The Pursuit of Excellence Through Education

Edited by

Michel Ferrari
University of Toronto

LAWRENCE ERLBAUM ASSOCIATES, PUBLISHERS
2002 Mahwah, New Jersey London

Attaining Excellence Through Deliberate Practice: Insights From the Study of Expert Performance

K. Anders Ericsson *The Florida State University*

Almost everyone can remember being awed by the public performances of elite musicians and athletes. All of us have looked at sculptures and paintings and read novels that clearly transcend a level of performance that we and other people in our immediate environment could attain. For a long time it has been considered obvious that some individuals' ability to achieve at a level superior to that of other motivated individuals must reflect an unobtainable difference, some genetically determined, and therefore innate, talent. If there were no immutable inborn limit, why wouldn't every highly motivated individual reach the highest level?

The most obvious approach to determining how individuals excel is to study those who have achieved mastery. As I show by quoting international masters discussing excellence later in this chapter, most masters emphasize the role of motivation, concentration, and the willingness to work hard on improving performance. In contrast to the general population and less accomplished performers, the masters seem to consider inborn capacities and innate talent as relatively unimportant in comparison to their attained abilities and skills. However, most people who have unsuccessfully pursued high excellence in a domain find it very difficult to accept the masters' emphasis on motivation and the continued need to work hard in improving performance. Many of us have worked hard to improve a skill over a period of weeks without catching up or perhaps not even markedly gaining on the individuals who perform at the highest levels. Could it be that the masters were praising motivation and effort due to false modesty? Perhaps they simply do not know the critical factors that lead them toward excellence.

In this chapter, I demonstrate how the masters' descriptions of the critical role played by motivation and willingness to work can be understood as a manifestation of the specially designed training activities that my colleagues and I refer to as deliberate practice (Ericsson, 1996, 1997, 1998; Ericsson & Charness, 1994; Ericsson, Krampe, & Tesch-Romer, 1993; Ericsson & Lehmann, 1996). In the first section, I argue that once we define excellence as consistently superior achievement in the core activities of a domain, an interpretable picture emerges. Even the level of achievement of the most "talented" develops gradually and, with rare exceptions, it takes at least 10 years of active involvement within a domain to reach an international level. However, the vast majority of active individuals in domains such as golf and tennis show minimal performance improvements even after decades of participation. In the second section, I discuss the difference between mere participation in domain-related activities, and activities designed to improve performance—deliberate practice.

THE SCIENTIFIC STUDY OF EXPERT PERFORMANCE

Many of the most dazzling and amazing accomplishments of geniuses, such as those by the famous musician, Paganini, and the famous mathematician, Gauss, refer to events that cannot be independently verified (Ericsson, 1996, 1997, 1998). Our only knowledge about most of these achievements is based on reports in the form of anecdotes about their childhood told by the famous individuals at the end of their career. Under these circumstances it would be reasonable to expect distortions of memory and even exaggerations. To study exceptional achievement scientifically, it is necessary that we disregard questionable anecdotes and focus on the empirical evidence that reflects stable phenomena that can be independently verified, and, ideally, reproduced under controlled circumstances. Once we restrict the research findings to this clearly defined empirical evidence then reviews (Ericsson & Lehmann, 1996; Ericsson & Smith, 1991) show an orderly and consistent body of knowledge even for exceptional achievements and performance.

In most domains of expertise, individuals have been interested in assessing the level of performance under fair and controlled circumstances. In athletic competitions, this has resulted in highly standardized conditions that approach the controlled conditions used to study performance in the laboratory. In a similar manner, musicians, dancers, and chess players perform under controlled conditions during competitions and tournaments. These competitions serve several purposes beyond identifying the best performers and presenting awards. For younger performers, successful performance at competitions is necessary to gain access to the best teachers and training environments, which, in turn, increases the chances of attaining one of the small number of openings as full-time professionals in the domain.

Ericsson and Smith (1991) discussed how one could use similar techniques to measure various types of professional expertise. More recent reviews show that efforts to demonstrate the superior performance of experts are not always successful. For example, highly experienced psychotherapists are not more successful in treatment of patients than novice therapists (Dawes, 1994). More generally, the length of professional experience after completed training has often been found to be a weak predictor of performance in representative professional activities, such as medical diagnosis (Norman, Coblentz, Brooks, & Babcook, 1992; Schmidt, Norman, & Boshuizen, 1990), auditing (Bedard & Chi, 1993; Bonner *Be* Pennington, 1991), text editing (Rosson, 1985), and judgment and decision making (Camerer & Johnson, 1991; Shanteau & Stewart, 1992). If we are interested in understanding the structure and acquisition of excellence in the representative activities that define expertise in a given domain, we need to restrict ourselves to domains in which experts exhibit objectively superior performance.

If expert performers can reliably reproduce their performance in public, it is likely that they could do the same during training, and even under laboratory conditions, a finding confirmed by recent research (Ericsson & Lehmann, 1996). Unfortunately, the conditions of naturally occurring expert performance are quite complex and frequently differ markedly among performers within a domain. For example, musicians are allowed to select their own pieces of music for their performance and the sequence of moves chess players make in a game is never the same. However, most domains of expertise require that experts are able to excel at certain types of representative tasks or else they would not meet the definition of a true expert. Ericsson and Smith (1991) discussed how to identify representative tasks that capture the essence of expert performance in a domain and how to reproduce this performance under controlled laboratory conditions so that investigators could identify the responsible mediating mechanisms.

Figure 2.1 illustrates three types of tasks that have been found to capture the essence of expertise, where the measured performance is closely related to the level of naturally occurring performance. To study chess expertise, players at different skill levels are asked to generate the best move for the same unfamiliar chess positions. Typists are given the same material to type as fast as possible. Musicians are asked to play familiar or unfa-

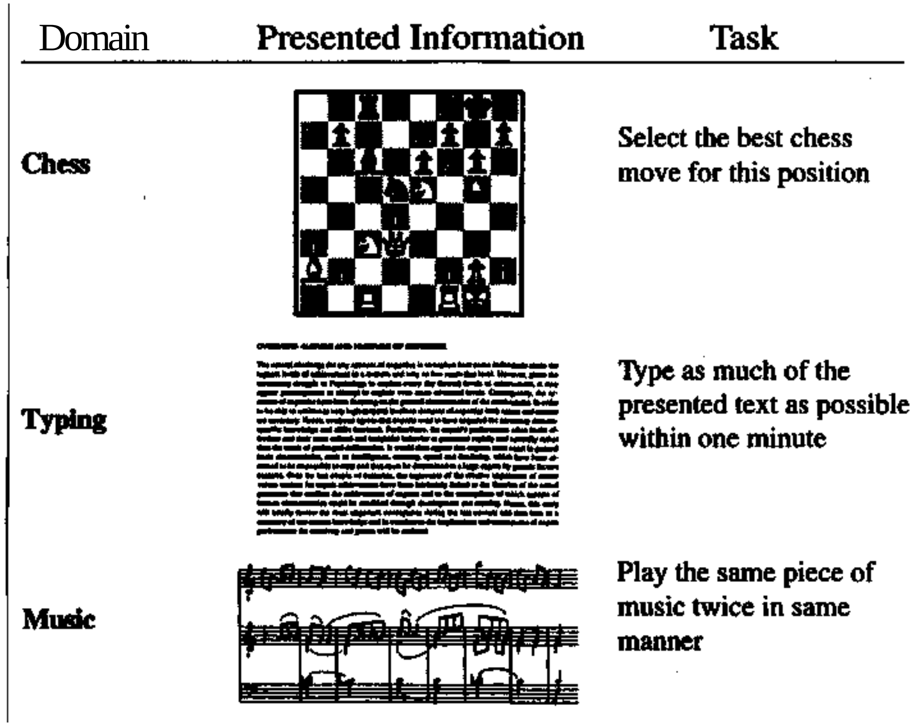


FIG. 2.1. Three examples of laboratory tasks that capture the consistently superior performance of domain experts in chess, typing, and music. From "Expertise," by K. A. Ericsson and Andreas C. Lehmann, 1999, *Encyclopedia of Creativity*. Copyright by Academic Press. Reprinted with permission of the authors.

miliar pieces, then asked to repeat their performance. When musicians are instructed to repeat their original performance, experts can do it with much less deviation than less skilled musicians, thus exhibiting greater control over their performance.

Considering only die superior performance of experts, it is possible to identify several claims about expertise that generalize across domains. First, I review evidence showing that superior expert performance is primarily acquired, and that extensive domain-related experience is necessary but not sufficient for its development. I show that many thousands of hours of deliberate practice and training are necessary to reach the highest levels of performance. Then I describe in depth the cognitive and physiological processes proposed to mediate the development of expert performance and show how deliberate practice optimizes the effect of these processes on performance.

The Necessity of Domain-Specific Experience

Recent reviews (Ericsson, 1996; Ericsson & Lehmann, 1996) show that extended engagement, in domain-related activities is necessary to attain expert performance in that domain. What is the process in acquiring expertise? First, longitudinal assessments of performance reveal that performance improves gradually, as illustrated in Fig. 2.2; there is no objective evidence for high initial level of performance without any relevant experience and practice nor for abrupt improvement of reproducible performance when it is regularly tested. Even die performance of child prodigies in music and chess, whose performance is vastly superior to that of their peers, show gradual, steady improvement over time. If elite performance was limited primarily by die functional capacity of the body and brain, one would expect performance to peak around the age of physical maturation: die late teens in industrialized countries. However, experts' best performance is often attained many years, and even decades, later, as illustrated in Fig. 2.2. The age at which performers typically reach their

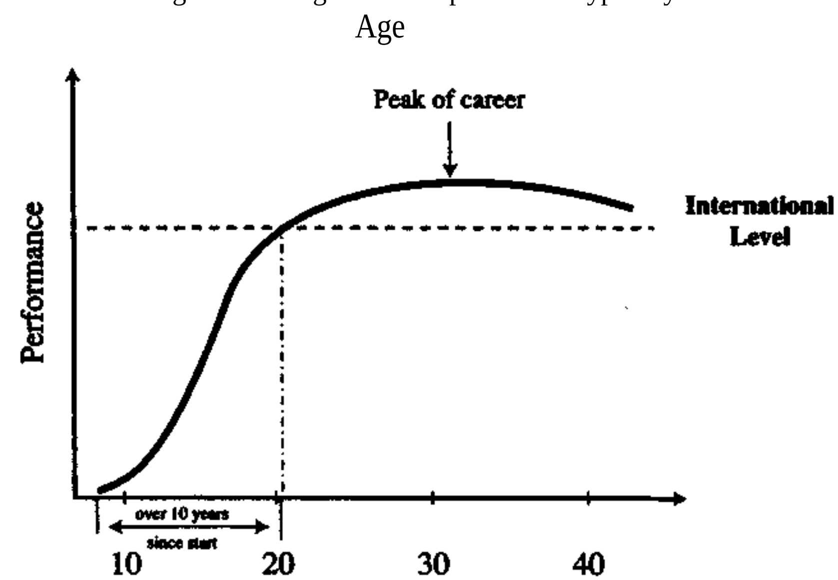


FIG. 2.2. An illustration of the gradual increases in expert performance as a function of age, in domains such as chess. The international level, which is attained after more than around 10 years of involvement in the domain, is indicated by the horizontal dashed line. From "Expertise," by K. A. Ericsson and Andreas C. Lehmann, 1999, *Encyclopedia of Creativity*. Copyright by Academic Press. Reprinted with permission of the authors.

highest level of performance in many vigorous sports is the mid to late 20s; for the arts and science, it is a decade later, in the 30s and 40s (see Simonton, 1997, for a review). Continued, often extended, development of expertise past physical maturity shows that experience is necessary for improving die experts' performance. Finally, the most compelling evidence for die role of vast experience in expertise is that even die most "talented" need around 10 years of intense involvement before they reach an international level, and for most individuals it takes considerably longer.

Simon and Chase (1973) originally proposed die 10-year rule, showing that no modern chess master had reached die international level in less than approximately 10 years of playing. Subsequent reviews show that the 10-year rule extends to music composition, as well as to sports, science, and arts (Ericsson, Krampe, & Tesch-Romer, 1993). In sum, the fact that engagement in specific, domain-related activities is necessary to acquire expertise is well established. Most importantly, given that very few individuals sustain commitment for more than a few months, much less years, most individuals will never know die upper limit of their performance.

Going Beyond Mere Experience: Activities That Mediate Improvements of Performance

Extensive experience and involvement in a domain is necessary for the select group of elite individuals who steadily increase their performance and reach very high levels. In contrast, die vast majority of individuals struggle to reach an acceptable level of performance, and having done so, allow their performance to remain relatively stable for years and even decades. Consider the example of recreational golfers, tennis players, and skiers. The striking difference between elite and average performance seems to result not just from the duration of an individual's activity, but from the particular types of domain-related activities they choose.

From retrospective interviews of international-level performers in many domains, Bloom (1985) showed that elite performers are typically introduced to their future domain in a playful manner. As soon as they enjoy die activity and show promise compared to peers in the neighborhood, they are encouraged to seek out a teacher and initiate regular practice. Bloom and his colleagues showed the importance of access to the best training environments and the most qualified teachers. The parents of the future elite performers spend large sums of money for teachers and equipment, and devote considerable time to escorting their child to training and weekend competitions. In some cases, the performer and their family even relocate to be closer to the teacher and the training facilities. Based on their interviews, Bloom (1985) argued that access to the best training resources was necessary to reach the highest levels.

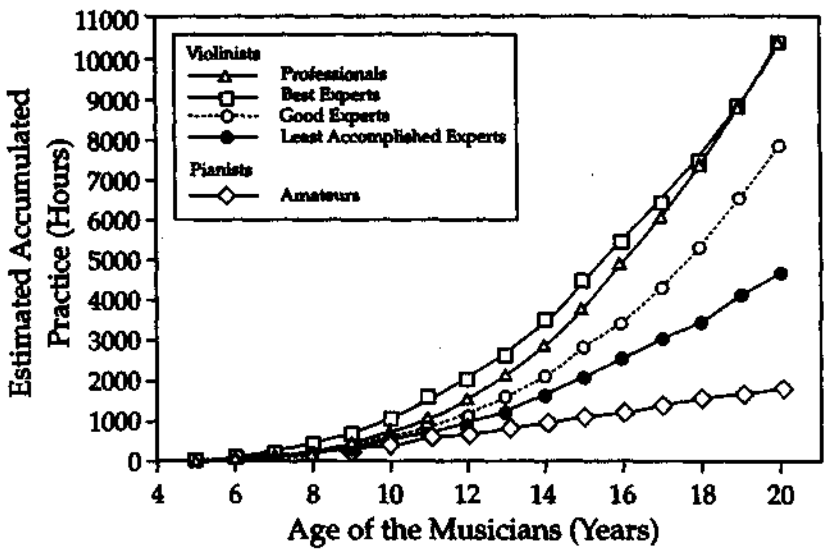
Given the limited opportunities available to work with the best teachers and training resources, only the most qualified individuals are admitted at each stage. Could it be that the superior training resources do not really enhance die rate of improvement, and the highly selected individuals would improve just as well by themselves? The best single source of evidence for the value of current training methods comes from historical comparisons (Ericsson, Krampe, & Tesch-Romer, 1993; Lehmann & Ericsson, 1998). The most dramatic improvements in the level of performance over historical time are found in sports. In some events, such as die marathon and swimming events, many serious amateurs of today could easily beat die gold medal winners of the early Olympic games. For example, after the IVth Olympic Games in 1908, they almost prohibited the double somersault in dives because they believed dial these dives were dangerous and no human would ever be able to control them. Similarly, some music compositions deemed nearly impossible to play in the 19th century have become part of the standard repertoire today. Exceptional levels of performance are originally attained only by a single eminent performer. However, after some time other individuals are able to figure out training methods so they can attain that same level of performance. Eventually, this training becomes part of regular instruction and all elite performers in the domain are expected to attain the new higher standard. In competitive domains, such as baseball, it is sometimes difficult to demonstrate the increased level of today's performers because both the level of the pitcher and the batter has improved concurrently (Gould, 1996).

If the best individuals in a discipline already differ from other individuals at die start of training with master teachers and coaches, how can we explain these differences in performance prior to this advanced level? Can we also explain individual differences in the rate of improvement among individuals in die same training environment? To determine which activities could improve individuals' performance development prior to advanced training, one should first consider activities with conditions beneficial to learning and effective performance improvement. A century of laboratory research has revealed that learning is most effective when it includes focused goals, such as improving a specific aspect of performance; feedback that compares the actual to the desired performance; and opportunities for repetition, so die desired level of performance can be achieved.

Based on interviews with expert violinists at the music academy in Berlin, my colleagues and I (Ericsson, Krampe, & Tesch-Romer, 1993) identified activities for which we could trace the duration of the music students' engagement during the period prior to their entry in die music academy. We were particularly interested in those activities that had been specifically designed to improve performance, which we called *deliberate* *practice.* A prime example of deliberate practice is the music students' solitary practice in which they work to master specific goals determined by their music teacher at weekly lessons. We were able to compare the time use among several groups of musicians differing in their level of music performance, based on daily diaries and retrospective estimates. Even among these expert groups we were able to find that the most accomplished musicians had spent more time in activities classified as deliberate practice during their development (see Fig. 2.3) and that these differences were reliably observable before their admittance to the academy at around age 18. By the age of 20, the best musicians had spent over 10,000 hours practicing, which is 2,500 and 5,000 hours more than two less accomplished groups of expert musicians, respectively, and 8,000 hours more than amateur pianists of the same age (Krampe & Ericsson, 1996).

Several studies and reviews have found a consistent relation between performance level and the quality and amount of deliberate practice in chess (Charness, Krampe, & Mayr, 1996), sports (Helsen, Starkes, &

FIG. 2.3. Estimated amount of time for solitary practice as a function of age



for the middle-aged *professional* violinists (triangles), the *best* expert violinists (squares), the *good* expert violinists (empty circles), the *least accomplished* expert violinists (filled circles) and *amateur* pianists (diamonds). From "The Role of Deliberate Practice in the Acquisition of Expert Performance," by K. A. Ericsson, R. Th. Krampe, and C. Tesch-Romer, 1993, *Psychological Review,* 700(3), p. 379 and p. 384. Copyright 1993 by American Psychological Association. Adapted with permission.

Hodges, 1998; Hodges & Starkes, 1996; Starkes, Deakin, Allard, Hodges, & Hayes, 1996), and music (Krampe & Ericsson, 1996; Lehmann & Ericsson, 1996; Sloboda, 1996). The concept of deliberate practice also provides accounts for many earlier findings in other domains, such as medicine, software design, bridge, snooker, typing, and exceptional memory performance (Ericsson & Lehmann, 1996), as well as for the results from the rare longitudinal studies of elite performers (Schneider, 1993).

When most people imagine a child practicing the piano, they tend to think of someone mindlessly repeating the same short piece, while the sound remains unmusical, aversive, and without any noticeable improvement. Nobody in their right mind would argue that poor or mediocre piano students could become outstanding musicians merely by spending more time on this type of mechanical practice. Mindless repetition is the direct opposite of deliberate practice, when individuals concentrate on actively trying to go beyond their current abilities. Consistent with the mental demands of problem solving and other types of learning, deliberate practice is done in limited periods of intense concentration. Diaries of the expert musicians revealed that they only engaged in practice without rest for around an hour and they preferred to practice early in the morning when their minds were fresh (Ericsson, Krampe, & Tesch-R6mer, 1993). Even more interesting, the best expert musicians were found to practice, on the average, the same amount every day, including weekends, and the amount of practice never consistently exceeded 4 to 5 hours per day. The experts told us during interviews that it was primarily their ability to sustain the concentration necessary for deliberate practice that limited their hours of practice. And their diaries reveal that the more the experts practiced, the more time they spent resting and sleeping; the increased sleep was primarily in the form of afternoon naps. Our review of other research (Ericsson, Krampe, & Tesch-Romer, 1993) showed that the limit of 4 to 5 hours of daily deliberate practice or similarly demanding activities held true for a wide range of elite performers in different domains, such as writing by famous authors (Cowley, 1959; Plimpton, 1977), as did their increased tendency to take recuperative naps. Furthermore, unless the daily levels of practice were restricted, such that subsequent rest and nighttime sleep allowed the individual to restore their equilibrium, individuals would encounter overtraining injuries, and eventually, incapacitating "burnout."

Do the best performers in a domain also need deliberate practice to perfect their skills, or are they fundamentally different? Fortunately, many of the famous musicians and acclaimed music teachers have been interviewed about the structure of their practice. Their answers are remarkably consistent and are eloquently summarized by one of the best-known violin teachers and virtuosi, Emil Sauer (1913):

> One hour of concentrated practice with the mind fresh and the body rested is better than four hours of dissipated practice with the mind stale and the body tired.… I find in my own daily practice that it is best for me to practice two hours in the morning and then two hours later in the day. When I am finished with two hours of hard study I am exhausted from close concentration. I have also noted that any time over this period is wasted, (p. 238)

It is clear that the need for specific types of practice, such as etudes and scales, diminishes for musicians who have already attained technical mastery, but not the need for deliberate practice in mastering new pieces: "With the limited time I have to practice nowadays, I apply myself immediately to works that I am preparing," writes Katims (1972, p. 238) and he argues that mastering pieces for upcoming concerts presents the specific challenges that guide deliberate practice. Many elite musicians are able to engage in mental practice: "I have a favorite silent study that I do all of the time, I do it before I start practicing. I do it on the train during my travel, and before I come out on the platform. I do it constantly" (Primrose, 1972, p. 248). With such a generalized definition of practice, even the famous violinist, Fritz Kreisler (1972, p. 98), who claimed to have never "practiced," would have engaged in practice: "How sad it is that in these days the emphasis is on how many hours one practices. When the Elgar concerto was dedicated to me I never put a finger on the fingerboard. Then I saw a passage I thought I could improve, and spent six hours on it."

The necessity of concentration for successful practice is recognized by all adult performers and some of them can even recall when they gained that insight: "For the first five years of musical experience, I simply played the piano. I played everything, sonatas, concertos—everything; large works were absorbed from one lesson to the next. When I was about twelve I began to awake to the necessity for serious study; then I really began to practice in earnest" (Schnitzer, 1915, p. 217). In fact, many of the individual differences among young music students practicing the same amount of time may be attributable to differences in the quality of their practice. The famous violin teacher Ivan Galamian (1972) argued:

> If we analyze the development of the well-known artists, we see that in almost every case the success of their entire career was dependent upon the quality of their practicing. In practically each case, the practicing was constantly supervised either by the teacher or an assistant to the teacher. The lesson is not all. Children do not know how to work alone. The teacher must constantly teach the child how to practice, (p. 351)

Recent analyses of famous child prodigies in music showed that all of them had been closely supervised from a young age by skilled musicians (Lehmann, 1997; Lehmann & Ericsson, 1998). The supervising adult

could then guide the young child's attention by appropriate activities and also help eliminate mistakes and poor technique. Equally important, the adult could monitor the child's attention and never push the child beyond their ability to sustain concentration. Thus, the training would be restricted to relatively brief periods at the start of systematic training. More generally, Starkes et al. (1996) showed that the duration of daily training given future expert performers was very similar across several domains, such as music and sports. During the first year, the daily level of practice was around 15 to 30 minutes, on average, with steady increases for each additional year, reaching 4 to 5 hours after around a decade. Starkes et al. found an intriguing similarity between increases in the amount of practice for sports when the athletes started practice around age 12, and music, when start of practice is closer to 6 to 7 years of age. If this pattern of results is found consistently across all domains, it would suggest that the level of increased training may require a slow physiological adaptation to the demands of sustained practice, which may be relatively insensitive to chronological age.

It has been shown that the attainment of expert performance requires an extended period of high level deliberate practice, where the duration of practice is limited by the ability to sustain concentration, a capacity that appears to increase as a function of years of practice in the domain. Consequently, a certain amount of deliberate practice may be necessary to reach the highest performance levels, and individual differences, even among experts, may reflect differences in the amount and quality of practice. However, most people would argue that there are distinct limits to the influence of practice, and that inborn capacities and innate talent will play a very important role in determining performance, especially at the highest levels within a domain. It has even been proposed by Sternberg (1996) that individuals with more innate talent would be more successful during practice, and thus more willing to engage in practice—possibly explaining at least part of the relation between amount of deliberate practice and performance.

In the remainder of this chapter, I propose how various types of training activities can, over time, change the body according to well-understood physiological principles, and that expert performance can be viewed as the end product of an extended series of psychological modifications and physiological adaptations. Most proposed individual differences between elite performers that have been attributed to innate talent can more parsimoniously be explained as adaptations to extended, intense practice. Furthermore, I explain how expert performance is mediated by complex memory mechanisms and representations that have been acquired as a result of practice, and how these mechanisms are critical to continued performance improvement.

CHANGE THROUGH DELIBERATE PRACTICE: SEARCHING FOR THE CAUSAL BIOLOGICAL AND COGNITIVE MECHANISMS UNDERLYING THE ACQUISITION OF EXPERT PERFORMANCE

Most people find it inconceivable that the dramatic differences between expert and novice performance can be explained by a series of incremental improvements starting at the novice level. They believe that most of the benefits of learning are attained rapidly within weeks or months as is the case for most everyday skills and leisure activities. They are surprised to hear that it takes years, even decades, of gradual improvements for even the most "talented" to reach the highest levels of performance.

Why is it that everyday performance rapidly reaches a stable level, whereas expert performance continues to improve? The reason appears to be primarily motivational. For example, why don't most of us reach a physical fitness level that we would like? In this case there is ample scientific evidence that increasing the duration and intensity of our daily exercise would eventually get us close. To keep doing what we normally do is easy, but changing our fitness level requires altering our habits. Change is effortful until a new habitual state has been attained. The primary challenge appears not to be maintaining the desired level of activity once it has been reached, but *the process of changing* from one steady state to another. However, to sustain improvements over extended periods, the aspiring expert performer must constantly keep working toward the next higher level of performance.

When considering physical fitness it is well known that merely wanting to be fit is simply not enough to attain fitness. Similarly, daydreaming about how good it would feel to be fit does not do it either. Desire to attain some level of mastery in a domain of expertise is not by itself enough to reach the desired level. Until we can specify the causal mechanisms that link deliberate practice directly to the observed improvements of performance, an account based on deliberate practice is not qualitatively different from one based on prayer or mere intensity of desire. Consequently, we need to show that deliberate practice influences performance in a manner consistent with scientifically well-established mechanisms— not through divine intervention or mere wish fulfillment.

A related obstacle is the common sense conception of the limited malleability of the body and mind as a function of extended activity. Most adults have very limited recent experience of changing their bodies through regular physical exercise or acquiring high levels of mastery in a new domain. Their experience is generally consistent with the view that gradual improvements are possible, but a relatively stable limit is soon reached that is determined by stable characteristics, presumably determined by unmodifiable genetic factors. Because most individuals never achieve very high levels of performance in a domain, they are unacquainted with highly refined, intense deliberate practice and the complex mechanisms mediating expert performance.

Discussions about expert performance and other types of superior achievement have revolved around dichotomies, such as whether this level of performance can be attributed to acquired strategies or basic abilities, hardware or software, environment or genetics. A more promising path toward better understanding of expert performance involves development of explicit models illustrating the mechanisms that mediate expert performance, how training changes these mechanisms, and how these changes alter the body and the nervous system.

Historically, various metaphors and models have been proposed to describe the structure of complex performance. The first proposals described complex activity as the result of an intricate mechanical clock or as a hydraulic system consisting of hoses filled with liquids under pressure. A major breakthrough came when electronic computers made it possible to efficiently program strategies using a small set of basic operations. However, all machine metaphors mislead us about the limits of human modifiability. After all, computer hardware remains fixed until changed by a human operator. Biological systems and animals can change in ways that machines cannot, and these biological comparisons have important implications for human performance. Let me give you one striking example.

As many of you probably know from introductory courses in biology, if a newt (a type of salamander) loses a leg, the leg regenerates. If mammals lose a leg it will not grow back, but some mammalian organs do regenerate. For instance, if a surgeon removes over half of the liver, the remaining tissue will grow back to 70% of its original size. If a kidney is removed during an organ donation, then the remaining kidney will grow as much as 50% in the following week. Most of the internal organs can regenerate lost parts, and, most importantly, many of their characteristics, including size, are adaptively determined by demand. Unlike older mechanical and electric machines that wear out with use, the human body's efficiency increases as a function of the amount of similar activity.

Several types of processes lead to physiological changes, and thereby to changes in performance. The processes that have been most studied in psychology correspond to associative learning, and the acquisition of knowledge, procedures, and skills—in essence, the traditional definition of learning in psychology. These processes result in specific neural changes in the central nervous system. I return to this type of learning later in the chapter. A second major type of process resulting in physiological change that has been studied extensively in exercise physiology involves adaptations at the level of individual cells. Given that, unlike human beings, these cells cannot be told what to do, changes in them occur as reaction to processes that influence their physical and chemical environment.

In the following overview, I focus on the changes in single cells and in the central nervous system, but I recognize the need to consider other types of learning and adaptation that I barely touch on, including learning processes that increase subjects' control over their emotional state, and their metacognitive insights into the long-term development of skill. I first discuss the processes of adaptation of individual cells and then return to processes in the central nervous system involved in the acquisition of skill.

Deliberate Modification of Bodily Systems and Individual Cells

Everyone knows that it is possible to improve many kinds of performance by training and exercise. Virtually all adults have increased their performance in some activity such as running or doing push-ups. To improve, individuals typically engage in the activity, but this is not enough. In addition, it is essential to push the limits of current capacity, applying the overload principle, to get into the aversive zone of "No strain, no gain." Research on aerobic fitness has found that young healthy adults have to maintain a heart rate above 70% of the maximal heart rate (over 140 to 150 for most adults) for an extended time on a regular basis (around three times a week) in order to attain measurable improvement in fitness. By inducing this strain or overload for an extended time, a chain reaction of metabolic processes and chemical changes is initiated to counteract deviations from equilibrium, triggering additional control processes and their chemical by-products. When sufficient strain is attained, chemical changes activate the processes responsible for regeneration and growth of the affected tissue. Of course, the level of intensity should not be so great to cause permanent damage to tissue. In fact, the intensity, duration, and frequency of practice has to be set at a level such that the body is given enough opportunity to recuperate between practice sessions, otherwise there is eventual risk for over-use injuries or even burn-out (Ericsson, Krampe, & Tesch-Romer, 1993). Finding the appropriate balance between strain and rest is one of the major challenges for individuals pursuing their limits of performance.

Most improvements in fitness occur following activity, when the body has a chance to recuperate. Through a delicate process of alternating strain and regeneration/growth, the body slowly adapts to the demands of the increased regular physical activity. As expected, large-scale studies (Bouchard, Shephard, & Stephens, 1994) have found a close relation between the amount and intensity of habitual physical activity for individuals and their physical fitness, as illustrated in Fig. 2.4.

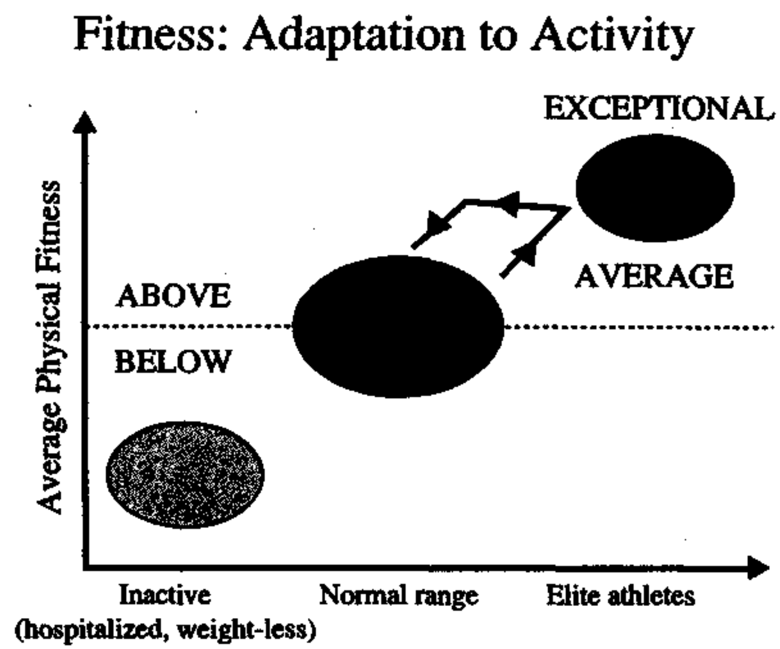


FIG. 2.4. A schematic illustration of the relation between the level of habitual activity and current fitness level.

When the level of habitual physical activity changes, the body adapts to the new situation. For example, the fitness of well-trained individuals is rapidly reduced when they cannot engage in demanding physical activity due to various conditions, such as weightless astronauts in space or injured athletes confined to bed rest. Fitness level also increases with the duration and intensity of daily training. It is important to note that the duration of weekly training necessary to improve fitness is often several times greater than the duration required to merely maintain an existing level, as is illustrated by the arrows in Fig. 2.4.

When intense daily training is sustained for months or years, the observable results are often dramatic. There is documented evidence of practice-related anatomical changes in elite athletes (see Ericsson, 1996; Ericsson & Lehmann, 1996; Roberts & Roberts, 1997, for reviews). For example, after years of intense practice, adaptive processes can increase the size and endurance of athletes' hearts so more oxygen-rich blood is pumped through the muscles. Even bones have been shown to change in response to training. The arm with which an elite tennis player holds the racquet not only has bigger muscles, but thicker, wider bones. It has been recognized for years that the mechanical vibration of the bones due to intense activity stimulates bone growth in the direction orthogonal to the plane of the vibrations.

One interesting hypothesis for controlling these adaptive processes suggests that when cell walls are deformed due to the mechanical vibration, molecules are torn off, which, in turn, stimulate the growth to counteract the effects on cell walls from future mechanical vibrations. This mechanism can also explain why only the thickness and width of bones are affected rather than their length. The inability of increasing the length of bones through physical activity means that height cannot be increased by practice. Height thus appears to be one of a very small number of innately determined factors that have been clearly shown to influence some types of sports performance, such as basketball (favorably) and gymnastics (unfavorably), that cannot be modified by physical training.

The most compelling evidence for physiological adaptation is provided by longitudinal studies showing that critical performance characteristics change favorably as a function of training, then revert back to the normal range when training is discontinued. Elite swimmers who stopped training in early adulthood were shown to lack any benefits of prior training compared to an age-matched control group when they tried to reacquire their fitness years later. The primary benefit of training for long-term fitness maintenance is that it requires much less effort to maintain already acquired adaptation than it took to acquire it originally. Recent research shows that many types of adaptations can be maintained with shorter periods of intermittent practice as long as the intensity of training activity is preserved. Perhaps the sustained intense effort leads to production of metabolic waste products, such as lactic acid, that stimulate chemical processes preserving the new state of equilibrium.

There are good reasons to believe that many of the mechanisms regulating adaptation to training are also involved in normal physiological development of children and adolescents (see Ericsson & Lehmann, 1996, for a brief review). Hence, training during certain periods of development appears to yield especially large adaptive responses. For example, recent research has shown that average children between 3 and 5 years of age can acquire perfect pitch, the ability to name individual tones when presented in isolation, given appropriate training. Differences in brain structure may be observed in individuals with perfect pitch compared to that of other musicians (Schlaug, Jancke, Huang, & Steinmetz, 1995). These differences can be explained by early childhood activities that lead to different patterns of neurological development. Numerous animal studies show that training influences neurological development through the growth of blood supply, the density of synapses, and even by restricting development of certain structures. For musicians who play stringed instruments, the size and elaboration of cortical mapping for the fingers, especially the

little finger on the left hand, is correlated with the onset of music training (Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995). Other performance-related physiological characteristics, such as the metabolic characteristics of muscle fibers, and the range of motion for classical ballet dancers, may be relatively easily influenced during development, but are much harder to influence through training in adolescence and adulthood.

These cellular and physiological characteristics will only result in performance change if they are integrated with skilled actions and movements. The next section discusses the acquisition of skilled and expert performance.

Everyday Skills and Expert Performance: The Acquisition of Integrated Appropriate Actions

Everyday skills and expert performance require that individuals efficiently generate appropriate actions when needed. A comprehensive theory needs to describe both the similarities and differences in the acquisition of everyday skills and expert performance. How individuals are able to acquire everyday life skills, such as typing, playing tennis, or driving a car, is extensively researched and well understood. It is therefore easiest to briefly review theories of everyday skill acquisition, then describe how the acquisition of expert performance differs.

The traditional theories of skill acquisition (Anderson, 1982,1987; Fitts & Posner, 1967) propose that during the initial "cognitive" phase (see Fig. 2.5) individuals learn the underlying structure of the activity and what aspects they must attend to. In the early stages of learning the activity, they get clear feedback about their misunderstandings as they make mistakes. Gradually they become able to avoid gross errors, and eventually, during the second "associative" phase, they can attain an acceptable level of performance. During the third and final "autonomous" phase, their goal is typically to achieve effortless performance as rapidly as possible. After some limited period of training and experience, frequently less than 50 hours for most recreational activities, such as skiing, tennis and driving a car, an acceptable standard of performance can be generated without much need for effortful attention. At this point, execution of the everyday activity has attained many characteristics of automated performance (Anderson, 1982,1987; Fitts & Posner, 1967; Shiffrin & Schneider, 1977) and requires only minimal effort.

Figure 2.5 illustrates the transition from the first stage, when everyday performance initially improves as individuals expend effort to reach an acceptable level, to adaptation as their performance becomes automatized, and the performance level fixated, as individuals lose conscious con-

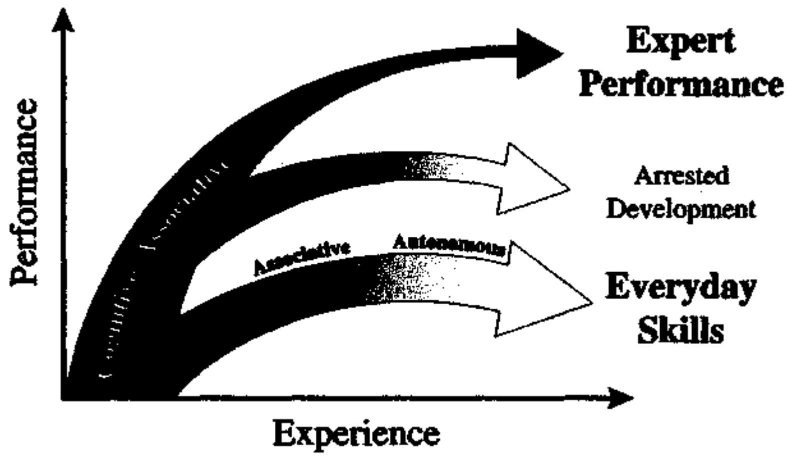


FIG. 2.5. An illustration of the qualitative difference between the course of improvement of expert performance and of everyday activities. The goal for everyday activities is to reach as rapidly as possible a satisfactory level that is stable and "autonomous." After individuals pass through the "cognitive" and "associative" phases they can generate their performance virtually automatically with a minimal amount of effort (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 give up their commitment to seeking excellence and thus terminate regular engagement in deliberate practice to further improve performance, which results in premature automation of their performance. Adapted from "The Scientific Study of Expert Levels of Performance: General implications for optimal learning and creativity" by K. A. Ericsson, 1998, *High Ability Studies, 9,* p. 90. Copyright 1998 by European Council for High Ability. Adapted with permission.

trol over intentionally modifying and changing it. Everyone can easily recall from their childhood and adolescence how many hours of rote memorization of the alphabet, the multiplication tables, and foreign vocabulary items are necessary for direct retrieval from memory. Once this occurs, increased experience will not be associated with increased accuracy. Within this simple view of skill acquisition, it is inevitable that the major improvements are limited to the first phases, but then performance reaches a stable automatic level determined by factors that are believed to be outside the individuals' control. Individual differences are thus believed to reflect stable immutable differences, such as innate capacities and neural speed.

This popular conception of how everyday skills are acquired has little in common with our view of the acquisition of expert performance through

deliberate practice. In contrast to the rapid automatization of everyday skills and the emergence of a stable asymptote for performance, expert performance continues to improve as a function of increased experience and deliberate practice, as illustrated in Fig. 2.5. One of the most crucial challenges for aspiring expert performers is to avoid the arrested development associated with generalized automaticity of performance and to acquire cognitive skills to support continued learning and improvement. Expert performers counteract the arrested development associated with automaticity by deliberately acquiring and refining cognitive mechanisms to support continued learning and improvement. These mechanisms increase experts' control and ability to monitor performance. The expert has to continue to design training situations where the goal is to attain a level beyond their current performance in order to keep improving. There are many methods for discovering new and higher levels of performance (Ericsson, 1996). One common method involves comparing one's performance to that of more proficient individuals in their domain of expertise. One can then identify differences and then attempt to reduce them gradually through extended deliberate practice.

In the next section I show that expert performance is not fully automated. I first briefly summarize empirical evidence demonstrating that experts retain cognitive control over detailed aspects of their performance at the highest levels and that experts rely on acquired representations to support planning and reasoning (Ericsson & Delaney, 1999). These cognitive representations allow the experts to generate internal images of a desired performance without having experienced it before and to design plans for producing a similar performance without having previously done so. In a second subsection I then discuss how future experts acquire representations, and how these representations allow them to identify new goals so that they can continue improving their performance. These representations form the foundation for continued learning without teachers, and ultimately allow for the very best of them to make innovative creative contributions to their domain of expertise.

The Cognitive Mediation of Expert Performance. An everyday skill like driving one's car to work is typically viewed as a means to an end, where the goals of the activity concern safety and minimization of effort. These goals differ completely from those for expert-performance version of that activity, such as professionals driving racecars. Like other expert performers, racecar drivers have to maintain full concentration as they try to push the limits of their best performance during training and competition without unduly increasing the risks for accidents.

To reach their highest possible level of performance, expert performers make adjustments appropriate to specific opponents or performance situations. For example, experts routinely make extensive adjustments to accommodate situational factors, such as weather and new equipment. A concert pianist will familiarize themselves with the piano and the acoustics of a concert hall. An expert billiard player will carefully examine any peculiarities of the billiard table before competing on it. Expert performers often study and prepare for competition against particular opponents, identifying their weaknesses to gain competitive advantage. As part of their expertise they are able to make fast, fluent adjustments to changes in their opponents' strategies. None of these adjustments would be possible if expert performance were fully automated. Furthermore, expert performers are well known for having accurate, detailed memories of their performance long after the competitions, which would be impossible if their performance during those events had been automated.

The most compelling scientific evidence for preserved cognitive control of expert performance comes from laboratory studies where experts reproduce their superior performance with representative tasks that capture the essence of expertise in their domain (Ericsson & Smith, 1991). In his pioneering work on expertise, de Groot (1946/1978) instructed good and world-class chess players to think aloud while selecting the best move to a set of unfamiliar chess positions. He found that the quality of selected moves was closely associated with the performers' chess skill. From verbal reports, he found that the chess players first perceived, then interpreted the chess position, and rapidly retrieved potential moves from memory. The moves were then evaluated by planning where the consequences of each move were explored by generating sequences of plausible counter moves using a mental representation of a chessboard. During the course of this evaluation even the world-class players would discover better moves. Consequently, experts' defining ability to generate better moves for chess positions than less skilled players (see Fig. 2.1) depends to a large extent on deliberate planning and reasoning, as well as on careful evaluation, in order to reduce the frequency of mistakes.

In sum, Ericsson and Lehmann (1996) found that experts' think-aloud protocols revealed how superior performance was mediated by deliberate preparation, planning, reasoning, and evaluation in a wide range of domains, such as medicine, computer programming, sports, and games. Therefore, the performance of experts cannot be completely automated, but remains mediated by complex control processes.

Recent reviews (Ericsson, 1996; Ericsson & Kintsch, 1995) show that individuals who perform at higher levels utilize specific kinds of memory processes. They have acquired refined mental representations to maintain access to relevant information and support more extensive, flexible reasoning about encountered tasks or situations. In most domains, better performers are able to rapidly encode, store, and manipulate relevant information for representative tasks in memory (Ericsson & Lehmann, 1996). To illustrate this ability, I describe a couple of examples from two different domains. With increased skill, chess players are able to do deep planning, to mentally generate longer sequences of chess moves and evaluate their consequences (Charness, 1981). Chess masters are even able to hold the image of the chess position in mind so accurately that they can play blindfold chess—play without perceptually available chessboards.

Similar evidence for mental representations has been shown for motor-skill experts, such as snooker players and musicians. In recent studies, Lehmann and Ericsson (1995, 1997) had expert pianists memorize a short piece of music. The pianists were then given an unexpected series of tasks in which they were asked to reproduce the piece at the same tempo under changed conditions, such as playing every other measure, and playing notes with only one hand. Although reliable individual differences were observed, accuracy was uniformly very high. Many subjects were even able to accurately transpose the music into a different key at regular tempo when unexpectedly asked to do so. During accurate transposition performance, the pianists pressed different piano keys with new finger combinations, which demonstrates mediation of a flexible memory representation of the music. In sum, the essence of expert performance is a generalized skill at successfully meeting the demands of new situations and rapidly adapting to changing conditions.

Even expert performance in activities where superior speed is the criterion, such as typing (see Fig. 2.1), appears to depend primarily on mediating representations rather than faster basic speed of neurons and muscles. The superior speed of expert typists is related to how far they look ahead in the text beyond the word that they are currently typing, as illustrated in Fig. 2.6. With increased acquired skill, expert typists can look further ahead in the text so they can prepare future keystrokes in advance, moving relevant fingers toward their desired locations on the keyboard. The importance of anticipatory processing has been confirmed by analysis of high-speed films of expert typists and experimental studies where expert typists have been restricted from looking ahead. Furthermore, the further someone looks ahead in a text when asked to read aloud rapidly, the higher their ability to read and the faster their silent reading speed (Levin & Addis, 1979).

Similarly, the rapid reactions of athletes, such as hockey goalies, tennis players, and hitters in baseball, have been found to reflect skills acquired primarily to avoid time stress by successfully anticipating future events (Abernethy, 1991). This evidence supports*the hypothesis that expert athletes have a learned, rather than a biological, speed advantage over their less accomplished peers. For example, when skilled tennis players are preparing to return a serve, they study the movements of the opponent lead-

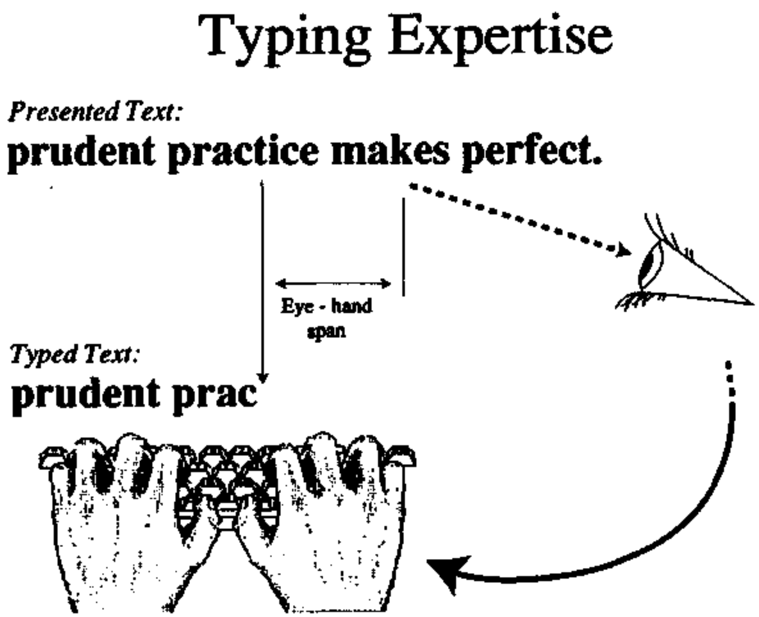


FIG. 2.6. An illustration of how the eyes of expert typists fixate material in the text well in advance of the currently typed text in order to gain advantages by advance preparation. Copyright 1999 by K. Anders Ericsson. Reprinted with permission.

ing up to contact between the ball and the racquet to identify the type of spin and the general direction. Given the ballistic nature of a serve, it is often possible for skilled players to accurately anticipate the consequences of these movements. It is important to note that novice tennis players use an entirely different strategy, and usually initiate their preparations to return the ball once it is sufficiently close to see where it will bounce. If the cues that immediately precede ball contact had become fully automated to guide the hitting of the ball, anticipatory perceptual skills would never develop. The anticipatory use of predictive cues must have been acquired later at a more advanced level of skill. The superior anticipation of the ball trajectory has frequently been misinterpreted as evidence for superior basic perceptual capacity. It is a common misconception that elite athletes have more accurate vision that allows them to see the balls better, when, in fact, their performance reflects a highly specialized perceptual skill. Consistent with this hypothesis, elite athletes are not consistency superior on standard vision tests compared to less accomplished performers and other control groups.

The increasingly refined representations allow expert performers to attain more control of relevant aspects of performance and greater ability to

anticipate, plan, and reason about alternative courses of action. In addition to providing better control, these mental representations play an essential role in helping individuals continue improving their performance: setting new goals for improvement, monitoring their performance, and refining skills necessary to maintaining the integrity and fluency of their current level of superior performance during continued learning. How are these representations acquired during development? Are there special training activities that allow individuals to refine them?

The Acquisition of Representation! That Mediate the Attainment of Expert Performance. The most important differences between autonomous everyday skills and expert performance are related to the experts' representations that allow them to keep controlling and monitoring their behavior. In an earlier section I showed that there is a natural tendency toward developing effortless automatized performance in which conscious access to mediating representations is not acquired. Fluent repeated performance appears to become highly automated unless the individual actively resists. I argue that experts and aspiring experts rely on deliberate practice to counteract complete automatization and to promote the development and refinement of representations. First, I briefly discuss how the mediating representations are acquired from the start of supervised practice to the attainment domain expertise. Then I discuss a few specific examples of how deliberate practice refines these representations and the associated mechanisms that improve the integrated performance.

In many domains of expertise, individuals are introduced into the domain as children and after short period of playful interaction the future expert performers start working with a teacher (see Fig. 2.7), illustrating the three stages proposed by Bloom (1985)). The playful interaction will not stop but it will be augmented by deliberate practice. When beginners are initially introduced to practice in a domain, the teacher instructs them using very simple objectives and tasks and will explicitly guide the beginners' attention to specific aspects of the training situations as part of the instruction. The beginner, often aided by a parent, must learn to regenerate the goals of the training activity and sustain focus on attaining them through repeated attempts.

The assigned goal of the training activity also provides the beginners with a means to generate feedback about the correctness of their performance, which would imply some mental representation although not necessarily a sophisticated one. During development, teachers often help their students identify errors and make necessary changes and specific corrections. As the student's performance improves, they acquire more complex representations to monitor and control the aspects of performance targeted by the teacher for correction during solitary practice. As the com-

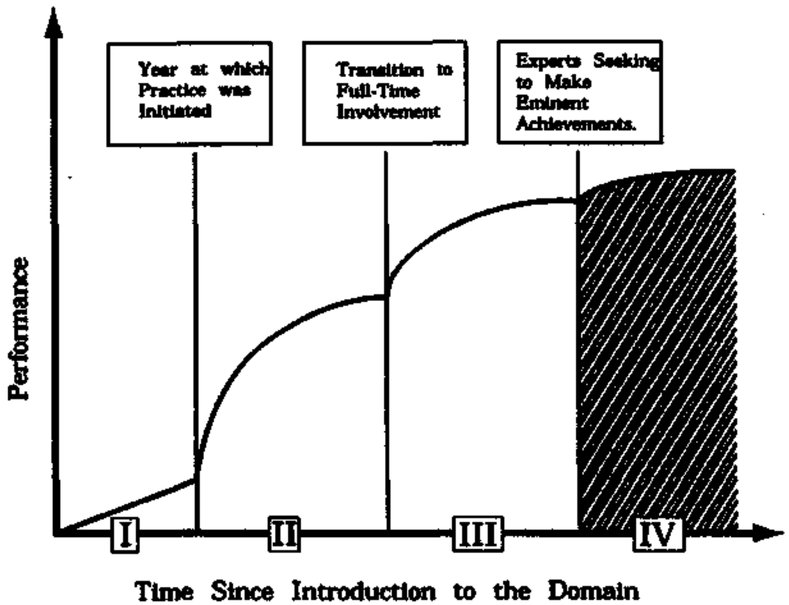


FIG. 2.7. Three phases of acquisition of expert performance, followed by a qualitatively different fourth phase when, in order to make a creative contribution, experts attempt to go beyond the available knowledge in the domain. From "Can We Create Gifted People?" by K. A. Ericsson, R. Th. Krampe, and S. Heizmann in G. R. Bock and K. Ackrill (Eds.), *The Origins and Development of High Ability* (pp. 222-249), 1993, Chichester, England: Wiley. Copyright 1993 by CIBA Foundation. Adapted with permission.

plexity of the acquired performance level increases, so does the complexity of practice goals and the associated training activities. At higher levels, the teacher will provide primarily general instructions and feedback, which requires the students to monitor their own performance, to actively engage in problem solving as errors occur, and to make appropriate adjustments to their performance. Hence, parallel to improvement of their performance, students develop complex mental representations of the desired performance so that they can monitor their concurrent performance to identify discrepancies between their desired and actual performance (Ericsson, 1996; Glaser, 1996). As students reach high levels of achievement, they will have acquired the knowledge of their teachers and have mental representations that enable them to independently monitor and improve their performance. They may also augment the training methods of their teachers by studying the performance and achievements of current and past masters in their domain (Ericsson, 1996, 1997). When indi-

viduals have mastered all the knowledge and techniques of their domain (see the fourth phase in Fig. 2.7), they are uniquely positioned to have a chance to make major creative contributions by adding something genuinely new, whether it is a new idea, a new training method, or a new interpretation of past achievements. This type of creative expansion of the space of conceivable achievements and accumulated knowledge in a specific domain represents the supreme level of achievement in any domain.

There is still an incomplete understanding of representations: how they are acquired and refined, and their close connection to performance, but I illustrate their involvement in deliberate practice with a few examples from chess, copying, and music.

Deliberate Practice in Chess: Planning and Anticipating the Consequences of an Opponents' Actions. Once an individual has reached a level of proficiency in a domain, when they are better than everyone else in the chess club, for example, how can they be challenged to find increasingly better chess moves? Expert chess players have been shown to collect books and magazines with the recorded games of chess masters (Charness et al., 1996). They can play through the games to see if their selected moves correspond to those originally selected by the masters. If the chess master's move differed from their own, it would imply that they must have missed something in their planning and evaluation. Through careful, extended analysis the chess expert is generally able to discover the reasons for the chess master's move. Similarly, the chess player can read published analyses of various opening combinations and supplement their own knowledge by examining the consequences of new variations of these openings. Serious chess players spend as much as 4 hours every day engaged in this type of solitary study (Charness et al., 1996; Ericsson, Krampe, & Tesch-Romer, 1993).

Deliberate Practice in "typing: A Focus on Improving Copying Speed. Once an individual has reached a stable typing speed, how can it be increased? During normal typing activities it is important to minimize errors and maintain a typing speed that can be sustained. On the other hand, typists can for short intervals sustain higher speeds with full concentration, at least 10 to 30% above normal rates. Consequently, the recommended practice to improve speed is setting aside time daily to type selected materials at the faster rate without concern about accuracy. Initially typists seem only to be able to sustain the concentration necessary to type 10 to 20% faster than normal speed for 10 to 15 minutes per day. After adaptation to this kind of regular practice, the duration of the training sessions can be increased (cf. the earlier discussion of the development of weekly practice time). When typists push themselves beyond the comfortable range of reliable typing, they will encounter keystroke combinations that slow them down, causing hesitations or awkward motor movements. By eliminating the specific problems through better anticipation or coordination of motor behavior, these problems can be corrected. Typists can then iteratively confront remaining typing combinations that limit typing speed. The recommended training to improve speed in other perceptual motor activities shares many of these same methods of progressive improvement.

Deliberate Practice in Expert Music Performance: The Importance of Mental Representations for Monitoring Performance. Now consider the different types of mental representations that are necessary for advanced music performers. For example, musicians must be able to internally represent many aspects involved in mastering the interpretation of a new piece of music. Three of them are illustrated in Fig. 2.8: the performer's image of how they want a given performance to sound to the audience, their plan of how the instrument should be played to achieve this goal, and their capacity to monitor the produced sound as they practice to produce the desired performance (Ericsson, 1997).

The importance of these representations and, in particular, the key role of critical listening to one's music performance, have been recognized and

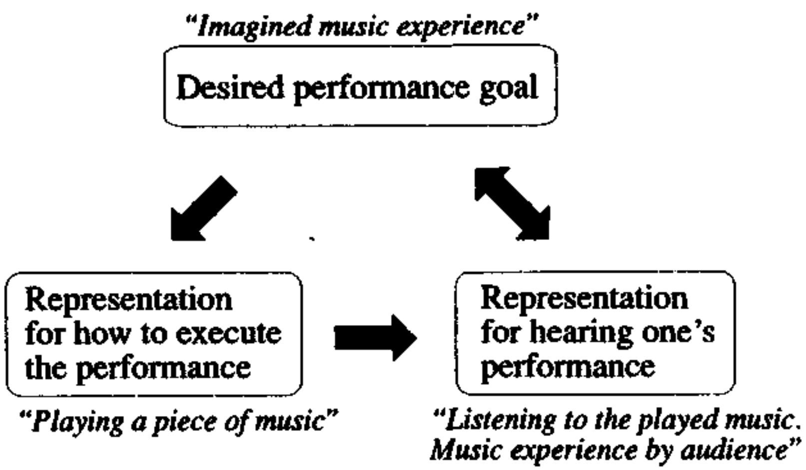


FIG. 2.8. Three types of internal representations that mediate expert music performance and its continued improvement during practice. From "The Scientific Study of Expert Levels of Performance: General Implications for Optimal Learning and Creativity," by K. A. Ericsson in *High Ability Studies, 9,* p. 92. Copyright 1998 by European Council for High Ability. Reprinted with permission.

articulated by master teachers. "One of the greatest difficulties which stand in the way of progress is the failure to hear what one is doing at the piano. ... When the moment comes that the pupil actually hears what he is doing, consciousness is awakened and the progress begins" (Buhlig, 1917, p. 218). Critical listening remains equally important at advanced levels. "In his practicing, the real art is for the pupil to acquire the uncanny ability to listen to his own work, to discover his own minute failing" (Szigeti, 1972, p. 205). Even experts must be wary of the risk of reducing the level of concentration and lowering their performance criteria. "The habit of not listening becomes worse and worse, and in a short time the player is unconscious of the slight inaccuracies in pitch. There is listening, and listening *intently"* (Tertis, 1972, p. 267). Expert musicians actively try to counteract the threat of automaticity and reliance of habitual performance. The famous cellist Pablo Casals carefully prepared and studied even very familiar music pieces before playing them in public. "To play it perfectly every piece should be studied with the constant idea of improvement in mind, and it is seldom, working in this way, that I do not find that I can improve some one or another detail" (Casals, 1923, p. 234). Working out the intended music experience in detail allows the musician to carefully monitor their performance. "I try to form an ideal conception of the piece, work this out in every detail, then always endeavor to render it as closely like the ideal as possible" (Lerner, 1915, p. 46). And perfection is never permanently attained. "I never neglect an opportunity to improve, no matter how perfect a previous interpretation may have seemed to me. In fact, I often go directly home from a concert and practice for hours upon the very pieces that I have been playing, because during the concert certain new ideas have come to me" (Busoni, 1913, p. 106)

Individual differences in the acquired representations responsible for musical abilities, such as sight-reading, rapid memorization of music, and improvisation, are frequently attributed to musical talent, perhaps because it has been difficult to understand how such abilities are acquired (Bamberger, 1991). However, there are several theoretically and empirically supported accounts of how they are acquired through practice-related activities (Lehmann & Ericsson, 1993,1995,1996;Sudnow, 1978).

In sum, the superficial characteristics of deliberate practice are unimportant and differ greatly across as well as within domains, but the defining common feature of deliberate practice refers to its ability to change and improve performance and will therefore depend on the desired changes in achievement. Once upon a time all effective methods for deliberate practice must have been discovered by individuals who experimented with different methods for practice. Today students do not need to rediscover these training techniques but they are passed along by their teachers and coaches. Recent accounts (Ericsson, 1996; Zimmerman, 1994) of the development of past and current masters describe how these individuals were able to invent techniques to increase their mastery of skilled activities with minimal instruction and external support. This type of extended self-guided search for effective practice methods in a domain is likely to foster the development of representations that benefit subsequent development of expertise supervised by skilled teachers.

Expert Performers' Learning: Generalizable Aspects and Specific Implementations

For anyone interested in general mechanisms mediating learning, the most striking findings from the study of expert performance concern its domain specificity and diversity. Not only does deliberate practice differ between domains, but the particular training that would be optimal for individual experts within a domain will differ and depend on the individual's strengths and weaknesses. For this reason, training in most domains is designed to develop independent performers so they can find their own path toward expertise through reflective self-evaluation and problem solving. In fact, individual differences and diversity are encouraged at the highest levels to prepare elite performers to go beyond the accumulated knowledge in their domain and extend its boundaries through major innovations.

Is it possible to extract some generalizable principles for experts' learning in light of this striking variability and diversity? Many significant efforts have been made to extract concepts, mechanisms, and characteristics of effective learning in the fields of education and professional development. Many of those findings capture several generalizable characteristics of experts' learning and deliberate practice: Changes in behavior and performance are facilitated by setting specific attainable goals (Locke & Latham, 1984), effective students optimize improvement by designing and monitoring their learning activities (Schunk & Zimmerman, 1994), and learning should be mindful and reflective, striving toward genuine understanding, rather than mindless memorization (Langer, 1997). These three abstract characteristics reveal important higher-level differences between how experts and amateurs tend to learn, and focus on necessary characteristics of effective learning and thus explain why the learning of the amateurs tends to be limited. How much of the experts' efficient learning is explained by these characteristics? Would it be possible to induce effective learning by merely instructing the amateurs to change the methods for learning? If not, which conditions and prerequisites are necessary for efficient types of learning?

The study of the acquisition of expert performance gives us insight into these issues. The more we learn about the development of expert performance in specific domains, the better our understanding of prerequisites for effective learning. First, before reflective monitoring of behavior and learning in a domain can occur, the individuals have to have acquired appropriate knowledge and domain-specific representations. Use of reflective analysis and self-regulation is feasible only after prerequisite representations have been sufficiently developed at more advanced levels of performance. Given that these domain-specific representations are acquired to meet specific demands of reasoning in the domain, their transfer across domains seem to be quite limited (cf. Ericsson & Lehmann, 1996). To become an effective learner within a domain would appear to require a sustained commitment to acquiring the necessary representations and relevant knowledge.

Second, acquisition of complex representations for monitoring and evaluation (self-regulation) have to be closely intertwined with the acquisition of task-specific performance. Consequently, it may not be reasonable to try to distinguish these representations and associated learning activities from the structure of domain-specific performance (Ericsson & Kintsch, 1995). In complex skills it may be necessary that the same representations mediate the generation of the desired performance as well as the subsequent reflective analysis and modification of the actual performance. It is essential that structural changes made to improve performance during learning will not have any undesirable side effects on other aspects of performance. By using the same representation to monitor their performance during deliberate practice as the expert performers use to control the final public performance, it is possible to make incremental adjustments without interfering with the integrity of the skill.

Finally, the research on deliberate practice has shown that concentration is necessary for optimal learning. Because most individuals seem to prefer less effortful activities that satisfy short-term learning goals, they must be motivated to attain high achievement in a domain before they will engage in sustained deliberate practice. Motivation is then an essential part of interventions to initiate acquisition of knowledge and representations that are necessary for effective learning. In sum, I believe that the study of expert performers will provide us with insights into the detailed structure of the complex, extended interactions required for the sustained efficient learning leading to mastery and expert performance.

CONCLUDING REMARKS ON THE GRADUAL ATTAINMENT OF EXCELLENCE THROUGH DELIBERATE PRACTICE

The general "law" of least effort predicts that activities are carried out with the minimum expenditure of effort. For this reason, the nervous system automates behavior whenever possible, and activities tend to be performed with the simplest possible mediating mechanisms. Individuals usually reach a satisfactory level of performance in most types of habitual everyday activities. At this level of achievement, repeating a similar series of actions doesn't change the structure of performance, it merely reduces the effort required for their execution. Any successful attempt to improve performance beyond this stable level thus requires active effort, changing the goal of performance, as well as designing new activities for training and improvement—deliberate practice. Depending on the domain, deliberate practice can range from simple repetitive activity aimed at increasing endurance or flexibility, to reflective analysis focused on identifying and improving aspects of skilled complex performance. Consequently, the specific activity of deliberate practice may differ dramatically across domains, but it always involves efforts to stretch performance toward higher, yet attainable, goals.

The emphasis on the sustained striving for improvement by expert performers may sound reminiscent of the arguments traditionally associated with motivational speakers advocating self-improvement. Both approaches agree that individuals tend to underestimate their achievement potential and that the first step in initiating change through training and practice requires that individuals are convinced that they are capable of attaining their new goals. Beyond that, the resemblance is superficial. For example, where motivational speakers tend to be rather general about which attributes can be improved, accounts in terms of deliberate practice are limited to domains of expertise with reproducible superior performance. From laboratory analyses of the experts' superior performance, scientists have consistently found evidence for the acquired mediating mechanisms discussed previously: very complex skills, highly refined representations, and large physiological adaptations. The complexity of these acquired mechanisms is consistent with the finding that not even the most "talented" can reach an international level of performance in less than a decade of dedicated practice. In this chapter I have shown how the acquisition of expert performance in several domains is closely related to engagement in deliberate practice. In particular I have focused on how well-understood mechanisms of skill acquisition and physiological adaptation can provide causal accounts of changes in the body and the nervous system that produce the desired improvements in performance.

The complex integrated structure of expert performance raises many issues about how these structures can be gradually acquired and perfected over time. It appears that teachers start guiding skill development from a child's initial introduction to training. The teacher knows the appropriate sequencing of skills and can provide training assignments of a challenging, yet attainable, difficulty level. Equally important, the teacher knows the future challenges at the highest levels and can therefore insist on mastery of the fundamentals during development to avoid the need for relearning at advanced levels. However, the best teachers in the world can never successfully train students without their full cooperation and active participation in the learning process. At all levels of performance, students who have representations supporting their planning, reasoning, and evaluation of the actual and intended performance will be better able to make appropriate adjustments to their complex skill. This advantage becomes absolutely essential at higher levels of achievement. Given that deliberate practice involves mastering tasks that students could not initially attain, or only attain imperfectly or unreliably, it is likely that more successful students acquire representations to support problem solving and learning through planning and analysis. Consequently, the faster learning of "talented" students might be explained by individual differences in acquired representations supporting effective learning.

Why would so many individuals engage in the strenuous, concentration-demanding activities of deliberate practice regularly over years and decades, when the research shows that the relaxed comfort zone provides the mood-enhancing effects of exercise and the states of high enjoyment associated with "flow" or the "runners' high"? An important part of the answer lies in their instrumentality: They offer the means to attaining superior performance with its many associated rewards and benefits, such as social recognition, relationships with teachers, playful interactions with like-minded peers, travel, scholarships and occupational opportunities, and the other benefits associated with improved performance. The myth that hard work at the start will enable one to coast into future success is not supported by the evidence, and it most likely reflects confusion between merely maintaining a performance at a high level and continued further improvement of performance. In fact, as an individual's performance level improves, the demand for effort to further improve performance remains high. In support of this claim, the rated level of effort during training is greater, not less, for elite athletes than it is for amateurs.

From the perspective of deliberate practice, the rarity of excellence is primarily attributable to the environmental conditions necessary for its slow emergence, and to the years required to develop the complex mediating mechanisms that support expertise. Even individuals considered to have natural gifts gradually attain their elite performance by engaging in extended amounts of designed deliberate practice over many years. Until ordinary individuals recognize that sustained effort is required to reach expert performance, they will continue to misattribute lesser achievement to lack of natural gifts, and thus will fail to reach their own potential.

The scientific study of expert performance and deliberate practice will increase our knowledge about how experts optimize their learning through the level of daily effort that they can sustain for days, months, and years. This knowledge should be relevant to any motivated individual aspiring to excel in any one of a wide range of professional activities. It is unlikely that we will ever be able to fully understand how excellence is acquired. Even if we were able to specify the exact path of development for the highest levels of performance at some point in time, such as today, excellence is protean, not static, and by the time we discovered that description expert performers will have reached even higher levels of performance. The highest levels of expertise and creativity will remain at the threshold of understanding, even for the masters dedicated to redefining the meaning of excellence in their domains.

ACKNOWLEDGMENTS

This research was supported by the FSCW/Conradi Endowment Fund of Florida State University Foundation. The author thanks Elizabeth Kirk for her most valuable comments on several earlier drafts of this chapter. Furthermore, Peter Delaney's and Len Hill's helpful comments on the final draft are gratefully acknowledged.

REFERENCES

Abernethy, B. (1991). Visual search strategies and decision-making in sport. *International Journal of Sport Psychology. 22,* 189-210.

Anderson, J. R. (1982). Acquisition of cognitive skill. *Psychological Review, 89,* 369-406.

Anderson, J. R. (1987). Skill acquisition: Compilation of weak-method problem situations. *Psychological Review, 94(2).* 192-210.

Bamberger, J. (1991). *The maul behind the musical ear: How children develop musical intelligence.* Cambridge, MA: Harvard University Press.

Bedard, J., & Chi, M. T. H. (1993). Expertise in auditing. *Auditing, 12(Supp\.),* 1-25.

Bloom, B. S. (1985). Generalizations about talent development. In B. S. Bloom (Ed.), *Developing talent* m *young people* (pp. 507-549). New York: Ballamine.

Bonner, S. E., & Pennington, N. (1991). Cognitive processes and knowledge as determinants of auditor expertise. *Journal of Accounting Literature, 10,* 1-50.

Bouchard, C., Shephard, R. J., & Stephens, T. (Eds.). (1994). *Physical activity, fitness, and health: International proceedings and consensus statement.* Champaign, IL: Human Kinetics.

Buhlig, R. (1917). The value of learning to hear. In H. Brower (Ed.), *Piano mastery, second series: Talks with master pianists and teachers* (pp. 215-223). New York: Frederick A. Stokes.

Busoni, F. B. (1913). Important details in piano study. In J. F. Cooke (Ed.), *Great pianists on piano playing: Study talks with foremost virtuosos* (pp. 97-107). Philadelphia: Theo Presser.

Camerer, C. F., & Johnson, E. J. (1991). The process-performance paradox in expert judgment: How can the experts know so much and predict so badly? In K. A. Ericsson & J. Smith (Eds.), *Towards a general theory of expertise: Prospects and limits* (pp. 195-217). Cambridge: Cambridge University Press.

Casals, P. (1923). The newer cello technique. In F. H Martens (Ed.), *String mastery: Talks with master violinists, viola players and violoncellists* (pp. 225-235). New York: Frederick A. Stokes.

Charness, N. (1981). Search in chess: Age and skill differences. *Journal of Experimental Psychology: Human Perception and Performance, 7,* 467-476.

Charness, N., Krampe, R. Th., & Mayr, U. (1996). The role of practice and coaching in entrepreneurial skill domains: An international comparison of life-span chess skill acquisition. In K. A. Ericsson (Ed.), *The road to excellence: The acquisition of expert performance in the arts and sciences, sports, and games* (pp. 51-80). Mahwah, NJ: Lawrence Erlbaum Associates.

Cowley, M. (Ed.). (1959). *Writers at work: The Paris Review interviews.* New York: Viking.

Dawes, R. M. (1994). *House of cards: Psychology and psychotherapy built on myth.* New York: Free Press.

de Groot, A. (1978). *Thought and choice and chess.* The Hague: Mouton. (Original work published 1946)

Elbert, T., Pantev, C., Wienbruch, C., Rockstroh, B., & Taub, E. (1995). Increased cortical representation of the fingers of the left hand in string players. *Science, 270,* 305-307.

Ericsson, K. A. (1996). The acquisition of expert performance: An introduction to some of the issues. In K. A. Ericsson (Ed.), *The road to excellence: The acquisition of expert performance in the arts and sciences, sports, and games* (pp. 1-50). Mahwah, NJ: Lawrence Erlbaum Associates.

Ericsson, K. A. (1997). Deliberate practice and the acquisition of expert performance: An overview. In H. Jorgensen & A. C. Lehmann (Eds.), *Does practice make perfect! Current theory and research on instrumental music practice* (NMH-publikasjoner 1997:1). Oslo, Norway: Norges musikkhogskole.

Ericsson, K. A. (1998). The scientific study of expert levels of performance: General implications for optimal learning and creativity. *High Ability Studies, 9,* 75-100.

Ericsson, K. A., & Charness, N. (1994). Expert performance: Its structure and acquisition. *American Psychologist, 49.* 725-747.

Ericsson, K A,, & Delaney, P. F. (1999). Long-term working memory as an alternative to capacity models of working memory in everyday skilled performance. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 257-297). Cambridge, England: Cambridge University Press.

Ericsson, K A., & Kintsch, W. (1995). Long-term working memory. *Psychological Review, 102,* 211-245.

Ericsson, K. A., Krampe, R. Th., & Heizmann, S. (1993). Can we create gifted people? In G. R. Bock & K. Ackrill (Eds.), *CIRA Foundation Symposium 178. The origin and development of high ability* (pp. 222-249). Chichester, England: Wiley.

Ericsson, K. A., Krampe, R. Th., & Tesch-Romer, C. (1993). The role of deliberate practice in the acquisition of expert performance. *Psychological Review, 100,* 363-406.

Ericsson, K. A., & Lehmann, A. C. (1996). Expert and exceptional performance: Evidence on maximal adaptations on task constraints. *Annual Review of Psychology, 47,* 273-305.

Ericsson, K A., & Lehmann, A. C. (1999). Expertise. In M. A. Runco & S. Fritter (Eds.), *Encyclopedia of creativity* (Vol. 1, pp. 695-707). San Diego, CA: Academic Press.

Ericsson, K. A., & Smith, J. (1991). Prospects and limits in the empirical study of expertise: An introduction. In K. A. Ericsson & J. Smith (Eds.), *Toward a general theory of expertise: Prospects and limits* (pp. 1-38). Cambridge, England: Cambridge University Press. Fitts, P., & Posner, M. I. (1967). *Human performance.* Belmont, CA: Brooks/Cole. Galamian, I. (1972). Ivan Galamian. In S. Applebaum & S. Applebaum (Eds.), *The way they play: Book I* (pp. 240-351). Neptune City, NJ: Paganiniana.

Glaser, R. (1996). Changing the agency for learning: Acquiring expert performance. In K. A. Ericsson (Ed.), *The road to excellence: The acquisition of expert performance in the arts and sciences, sports, and games* (pp. 1-50). Mahwah, NJ: Lawrence Erlbaum Associates.

Could. S. J. (1996). *Full house: The spread of excellence from Plato to Darwin.* New York: Harmony.

Helsen, W. F., Starkes, J. L., & Hodges, N. J. (1998). Team sports and the theory of deliberate *practice. Journal of Sport and Exercise Psychology, 20,* 12-34.

Hodges, N. J., & Starkes, J. L. (1996). Wrestling with the nature of expertise: A sport specific test of Ericsson, Krampe and Tesch-Romer's (1993) theory of "Deliberate Practice." *International Journal of Sport Psychology,* 1-25.

Katims, M. (1972). Milton Katims. In S. Applebaum & S. Applebaum (Eds.), *The way they play: Book I* (pp. 233-242). Neptune City, NJ: Paganiniana.

Krampe, R. Th., & Ericsson, K. A. (1996). Maintaining excellence: Deliberate practice and elite performance in young and older pianists. *Journal of Experimental Psychology: General, 125,* 331-359.

Kreisler, F. (1972). Fritz Kreisler. In S. Applebaum & S. Applebaum (Eds.), *The way they play: Book I* (pp. 95-109). Neptune City, NJ: Paganiniana.

Langer, E. J. (1997). *The power of mindful learning.* Reading, MA: Addison-Wesley.

Lehmann, A. C. (1997). Acquisition of expertise in music: Efficiency of deliberate practice as a moderating variable in accounting for sub-expert performance. In I. Deliege & J. A. Sloboda (Eds.), *Perception and cognition of music* (pp. 165-191). Mahwah, NJ: Lawrence Erlbaum Associates.

Lehmann, A. C., & Ericsson, K. A. (1993). Sight-reading ability of expert pianists in the context of piano accompanying. *Psychomusicology, 12,* 182-195.

Lehmann, A. C., & Ericsson, K. A. (1995, November). *Expert pianists' mental representation of memorized music.* Poster session presented at the 36th annual meeting of the Psychonomic Society, Los Angeles, CA.

Lehmann, A. C., & Ericsson, K. A. (1996). Music performance without preparation: Structure and acquisition of expert sight-reading. *Psychomusicology, 15,* 1-29.

Lehmann, A. C., & Ericsson K. A. (1997). Expert pianists' mental representations: Evidence from successful adaptation to unexpected performance demands. *Proceedings of the Third Triennial ESCOM Conference,* 165-169. Uppsala, Sweden: SLU Service/Reproenheten.

Lehmann, A. C., & Ericsson K. A. (1998). The historical development of domains of expertise: Performance standards and innovations in music. In A. Steptoe (Ed.), *Genius and the mind* (pp. 67-94). Oxford, England: Oxford University Press.

Lerner, T. (1915). An audience is the best teacher. In H. Brower (Ed.), *Piano mastery: Talks with master pianists and teachers* (pp. 38-46). New York: Frederick A. Stokes.

Levin, H., & Addis, A. B. (1979). *The eye-voice span.* Cambridge, MA: MIT Pi-ess.

Locke, E. A., & Latham, G. P. (1984). *Goal setting: A motivational technique that works!* Englewood Cliffs, NJ: Prentice-Hall.

Norman, D. A., Coblentz, C. L.. Brooks, L. R., & Babcook, C. J. (1992). Expertise in visual diagnosis: A review of the literature. *Academic Medicine Rime Supplement, 67,* 78-83.

Plimpton, G. (Ed.). (1977). Interviews, second series. In *Writers at work: The Paris Review.* New York: Penguin.

Primrose, W. (1972). William Primrose. In S. Applebaum & S. Applebaum (Eds.), *The way they play: Book I* (pp. 243-261). Neptune City, NJ: Paganiniana.

Robergs, R. A., & Roberts, S. O. (1997). *Exercise physiology: Exercise, performance, and clinical applications.* St. Louis, MO: Mosby-Year Book.

Rosson, M. B. (1985). The role of experience in editing. *Proceedings of INTERACT '84 IFIP Conference on Human-Computer Interaction,* 45-50.

Sauer, E. (1913). The training of the virtuoso. InJ. F. Cooke (Ed.), *Great pianists on piano playing: Study talks with foremost virtuosos* (pp. 236-250). Philadelphia: Theo Presser.

Schlaug, G., JSncke, L., Huang Y., & Steinmetz, H. (1995). In vivo evidence of structural brain asymmetry in musicians. *Science, 267,* 699-701.

Schmidt, H. G., Norman, G. R., & Boshuizen, H. P. A. (1990). A cognitive perspective on medical expertise: Theory and implications. *Academic Medicine, 65,* 611-621.

Schneider, W. (1993). Acquiring expertise: Determinants of exceptional performance. In K. A. Heller, J. Mdnks, & H. Passow (Eds.), *International handbook of research and development ofgiftedness and talent* (pp. 311-324). Oxford, England: Pergamon Press.

Schnitzer, G. (1915). Modem methods in piano study. In H. Brower (Ed.), *Piano mastery: Talks with master pianists and teachers* (pp. 215-224). New York: Frederick A. Stokes.

Schunk, D. H., & Zimmerman, B. J. (Eds.). (1994). *Self-regulation of learning and performance: Issues and educational applications* (pp. 1-21). Hillsdale, NJ: Lawrence Erlbaum Associates.

Shanteau, J., & Stewart, T. R. (1992). Why study expert decision-making? Some historical perspectives and comments. *Organizational Behaviour and Human Decision Processes, 53,* 95-106.

Shiffrin, R, M., & Schneider, W. (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending and a general theory. *Psychological Review, 84,* 127-189.

Simon, H. A., & Chase, W. G. (1973). Skill in chess. *American Scientist, 61,* 394-403.

Simonton, D. K, (1997). Creative productivity: A predictive and explanatory model of career trajectories and landmarks. *Psychological Review, 104,* 66-89.

Sloboda, J. A. (1996). The acquisition of musical performance expertise: Deconstructing the "talent" account of individual differences in musical expressivity. In R. A. Ericsson (Ed.), *The road to excellence: The acquisition of expert performance in the arts and sciences, sports, and games* (pp. 107-126). Mahwah, NJ: Lawrence Erlbaum Associates.

Starkes, J. L., Deakin, J., Allard, F., Hodges, N. J., & Hayes, A. (1996). Deliberate practice in sports: What is it anyway? In K. A. Ericsson (Ed.), *The road to excellence: The acquisition of expert performance in tile arts and sciences, sports, and games* (pp. 81-106). Mahwah, NJ: Lawrence Erlbaum Associates.

Sternberg, R. J. (1996). Costs of expertise. In K. A. Ericsson (Ed.), *The road to excellence: The acquisition of expert performance in the arts and sciences, sports, and games* (pp. 347-354). Mahwah, NJ: Lawrence Erlbaum Associates.

Sudnow, D. (1978). *Ways of the hand: The organization of improvised conduct.* Cambridge, MA: Harvard University Press.

Szigeti, J. (1972). Joseph Szigeti. In S. Applebaum & S. Applebaum (Eds.), *The way they play: Book I* (pp. 95-109). Neptune City, NJ: Paganiniana.

Tertis, L. (1972). Lionel Tertis. In S. Applebaum & S. Applebaum (Eds.), *The way they play: Book I* (pp. 262-270). Neptune City, NJ: Paganiniana.

Zimmerman, B. J. (1994). Dimensions of academic self-regulations: A conceptual framework for education. In D. H. Schunk & B. J. Zimmerman (Eds.), *Self-regulation of learning and performance: Issues and educational applications* (pp. 1-21). Hillsdale, NJ: Lawrence Erlbaum Associates.