Advanced Review

Expertise

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The study of expertise is based on the premise that experts in different domains follow a similar path of acquisition and development. This article distinguishes two research approaches to the study of expertise. The traditional approach assumes a steady progression from novice to expert as a function of training as well as years of experience often without measures of reproducible skill. A second and more recent one focuses on the identification of individuals with reproducibly superior performance for representative tasks that capture expertise in the domain. The focus of this review is on the latter, namely the expert-performance approach. The article describes how superior performance can be captured by standardized tasks, and how analyses of that superior performance can identify superior abilities, cognitive mechanisms, and physiological adaptations. The last part of the article reviews how deliberate practice and training can lead to the acquisition of complex mechanisms and physiological adaptations, which in turn can explain the experts' attained superior performance. The review is concluded with a discussion of future directions of studies of expert performance and the challenges in understanding the development of general abilities and the motivation to engage in sustained daily deliberate practice. © 2010 John Wiley & Sons, Ltd. *WIREs Cogn Sci* 2010 1 404–416

Expertise is generally defined as 'expert skill or knowledge: the skill, knowledge, or opinion possessed by an expert.'[1] The Merriam-Webster Dictionary[2] defines an expert as 'having, involving, or displaying special skill or knowledge derived from training or experience.' Research on expertise in psychology has been motivated by a hypothesis proposed by Simon and Chase[3] that there are general characteristics of experts that differentiate them from novices and less experienced people in a wide range of domains of expertise and that these differences can be attributed to mechanisms acquired in response to their extensive experience in their respective domains.

When people generate images of experts, they typically think of highly experienced professionals, such as brain surgeons, rocket scientists or wise judges, who had been active in their respective domains of expertise for several decades. In most professional domains, such as medicine, science, and law, extensive knowledge and skills must be acquired, typically in a college or university setting before an individual is allowed and able to be engaged as a participant in the domain. Once in the domain the individual often works as an apprentice and is supervised by an experienced professional until they are capable of acting independently without supervision. During this learning period they get many opportunities to learn how to apply the knowledge and rules efficiently in professional contexts until the appropriate actions in a context have been so often repeated that the actions are immediately accessed by intuition.[4] In the course of the dramatic increase in research on expertise in 1970s and 1980s researchers considered the association between domain-related experience and resulting increases in level of perceived expertise increasingly more important. In fact, many researchers started to define level of expertise operationally by the amount of accumulated experience in the domain, where 10 or more years of experience became synonymous with reaching the status of expert (see Refs 5,6 for discussions). However, this experience-based definition of expertise was shown to be problematic in the early 1990s,[7,8] as we describe in the following section.

DEFINING CHARACTERISTICS OF EXPERTISE: EXPERIENCE VERSUS SUPERIOR REPRODUCIBLE PERFORMANCE

Experience is clearly necessary to acquire skill for an unfamiliar task and perform adequately in a domain of expertise. Currently, the most influential model for

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DOI: 10.1002/wcs.47

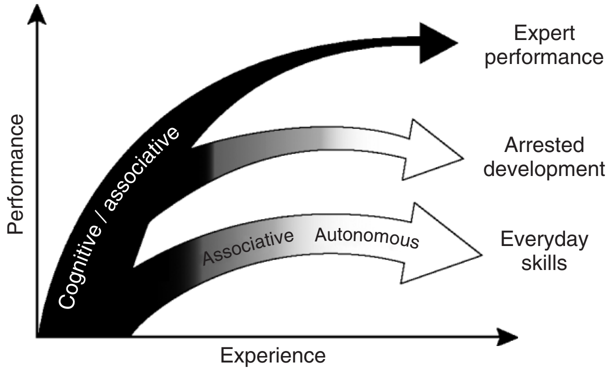


FIGURE 1 | An illustration of the qualitative difference between the course of improvement of expert performance and of everyday activities. The goal for everyday activities is to reach as rapidly as possible a satisfactory level that is stable and 'autonomous.' (See the gray/white plateau at the bottom 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.)

acquisition of everyday skills, such as type writing, driving, and other skills, was proposed by Fitts and Posner[9] and it distinguished three distinct stages—they are illustrated graphically in the lower arm in Figure 1. When people are introduced to an unfamiliar domain of activity, they first need to understand its structure and acquire knowledge and learn rules for how to respond appropriately in different situations. For example, in the case of touch typing, beginners need to learn the location of all the keys, so that they are able to retrieve the location of each letter and can move their fingers to the key and strike it.

During this first 'cognitive' stage, generation of behavior is slow and occasionally associated with failures of memory retrieval and errors of execution. These errors are easily noticeable and thus can be corrected by 'look up' and repeated actions. With sufficient experience and with mental concentration on producing the correct actions, individuals are able to increase their speed and control of actions, especially for frequently encountered patterns and familiar situations. During the second 'associative' stage they are able to learn and execute sequences of associated actions, and they become increasingly able to access and execute complex actions rapidly with less and less effort, consistent with theories of skill acquisition.[10] After some more training and experience—frequently around 50 h for most recreational activities, such as skiing, tennis, and driving a car as well as professional activities such as telegraphy and typing (see Ref 11 for a review)—the performance of individuals is successfully adapted to the typical situational demands and has become increasingly automated, and the performers lose conscious control over discrete aspects of their behavior and are no longer able to adjust and modify these aspects of their performance.[9]

According to this framework, the representation of the task is established during the first stage of skill acquisition, and improvements during the second two stages are primarily concerned with speed of execution and reduction of effort. When performance has reached the level of automaticity and execution is effortless, additional experience will neither change the accuracy of behavior nor refine the structure of the mediating mechanisms, and consequently, increases in accumulated experience will not lead to higher levels of performance,[11–13] as illustrated in the lower arm of Figure 1.

Most people know from first-hand experience that the number of times or for what duration a person has engaged in an every-day activity, like driving, playing tennis, and typing, is not closely related to one's level of objective performance. Several reviews[7,8,14] criticized the assumption that performance invariably improves with further experience and showed that increased domain-related experience is not always associated with improved professional performance in many domains. Highly experienced individuals do not exhibit superior performance in several domains, including psychotherapy,[15] financial forecasting,[16,17] and even academia.[18] Indeed, several reviews [14,19–21] have shown that length of domain experience is frequently unrelated to improvements in professional performance, and in some cases the time since graduation (highly correlated with professional experience) is even associated with decrements in performance, most likely due to forgetting.

In the *Cambridge Handbook of Expertise and Expert Performance* one can distinguish two approaches to the study of superior human performance. The traditional expertise approach studies the changes in characteristics of individuals' expertise as defined by increased amount of experience and training, namely from novice to intermediate and to experts. The first has also historically relied on selection methods such as peer nomination where successful professionals would recommend those colleagues, who they believed to be the most able and proficient.[5,6] The second approach, called the expert-performance approach, is only concerned with the study of the structure and development of reproducibly superior (expert) performance that captures the essence of expertise in a domain.[11,13] These two approaches overlap for domains, like chess, where different levels of expertise are defined in terms of objective success at tournaments, but diverge for domains and tasks, where no objective measures for superior performance 'experts' or other individual performers have been found or agreed upon. In the following we will review the evidence on the structure and acquisition of superior performance and will start with the issues surrounding measurement of representative performance and demonstration of reliable individual differences.

MEASUREMENT OF REPRODUCIBLY SUPERIOR (EXPERT) PERFORMANCE

In many individual sports—such as running and swimming—performance can be measured objectively and some individuals are consistently more skilled than others. Superior performance in running and swimming can be easily measured by the time to complete a race. In other performance areas, such as ballet, music, diving, and figure skating, there are public competitions with experienced judges, where many of the elements of performance, such as dives and jumps, have been objectively assigned a level of technical difficulty to help the judges rate the competitors' performance.

Measurement of performance in professional domains is more difficult, because different surgeons treat different patients, different sales people promote the same product in different territories, and programmers rarely design independent computer programs for identical tasks. There is a similar problem in domains such as chess, fencing, and tennis because each game in a tournament will consist of very different sequences of actions in particular situations. Even if one can estimate the skill level of various players by analyzing the results for around 20–30 tournament games (roughly corresponding to 50–150 h of competitive activity), it would be very difficult to identify those particular activities and associated superior mechanisms that are responsible for the superiority of the overall performance.

To address this central problem, Ericsson and Smith[7] proposed the expert-performance approach based on the pioneering research on chess experts by de Groot.[22] This approach starts by identifying challenging, representative situations in the domain of expertise, where there is a demand for immediate action, as illustrated in Figure 2. For example, de Groot identified complex positions from real chess games that required decisions regarding the next move. By presenting the same set of game positions and asking players to select the best move for all the positions, the accuracy of move selection can be measured and compared among players at different skill levels. Performance on this move-selection task was highly related to past chess tournament success. Subsequent research has confirmed de Groot's methodology as the best available laboratory measure of expertise in chess,[23,24] but also in several other domains,[13,25] such as medicine,[20,26] sport,[27] SCRABBLE,[28] and music.[29] Figure 2 illustrates how the speed of typists can be measured by having individuals type as much as possible from a provided text during a 3-min test period. It is also possible to measure the performance of musicians by having them perform a relatively simple piece and then play the same piece again in exactly the same manner as before (Figure 2). Expert pianists are found to be able to reproduce their original playing better than less skilled pianists.[30,31]

MECHANISMS THAT MEDIATE EXPERT LEVELS OF PERFORMANCE

Once investigators have successfully reproduced experts' superior performance on representative tasks, the second step in the expert-performance approach is to identify the specific physiological and cognitive mechanisms responsible for the experts' performance advantage. Traditionally, researchers gave experts and novices psychometric tests to measure their general abilities, such as intelligence and cognitive/perceptual abilities, without any explicit theoretical model for how these abilities could explain differences in the observed performance.[32] These efforts have not been successful, and individual differences in performance have not been found to be related to differences in general abilities among skilled performers in the domains (cf. Refs 33,34).

The expert-performance approach uses a different paradigm and collects data on the concurrent processes that mediate individual differences in the superior performance. There are several techniques from cognitive psychology that can successfully identify the mechanisms and processes that mediate expert performance, such as the analysis of latency components, eye-tracking, and concurrent and retrospective verbal reports (for a description, see Ref 35). These types of data can allow the investigators to identify critical processes and mechanisms. For example, research has demonstrated that it is possible to measure and examine the decision-making processes in various sports, such as soccer,[27] and the reliability of outcomes of specific motor actions, such as reproducing the same putt many times, which is one of the most reliable differences between expert and novice golfers.[36,37]

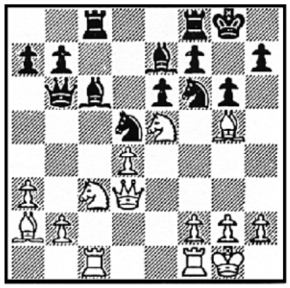
Domain	Presented information	Task
Chess		Select the best chess move for this position
Typing	OVERVIEW--NATURE AND NURTURE OF EXPERTISE The central challenge for any account of expertise is to explain how some individuals attain the highest levels of achievement in a domain and why so few reach that level. However, given the continuing struggle in Psychology to explain every day (lower) levels of achievement, it may appear presumptuous to attempt to explain even more advanced levels. Consequently, the accounts of expertise have been focusing on the general characteristics of the mechanisms. In order to be able to achieve at very high (expert) levels in domains of expertise both nature and nurture are necessary. Hence, everyone agrees that experts need to have acquired the necessary domain-specific knowledge and skills (nurture). Furthermore, the expert's performance often looks effortless and their most refined and insightful behavior is generated rapidly and naturally rather than the result of prolonged deliberation. It would thus appear that experts must excel in general basic characteristics, such as intelligence, memory, speed and flexibility, which have been assumed to be impossible to train and thus must be determined to a large degree by genetic factors (nature). Over the last couple of centuries, the arguments of the relative importance of nature versus nurture for expert achievement have been intricately linked to the theories of the actual processes that mediate the achievement of experts and to the conceptions of which aspects of human characteristics could be modified through development and training. Hence, this entry will briefly review the most important conceptions during the last century and then turn to a summary of our current knowledge and in conclusion the implications and connections of expert performance for creativity and genius will be outlined.	Type as much of the presented text as possible withinin one minute
Music		Play the same piece of music twice in same manner

FIGURE 2 | Three examples of laboratory tasks that capture the consistently superior performance of domain experts in chess, typing, and music. (From 'Expertise,' by Ericsson and Lehmann,[14] Encyclopedia of Creativity. Copyright by Academic Press.)

Other types of analyses have demonstrated superior ability of experts to monitor and control overall aspects of performance execution. For instance, elite long-distance runners who have increased their running economy have been shown to verbally report monitoring their internal states; they also plan their races more thoroughly than sub-elite runners.[38,39]

Research on expert performance in domains such as chess, music, and sports has given compelling scientific evidence for cognitive representations and mechanisms being responsible for the experts' performance advantage.[7] For example, de Groot[22] analyzed chess players' thought processes by collecting think-aloud protocols while they selected the best move for chess positions. These protocols revealed that chess players first rapidly perceived and evaluated the structure of the chess position, and from this process accessed promising moves and lines of attack. Players evaluated the structure mentally and formulated a set of possible moves from which they selected their 'best' move. Subsequent investigations have confirmed these results by selectively interfering with the outlined processes, and they have demonstrated similar results in domains such as medicine, computer programming, and games.[7,13,23,25,40] In a recent review, Hodges et al.[41] examined athletes' superior performance in the laboratory and the field. Of particular interest are studies that capture both the perceptual context of the sport with video recordings as well as the temporal constraints with representative motor actions rather than ratings and other verbal responses. Taken together, the results of these investigations suggest that experts maintain a highly complex and sophisticated representation of domain-specific situations relative to novices.

Many traditional accounts have put forth increased acuity of the perceptual system or faster basic speed of the motor system as explanations of superior performance. However, reviews have shown that this superiority is restricted to domain-specific stimuli and situations and thus is more likely acquired as the result of training (see Refs 42–44). In a pioneering series of studies, Salthouse[45] demonstrated that superior typing ability was linked to looking ahead in the text. Restricting experimentally how far skilled typists were able to look ahead in the text markedly reduced their typing speed. More elaborate preparation of appropriate actions by expert performers has been documented in several domains, such as baseball,[46] tennis,[47] and music,[48] whereas experts consistently and extensively plan their actions in advance leading some to assume faster physiological speed.

The investigations cited above have provided compelling evidence that superior speed depends primarily on acquired cognitive representations as opposed to faster neural or perceptual speed. In addition to superior anticipation skills and more refined cognitive representations, experts also acquire superior control over their motor actions in order to perform very complex motor behaviors consistently. Research has demonstrated this finding not only in sports, but in other domains such as medicine[20] and music.[31,49] These complex mental representations can also permit sophisticated and precise access and execution of appropriate actions.[44] The cognitive mechanisms that allow experts to reason and plan, to anticipate, and to control and monitor their actions implies that they have a much expanded working memory capacity to support these cognitive activities.

EXPERTISE AND LONG-TERM WORKING MEMORY

Many studies have put forth evidence for acquired complex encoding mechanisms and mental representations in superior memory performance.[50] One of the first attempts to uncover the processes responsible for this superiority was Ericsson and Chase's[51] skilled memory theory. They showed how—after considerable practice—individuals could increase their performance on a digit span task from 7 to over 80 digits. Ericsson and Kintsch[40] expanded this theory to explain memory superiority in a broader range of domains of expertise, such as chess, medicine, and mental calculation, and proposed that expert performers acquire encoding methods to allow them to store information and later retrieve it from long-term memory (LTM). Given that many expert performers were able to retrieve information from LTM virtually as rapidly as if it had been stored in short-term memory, they termed this acquired memory capacity long-term working memory (LTWM).

The concept of LTWM has been very useful to explain the superior memory of mental calculators, waiters, and people with exceptional memory, where memory is at the core of the exceptional performance. For example, one study examined the superior memory abilities of Rajan, a man who had memorized over 30,000 digits of the mathematical constant π. Contrary to prior claims that Rajan was endowed with an innate advantage,[52] a subsequent study found that Rajan had learned and used complex encoding techniques to remember the decimals of π, which explained his superior ability to remember numbers.[53]

LTWM has been particularly important for accounting for the superior working memory of experts in their domain of expertise. Ericsson et al.[23] demonstrated that as expert performers engage in deliberate practice to improve their performance they develop methods for encoding and retrieval that allow them to support demanding activities. For example, when selecting a move for chess positions, skilled chess players explore the consequences of sequences of moves by planning, and the depth of planning is correlated with chess skill.[54] Similarly, expert doctors are able to encode information about patients in a higher level representation that allows them to reason about different diagnostic alternatives.[55] Finally, elite athletes develop more complex and refined representations of the current game situation when they play tennis[56] and baseball.[57] Although there is general agreement about the empirical evidence for superior memory of experts, there has been considerable disagreements about the theoretical mechanisms accounting for it as shown by a couple of heated exchanges.[23,58–64]

DEVELOPMENT OF THE STRUCTURE OF EXPERT PERFORMANCE

The identification of complex mechanisms and physiological adaptations that differ between expert and less accomplished performers raises the questions of if—and how—these mechanisms have been acquired by engagement in training. In the third step of the expert performance approach, the focus is on describing how elite performers develop their skill and any complex cognitive mechanisms and physiological adaptations that mediate their superior performance. Research from this approach has been successful at measuring individuals' performance as a function of age (Figure 3). Examining such data shows that no experts began their training as superior performers, nor did they spontaneously obtain high levels of performance.[65] Only after years of gradual improvement do they obtain elite status. Even those who are historically defined as the most 'gifted' do not succeed at international levels of competition in less than 10 years in the majority of the highly competitive domains.[3,30] Additionally, performance typically

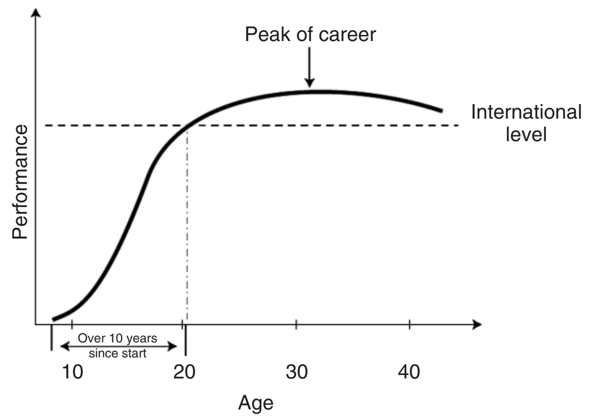


FIGURE 3 | An illustration of the gradual increases in expert performance as a function of age, in domains such as chess. The international level, which is attained after more than around 10 years of involvement in the domain, is indicated by the horizontal dashed line. (From 'Expertise,' by Ericsson and Lehmann,[14] Encyclopedia of Creativity. Copyright by Academic Press.)

peaks when the performers reach their late 20s, 30s, or even early 40s for some professional domains, which occurs over a decade after physical maturation has been attained (around age 18 for most developed countries).

Many expertise studies in domains such as swimming and music have demonstrated that superior performers have developmental histories quite different from their peers. Primarily, elite performers often start training in their domain very early and have access to superior training resources at very young ages. Supportive environments also encourage individuals to engage in large amounts of specific practice activities.

All children are not equally likely to reach elite levels in sport. In sports, such as soccer and hockey, children are grouped in age groups. In a review, Musch and Grondin[66] described the extensive evidence that those children that were oldest in their age cohort were more likely to be successful—the oldest were almost a year older than the youngest. Even more remarkably, the oldest children were more encouraged and much more likely to eventually become professional players. Côté et al.[67] showed that children living in medium-sized cities were more likely to become successful in sports than children growing up in large cities.

In an extensive review by Ericsson et al.,[30] it was found that improvement and maintenance of superior performance were uniformly observed when individuals were given tasks with well-defined goals, were given feedback, and had appropriate opportunities for repetition. Individuals who worked to improve performance engaged in problem solving as well as searches for better methods to perform the tasks.

As discussed earlier, it is not simply prolonged engagement in domain-specific activities that is associated with expert performance. Only with full concentration on improving a specific aspect of performance during practice activities would those activities be considered 'deliberate practice.' This type of practice requires intense concentration on improving particular aspects of performance and thus leads to modification of mechanisms responsible for improvement, unlike mere engagement which leads to repeated execution of the performance and development of automaticity (lower arm of Figure 1) or arrested development (middle arm of Figure 1).

In a study, Ericsson et al.[30] found that expert violinists worked on assignments and exercises designed by their music teachers as the primary activities during their solitary practice. Individual differences in the amount of this type of solitary practice were found to be closely related to the levels of attained music performance. By the time the best expert musicians had reached age 20, they estimated that they had accumulated more than 10,000 h of deliberate practice, which was several thousand hours more than their less accomplished peers at the same music academy. Solitary study in chess has been correlated with higher chess performance.[68] Once the amount of deliberate practice has been statistically controlled, the number of games played in tournaments has not been found to have a unique contribution in predicting chess skill. In sports, higher level of competitive events (amateur, local, district, national, and international) is reliably related to higher amounts of different types of practice activities.[27,69,70] In sports there are some controversies about which practice activities constitute deliberate practice as opposed to more playful activities.[71] Côté[72] has proposed that practice activities that combine deliberate practice and play (deliberate play) also contribute to the acquisition of highly skilled performance.[73]

The role of feedback has been found to be critical for deliberate practice. For example, during deliberate practice in chess, players read books and try to predict the moves made by masters in published games. Players can generate the move for each chess position in the game one at a time, then compare their moves to those of the masters, and thus receive immediate feedback on the quality of their moves and then try to figure out why they did not identify the best move so that they can improve their analysis for the future.[30]

Another important facet of deliberate practice is the direction or coaching to practice appropriately challenging tasks, such as the technical mastery of difficult shots in darts,[74] difficult jumps in figure skating[70,75] and difficult routines in rhythmic gymnastics.[76] In all of these cases the performers get almost immediate feedback by the observable outcome itself and often additional feedback from coaches.

Immediate, informative feedback and the opportunity for subsequent correction of non-optimal actions as well as repetition of the correct actions in the same and similar situations is a key component of deliberate practice. One critical issue concerns significant delay of feedback. In many activities feedback regarding failures is almost instantaneous such as sports (i.e. missed shots and passes in basketball) and surgery (i.e. incisions with aversive side-effects such as ruptured arteries). In contrast, the accuracy of many of the decisions made by managers or diagnostic assessments by doctors are never known or at least not known until weeks, months, or even years later. There have been several proposals for how one would be able to provide the opportunities for immediate feedback and thus deliberate practice. One such suggestion is to present professionals with descriptions or simulations of past situations in which the correct actions and outcome are known. As soon as the aspiring expert performers have generated their actions it is possible to provide immediate feedback following their decision.[11,12,20]

The relation between accumulated amount of deliberate practice and attained skill level could be an artifact of bias introduced by 'drop-outs.' More specifically, Sternberg[77] suggested that more talented individuals see larger benefits from the same amount of deliberate practice. Those benefiting less from practice would be more likely to be discouraged and reduce their practice and eventually discontinue their engagement in practice for the domain in question. This process would lead to more talented individuals persisting with high levels of practice in a domain and thus creating a false impression that increased practice was the primary cause of superior performance. In a recent article, de Bruin et al.[78] directly evaluated this hypothesis by collecting information on the amount of deliberate practice in a group of young elite chess players. Most importantly, this study showed that the amount of deliberate practice was related to the development of performance for all players. They found that a reduction in weekly deliberate practice led to a decrease in performance and eventually to the dropping out of this elite group. Hence, reduced practice leads to reduced performance rather than inferior performance leading individuals to be discouraged and thus reducing their practice. Sloboda et al.[79] reported similar findings in the field of music where music students were required to keep daily practice journals. They found that contrary to accounts proposed by talent proponents, none of the highest scoring students reached objectively defined levels of music performance with significantly less practice than their low-performing counterparts.

A recent study by Roring and Charness[80] suggests that mental performance in chess shows only very slight decline with age, and furthermore that the declines are smallest for the most skilled individuals, who more frequently engage in deliberate practice activities. Even domains requiring physical movement may show little age decline, as shown by studies of the aging musicians,[31] who maintain regular engagement in deliberate practice. A study of master athletes in track by Young et al.[81] compared the performance of a longitudinal sample to a cross-sectional sample in three track events. Their analysis indicated that runners, who maintained higher levels of practice, saw a much slower decline of performance as they aged. Taken together, these studies suggest that individuals in their 60s and 70s are not subject to inevitable loss of mastery and acquired mechanisms, but rather that engagement in deliberate practice contributes to the maintenance of performance.[82]

DELIBERATE PRACTICE AND CHANGES IN ANATOMICAL AND PHYSIOLOGICAL CHARACTERISTICS

The expert performance approach proposes that improvements (changes in performance) have definite, traceable causes. A complete theory of expert performance should be able to account for all specific cognitive and physiological changes that contribute to the acquisition of expert skill. Ultimately, it is essential to search for causal (preferably biological) factors that can explain how deliberate practice activities lead to sustained elite performance.

In many sports, experts continually strive to achieve beyond their current performance levels, and deliberately push themselves during practice beyond their comfort zone.[34,36,83] They engage in sustained strenuous physical activity that consumes oxygen and energy at a high level and thus challenges homeostasis by inducing an abnormal state for cells in some physiological systems. These states with depleted resources force the cells to change their metabolism to produce alternative biochemical compounds leading to the activation of 'dormant' genes within the affected cells' DNA. The activated genes in turn will stimulate bodily reorganization and adaptive change. In another example, research has analyzed the chemical contents of cells such as activated genes and proteins, and study changes in response to vigorous physical activity. Researchers found that over 100 different genes are activated and expressed in mammalian muscle when they are exposed to intense physical exercise.[84]

There are many types of physiological and anatomical characteristics of expert athletes which appear to be acquired adaptations to increased demands induced by their intense and extended engagement in practice activities (see Refs 26,30 for reviews). Physiological adaptations resulting from intense extended practice have been demonstrated in domains such as endurance running where athletes' hearts increased in size as a response to continued physical challenges (increased intensity and duration of physical training). When training is reduced or ceased toward the end of their athletic careers their enlarged hearts eventually revert back toward average size.[85] Furthermore, there are practice activities that—when carried out during critical developmental periods—result in dramatic and permanent physical adaptations. Examples are ballet dancers' ability to turn their feet, and baseball pitchers' ability to stretch back with their throwing arm. These abilities are related to stretching while practicing the associated movements before the children's bones and cartilage in joints are calcified in late childhood.[14]

DELIBERATE PRACTICE ACTIVITIES CHANGING PARTICULAR ASPECTS OF PERFORMANCE

Many types of changes in performance concern changes in the cognitive structure of mechanisms mediating higher speed, better selection of actions, and higher consistency of executed motor actions, and the development of these mechanisms require different types of deliberate practice. Some of the best evidences for how speed of performance can be increased through deliberate practice involve the refinement of the representations of future actions, as illustrated by extensive research on typing. The main finding is that expert typists have modified their mental representations, and this allows them to look further ahead in the text while typing, in order to prepare future key strokes in advance (as shown by high-speed filming of anticipatory movements of the fingers of typists). Typists can spend several years typing at the same rate without improvement. However, they are also able to increase their speed of typing well beyond their normal speed for short periods. They can reach increases of 10–20% as long as they are able to maintain full concentration which is typically between 15 and 30 min per day in the beginning of training.[86] Typing at faster speeds helps them identify keystroke combinations that are comparatively slow. They can then improve these weaker components of their skill that will allow them to gradually increase performance during sessions of deliberate practice. A similar type of deliberate practice can explain the superior speed of expert performers in domains, such as tennis, soccer, and ice-hockey, and it involves acquisition of cognitive representations to anticipate future outcomes and events (for reviews see Ref 42,43).

Improvement in the selection of actions in representative situations requires different types of deliberate practice tasks where the trainees' selected actions can be evaluated by comparisons against gold standards, such as the best possible action or the action taken by expert performers with the highest performance index. Methods mentioned in the above section on the development of the structure of expert performance rely on archival data from masters to allow aspiring expert performers to take on the same task as the masters and try to reproduce their performance and then compare their products or actions with those of the masters. The central argument is that students are able to use their mental representations to diagnose how they need to change them so that they would be able to reproduce the correct action (that of the master) if they were to encounter that or a similar situation in the future. Chess students are able to increase the quality of their moves with enough time for planning (that would not be possible in tournament play) such that their move selections will increase to a level attained by much better players with a time constraint. As chess students' skill increases from deliberate practice, such as the study of openings of chess games and of games between masters, their mental representations are refined in a way that allows them to access domain-specific information more efficiently, increasing the speed at which they can play at a high level.[12,30,68,87] Similarly, even the best chess players demonstrate improved play when given more time as shown by them making more mistakes under time pressure (viz., in speed chess: Ref 88).

More recently, a study of soccer players by Ward and Williams[44] demonstrated that as players acquire better control and can execute several alternative actions they develop more sophisticated representations of game situations. By constantly improving mental representations of game situations they are better able to select actions in a given situation. Studies of sports such as baseball and tennis have indicated that superior performances are linked to refined representations of game situations.[47,56]

CONCLUSION

The scientific study of expertise requires that phenomena of superior performance be reproducible and ideally captured with standardized tasks under controlled conditions. The expert-performance approach has shown that when analytic techniques from cognitive psychology and applied physiology are used to study expert performance, it has been found to be primarily mediated by acquired mental and physiological representations. These acquired representations have been shown to allow experts to evaluate alternative courses of action, anticipate future actions, and control relevant internal and external factors in order to generate superior performance.

The engagement in deliberate practice has—in several domains—been shown to be closely associated with the acquisition of mental representations, which in turn permit monitoring, refinement, and improvement of performance during deliberate practice. Moreover, the psychological and physiological demands of deliberate practice restrict the time that performers can devote without a break. These limits also constrain the daily practice amounts, where even experts need sleep and rest in order to recuperate prior to the next training sessions.[11,30] These findings have been further supported by evidence that athletes in multi-sport events such as triathlons devote similar durations of weekly practice as their single-sport counterparts.[89] Additionally, similar daily durations of practice are reported by experts across domains such as sport, chess, and music, suggesting that deliberate practice at elite levels of performance is very demanding and its daily duration is limited to 4–5 h every day to permit rest and recuperation in order to avoid exhaustion, injury, and burnout.[30]

The most exciting future direction in research on expert performance involves the identification and specification of causal biological mechanisms that mediate the development of expert performance. Identifying the critical training activities (cf. deliberate practice) that induce adaptations of the neural and physiological systems contributing to superior performance could help us better understand the improvement of skill in a variety of domains. For example, the degree of myelinization of specific brain systems have been found to be linked to the level of music practice during specific age intervals.[90] Furthermore, Ericsson[91] discusses the issue of identifying biological markers of increased performance in sports, particularly the activation of genes in DNA that could be interpreted as innate abilities but are in fact a physiological response to extended deliberate practice. He argues that all healthy children possess genes that can be activated with a sufficient amount of prerequisite practice and that these genes are not the result of genetically predetermined activation or genetic 'giftedness.' Ericsson et al.[32,34] argue that the expert performance approach can be applied equally well to disparate theoretical backgrounds such as deliberate practice theory and others that posit a genetic basis for superior performance. Once the crucial genes have been identified it will be possible to assess whether the genes are prevalent in healthy children or whether only a small proportion of talented individuals have them as part of the DNA. It is essential that all researches regarding exceptional individuals begin with testable hypotheses able to adequately explain development of expert performance.

In spite of some significant advances in our understanding of the factors that influence the development of reproducibly superior performance, it is only a modest beginning. Perhaps the greatest challenge is to develop methods to measure and capture the full range of performance in many professions and creative domains, such as writing, acting, and painting. Until we are able to capture essential aspects of these types of performances with representative tasks, it seems unlikely that we will make progress in assessing its structure and development. Another major challenge is the identification and measurement of more general skills that will be beneficial for the development of superior expert performance. Our current school system is committed to develop skills, such as reading, writing, and arithmetic, but it is still less clear how the structure of these acquired skills is related to future development of professional expertise and future work skills.

The greatest challenge concerns understanding the individual differences that are related to engagement in the demanding deliberate practice activities for months, years, and decades. Only future research will tell us about potential factors related to early development and support by parents and coaches and about continued support by peers and teachers. This research will inform us about differential development trajectories, stumbling blocks, and sustainable practice levels.

At the basis for research on expert performance is the desire to learn how exceptional individuals do what they do. Only when specific mediating factors are identified, and their acquisition history uncovered can we coach novices how to start and continue on the road to expertise.

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