Toward a Science of Exceptional Achievement

Attaining Superior Performance through Deliberate Practice

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Exceptional performance is frequently attributed to genetic differences in talent. Since Sir Francis Galton's book, *Hereditary Genius*, many scientists have cited heritable factors that set limits of performance and only allow some individuals to attain exceptional levels. However, thus far these accounts have not explicated the causal processes involved in the activation and expression of unique genes in DNA that lead to the emergence of distinctive physiological attributes and cognitive capacities (innate talent). This article argues on the basis of our current knowledge that it is possible to account for the development of elite performance among healthy children without recourse to innate talent (genetic endowment)—excepting the innate determinants of body size. Our account is based on the expert-performance approach and proposes that the distinctive characteristics of exceptional performers are the result of adaptations to extended and intense practice activities that selectively activate dormant genes that are contained within all healthy individuals' DNA. Furthermore, the theoretical framework of expert performance explains the apparent emergence of early talent by identifying factors that influence starting ages for training and the accumulated engagement in sustained extended deliberate practice, such as motivation, parental support, and access to the best training environments and teachers. In sum, our empirical investigations and extensive reviews show that the development of expert performance will be primarily constrained by individuals' engagement in deliberate practice and the quality of the available training resources.

Key words: **physiological adaptation; expertise; aging; expert performance; ability**

The discussion of exceptional performance and the factors that cause the large variability in achievement has a long history. In his pioneering book, *Hereditary Genius*, Sir Francis Galton[1] presented evidence that limits on height and body size were genetically determined, and by analogy that similar innate mechanisms must determine mental capacities: "Now, if this be the case with stature, then it will be true too as regards every other physical feature – as circumference of head, size of brain, weight of grey matter, number of brain fibres, & c.; and thence, *a step on which no physiologist will hesitate, as regards mental capacity*" [italics added]. (pp. 31–32). Although, Galton acknowledged that domain practice and training lead to performance improvements, he argued that such improvements are rapid only in the beginning of training and that subsequent increases become increasingly smaller, until "Maximal performance becomes a rigidly determinate quantity" (p. 15). In this view, heritable capacities set the upper bound for an individual's physical and mental achievements that no amount of practice can overcome. Galton's compelling arguments for the importance of innate factors have had a lasting impact on our culture's view of ability and expertise.

Many contemporary theories of skill acquisition[2,3] are consistent with Galton's general

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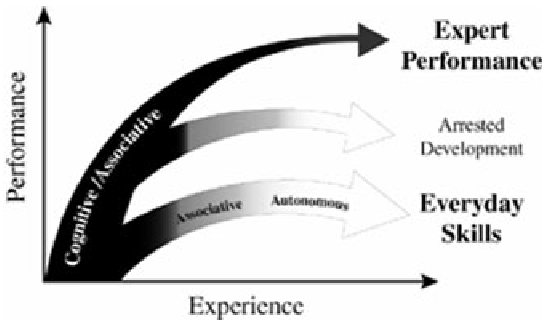

Figure 1. The qualitative difference between the course of improvement of expert performance and of everyday activities. The goal for everyday activities is to reach as rapidly as possible a satisfactory level that is stable and "autonomous" (see the gray/white plateau at the bottom of the graph). In contrast, expert performers counteract automaticity by developing increasingly complex mental representations to attain higher levels of control of their performance and will therefore remain within the "cognitive" and "associative " phases. Some experts will at some point in their career stop engaging in deliberate practice and prematurely automate their performance. (Adapted from "The scientific study of expert levels of performance: General implications for optimal learning and creativity" by K. A. Ericsson in *High Ability Studies, 9*, p. 90. Copyright 1998 by European Council for High Ability.)

assumptions and fit with casual observations on the development of everyday activities. After being introduced to activities such as driving a car, typing, or playing golf, an individual's primary goal is to reach an acceptable level of performance. During the first phase of learning[3] novices try to understand the activity and concentrate on completing their first attempts for successful actions, as is illustrated in the lower arm of Figure 1. With more experience in the middle phase of learning, large mistakes become increasingly rare, performance appears smoother, and learners no longer need to concentrate as hard to perform the task. After a limited period of training and experience—frequently less than 50 hours for most recreational activities—an acceptable standard of performance is attained. Once performance is automated, individuals no longer attempt further modifications and improvements, and typically this leads to a stable plateau of performance, which is consistent with Galton's[1] description. Galton, however, would argue that these stable plateaus exist not only for the acquisition of acceptable performance in casual, recreational activities, but also for the acquisition of exceptional ability in most domains. Many current researchers agree with this view (e.g., Ref. 4).

There is a body of research that questions the assumption that these plateaus are set by genes. The first author's views were greatly influenced by research on the effects of practice on memory performance[5–7] and demonstrated that average college students could dramatically improve their memory with training. After hundreds of hours of practice for lists of rapidly presented digits, students' memory increased from the typically observed seven digits[8] to over 80 digits—an improvement corresponding to an effect size of over 70 standard deviations. Similarly large training effects on memory performance have been replicated several times in many other (independent) laboratories, not only with digit lists, but with other memory tasks as well (see Refs. 9–11). Furthermore, a recent neuroimaging study[12] found no evidence for neurostructural differences between some of the world's top memorizers and a matched control group, but the two groups differed in the distribution of increased brain activity during memorization. These differences in the brain regions with increased activity can be explained by the fact that the experts used different, more complex memory strategies. Furthermore, recent reviews have not found any reliable evidence of limiting factors that would impede healthy, motivated individuals from acquiring exceptional performance in specific memory tasks with appropriate instruction and training.[9,10,13] This research suggests that unique genes (innate talent), not possessed by other healthy adults, are most likely *unnecessary* for reaching such high levels of memory improvement.

The effects of specialized training are not limited to memory and other cognitive capacities. With specific practice, the speed of performance in many performance domains considerably increases, and even physiological capacities can be shown to markedly change.[14] The record for the number of consecutive push-ups illustrates one striking example of the far-reaching effects of practice. High-school and college students in physical education classes can complete, on average, about 20 push-ups in a row.[15] However, after specialized practice, adults have been able to complete over 6,000 push-ups and set the first official record in 1965. The Guinness Book of Records[16] has shown that this record has been regularly broken; in fact, now the rules of the event have even been changed such that all push-ups must be completed within 24 hours. More recent records[17] exceed 26,000 push-ups—this value represents an average of nearly a completed push-up every 3 seconds for 24 hours.

These striking examples, as well as numerous other findings, raise doubts about existence of fixed innate capacities that limit a healthy individual's ability to reach the highest levels of performance. In this paper we will describe the theoretical framework of the expert-performance approach and evaluate accounts of superior performance based on genetics and on the acquisition of physiological and cognitive adaptations brought about by specific practice activities. We conclude with a discussion of how the study of high levels of performance informs us about how optimal performance can be attained and maintained during adulthood.

The Expert-Performance Approach

Ericsson and Smith[18] originally proposed a framework for the empirical analysis of the mechanisms mediating expert performance involving three key stages. In the first stage, the naturally observable superior performance is replicated in controlled laboratory settings using well-designed representative tasks. In the next stage, the performance is analyzed using standard methodologies for tracing the mediating processes, such as latencies, eye fixations and verbal reports. Finally, once the mechanisms mediating experts' superior performance have been identified, researchers attempt to identify factors that influence the acquisition of these mechanisms by examining the effects of specific practice activities at various stages of the development of performance.

Capturing Superior Performance of Experts Rather Than Studying Mere Behavior of Experts

In some sports, such as running and swimming, superior performance can be easily identified by timing competitors. In other performance areas, such as ballet, music, and figure skating, the level of complexity can be recorded and objectively scored according to level of difficulty. While it is relatively straightforward to separate experts from novices in domains where there are clear-cut methods to measure performance, identifying the abilities and attributes that distinguish experts from sub-experts (and even novices) is a more daunting task in several other professional, artistic, and academic domains. Early investigators attempted to examine individuals who were *perceived* to be experts by reputation. It was taken for granted that these individuals, with their apparent wealth of experience and knowledge, would outperform most (if not all) of their contemporaries if they were given relevant tests or tasks. It was discovered, however, that under controlled conditions, many of these "experts" frequently failed to outperform sub-experts and even advanced amateurs. Failure of demonstrating superior performance of "experts" has been documented in several domains, including psychotherapy,[19] financial forecasting,[20,21] and even academia.[22] Indeed, several reviews have revealed that length of domain experience is unrelated to improvements in ability, and is sometimes even associated with *decrements* in performance.[23–26] Such findings have discouraged reliance on reputation and peer-nomination for the identification of experts.

Indeed, the focus should be on *superior reproducible representative performance*; thus, the first challenge to the examination of expert performance is to identify tasks that *reliably* discriminate different levels of performance for any given domain.

Domains such as chess, fencing, and tennis pose such challenges to the examination of expertise, as each game will consist of very different sequences of specific situations and actions. In his pioneering research on chess experts, de Groot[27] identified challenging, representative situations in chess games that required decisions regarding the next move. He then presented the same set of situations to chess players and asked participants to try to find the best moves. De Groot revealed that chess players with a history of tournament success at the world class level consistently chose better moves than players with less success. Subsequent research has confirmed that this methodology of presenting challenging, representative situations requiring the generation of appropriate actions is the best available laboratory measure of chess expertise, namely tournament ratings.[28,29] Similarly, extensive empirical investigations and reviews have demonstrated that the presentation of representative tasks to measure superior performance has been applied to many domains, such as medical diagnosis, nursing, financial forecasting, snooker, soccer, dart throwing, and several others[24,30,31] (see Refs. 25,32 for a review). Although reviews indicate that representative tasks can be designed for several domains, an additional challenge is faced when the judgment of performance is potentially unreliable. Generally, as discussed above, there is high agreement between judges on detecting *errors* in the performance of routines, such as ballet, gymnastic and figure skating routines, and musical performances. There is, however, much less reliability in judgments of artistic quality of performance. Research has shown, for example, that there is surprisingly low inter-rater reliability in the evaluation of error-free performance, and that judgment is often biased by irrelevant factors such as reputation and even gender and physical attractiveness.[33] More recent research has demonstrated that, with careful planning, it is possible to eliminate potential bias factors and objectively judge performance in even these domains.[34]

In sum, in order to identify the essence of expertise in a domain, the initial challenge is to design representative tasks that allow expert performers to reproduce their superior performance consistently under standardized conditions. Studies and reviews from the expert performance approach have demonstrated that this is possible for several domains in which the identification of representative tasks was considered problematic, including sports, games, music, and professional domains such as medicine and nursing.[32,35] Furthermore, although the judgment of technical proficiency was thought to be tenuous for several domains, there have been recent improvements in the objectivity of these measurement techniques, resulting in even better methods to identify and examine expertise.

Identifying the Mechanisms That Mediate Expert Levels of Performance

When experts' superior performance on representative tasks has been reproduced, the second step is to identify the specific physiological and cognitive mechanisms responsible for the experts' performance advantage. In order to do so, it is necessary to identify the intermediate processes that make the expert performance superior to that of the less accomplished performers. Traditionally, researchers investigated several potential types of differences between experts and novices, such as intelligence, cognitive and perceptual abilities, and anatomical characteristics, without any explicit theoretical account for how these specific characteristics could result in differences in the observed performance.[36] As such, it is perhaps not surprising that most of these attempts were unsuccessful (cf. Ref. 37). In contrast, the expert-performance approach restricts itself to the examination of empirical investigations that evaluate the causal role of the mechanisms that are proposed to account for the observed differences in performance.

Several techniques developed by cognitive psychologists have been used to successfully analyze the mediating processes of expert performance, such as the analysis of latency components, eye-tracking, and concurrent and retrospective verbal reports (for a review, see Ref. 38). For example, one can examine the latencies of sprinters to determine the specific advantages of elite sprinters over sub-elite sprinters during various phases of a task, such as the time to accelerate to maximum speed and the remaining time to finish the event. Similarly, research has demonstrated that it is possible to measure and examine the reliability of outcomes of specific motor actions, such as putting and driving in golf, in order to separate expert golfers from sub-experts.[39] Collaborations between cognitive psychologists and applied physiological researchers have further demonstrated specific differences mediating advantages of experts. For instance, elite long-distance runners are able to run with superior running economy (the metabolic efficiency of maintaining their pace) in comparison to sub-elite runners. Indeed, interviews and field experiments show that these runners verbally report monitoring their internal states more intently and planning their race more thoroughly than sub-elite runners.[40,41]

As mentioned above, research from the expert performance approach has demonstrated that it is possible to design representative tasks for games such as chess, tennis, and fencing, where situations may differ substantially between games. Indeed, such investigations have revealed compelling scientific evidence for cognitive accounts of experts' performance advantage.[18] For example, de Groot's[27] analyses of the verbal protocols revealed that chess players first rapidly perceived and interpreted the chess position, and then began generating promising moves. These moves were then evaluated mentally by planning the consequences of potential moves. The chess players would either select their best move among the initially generated set of possible moves or often discover new and even better moves during the planning phase. Subsequent investigations have confirmed these results by selectively interfering with the outlined processes, and have demonstrated similar results with memory experts.[13,28,42] Reviews of studies of representative problem solving have revealed similar patterns in several domains, such as medicine, computer programming, and games.[25,32] In general, as skill improves, individuals acquire more refined mental representations that allow them to consider and mentally evaluate potential moves and situations better than less skilled individuals. Furthermore, studies have also shown that experts' performance advantages are mediated by more advanced preparation and anticipation. The first investigations demonstrating compelling empirical evidence were conducted on expert typists. Salthouse[43] found that elite typists maintain their speed advantage by looking further ahead in the text to prepare future keystrokes in advance. Indeed, when typists are restricted from looking ahead in the text, their speed is dramatically reduced to almost that of a novice. Similarly, superior preparation of appropriate actions by expert performers has been documented in several sports, such as baseball[44] and tennis.[45] Similar evidence has also revealed that expert musicians are better able to plan and anticipate future movements than novices.[46] Moreover, traditional accounts would cite better acuity of the perceptual system or faster basic speed of the motor system as potential mediators of superior performance (for reviews see Refs. 31,47,48). However, the investigations cited above have provided compelling evidence that the superior speed depends primarily on the acquired cognitive representations, which allow performers to be prepared well in advance of less skilled individuals for the rapid execution of appropriate actions. In addition to superior anticipation skills and more refined cognitive representations, experts also acquire superior control over their motor actions. For example, at the elite level of performance figure skaters are able to complete increasingly complex behaviors, such as triple-axel jumps. Additionally, experts are able to perform these behaviors in the same manner consistently. Research has demonstrated this finding not only in sports, but in other domains such as medicine[24] and music.[49]

In sum, analytic techniques from cognitive psychology and applied physiology have demonstrated that expert performance is primarily mediated by acquired mental and physiological representations that allow experts to evaluate alternative courses of action, to anticipate courses of action, and to control relevant internal and external factors in order to generate superior performance.

Scientific Accounts of the Acquisition of Expert Performance and Its Mediating Mechanisms

Thus far, we have discussed how the expert performance approach is able to identify and reproduce superior performance in laboratory settings and isolate cognitive and physiological mechanisms that allow experts to maintain their performance advantage. However, any complete account of exceptional performance must also explain how elite performers *develop* the complex cognitive mechanisms and improved physiological adaptations that mediate superior performance. Our central thesis is that experts engage in *deliberate practice* activities[14,35,49,50] that are designed to lead to improvements of specific aspects of performance.

When people first engage in an activity they need to understand what to do and mistakes, such as failure to return a tennis ball, are perceptually salient, as is shown by the lower arm in Figure 1. With further practice their performance improves and it becomes less clear how to attain additional improvements when engaging in casual activities, such as a tennis game between friends. After more extended experience in the domain amateurs automate their behavior, such as tennis strokes, and their performance can remain stable for decades of regular participation in the domain. Those children, adolescents and adults who are committed to attaining expert levels of performance start working with coaches and propose new training tasks where they remain challenged and where feedback about performance and opportunities to repeat the task are available (deliberate practice), as is illustrated by the upper arm of Figure 1. These training tasks are typically not part of normal play but provide special opportunities to improve some particular aspects of performance by modifying the control of actions and the cognitive representations of relevant situational factors. Some expert performers will give up their quest for reaching the highest levels by reducing or even stopping the engagement in deliberate practice. As a result they start automating their performance at a higher level, as is illustrated by the middle arm in Figure 1.

The Development of Expert Performance

Research from the expert performance approach has successfully measured individuals' performance as a function of age, as illustrated in Figure 2. It is possible to refute claims from traditional approaches through the examination of such data; for instance, this research shows that individuals that eventually reach expert levels of performance do not begin their training with an exceptional level of performance, nor do they suddenly attain exceptional abilities at any stage of development.[51] The improvement of performance has been found to be gradual and generally takes several years of active pursuit to reach elite status. Indeed, even those historically identified as the most "talented" do not win at international levels of competition in less than a decade.[14,52] Additionally, performance typically peaks in the late 20s, 30s, or even early 40s for some professional domains, which occurs

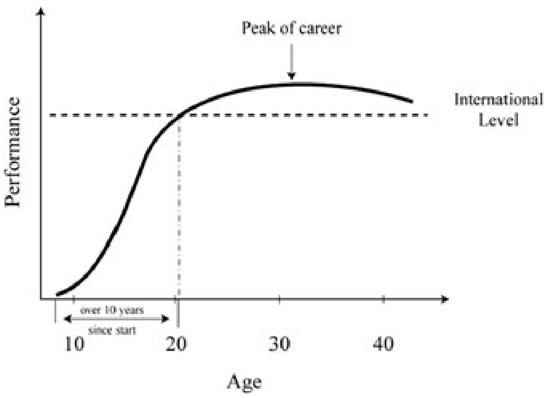

Figure 2. The gradual increases in expert performance as a function of age, in domains such as chess. The international level, which is attained after more than around 10 years of involvement in the domain, is indicated by the horizontal dashed line. (From "Expertise," by K. A. Ericsson and Andreas C. Lehmann, 1999, *Encyclopedia of Creativity*. Copyright by Academic Press.)

over a decade *after* physical maturation has been attained (around age 18 for most developed countries).

Studies of expert performers have also demonstrated that these individuals have different developmental histories as compared to their peers. First, elite performers generally start training in their domain of expertise early, and are given access to superior training resources at very young ages. Supportive environments encourage these individuals to engage in large amounts of specific practice activities. Ralf Krampe, Clemens Tesch-Römer, and the first author[14] investigated the training activities that could explain the acquisition and maintenance of expert performance. In this extensive review, it was found that improvements in performance were uniformly observed when individuals were given tasks with well-defined goals, were provided feedback, and had ample opportunities for repetitions. Efforts to improve performance involved problem solving and the search for better methods to perform tasks. When individuals engage in practice activities (which are, at least initially, designed by teachers and coaches) with full concentration on improving some specific aspect of performance, we call that activity *deliberate practice*. Unlike mere engagement in domain-related activities, which, as discussed, leads to arrested development and is *not* associated with further performance improvements, deliberate practice requires *concentration on improving performance*. Thus, while mindless, routine engagement and playful, effortless activities would serve to merely strengthen current cognitive mechanisms, engagement in deliberate practice ensures the improvement of performance through the modification of these mechanisms.

The initial studies of deliberate practice[14] (see also Ref. 53) revealed that violinists' attempted to master specific goals by working on exercises determined by their music teachers during lessons. Furthermore, higher levels of attained music performance were associated with greater amounts of solitary practice. Similar results have been demonstrated in chess research.[54] In contrast, other factors, such as number of games played in chess tournaments, have a minimal unique contribution to chess skill prediction. More generally, studies on sports have revealed a consistent relation between the level of competitive events (amateur, local, district, national, and international) and total amount of different types of practice activities.[55–57]

Research has also confirmed the importance of immediate, specific feedback through deliberate practice. Solitary study in chess primarily involves the examination of previous chess games by masters. When studying moves, chess players are able to compare their own plans and decisions to those of the masters, and thus receive immediate feedback on the quality of their moves.[14] It is important to be able to work on appropriately challenging tasks, such as technical mastery of difficult shots in darts,[58] difficult jumps in figure skating,[56,59] and difficult routines in rhythmic gymnastics.[60] In all of these cases the performers get virtually immediate feedback by the observable outcome itself and often additional feedback from coaches and from delayed viewing of video recordings of the performance.

Some professional activities, such as surgery, often yield immediate feedback about failures, such as incorrect cuts and insufficient repairs, and more delayed feedback about complications in the post-operative hospital wards. In contrast, the outcomes of many decisions by managers or diagnostic assessments by doctors are not known until weeks, months, or even years later. There are proposals for how one would be able to provide for opportunities for deliberate practice where professionals make decisions for re-presentations of archival situations, where the outcome is known and thus can be presented immediately after the decision has been made.[24,35,61]

The development of expert performance has been found to relate closely to engagement in deliberate practice activities. In the next section we will discuss how the acquisition of expert performance can be viewed as a sequence of specific changes.

Toward Detailed Causal Accounts of the Development of Expert Performance in Sports

The development of expert performance occurs gradually, through a sequence of incremental changes and refinements of the mediating mechanisms. More specifically, these findings suggest that it is possible, at least in principle, to describe the development of each individual's performance as an ordered sequence of cognitive and physiological changes, brought about in response to specific practice experiences, which ultimately generate integrated structures that can explain expert performance, as shown in Figure 3. In general, the expert performance approach proposes that improvements in performance have definite, traceable causes, thus each observable change in the structure of the mechanisms illustrated in Figure 3 needs to be explained. A complete theory of exceptional performance should be able to account for all specific cognitive and physiological refinements contributing to the acquisition of expertise. To fully understand the causal mechanisms underlying the relationship between practice and level of performance, we must ultimately search for causal (preferably biological) factors that explain how the adaptations necessary to sustain elite performance are the results of specific practice activities.

In many sports, experts continually strive to achieve beyond their current performance levels, and thus push their bodies beyond their limits. Indeed, the field of applied physiology has made several important contributions in describing the specific efforts associated with the physiological and anatomical changes necessary to maximize performance. In the next section, we review this research in sports and describe how similar accounts can be extended to changes mechanisms that mediate improvements in performance in other domains.

Improving the Physiological and Anatomical Mechanisms That Mediate Performance

When most healthy individuals reach adulthood they can assume that their bodies and physiological systems will remain virtually unchanged for several decades while they continue their habitual level of activity. However, simply because the characteristics of the body tend to remain stable does not imply the body is incapable to change as a consequence of dramatic changes in the duration and intensity of mental or physical activities.

The adult body has evolved to cope with short-term fluctuations in physiological demands. A fundamental role of the human body is to protect the homeostasis of its many trillions of cells, so they can survive and function within their preferred temperature range and be provided a sufficient supply of oxygen, water, and energy. Whenever individuals engage in physical sport activities, the metabolism of their muscle fibers increases, the supply of oxygen and energy within the muscle cells is rapidly reduced, and supplies are extracted from the

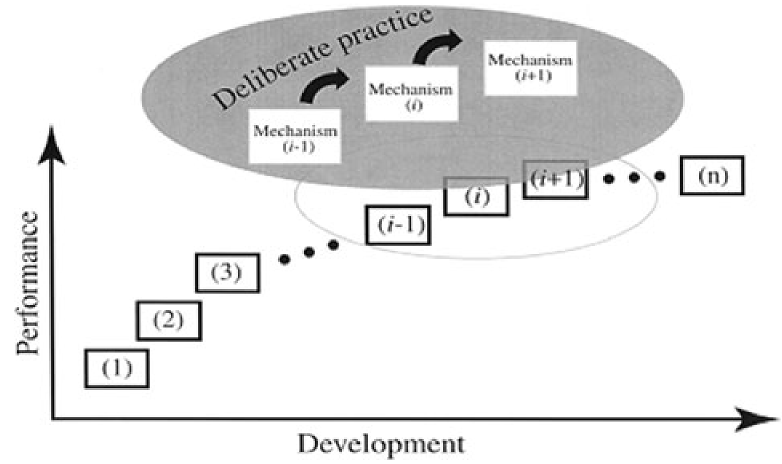

Figure 3. A scheme of the acquisition of expert performance as a series of states with mechanisms for monitoring and guiding future improvements of specific aspects of performance (Adapted from "The development of elite performance and deliberate practice: An update from the perspective of the expert-performance approach" by K. A. Ericsson in J. L. Starkes and K. A. Ericsson, Eds., *Expert Performance in Sport: Recent Advances in Research on Sport Expertise*, p. 70. Copyright 2003 by Human Kinetics).

nearest blood vessels. To preserve homeostasis, the body activates various counter measures (negative feedback loops); for example, increased breathing rates increase oxygen concentrations and decrease carbon dioxide concentrations in the blood. By converting energy from stores in the liver and elsewhere, the available expendable energy circulating in the blood is replenished, and the increased rate of blood circulation distributes these commodities to the systems of the body with the greatest needs. However, when individuals deliberately push themselves beyond the comfort zone[39,53] and engage in sustained strenuous physical activity, they will challenge the available mechanisms protecting homeostasis and induce an abnormal state for cells in some physiological systems. These states involve insufficient levels of certain vital elements and compounds, such as oxygen, and energy-related compounds (e.g., glucose, ADP, and ATP), which force metabolic processes to change and produce alternative biochemical products. These biochemical compounds will trigger the activation of some genes within the affected cells' DNA. The activated genes in turn will stimulate and "turn on" biochemical systems designed to cause bodily reorganization and adaptive change. Recent research has analyzed the chemical contents of cells such as activated genes and proteins and study changes in response to vigorous activity, such as physical exercise. For example, over one hundred different genes are activated and expressed in mammalian muscle in response to the involvement in intense physical exercise.[62]

The process of causing physiological change by overloading the physiological system is well illustrated in efforts to increase aerobic fitness. For example, it is well known that jogging and exercise of modest intensity and duration does not improve young active adults' aerobic fitness. Scientific studies show that it is necessary for young adults to go beyond a certain threshold in the intensity of their sustained physical exercise in order to reliably improve their aerobic fitness.[63] Specifically, young adults have to exercise at least two or three times each week for at least 30 minutes per session with a sustained heart rate that exceeds 70% of their maximal level (around 140 beats per minute for a maximal heart rate of 200). Extended physical activity at these levels of intensity will cause abnormal metabolic conditions that will induce changes in cells. It is, however, not simple to induce the metabolic conditions that cause change. For example, when adults start to jog on a weekly basis, early weeks involve the coordination of firing of the involved muscles fibers. Once the individual is able to induce coordinated sustained activity of the muscles, the muscle fibers can be activated as long as there is sufficient transport of blood to sustain a steady supply of oxygen and glucose. When these concentrations become too low, it will trigger biochemical activity which, in turn, stimulates the growth of new capillaries (angiogensis[64]). Similarly, it is possible to attain improvements of strength and endurance when individuals keep engaging in a cycle of overloading some system or sub-system (i.e. increasing intensity, frequency, or duration on a weekly basis), that will eventually induce a physiological adaptation. Once the new adaptation is attained, the individuals must induce a new overload by pushing the adapted physiological systems outside the current comfort zone to trigger additional physiological growth and further adaptation.[39,53]

Induced Changes in Elite Athletes' Physiological and Anatomical Characteristics

There are many types of physiological and anatomical characteristics that distinguish elite performers from less accomplished performers. Acquisition of these characteristics is consistent with acquired adaptations to increased demands induced by their intense and extended engagement in practice activities (for reviews see Refs. 14,25,65,66). For example, the larger heart sizes of endurance runners have been shown to emerge only after years of extended intense practice, and their hearts appear to grow in response to continued physiological challenge (increased intensity and duration of physical training). More recent evidence on Olympic level athletes' enlarged hearts is even more compelling support for the acquired nature of these adaptations. When athletes stop or even significantly reduce their training amounts at the end of their careers their enlarged hearts eventually revert back toward average size.[67]

The expert-performance approach portrays the acquisition of the physiological characteristics as a sequence of adaptations where practice activities induce critical states in cells in physiological systems that trigger, as well as maintain, these adaptations. This means that adaptations cannot easily be acquired in any order and that the possibility of inducing adaptations will depend on the stage of general development of children and adolescents. For example, some specific practice activities appear to change anatomical characteristics in an irreversible manner when they are carried out during certain critical developmental periods. Ballet dancers' ability to turn out their feet, and the baseball pitchers' and handball players' ability to stretch back with their throwing arm are linked to stretching while practicing the associated movements when the children's bones and cartilage in joints are calcified in late childhood.[25] Attempts by handball players to attain similar adaptations at much older ages through practice have been found to be unsuccessful and often result in chronic shoulder pain.[68]

Physiological changes are not limited to muscles, cartilage, bones, hearts, and capillaries. Recent research suggests that there is a relationship between reading ability and the development of white matter in children (primary increases in the neurons' myelin shields for achieving faster and better targeted signals), and that this effect strengthens over time with increased reading experience.[69] For instance, Elbert *et al.*[70] have shown how skilled string players display neuro-physiological differences in the cerebral cortex associated with the representation of their left hand, and that these differences are correlated with the age at which the subjects had started playing the musical instrument. Subsequent research has further demonstrated how patterns of cortical changes may be unique for specific activities, such as areas relevant to lip stimulation in brass players,[71] finger stimulation of Braille readers,[72] and auditory space perception in conductors.[73] Musical training is also associated with increased gray matter volume in the primary motor, somatosensory, and auditory cortex.[74,75]

The causes of the observed neurological differences are more difficult to assess. They may reflect training related adaptations or hereditary, inborn differences that ultimately determine musical ability. Interestingly, recent research demonstrates very specific adaptations that would seem to be implausible from an evolutionary perspective. For example, expert musicians display greater neurological excitation levels to tones from their own instruments (e.g., piano tones in pianists) than other instruments or pure tones.[71,76] Furthermore, the adaptations have been found to be related to differences in experience and start of training. For example, expert musicians display higher levels of relevant excitation and mapping to a larger cortical area when they started training early.[71,76–78] Most importantly, there is now intriguing evidence from studies of expert musicians that have successfully related the degree of myelinization of different areas of the brain and the amount of practice during development. Fredrik Ullen and his colleagues[79] were able to find several regions where the level of myelinization was related to the amount of practice between different ages. These findings highlight the importance of early exposure to training that cannot easily be explained by innate differences. Although the brain may be particularly modifiable during development in childhood and adolescence, adult brains can still be modified in response to training. For instance, increased levels of excitation and cortical representations can be seen even after relatively short-term training sessions in finger exercises,[80] pitch perception,[76] and melody perception.[71]

According to the expert-performance approach, most individual differences in elite achievement can be explained by physiological characteristics acquired through a long series of adaptations, engendered by biochemical responses to the strain induced by particular practice activities at appropriate ages or stages of physiological development. There appear to be at least three *possible* reasons why some adults are unable to attain the highest levels of achievement. First, it is possible that certain types of genes need to be part of individuals' genetic endowment (innate talent) in order to permit the acquisition of expert performance. This is the position of Galton discussed earlier, where no amount of training could ever improve performance beyond a certain upper limit. Second, it is possible that individuals differ in their motivation to engage in the required practice intensity (often taking over 10 years) necessary to induce the extended series of adaptations. Finally, it is possible that the differences are related to environmental support, such as access to early training/instruction and availability of the best resources. We will consider these three possibilities in turn.

Genetic Constraints on the Attainment of Elite Athletic Performance

In line with a Galtonian perspective, many modern scientists contend that the demonstrated genetic influences on the development of physical characteristics and mental abilities contributing to performance differences in everyday activities imply that genetic differences (innate talents) similarly influence the acquisition of elite athletic performance (e.g., Ref. 81). Still, these researchers also acknowledge that any generalization of heritability estimates depends directly on the similarity of environmental conditions of everyday activities to those of expert training. However, extrapolations from everyday activities to expert performance are questionable in light of our earlier reviewed findings that most aspects of elite performance are highly modifiable in response to deliberate practice activities. The type and intensity of physical and mental activity exerted by individuals, who are generally sedentary, engaged in everyday activities is substantially different from those of expert performers, who train daily for several hours at very intense training levels. Indeed, the level of exertion is intense enough to promote physiological and cognitive adaptations—something that cannot be said of everyday activities. Researchers in support of a genetic account of exceptional performance have also cited several investigations demonstrating possible heritable components of performance. The research of elite athletes has focused on two characteristics that would seem likely to be innately determined. It was found in the 1940s that the muscle fibers of elite sprinters were capable of rapid intense action of short duration (fast twitch muscle fibers) and different from elite long-distance runners, who had predominantly fibers that were able to sustain activity for hours (slow-twitch muscle fibers). Another characteristic of elite endurance runners was that they had an exceptional capacity to metabolize oxygen during maximal exercise and it is measured by the number of liters of oxygen that a runner can metabolize (convert oxygen into carbon dioxide) per minute as a function of the body weight (VO_2max). The more oxygen metabolized, the more energy and sustained running speed can be generated during the race. In the paragraphs that follow, we critically evaluate the assumption that the muscle fibers and VO_2max are determined by unique genes and thus primarily heritable.

An important review of twin studies[82] found that "a significant genetic variance has been found on dizygotic and monozygotic twin data for all variables, with the *exception* of VO_2max. kg^{-1} FFW *[V_{O2} max/kg controlled for fat free weight]*" (p. 645, italics added) (a discussion of the hereditary constraints of VO_2max and other genetic constraints on athletic performance is available elsewhere).[65,82] It appears that a large portion of the heritable variance in VO_2max is attributable to differences in weight, especially in the form of fat. Bouchard has also acknowledged that among athletes it is quite possible to increase VO_2max/kg significantly, even as much as 40% with training.[79] From this evidence it would appear that VO_2max/kg (aerobic capacity) would not be a good candidate for a factor that was *constrained* by heredity.

Similarly, an early study[85] estimated that the type of fibers in different muscles was almost completely determined by genetic factors—93% of the variance was determined by heredity. However, when investigators increased the number of twins studied they were unable to replicate these earlier findings. Bouchard *et al.*[86] found with a larger sample size no evidence of genetic determination of muscle fiber types—estimating instead a heritability close to 0%. In fact, other evidence exists that slow twitch muscles can be converted to fast-twitch tissues as a result of large changes in the level of physical activity[87] or with electric stimulation.

In sum, the concept that an individual's maximum capacity to metabolize oxygen (VO_2max) is a fixed, inherited capacity that limits endurance has been rejected by recent research. St. Clair Gibson and Noakes[88] describe a wide range of physiological, metabolic, and mechanical factors that influence endurance performance. Consistent with these accounts is the finding that the differences among highly skilled long-distance athletes is better predicted by the efficiency of sub-maximal performance (running economy[89]), and by physiological adaptations[90] than by VO_2max.

Shifts in the views of researchers have become apparent even for the effects of specific genes originally identified as relevant to elite running performance. In a recent review, McArthur and North[91] found the results for the most extensively studied gene—the polymorphism of Angiotensin Converting Enzyme (ACE) gene—are inconsistent among studies, where the studies with larger samples have failed to find reliable relationships despite some genetic differences found with smaller samples. McArthur and North argued that no firm conclusions should be drawn based on the available evidence, which has been supported by other authors.[92] More recently, a study of Kenyan elite runners failed to find relationships between ACE and performance when comparing these runners to controls from the same population.[93]

Most interestingly, research on twins has shown that attained level of expert performance is not directly determined by genetic endowment and physical environment. Not even when a pair of identical twins both engage in extended practice in the same domain of sports expertise will the twins necessarily attain the same, or even a similar, level of performance.[94] Given that the frequency of twins (even a single member of a twin pair) who attain an elite level of performance is much lower than would be expected by chance (including in science, literature, and the arts[95]), twin studies are unlikely to resolve the issues of heritable elite performance. The under-representation of twins among eminent individuals may be a consequence of how twins are reared and that deliberate practice by one or both twins may not be encouraged by their parents during childhood and adolescence due to its solitary, non-social nature, or due to financial or time constraints. More generally, recent reviews argue[66,96] that any analysis of the attained adaptations (phenotypes) has the fundamental problem of distinguishing whether the willingness/ability to practice at the necessary exercise intensity repeatedly for extended time is lacking, or if the physiological response to the assigned training intensity differs between people. Overall, however, we have been unable to find objective evidence for the innate talent account.

The Necessity of Ability to Engage in Extended Sustained Deliberate Practice—Motivation

The expert-performance approach[14] recognized early on the difference between genetically determined capacities (innate talent) and the ability to engage in deliberate practice: "we reject an important role for innate *ability*. It is quite plausible, however, that heritable individual differences might influence processes related to motivation and the original enjoyment of the activities in the domain and, even more important, affect the inevitable differences in the proclivity to engage in hard work (deliberate practice)" (p. 399, *underline* added). But how could scientists demonstrate that nearly all healthy individuals are capable of acquiring the required physiological adaptations, if random samples of these individuals are not willing and sufficiently motivated to engage in the intense physical exercise required to produce such adaptations? One example is animal research. Ericsson *et al.*[14] found that researchers have been able to push animals by motivational factors that would be unacceptable for humans. Random samples of animals acquire the same or similar adaptations as those observed by elite athletes after training intensively. More recent studies have extended these findings by using treadmills with electric shocks where intense physical activity was induced with the threat of electric shock. For example, Iemitsu *et al.*[97] found that the size and structure of hearts of rats can be reliably modified by common genes that were expressed in response to such training. Studies with thoroughbred racing horses show similar physiological adaptation in response to training in jumping versus racing on flat racing tracks.[98] These animal studies show that even animals (in the same manner as humans) do not develop their maximal physiological potential spontaneously, but much greater physiological adaptations can be induced by designing training environments where these animals are pushed to exert themselves.

The Necessity of Environmental Factors: Instruction, Opportunity, and Support

The expert-performance approach has found ample evidence that children and adolescents do not spontaneously engage in the deliberate practice that ultimately leads to maximal performance. Consequently, children need help to identify the appropriate training activities, to learn how to concentrate, and to find the optimal training environments. An early introduction to instruction and supervised training in the domain has been found to be associated with greater likelihood of reaching the highest levels in many different types of domains.[14] When children start competing against each other in sport, a slight advantage in skill or maturation has been found to have great consequences for success as adult professionals. It is now established that in most sports, especially in soccer and hockey, children who have a greater relative age compared to their peers in their age cohort are more likely to become more successful as elite older players.[99,100] Although the detailed mechanisms are not fully understood it appears that the age advantage leads to greater probability of initial success and being perceived as more talented, which may influence treatment and access to the best training resources. A more recent study[101] has shown that the population density of the community that children grow up in influence their chances of becoming a professional player in hockey, baseball, golf, and basketball in Canada and the United States. Growing up in cities with more than half a million of inhabitants was associated with much lower chances of becoming a professional athlete. Similarly, the participation rates of countries in a given domain of activity are closely related to their success in international competitions, such as chess.[102] The changes in athletic performance across historical time have been dramatic even in events where changes in rules and equipment have been minimal, such as swimming and running.[25,103] These four types of very large systematic differences at the very highest levels of performance cannot be easily explained by differences in genetic endowment; therefore, they demonstrate together the important role of environmental influences on the acquisition of elite performance.

To be sure, there is no disagreement regarding the importance of genetic activity in the development of the human body and expert performance. The activation of genes is critical for developing physiological adaptations of the body and nervous system that enable expert performance in the particular domain. However, so far the scientific evidence of genetic mediation suggests that *healthy children* seem to have the critical genes required for the desired changes as part of their cells' dormant DNA. A recent review[91] found that individual differences in attained elite performance cannot, at least currently, be explained by differential genetic endowment, barring only a few known exceptions of characteristics that directly mediate the performance, such as body-size and height (see Ref. 14, for a discussion of the evidence for genetic control of height in industrialized countries). It is entirely possible that future discoveries will uncover unique genes or combinations of genes that are associated with higher levels of expert performance, but until then we need to avoid assuming that individual differences in genetic endowment exist. In the future when we understand the detailed biochemical processes of adaptation, we also need to understand the processes that induce the appropriate strain on the cells and the body by physical and cognitive activity as well as the individual's ability to sustain engagement in appropriate practice activities (cf. deliberate practice). These issues concerning deliberate practice are likely to lead back to the fundamental issues of differences in motivation and sustained concentration where some role of heritable differences is not controversial.

Concluding Remarks: Implications for Longevity and Optimal Health

The theoretical framework of expert performance makes the fundamental claim that improvements in superior reproducible performance of adult experts do not occur automatically or without discernible reason. Superior performance can be linked to changes in physiological adaptations or cognitive mechanisms mediating how the brain and nervous system control performance. However, it is difficult to attain stable changes that allow performance to be incrementally improved. The general rule (or law) of least effort predicts that the human body and brain have been designed to conduct activities with minimal strain. When physiological systems, including the nervous system, are pushed beyond the limits of everyday adaptation by task-directed activity, such systems initiate processes that lead to physiological adaptation to reduce metabolic costs and changes in cognitive processes. This phenomenon is evident in most types of habitual everyday activities such as driving a car, typing, or strenuous physical work in which individuals tend to automate their behavior so as to minimize the effort required. Merely performing the same practice activities repeatedly on a regular daily schedule will not lead to further change once a physiological and cognitive adaptation to the current demand has been achieved. The central attribute of deliberate practice is that individuals seek out new challenges that demand concentration and effort as long as they want to keep improving their performance beyond its current level. As individuals' level of performance increases, the effort required to improve performance increases as well. Further improvement requires increased challenges and engagement in activities selected to improve current performance—deliberate practice.

Further evidence for the primary and crucial role of sustained extended development is found in studies of aging experts. Critically, despite showing the usual declines in basic laboratory tasks, aging experts show a tendency to maintain their skill level even into old age. In many basic cognitive tasks, psychology has long established that simple measures of memory and mental performance are strongly negatively correlated with advanced age (e.g., Ref. 104). However, the performance of experts in cognitive domains of skill shows very little age-related decline. Chess research provides a particularly clear example, as level of chess skill can be derived from tournament ratings accumulated from actual tournament successes and failures. As in many other domains of skill, chess players tend to peak around age 40 (e.g., Refs. 105,106); however, the subsequent decline is quite small and is probably less than half a standard deviation.[107] Hence, chess experts are able to maintain their chess skill despite other forms of decline. Similarly, expert Go players show no age decline on representative tasks from their domain even when they show decline on the typical lab tasks.[108] Even domains requiring physical movement may show little age decline; for instance, Krampe and Ericsson[49] found little evidence for age decline in expert pianists' performance. If anything, these studies suggest that aging need not lead to inevitable loss of acquired mechanisms, but rather that with sufficient maintenance expert performance can be preserved.

Once one conceives of expert performance as being mediated by complex integrated systems of representations for the execution, monitoring, planning, and analyses of performance, it becomes clear that skill acquisition requires an orderly and deliberate approach. Deliberate practice focuses on improving a specific aspect of performance. By training under representative conditions, the performer will engage the complex cognitive mechanisms that mediate superior performance. During deliberate practice, it is possible for the performer to design training tasks that give feedback, and the mediating representations assist the performer in isolating specific problems and weaknesses. Through problem solving and deliberate practice, performers can make the required changes to their specific representations. Improvements are always conditional on the performers' preexisting mechanisms and entail modifications of their own specific representations. The tight interrelation between representations that monitor and generate performance minimizes the risk of unwanted side effects from modifications.

Our analyses of the highest levels of performance have produced new insights into the complexity of skill that is attained after thousands of hours of deliberate efforts to improve. We believe that researchers will continue to uncover evidence of how effective learning and specialized practice methods can be used to target particular training goals. Rather than celebrate high achievement as a sign of innate talent and natural gifts for which little evidence actually exists, we recommend marveling at the discipline and the monumental effort highlighting the complex struggle for domain mastery.

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Conflicts of Interest

The authors declare no conflicts of interest.

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