practice along with their reduced discipline-specific practice.

Theoretical implications

There have been fewer investigations of adult world-class performers than of young and sub-elite performers. Yet, the evidence that is available is highly consistent for world-class performers across different domains. The evidence suggests that the development of the world's best performers is distinctive: The pattern of predictor effects that distinguishes among the highest performance levels is qualitatively different from the pattern that distinguishes among lower performance levels.

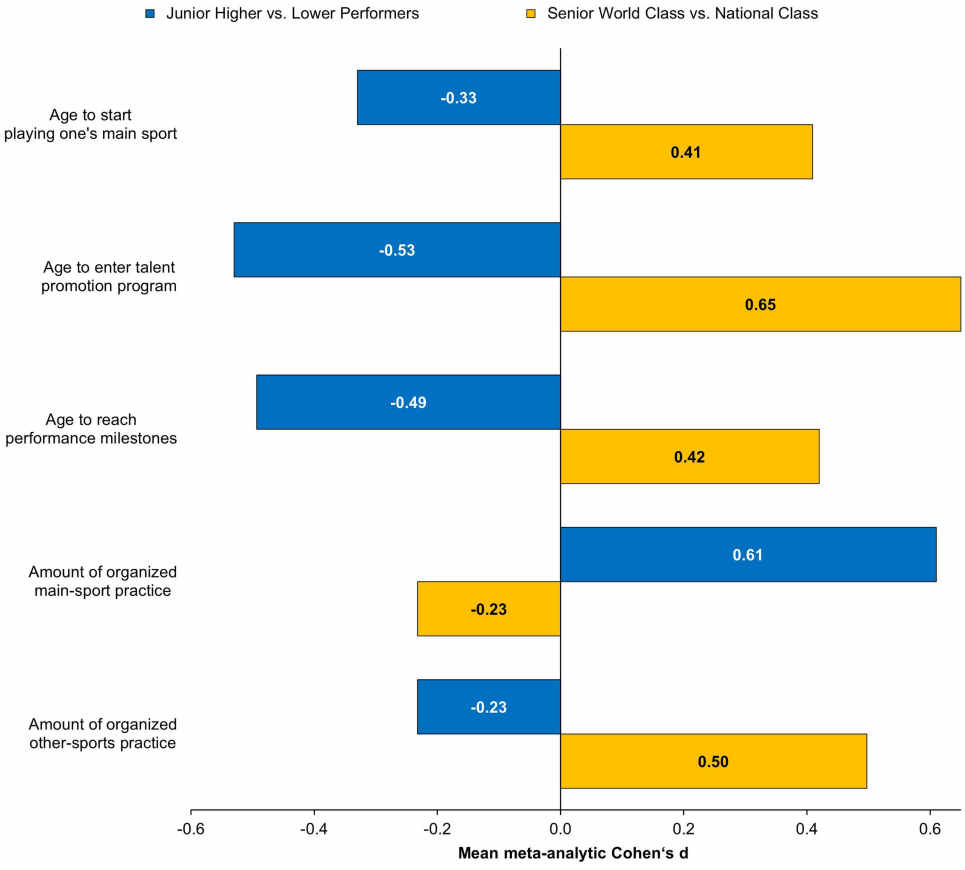

Fig. 3. Meta-analytic evidence of predictors of athletic performance. Blue bars: Predictor effects on higher versus lower junior performance. Orange bars: Predictor effects on senior world-class (adult international medalists or top 10) versus national-class performance (national-level top 10 and/or playing national premier league, but not world-class). Differences between higher- and lower-performing populations are expressed as mean meta-analytic Cohen's $\bar{d}$. For age-related predictors, a positive effect indicates that higher performance is associated with older (higher) age; for practice-related predictors, a positive effect indicates that higher performance is associated with larger practice amounts. Based on data from (*57*), $k = 38$, $N = 5004$, and (*60*), $k = 260$, $N = 7365$. See Table1 for study characteristics.

Table 2. Predictor effects on world-class performance across domains. A dash (–) indicates not available. Effect sizes computed as *r* or φ in original studies were converted to Cohen's *d*. Pooling of multiple effect sizes as sample-weighted mean. All differences between effect sizes across domains are nonsignificant ($0.29 < z < 1.01$). References: (*57*,*59*,*60*,*70*–*72*,*76*).

	Effect (Cohen's *d*) on world-class performance in:			
	Athletics	**Science**	**Music**	**Chess**
Increased multidisciplinary practice*	0.51	0.58	0.39	–
More gradual early performance progress†	0.43	0.41	–	0.56

*24 samples, $N = 5195$.
†47 samples, $N = 4803$; indicators of more gradual early progress: in athletics, age to reach first national and international championships; in science, obtaining a scholarship and age to earn first professorship; in chess, age to earn the International Chess Federation's (FIDE) grandmaster title.

Ample evidence from young and sub-elite performers shows that, in these populations, higher achievement is associated with faster early performance progress, higher early discipline-specific performance, larger amounts of discipline-specific practice, and less multidisciplinary practice (Table 3). Yet, across the highest levels of human achievement at peak performance age, predictors are inconsistent with the findings from young and sub-elite performers: Better peak performance is typically associated with more gradual discipline-specific performance progress during performers' early years, reduced amounts of discipline-specific practice, and larger amounts of early multidisciplinary practice (Table 3). Furthermore, consistent with the different patterns of predictor effects on early performance and on later exceptional peak performance, young exceptional performers and later exceptional performers are largely discrete populations over time.

This evidence does not conflict with the finding that early exceptional performers are more likely to become adult exceptional performers compared with the remainder of the population in a domain, ranging from hobbyists to near-exceptional performers [e.g., (*15*, *18*, *20*, *50*, *62*, *73*)]. One reason is that the number of young people who are not early top performers is much larger than those who are. This point can be illustrated with estimates from sports in countries with known numbers of athletes along with early and adult success rates (*66*). Those who reach international junior championships, compared with the remainder of the population, are 49 times as likely to go on to reach international senior championships (sample-weighted mean odds ratio = 49.43, 7 samples, total $N = 1{,}809{,}724$). However, the number of young athletes who do not reach international junior championships is much larger (>99% of all athletes) than those who do (<1%). Relatedly, the majority of adult athletes who reach international senior championships (>70%) come from the former group.

Those who do not achieve early top performance include a number of young people who experience increased performance improvement at later ages; surpass many of the early top achievers; and eventually become the world's best adult performers (Fig. 2). Following from the evidence synthesized in this Review, this group's developmental trajectory is associated with reduced earlier discipline-specific practice and increased multidisciplinary practice. This group is a small minority of the population. At the same time, this group is larger than the even smaller group of early top performers who later become adult top performers, and so becomes the majority of the exceptional performers at peak age.

In addition, across domains, many adult world-class performers did engage in considerable amounts of discipline-specific practice, and many already performed above most of their peers during their early years [e.g., (*59*, *60*, *80*, *91*–*97*)]. That is, the top-performing adults and their peers performing just below are more similar to one another in these regards than to people who neither achieve early nor later exceptional performance. However, a pattern of early acceleration of performance is frequent among early exceptional performers but is infrequent among adult world-class performers. Reinforced acceleration of early performance development is often pursued via early start, focus on a single discipline, intensified discipline-specific practice, and little or

Table 3. Predictors of performance in various populations. A dash (–) indicates not considered in previous research.

Population	Association of performance with: Earlier performance	Discipline-specific practice amount	Multidisciplinary practice amount	References
Previous research among the general population and young and sub-elite performers				
Young* general population	Positive	Positive	–	†
Young* sub-elite in their discipline	Positive	Positive	Negative	‡
Adult general population	Positive	Positive	–	§
Adult sub-elite in their discipline	Positive	Positive	Negligible	¶
Research among the highest levels at peak performance age				
Adult world class in their discipline	Negative	Negative	Positive	#

*Young in chess and sports: until age of secondary school graduation (peak performance is typically in performers' 20s and 30s); in formal education, music, and other professions: until college age (peak performance is typically in performers' middle age) (*45*, *64*).
†e.g., (*6*, *7*, *10*, *13*, *14*, *16*–*18*, *20*–*23*, *25*, *27*, *29*, *34*, *36*–*38*), 5,213 samples, $N = 695{,}878$.
‡e.g., (*3*, *4*, *6*, *9*, *11*, *12*, *19*, *24*, *26*, *30*, *35*, *39*, *57*, *59*, *60*), 133 samples, $N = 14{,}261$.
§e.g., (*6*, *8*, *15*, *23*, *31*, *74*, *75*, *116*, *117*), 481 samples, $N = 99{,}117$.
¶e.g., (*5*, *6*, *23*, *28*, *33*, *40*, *59*, *60*, *118*), 235 samples, $N = 11{,}689$.
#(*57*, *59*, *60*, *68*, *70*–*72*, *76*), 50 samples, $N = 11{,}131$.

no multidisciplinary practice. For example, a child engages in intensive swimming while forgoing other sports like soccer or gymnastics; or a child focuses on intensive violin practice while forgoing learning other instruments like the flute or piano.

The recent evidence from the highest echelons of human performance cannot be sufficiently explained by extrapolating from previous research on young and sub-elite performers. The primary reason is that critical assumptions—that young exceptional performers and later exceptional performers are largely the same individuals over time and that predictors of early exceptional performance also predict later exceptional performance at peak age—are not supported by the evidence. How, then, can we explain the recent evidence on the highest levels of peak performance?

One may question whether the evidence simply reflects statistical artifacts—namely, restriction of range (limited variance among the highest performance levels) or regression to the mean (extreme scores will be less extreme with repeated measurements, such as at early and peak performance age). However, assuming the evidence rests on these statistical artifacts would be at odds with the negative association between early and peak performance when comparing adult performers across the highest levels. Such an assumption would also be at odds with opposite predictor effects on early performance and on later peak performance.

Several further considerations have also been discussed in the literature, comprising characteristics of the task, the performer, and the environment. In supplementary table S1, we describe how current approaches are either inconsistent with the recent evidence, fail to provide an adequate explanation for this evidence, or both. Notably, none of the approaches can adequately explain why early and later exceptional performers are largely two discrete populations; why, when comparing performers across the highest levels, peak performance is negatively associated with early performance; or why early multidisciplinary practice is associated with later exceptional discipline-specific performance. Thus, to better explain the recent evidence on the acquisition of the highest level of human capability, existing approaches may be complemented by additional hypotheses (*98*), or new explanations may be proposed (*98*, *99*).

As a starting point, we discuss three explanatory hypotheses that are consistent with the pattern of empirical evidence from this review but have received little, if any, attention in previous expertise research: the search-and-match hypothesis, the enhanced-learning-capital hypothesis, and the limited-risks hypothesis. These explanations may be considered in future research to help better understand the acquisition of the highest human performances (*57*, *59*, *60*).

The first is the search-and-match hypothesis, which is derived from labor market economics (*100*, *101*): Experiences in various disciplines increase the odds that performers find a discipline optimally suited for their talents and individual preferences. Performers who find an optimal discipline match are more likely to develop exceptional peak performance.

The second is the enhanced-learning-capital hypothesis, which is derived from general learning transfer theory (*102*): Varied learning tasks, situations, and methodologies in different disciplines may expand performers' potential for future long-term discipline-specific learning—i.e., their learning capital—in three interrelated ways. (i) Varied learning experiences from different disciplines may facilitate the performer's flexible thinking; ability to recognize problem patterns; and integration of different insights, ideas, and methods in the exploration of varying solutions (*76*, *89*, *90*, *103*–*105*). Indeed, on the basis of his review, Simonton (*105*) suggested that creative potential requires diversifying and challenging experiences. (ii) The varied learning experiences may also facilitate the learner's ability to adapt to different learning tasks, situations, methodologies, and available information. The performer becomes a more adaptable learner and can exploit more learning opportunities effectively (*59*, *60*, *102*, *106*). (iii) Experiences with greater variation in learning designs and methodologies may provide enhanced opportunities to understand the principles that lead to more and less effective learning solutions for the individual learner (*59*, *60*). An enhanced learning capital for long-term discipline-specific learning facilitates the acquisition of exceptional peak performance.

The third is the limited-risks hypothesis (*59*, *60*, *76*): Early engagement in multidisciplinary practice—often associated with reduced early discipline-specific practice (*60*)—limits the risks of factors that may hinder or even end one's career. These may include the risks of misbalance between work and rest, potentially associated with overtraining, wear-down, and burnout; excess opportunity costs (i.e., the lost benefits of forgone other activities, such as time with family and friends, engagement in other disciplines, hobbies, or time for education); being stuck in a discipline one ceases to enjoy; or overuse injuries in disciplines involving psychomotor performance such as sports and music (*59*, *60*, *107*–*111*). Performers who have reduced risks of career-hampering factors are more likely to develop exceptional peak performance.

Implications for future research

To facilitate the development of future top performers who push the boundaries of human capability, we need to better understand their development. To this end, it will be critical for scientists to further advance research approaches—in particular, regarding samples, variables, and data analyses.

Samples: Given that early exceptional performers and later exceptional performers at peak performance age are largely two discrete populations, the acquisition of the highest levels of human performance cannot be explained by extrapolating from young and sub-elite performers [e.g., (*3*, *4*, *9*–*12*, *16*–*19*, *22*, *24*, *26*, *30*, *34*, *35*, *39*, *57*, *59*, *60*, *66*)]. To understand how the world's best performers differentiate themselves, we must compare the best performers at peak performance age themselves with their high-performing but less exceptional peers. In this context, matched-pairs designs may be useful to control for potential confounds.

Furthermore, this review focused on international top performers in science, classical music, chess, athletics, and other professions. Future research may extend to the top performers in other domains.

Variables: Future research may consider individuals' performance and both discipline-specific and multidisciplinary practice throughout performers' entire careers. This enables consideration of sustainability by comparing short-term and long-term predictor effects. In light of the three explanatory hypotheses above, investigations may also consider performers' discipline match, learning capital, and risks throughout their career.

Data analysis: Given that associations of performance with predictors may be nonlinear, and predictors may interact with one another, multivariable nonlinear analyses may be particularly illuminating [for empirical examples, see (*76*, *112*, *113*)].

The recent evidence also raises new research questions: (i) Why are early and later exceptional performers largely discrete populations? (ii) Why are early performance and later peak performance negatively correlated when comparing performers across the highest levels? (iii) Why are predictor effects on early performance and on later peak performance different? (iv) Why is early multidisciplinary practice associated with eventual long-term discipline-specific peak performance?

To answer these questions, the explanatory search-and-match hypothesis, enhanced-learning-capital hypothesis, and limited-risks hypothesis appear to be promising candidates, especially when investigated in combination.

Finally, to inform evidence-based policies and practices of institutional elite training programs, the following may be a fruitful research strategy: (i) Identify the factors that differentiate the world's best performers, and then (ii) investigate which organizational features of elite training programs facilitate those factors among participants (such as selection age and criteria, type and amount of training, qualification of teachers, living arrangements, or psychosocial support).

Practical implications

Around the world, admission and training policies of many elite training institutions emphasize early performance and discipline-specific practice. These programs typically aim to select the top early performers and then seek to further accelerate their performance through intensified discipline-specific training (*3*, *8*, *9*, *11*, *12*, *56*–*58*, *61*–*63*). In light of the reviewed evidence, such practices likely foster young high-achievers—but, in many cases, at the expense of long-term acquisition of the most exceptional human achievements.

Among managers, practitioners, and stakeholders of elite training programs, awareness may be raised that, when selecting the top early performers for admission, the selected group only includes a minority of the future adult top achievers, while the majority of future top achievers are outside the selected group. Thus, to design programs that foster the development of the most exceptional human performers, a first step is to identify young people who possess the potential to achieve world-class performance in the long term. For this purpose, early top performance is not a sensible selection criterion. Further, selecting by early top performance, such as for elite training programs or scholarships, may have a dysfunctional "radiating" effect: Young people, their teachers, and their parents are incentivized to reinforce acceleration of early performance years in advance of the selection age for these programs. This is often pursued by starting in a discipline early, focusing exclusively on that discipline, and maximizing discipline-specific practice—the participation pattern associated with early, but not long-term, exceptional performance. Rather, the identification of the young performers with the greatest long-term potential requires early indicators beyond early top performance. The evidence suggests that above-average, but not top, early performance together with considerable, but not excessive, discipline-specific practice, and considerable multidisciplinary practice are indicators of long-term exceptional potential.

Further, when evaluations of elite training programs and their teachers—often critical to funding and continuation—are based on the current or short-term performance of young participants, this may also lead to dysfunctional incentive structures: Managers and teachers are encouraged to select the top early performers and then further accelerate their short-term performance. By contrast, to consider sustainability, evaluations of programs and teachers should assess participants' development during subsequent years through peak performance (*45*, *57*, *65*, *66*, *80*, *81*).

To facilitate exceptional achievements at peak performance age, the recent evidence suggests limiting the amount of discipline-specific practice while increasing multiyear multidisciplinary practice. Accordingly, teachers, coaches, and managers of youth programs may recommend that young people engage in dedicated practice in various disciplines before focusing on a single discipline. This may include that programs forgo some weekly discipline-specific practice sessions for the sake of allowing time for practice in other disciplines. For example, rather than focusing only on soccer 4 to 6 days per week, a youth soccer coach may encourage their players to undertake two weekly sessions in another sport such as basketball, tennis, or gymnastics. The piano instructor may encourage their students to pick up an additional instrument such as the flute, violin, or percussion. Likewise, the teacher of the extracurricular gifted program in physics may encourage their students to also enroll in another program such as computer science, ecology, or philosophy.

The multidisciplinary practice may be undertaken within or outside of institutional elite training programs (*57*, *71*, *72*, *114*). Notably, the tasks within the different disciplines one practices need not be similar (*59*, *60*, *72*, *76*, *89*). Finally, the evidence from world-class athletes and Nobel laureates suggests that practice in around two additional disciplines may provide a well-suited breadth-depth relationship. Such policies and practices may enhance opportunities to develop the highest levels of human achievement.

Conclusions

Exceptional performers at the highest levels drive innovation and societal progress. Recent evidence suggests that, across multiple domains, adult world-class performers develop differently than previous research on young exceptional performers suggested. In particular, substantial early multidisciplinary practice and gradual early performance development characterize many eventual world-class performers.

The similar developmental pattern across different domains suggests widespread, and possibly universal, principles underlying the acquisition of the highest levels of achievement. On the basis of the recent evidence, scientists can enhance theory development, program managers can promote evidence-based practices, and policy-makers can better allocate government and organizational funding. Such efforts may foster opportunities to enhance world-class performance across science, sports, music, and other fields.

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SUPPLEMENTARY MATERIALS

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Fig. S1; Table S1; References (*119*–*143*)

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