Expert Performance

Its Structure and Acquisition

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Counter to the common belief that expert performance reflects innate abilities and capacities, recent research in different domains of expertise has shown that expert performance is predominantly mediated by acquired complex skills and physiological adaptations. For elite performers, supervised practice starts at very young ages and is maintained at high daily levels for more than a decade. The effects of extended deliberate practice are more far-reaching than is commonly believed. Performers can acquire skills that circumvent basic limits on working memory capacity and sequential processing. Deliberate practice can also lead to anatomical changes resulting from adaptations to intense physical activity. The study of expert performance has important implications for our understanding of the structure and limits of human adaptation and optimal learning.

In nearly every field of human endeavor, the performance of the best practitioners is so outstanding, so superior even to the performance of other highly experienced individuals in the field, that most people believe a unique, qualitative attribute, commonly called innate talent, must be invoked to account for this highest level of performance. Although these differences in performance are by far the largest psychologists have been able to reliably measure among healthy adults, exceptional performance has not, until recently, been extensively studied by scientists.

In the last decade, interest in outstanding and exceptional achievements and performance has increased dramatically. Many books have been recently published on the topic of genius (for example, Gardner, 1993a; Murray, 1989a; Simonton, 1984, 1988b; Weisberg, 1986, 1993), exceptionally creative individuals (D. B. Wallace & Gruber, 1989), prodigies (Feldman, 1986; A. Wallace, 1986), and exceptional performance and performers (Howe, 1990; Radford, 1990; Smith, 1983). Of particular interest to the general public has been the remarkable ability of idiot savants or savants, who in spite of a very low general intellectual functioning display superior performance in specific tasks and domains, such as mental multiplication and recall of music (Howe, 1990; Treffert, 1989). The pioneering research comparing the performance of experts and beginners (novices) by de Groot (1946/1978) and Chase and Simon (1973) has generated a great deal of research (Chi, Glaser, & Farr, 1988; Ericsson & Smith, 1991b). A parallel development in computer science has sought to extract the knowledge of experts by interviews (Hoffman, 1992) to build expert systems, which are computer models that are designed to duplicate the performance of these experts and make their expertise generally available. These efforts at artificial intelligence have been most successful in domains that have established symbolic representations, such as mathematical calculation, chess, and music (Barr & Feigenbaum, 1981–1982: Cohen & Feigenbaum, 1982), which incidentally are the main domains in which prodigies and savants have been able to display clearly superior performance (Feldman, 1980, 1986).[1]

The recent advances in our understanding of exceptional performance have had little impact on general theories in psychology. The new knowledge has not fulfilled the humanistic goals of gaining insights from the lives of outstanding people about how people might improve their lives. Maslow (1971) long ago eloquently expressed these goals:

> If we want to know how fast a human being can run, then it is no use to average out the speed of a "good sample" of the pop-

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[1] The field of visual art may offer at least one recent exception (Feldman, 1986). The Chinese girl Yani produced some acclaimed paintings between the ages of three and six (Ho, 1989), but matters are complicated by the fact that these paintings were selected by her father (a professional painter) from more than 4,000 paintings completed by Yani during this three-year period (Feng, 1984).

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ulation; it is far better to collect Olympic gold medal winners and see how well they can do. If we want to know the possibilities for spiritual growth, value growth, or moral development in human beings, then I maintain that we can learn most by studying our moral, ethical, or saintly people. . . . Even when "good specimens," the saints and sages and great leaders of history, have been available for study, the temptation too often has been to consider them not human but supernaturally endowed. (p. 7)

The reasons for the lack of impact become clear when we consider the two most dominant approaches and their respective goals. The human information-processing approach, or the skills approach, has attempted to explain exceptional performance in terms of knowledge and skills acquired through experience. This approach, originally developed by Newell and Simon (1972), has tried to show that the basic information-processing system with its elementary information processes and basic capacities remains intact during skill acquisition and that outstanding performance results from incremental increases in knowledge and skill due to the extended effects of experience. By constraining the changes to acquired knowledge and skill, this approach has been able to account for exceptional performance within existing general theories of human cognition. According to this approach the mechanisms identified in laboratory studies of learning can be extrapolated to account for expertise and expert performance by an incremental accumulation of knowledge and skill over a decade of intense experience in the domain. The long duration of the necessary period of experience and the presumed vast complexity of the accumulated knowledge has discouraged investigators from empirically studying the acquisition of expert performance. Similarly, individual differences in expert performance, when the amount of experience is controlled, have not been of major interest and have been typically assumed to reflect differences in the original structure of basic processes, capacities, and abilities.

The other major approach focuses on the individual differences of exceptional performers that would allow them to succeed in a specific domain. One of the most influential representatives of this approach is Howard Gardner, who in 1983 presented his theory of multiple intelligence in his book *Frames of Mind: The Theory of Multiple Intelligences* (hereinafter referred to as *Frames of Mind*). Gardner (1983, 1993a, 1993b) drew on the recent advances in biology and brain physiology about neural mechanisms and localization of brain activity to propose an account of the achievements of savants, prodigies, and geniuses in specific domains. He argued that exceptional performance results from a close match between the individual's intelligence profile and the demands of the particular domain. A major concern in this approach is the early identification and nurturing of children with high levels of the required intelligence for a specific domain. Findings within this approach have limited implications for the lives of the vast majority of children and adults of average abilities and talents.

In this article we propose a different approach to the study of exceptional performance and achievement, which we refer to as the study of expert performance. Drawing on our earlier published research, we focus on reproducible, empirical phenomena of superior performance. We will thus not seriously consider anecdotes or unique events, including major artistic and scientific innovations, because they cannot be repeatedly reproduced on demand and hence fall outside the class of phenomena that can be studied by experimental methods. Our approach involves the identification of reproducible superior performance in the everyday life of exceptional performers and the capture of this performance under laboratory conditions. Later we show that the analysis of captured superior performance reveals that extended training alters the cognitive and physiological processes of experts to a greater degree than is commonly believed possible. In the final section of the article we review results from studying the lives of expert performers and identify the central role of large amounts of focused training (deliberate practice), which we distinguish from other forms of experience in a domain. The recent evidence for far-reaching effects of training leads us to start by reexamining the available evidence for innate talent and specific gifts as necessary conditions for attaining the highest levels of performance in a domain.

Traditional View of the Role of Talent in Exceptional Performance

Since the emergence of civilization, philosophers have speculated about the origin of highly desirable individual attributes, such as poetic ability, physical beauty, strength, wisdom, and skill in handiwork (Murray, 1989b). It was generally believed that these attributes were gifts from the gods, and it was commonly recognized that "On the whole the gods do not bestow more than one gift on a person" (Murray, 1989b, p. 11). This view persisted in early Greek thought, although direct divine intervention was replaced by natural causes. Ever since, there has been a bias toward attributing high abilities to gifts rather than experience, as expressed by John Stuart Mill, there is "a common tendency among mankind to consider all power which is not visibly the effect of practice, all skill which is not capable of being reduced to mechanical rules, as the result of a particular gift" (quoted in Murray, 1989b, p. 12).

One important reason for this bias in attribution, we believe, is linked to immediate legitimatization of various activities associated with the gifts. If the gods have bestowed a child with a special gift in a given art form, who would dare to oppose its development, and who would not facilitate its expression so everyone could enjoy its wonderful creations? This argument may appear strange today, but before the French Revolution the privileged status of kings and nobility and the birthright of their children were primarily based on such claims.

The first systematic development of this argument for gaining social recognition to artists can be found in classic work on *The Lives of the Artist* by Vasari (Bull, 1987), originally published in 1568. This book provided the first major biography of artists and is generally recognized as a major indirect influence on the layman's conceptions of artists even today (Barolsky, 1991). Although Vasari's expressed goal was simply to provide a factual history of art, modern scholars argue that "the *Lives* were partly designed to propagate ideas of the artist as someone providentially born with a vocation from heaven, entitled to high recognition, remuneration and respect" (Bull, 1987, Vol. 2, p. xxvi). To support his claim, Vasari tried to identify early signs of talent and ability in the lives of the artists he described. When facts were missing, he is now known to have added or distorted material (Barolsky, 1991). For example, Vasari dated his own first public demonstration of high ability to the age of 9, although historians now know that he was 13 years old at that event (Boase, 1979). His evaluations of specific pieces of art expresssed his beliefs in divine gifts. Michelangelo's famous painting in the Sistine Chapel, the *Final Judgment*, was described by Vasari as "the great example sent by God to men so that they can perceive what can be done when intellects of the highest grade descend upon the earth" (quoted in Boase, 1979, pp. 251–252). Vasari also tried to establish a link between the noble families and the families of outstanding artists by tracing the heritage and family trees of the artists of his time to the great families of antiquity and to earlier great artists. However, much of the reported evidence is now considered to have been invented by Vasari (Barolsky, 1992). In the centuries following Vasari, our civilization underwent major social changes leading to a greater social mobility through the development of a skilled middle class and major progress in the accumulation of scientific knowledge. It became increasingly clear that individuals could dramatically increase their performance though education and training, if they had the necessary drive and motivation. Speculation on the nature of talent started to distinguish achievements due to innate gifts from other achievements resulting from learning and training. In 1759 Edward Young published a famous book on the origin of creative products, in which he argued that "An *Original* may be said to be of *vegetable* nature: it rises spontaneously from the vital root of Genius; it *grows,* it is not *made*" (quoted with original italics in Murray, 1989b, p. 28). Hence, an important characteristic of genius and talent was the apparent absence of learning and training, and thus talent and acquired skill became opposites (Bate, 1989). A century later Galton (1869/1979) presented a comprehensive scientific theory integrating talent and training that has continued to influence the conception of exceptional performance among the general population.

Sir Francis Galton was the first scientist to investigate empirically the possibility that excellence in diverse fields and domains has a common set of causes. On the basis of an analysis of eminent men in a wide range of domains and of their relatives, Galton (1869/1979) argued that three factors had to be present: innate ability, eagerness to work, and "an adequate power of doing a great deal of very laborious work" (p. 37). Because the importance of the last two factors—motivation and effort—had already been recognized (Ericsson, Krampe, & Heizmann, 1993), later investigators concentrated primarily on showing that innate abilities and capacities are necessary to attain the highest levels of performance.

Galton (1869/1979) acknowledged a necessary but not sufficient role for instruction and practice in achieving exceptional performance. According to this view, performance increases monotonically as a function of practice toward an asymptote representing a fixed upper bound on performance. Like Galton, contemporary researchers generally assume that training can affect some of the components mediating performance but cannot affect others. If performance achieved after extensive training is limited by components that cannot be modified, it is reasonable to assert that stable, genetically determined factors determine the ultimate level of performance. If all possible changes in performance related to training are attained after a fairly limited period of practice, this argument logically implies that individual differences in final performance must reflect innate talents and natural abilities.

The view that talent or giftedness for a given activity is necessary to attain the highest levels of performance in that activity is widely held among people in general. This view is particularly dominant in such domains of expertise as chess, sports, music, and visual arts, where millions of individuals are active but only a very small number reach the highest levels of performance.

One of the most prominent and influential scientists who draw on evidence from exceptional performance of artists, scientists, and athletes for a biological theory of talent is Howard Gardner. In *Frames of Mind,* Gardner (1983) proposed seven intelligences: linguistic, musical, spatial, logical-mathematical, bodily kinesthetic, and interpersonal and intrapersonal intelligence—each an independent system with its own biological bases (p. 68). This theory is a refinement and development of ideas expressed in an earlier book (Gardner, 1973), in which the talent position was more explicitly articulated, especially in the case of music. Gardner (1973) wrote,

> Further evidence of the strong hereditary basis of musical talent comes from a number of sources. Most outstanding musicians are discovered at an early age, usually before 6 and often as early as 2 or 3, even in households where relatively little music is heard. Individual differences are tremendous among children, and training seems to have comparatively little effect in reducing these differences. (p. 188)

He discussed possible mechanisms for talent in the context of music savants, who in spite of low intellectual functioning display impressive music ability as children: "it seems possible that the children are reflecting a rhythmic and melodic capacity that is primarily hereditary, and which needs as little external stimulation as does walking and talking in the normal child" (Gardner, 1973, p. 189). Although Gardner (1983) did not explicitly discuss his earlier positions, the evidence from prodigies and savants remains central. *Frames of Mind* contains a careful review of the then available research on the dramatic effects of training on performance. In particular, he reviewed the exceptional music performance of young children trained with the Suzuki method and noted that many of these children who began training without previous signs of musical talent attained levels comparable to music prodigies of earlier times and gained access to the best music teachers in the world. The salient aspect of talent, according to Gardner (1983), is no longer the innate structure (gift) but rather the potential for achievement and the capacity to rapidly learn material relevant to one of the intelligences. Gardner's (1983) view is consistent with Suzuki's rejection of inborn talent in music and Suzuki's (1963/1981) early belief in individual differences in innate general ability to learn, although Suzuki's innate abilities were not specific to a particular domain, such as music. However, in his later writings, Suzuki (1980/1981) argued that "every child can be highly educated if he is given the proper training" (p. 233), and he blamed earlier training failures on incorrect training methods and their inability to induce enthusiasm and motivation in the children. The clearest explication of Gardner's (1983) view is found when he discussed his proposal for empirical assessments of individuals' profiles in terms of the seven intelligences. He proposed a test in which "individuals were given the opportunity to learn to recognize certain patterns [relevant to the particular domain] and were tested on their capacities to remember these from one day to the next" (p. 385). On the basis of tests for each of the intelligences, "intellectual profiles could be drawn up in the first year or two of life" (p. 386), although reliable assessments may have to wait until the preschool years because of "early neural and functional plasticity" (p. 386). Gardner's own hunch about strong intellectual abilities was that "an individual so blessed does not merely have an easy time learning new patterns; he learns them so readily that *it is virtually impossible for him to forget them*" (pp. 385–386).

Our reading of Gardner's (1993a, 1993b)[2] most recent books leads us to conclude that his ideas on talent have not fundamentally changed. According to Gardner's (1983) influential view, the evidence for the talent view is based on two major sources of data on performance: the performance of prodigies and savants and the ability to predict future success of individuals on the basis of early test results. Given that our knowledge about the exceptional performance of savants and prodigies and the predictive validity of tests of basic abilities and talents have increased considerably in the past decade, we briefly review the evidence or rather the lack of evidence for innate abilities and talent.

Performance of Prodigies and Savants

When the large collection of reports of amazing and inexplicable performance is surveyed, one finds that most of them cannot even be firmly substantiated and can only rarely be replicated under controlled laboratory conditions. Probably the best established phenomenon linked to talent in music is perfect pitch, or more accurately absolute pitch (AP). Only approximately 0.01% of the general population have AP and are able to correctly name each of the 64 different tones, whereas average musicians without AP can distinguish only approximately five or six categories of pitches when the pitches are presented in isolation (Takeuchi & Hulse, 1993). Many outstanding musicians display AP, and they first reveal their ability in early childhood. With a few exceptions, adults appear to be unable to attain AP in spite of extended efforts. Hence the characteristics of absolute pitch would seem to meet all of the criteria of innate talent, although there is some controversy about how useful this ability is to the expert musicians. In a recent review of AP, Takeuchi and Hulse (1993) concluded that the best account of the extensive and varied evidence points toward a theory that "states AP can be *acquired by anyone* [italics added], but only during a limited period of development" (p. 355). They found that all individuals with AP had started with music instruction early—nearly always before age five or six—and that several studies had been successful in teaching AP to three- to six-year-old children. At older ages children perceive relations between pitches, which leads to accurate relative pitch, something all skilled musicians have. "Young children *prefer* to process absolute rather than the relative pitches of musical stimuli" (p. 356). Similar developmental trends from individual features to relational attributes are found in other forms of perception during the same age period (Takeuchi & Hulse, 1993). Rather than being a sign of innate talent, AP appears to be a natural consequence of appropriate instruction and of ample opportunities to interact with a musical instrument, such as a piano, at very young ages.

Other proposed evidence for innate talent comes from studies of prodigies in music and chess who are able to attain high levels of performance even as young children. In two influential books, Feldman (1980, 1986) showed that acquisition of skills in prodigies follows the same sequence of stages as in other individuals in the same domain. The primary difference is that prodigies attain higher levels faster and at younger ages. For example, an analysis of Picasso's early drawings as a child shows that he encountered and mastered problems in drawing in ways similar to less gifted individuals (Pariser, 1987). Feldman (1986) also refuted the myth that prod-

[2] In his recent book *Creating Minds*, Gardner (1993a) examined the lives of seven great innovators, such as Einstein, Picasso, Stravinsky, and Gandhi. Each was selected to exemplify outstanding achievements in one of seven different intelligences. Gardner's careful analysis reveals that the achievements of each individual required a long period of intense preparation and required the coincidence of many environmental factors. Striking evidence for traditional talent, such as prodigious achievements as a child, is notably absent, with the exception of Picasso. The best evidence for talent, according to Gardner, is their rapid progress once they made a commitment to a particular domain of expertise. These findings are not inconsistent with Gardner's views on talent because innovation and creation of new ideas are fundamentally different from high achievements in a domain due to talent. Gardner wrote, "in the case of a universally acclaimed prodigy, the prodigy's talents mesh perfectly with current structure of the domain and the current tastes of the field. Creativity, however, does not result from such perfect meshes" (pp. 40–41).

igies acquire their skills irrespective of the environment. In fact, he found evidence for the exact opposite, namely that "the more powerful and specific the gift, the more need for active, sustained and specialized intervention" (p. 123) from skilled teachers and parents. He described the classic view of gifts, in which parents are compelled to support their development, when he wrote, "When extreme talent shows itself it demands nothing less than the willingness of one or both of the parents to give up almost everything else to make sure that the talent is developed" (p. 122). A nice case in point is the child art prodigy Yani (Ho, 1989), whose father gave up his own painting career so as not to interfere with the novel style that his daughter was developing. Feldman (1980, 1986) argued that prodigious performance is rare because extreme talent for a specific activity in a particular child and the necessary environmental support and instruction rarely coincide.

Contrary to common belief, most child prodigies never attain exceptional levels of performance as adults (Barlow, 1952; Feldman, 1986). When Scheinfeld (1939) examined the reported basis of the initial talent assessment by parents of famous musicians, he found signs of interest in music rather than objective evidence of unusual capacity. For example, Fritz Kreisler was "playing violin" (p. 239) with two sticks at age four, and Yehudi Menuhin had a "response to violins at concerts" (p. 239) at the age of one and a half years. Very early start of music instruction would then lead to the acquisition of absolute pitch. Furthermore, the vast majority of exceptional adult performers were never child prodigies, but instead they started instruction early and increased their performance due to a sustained high level of training (Bloom, 1985). The role of early instruction and maximal parental support appears to be much more important than innate talent, and there are many examples of parents of exceptional performers who successfully designed optimal environments for their children without any concern about innate talent (see Ericsson, Krampe, & Tesch-Römer, 1993, and Howe, 1990). For example, as part of an educational experiment, Laslo and Klara Polgar (Forbes, 1992) raised one of their daughters to become the youngest international chess grand master ever—she was even younger than Bobby Fischer, who was the youngest male achieving that exceptional level of chess-playing skill. In 1992 the three Polgar daughters were ranked first, second, and sixth in the world among women chess players, respectively.

Although scientists and the popular press have been interested in the performance of prodigies, they have been especially intrigued by so-called savants. Savants are individuals with a low level of general intellectual functioning who are able to perform at high levels in some special tasks. In a few cases the parents have reported that these abilities made their appearances suddenly, and they cited them as gifts from God (Ericsson & Faivre, 1988; Feldman, 1986). More careful study of the emergence of these and other cases shows that their detection may in some cases have been sudden, but the opportunities, support, and encouragement for learning had preceded the original performance by years or even decades (Ericsson & Faivre, 1988; Howe, 1990; Treffert, 1989). Subsequent laboratory studies of the performance of savants have shown them to reflect acquired skills. For example, savants who can name the day of the week of an arbitrary date (e.g., November 5, 1923) generate their answers using instructable methods that allow their performance to be reproduced by a college student after a month of training (for a review see Ericsson & Faivre, 1988). The only ability that cannot be reproduced after brief training concerns some savants' reputed ability to play a piece of music after a single hearing.

However, in a carefully controlled study of a music savant (J.L.), Charness, Clifton, and MacDonald (1988) showed that reproduction of short (2- to 12-note) tonal sequences and recall of from two to four chords (4 notes each) depended on whether the sequences or chords followed Western scale structure. Unfamiliar sequences that violated musical conventions were poorly recalled past 6 notes. Short, familiar sequences of notes and chords were accurately recalled, although recall dropped with length of sequence so that only 3 (of 24) 12-note familiar sequences were completely correct. Attempts to train J.L. to learn temporally static 16-note melodies were unsuccessful. Even in the case of the musical savant studied by Sloboda, Hermelin, and O'Connor (1985), who was able to memorize a new piece of music, there was a marked difference in success with a conventional versus a tonally unconventional piece. Thus, music savants, like their normally intelligent expert counterparts, need access to stored patterns and retrieval structures to enable them to retain long, unfamiliar musical patterns. Given that savants cannot read music—most of them are blind—they have to acquire new music by listening, which would provide motivation and opportunities for the development of domain-specific memory skills.

In summary, the evidence from systematic laboratory research on prodigies and savants provides no evidence for giftedness or innate talent but shows that exceptional abilities are acquired often under optimal environmental conditions.

Prediction of Future Success Based on Innate Abilities and Talent

The importance of basic processes and capacities is central to many theorists in the human information-processing tradition. In conceptual analogies with computers, investigators often distinguish between hardware (the physical components of the computer) and software (computer programs and stored data). In models of human performance, "software" corresponds to knowledge and strategies that can be readily changed as a function of training and learning, and "hardware" refers to the basic elements that cannot be changed through training. Even theorists such as Chase and Simon (1973), who acknowledge that "practice is the major independent variable in the acquisition of skill" (p. 279), argue in favor of individual differences in talent that predispose people to be successful in different domains: "Although there clearly must be a set of specific aptitudes (e.g., aptitudes for handling spatial relations) that together comprise a talent for chess, individual differences in such aptitudes are largely overshadowed by immense differences in chess experience" (p. 297). Bloom (1985) went through many different domains to point out some necessary qualities that are likely to be mostly inborn, such as "*motor coordination, speed of reflexes* and *hand-eye coordination*" (p. 546). These views were consistent with the available information at the time, such as high heritabilities for many of these characteristics. In their review of sport psychology, Browne and Mahoney (1984) argued for the importance of fixed physiological traits for elite performance of athletes and wrote that "there is good evidence that the limits of physiological capacity to become more efficient with training is determined by genetics" (p. 609). They cited research reporting that percentage of muscle fibers and aerobic capacity "are more than 90% determined by heredity for both male and female" (p. 609). However, more recent reviews have shown that heritabilities in random samples of twins are much lower and range between zero and 40% (Malina & Bouchard, 1991).

It is curious how little empirical evidence supports the talent view of expert and exceptional performance. Ever since Galton, investigators have tried to measure individual differences in unmodifiable abilities and basic cognitive and perceptual capacities. To minimize any influence from prior experience, they typically base their tests on simple tasks. They measure simple reaction time and detection of sensory stimuli and present meaningless materials, such as nonsense syllables and lists of digits, in tests of memory capacity. A recent review (Ericsson, Krampe, & Tesch-Römer, 1993) showed that efforts to measure talent with objective tests for basic cognitive and perceptual motor abilities have been remarkably unsuccessful in predicting final performance in specific domains. For example, elite athletes are able to react much faster and make better perceptual discriminations to representative situations in their respective domains, but their simple reaction times and perceptual acuity to simple stimuli during laboratory tests do not differ systematically from those of other athletes or control subjects (for reviews see Regnier, Salmela, & Russell, 1993, and Starkes & Deakin, 1985). Chess players' and other experts' superior memory for brief presentation of representative stimuli from their domains compared with that of novices is eliminated when the elements of the same stimuli are presented in a randomly arranged format (Chase & Simon, 1973; see Ericsson & Smith, 1991a, for a review). The performance of elite chess players on standard tests of spatial ability is not reliably different from control subjects (Doll & Mayr, 1987). The domain specificity of superior performance is striking and is observed in many different domains of expertise (Ericsson, Krampe, & Tesch-Römer, 1993).

This conclusion can be generalized with some qualifications to current tests of such general abilities as verbal and quantitative intelligence. These tests typically measure acquired knowledge of mathematics, vocabulary, and grammar by successful performance on items testing problem solving and comprehension. Performance during and immediately after training is correlated with IQ, but the correlations between this type of ability test and performance in the domain many months and years later is reduced (even after corrections for restriction of range) to such low values that Hulin, Henry, and Noon (1990) questioned their usefulness and predictive validity. At the same time, the average IQ of expert performers, especially in domains of expertise requiring thinking, such as chess, has been found to be higher than the average of the normal population and corresponds roughly to that of college students. However, IQ does not reliably discriminate the best adult performers from less accomplished adult performers in the same domain.

Even physiological and anatomical attributes can change dramatically in response to physical training. Almost everyone recognizes that regular endurance and strength training uniformly improves aerobic endurance and strength, respectively. As the amount and intensity or physical training is increased and maintained for long periods, far-reaching adaptations of the body result (see Ericsson, Krampe, & Tesch-Römer, 1993, for a review). For example, the sizes of hearts and lungs, the flexibility of joints, and the strength of bones increase as the result of training, and the nature and extent of these changes appear to be magnified when training overlaps with physical development during childhood and adolescence. Furthermore, the number of capillaries supplying blood to trained muscles increases, and muscle fibers can change their metabolic properties from fast twitch to slow twitch. With the clear exception of height, a surprisingly large number of anatomical characteristics show specific changes and adaptations to the specific nature of extended intense training, which we describe in more detail later in this article.

If one accepts the necessity of extended intense training for attaining expert performance—a claim that is empirically supported later in this article—then it follows that currently available estimates of heritability of human characteristics do not generalize to expert performance. An estimate of heritability is valid only for the range of environmental effects for which the studied subjects have been exposed. With a few exceptions, studies of heritabilities have looked only at random samples of subjects in the general population and have not restricted their analyses to individuals exposed to extended training in a domain. The remaining data on exceptional and expert performers have not been able to demonstrate systematic genetic influences. Explanations based on selective access to instruction and early training in a domain provide as good or in some cases better accounts of familial relations of expert performers, such as the lineage of musicians in the Bach family (see Ericsson, Krampe, & Tesch-Römer, 1993, for a review).

In summary, we argue that the traditional assumptions of basic abilities and capacities (talent) that may remain stable in studies of limited and short-term practice do not generalize to superior performance acquired over years and decades in a specific domain. In addition, we will later review evidence showing that acquired skill can allow experts to circumvent basic capacity limits of short-term memory and of the speed of basic reactions, making potential basic limits irrelevant. Once the potential for change through practice is recognized, we believe that a search for individual differences that might be predictive of exceptional and expert performance should refocus on the factors advocated by Charles Darwin (quoted in Galton, 1908) in a letter to Galton after reading the first part of Galton's (1869/1979) book: "You have made a convert of an opponent in one sense, for I have always maintained that excepting fools, men did not differ much in intellect, only in zeal and hard work; I still think this is an *eminently* important difference" (p. 290). In commenting on Darwin's remark, Galton (1908) agreed but argued that "character, including the aptitude for work, is heritable" (p. 291). On the basis of their review, Ericsson, Krampe, and Tesch-Römer (1993) found that motivational factors are more likely to be the locus of heritable influences than is innate talent. We explicate the connection between these "motivational" factors and the rate of improving performance in a specific domain in the last section of this article.

There are two parts to the remaining portion of this article. First, we show that it is possible to study and analyze the mechanisms that mediate expert performance. We also show that the critical mechanisms reflect complex, domain-specific cognitive structures and skills that performers have acquired over extended periods of time. Hence, individuals do not achieve expert performance by gradually refining and extrapolating the performance they exhibited before starting to practice but instead by restructuring the performance and acquiring new methods and skills. In the final section, we show that individuals improve their performance and attain an expert level, not as an automatic consequence of more experience with an activity but rather through structured learning and effortful adaptation.

The Study of Expert Performance

The conceptions of expert performance as primarily an acquired skill versus a reflection of innate talents influence how expert performance and expert performers are studied. When the goal is to identify critical talents and capacities, investigators have located experts and then compared measurements of their abilities with those of control subjects on standard laboratory tests. Tests involve simple stimuli and tasks in order to minimize any effects of previously acquired knowledge and skill. Given the lack of success of this line of research, we advocate a different approach that identifies the crucial aspects of experts' performance that these experts exhibit regularly at a superior level in their domain. If experts have acquired their superior performance by extended adaptation to the specific constraints in their domains, we need to identify representative tasks that incorporate these constraints to be able to reproduce the natural performance of experts under controlled conditions in the laboratory. We illustrate this method of designing representative test situations with several examples later in this section. Once the superior performance of experts can be reliably reproduced in a test situation, this performance can then be analyzed to assess its mediating acquired mechanisms. Following Ericsson and Smith (1991a), we define expert performance as consistently superior performance on a specified set of representative tasks for the domain that can be administered to any subject. The virtue of defining expert performance in this restricted sense is that the definition both meets all the criteria of laboratory studies of performance and comes close to meeting those for evaluating performance in many domains of expertise.

Perceived Experts Versus Consistent Expert Performance

In many domains, rules have evolved and standardized conditions, and fair methods have been designed for measuring performance. The conditions of testing in many sports and other activities, such as typing competitions, are the same for all participating individuals. In other domains, the criteria for expert performance cannot be easily translated into a set of standardized tasks that captures and measures that performance. In some domains, expert performance is determined by judges or by the results of competitive tournaments. Psychometric methods based on tournament results, most notably in chess (Elo, 1986), have successfully derived latent measures of performance on an interval scale. In the arts and sciences, selected individuals are awarded prizes and honors by their peers, typically on the basis of significant achievements such as published books and research articles and specific artistic performances.

Some type of metric is of course required to identify *superior performance.* The statistical term *outlier* may be a useful heuristic for judging superior performance. Usually, if someone is performing at least two standard deviations above the mean level in the population, that individual can be said to be performing at an expert level. In the domain of chess (Elo, 1986), the term *expert* is defined as a range of chess ratings (2000–2199) approximately two to three standard deviations (200 rating points) above the mean (1600 rating points) and five to six standard deviations above the mean of chess players starting to play in chess tournaments.

In most domains it is easier to identify individuals who are socially recognized as experts than it is to specify observable performance at which these individuals excel. The distinction between the perception of expertise and actual expert performance becomes increasingly important as research has shown that the performance of some individuals who are nominated as experts is not measurably superior. For example, studies have found that financial experts' stock investments yield returns that are not consistently better than the average of the stock market, that is, financial experts' performance does not differ from the result of essentially random selection of stocks. When successful investors are identified and their subsequent investments are tracked, there is no evidence for sustained superiority. A large body of evidence has been accumulated showing that experts frequently do not outperform other people in many relevant tasks in their domains of expertise (Camerer & Johnson, 1991). Experts may have much more knowledge and experience than others, yet their performance on critical tasks may not be reliably better than that of nonexperts. In summary, researchers cannot seek out experts and simply assume that their performance on relevant tasks is superior; they must instead demonstrate this superior performance.

Identifying and Capturing Expert Performance

For most domains of expertise, people have at least an intuitive conception of the kind of activities at which an expert should excel. In everyday life, however, these activities rarely have clearly defined starting and end points, nor do the exact external conditions of a specific activity reoccur. The main challenge is thus to identify particular well-defined tasks that frequently occur and that capture the essence of expert performance in a specific domain. It is then possible to determine the contexts in which each task naturally occurs and to present these tasks in a controlled context to a larger group of other experts.

De Groot's (1946/1978) research on expertise in chess is generally considered the pioneering effort to capture expert performance. Ability in chess playing is determined by the outcomes of chess games between opponents competing in tournaments. Each game is different and is rarely repeated exactly except for the case of moves in the opening phase of the game. De Groot, who was himself a chess master, determined that the ability to play chess is best captured in the task of selecting the next move for a given chess position taken from the middle of the game between two chess masters. Consistently superior performance on this task for arbitrary chess positions logically implies a very high level of skill. Researchers can therefore elicit experts' superiority in performing a critical task by presenting the same unfamiliar chess position to any number of chess players and asking them to find the best next move. De Groot demonstrated that performance on this task discriminates well between chess players at different levels of skill and thus captures the essential phenomenon of ability to play this game.

In numerous subsequent studies, researchers have used a similar approach to study the highest levels of thinking in accepted experts in various domains of expertise (Chi et al., 1988; Ericsson & Smith, 1991b). If expert performance reflects extended adaptation to the demands of naturally occurring situations, it is important that researchers capture the structure of these situations in order to elicit maximal performance from the experts. Furthermore, if the tasks designed for research are sufficiently similar to normal situations, experts can rely on their existing skills, and no experiment-specific changes are necessary. How similar these situations have to be to real-life situations is an empirical question. In general, researchers should strive to define the simplest situation in which experts' superior performance can still be reliably reproduced.

Description and Analysis of Expert Performance

The mere fact that it is possible to identify a set of representative tasks that can elicit superior performance from experts under standardized conditions is important. It dramatically reduces the number of contextual factors that can logically be essential for reproducing that superior performance. More important, it allows researchers to reproduce the phenomenon of expert performance under controlled conditions and in a reliable fashion. Researchers can thus precisely describe the tasks and stimuli and can theoretically determine which mechanisms are capable of reliably producing accurate performance across the set of tasks. Part of the standard methodology in cognitive psychology is to analyze the possible methods subjects could use to generate the correct response to a specific task, given their knowledge about procedures and facts in the domain. The same methodology can be applied to tasks that capture expert performance. Because, however, the knowledge experts may apply to a specific task is quite extensive and complex, it is virtually impossible for nonexperts to understand an analysis of such a task. Instead of describing such a case, we illustrate the methodology and related issues with a relatively simple skill, mental multiplication.

Mental Multiplication: An Illustration of Text Analysis

In a study of mental multiplication, the experimenter typically reads a problem to a subject: What is the result of multiplying 24 by 36? The subject then reports the correct answer—864. It may be possible that highly experienced subjects recognize that particular problem and retrieve the answer immediately from memory. That possibility is remote for normal subjects, and one can surmise that they must calculate the answer by relying on their knowledge of the multiplication table and familiar methods for complex multiplication. The most likely method is the paper-and-pencil method taught in the schools, where 24×36 is broken down into 24×6 and 24×30 and the products are added together (illustrated as Case B in Table 1). Often students are told to put the highest number first. By this rule, the first step in solving 24×36 is to rearrange it as 36×24 and then to break it down as 36×4 and 36×20 (Case A). More sophisticated subjects may recognize that 24×36 is equivalent to $(30 - 6) \times (30 + 6)$ and use the formula $(a - b) \times (a + b) = a^2 - b^2$, thus calculating 24×36 as $30^2 - 6^2 = 900 - 36 = 864$ (Case C). Other subjects may recognize other shortcuts, such as $24 \times 36 = (2 \times 12) \times (3 \times 12) = 6 \times 12^2 = 6 \times 144$ (Case D). Skilled mental calculators often prefer to calculate the answer in the reverse order, as is illustrated in Case E. Especially for more complex problems this procedure allows them to report the first digit of the final result long before they have completed the calculation of the remaining digits. Because most

Table 1
Five Possible Methods of Mentally Multiplying 24 by 36 and a Think-Aloud Protocol from a Subject Generating the Correct Answer

Mental multiplication	Think-aloud protocol
Method A 24 × 36 144 72 864	36 times 24 4 carry the—no wait 4 carry the 2 14 144 0 36 times 2 is 12 6 72 720 plus 144 4 uh, uh 6 8 uh, 864
Method B 36 × 24 144 72 864	
Method C $24 \times 36 =$ $= (30 - 6) \times (30 + 6) =$ $= 30^2 - 6^2 =$ $= 900 - 36 = 864$	
Method D $24 \times 36 = 2 \times 12 \times 3 \times 12 =$ $= 6 \times 12^2 = 6 \times 144 = 864$	
Method E AB — 24 × CD — × 36 100 × A × C — 600 10 × A × D — 120 10 × C × B — 120 B × D — 24 864	

people expect that the entire answer has to be available before the first digit can be announced, the last method gives the appearance of faster calculation speeds.

An investigator cannot determine on which of the methods in Table 1 a subject relied. However, if the subject was instructed to think aloud (see Ericsson & Simon, 1993, for the detailed procedure) while completing the mental multiplication, the investigator could record in detail the mediating sequences of the subject's thoughts, as is illustrated in the right panel of Table 1. Although methodologically rigorous methods for encoding and evaluating think-aloud protocols are available (Ericsson & Simon, 1993), the visual match between Case B and the protocol in Table 1 is sufficiently clear for the purposes of our illustration. Even with a less detailed record of the verbalized intermediate products in the calculation, it is possible to reject most of the alternative methods as being inconsistent with a recorded protocol.

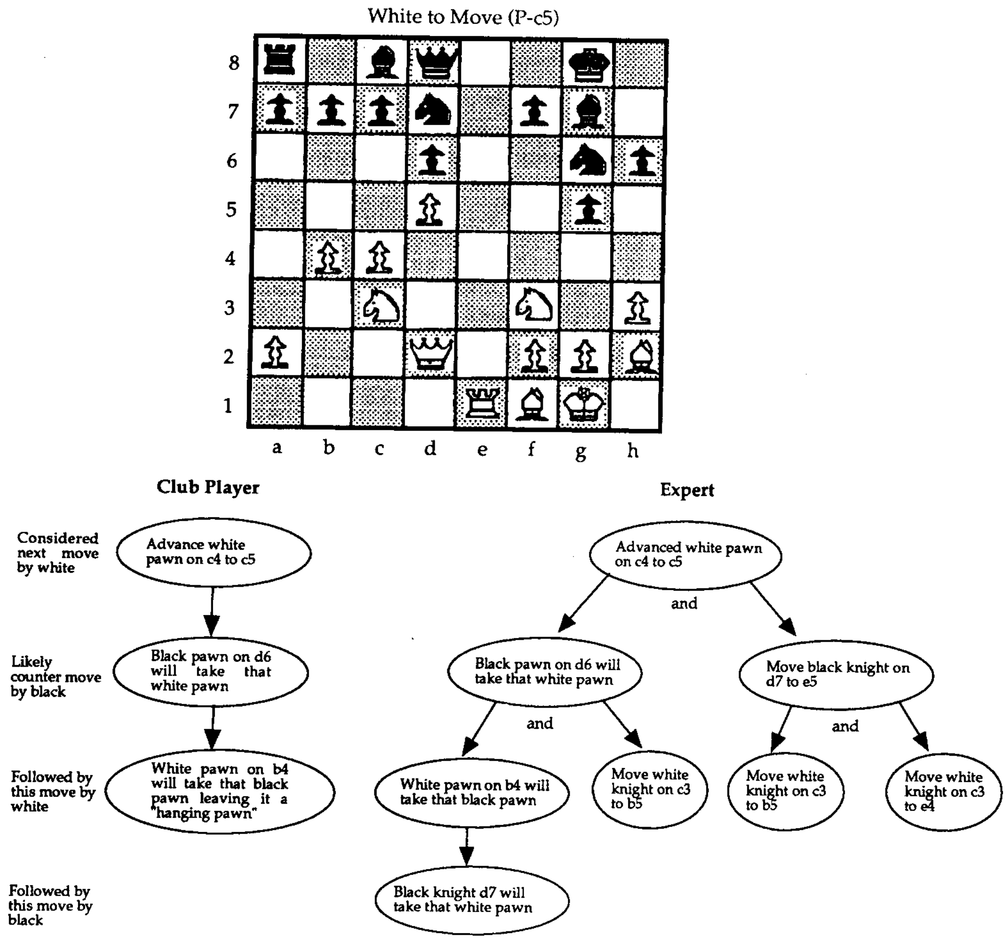
Think-Aloud Protocols and Task Analysis in Research on Expert Performance

Since the demise of introspective analysis of consciousness around the turn of the century, investigators have been reluctant to consider any type of verbal report as valid data on subjects' cognitive processes. More recently investigators have been particularly concerned that having subjects generate verbal reports changes the underlying processes. In a recent review of more than 40 experimental studies comparing performance with and without verbalization, Ericsson and Simon (1993) showed that the structure of cognitive processes can change if subjects are required to explain their cognitive processes. In contrast, if subjects were asked simply to verbalize the thoughts that come to their attention (think aloud), Ericsson and Simon found no reliable evidence that structural changes to cognitive processing occurred. Thinking aloud appears only to require additional time for subjects to complete verbalization and therefore leads to somewhat longer solution times in some cases.

A critical concern in applying this methodology to expert performance is how much information the think-aloud protocols of experts contain about the mediating cognitive processes. Obviously many forms of skilled perceptual-motor performance are so rapid that concurrent verbalization of thought would seem impossible. We later consider alternative methodologies for such cases; but for a wide range of expert performance, think-aloud protocols have provided a rich source of information on expert performance. In his work on chess masters, de Groot (1946/1978) instructed his subjects to think aloud as they identified the best move for chess positions. From an analysis of the verbal reports, de Groot was able to describe how his subjects selected their moves. First they familiarized themselves with the position and extracted the strengths and weaknesses of its structure. Then they systematically explored the consequences of promising moves and the opponent's likely countermoves by planning several moves ahead. From subjects' verbalizations, de Groot and subsequent investigators (Charness, 1981a) have been able to represent the sequences of moves subjects explored as search trees and to measure the amount and depth of planning for chess players at different levels of expertise (see Figure 1). The results of these analyses show that the amount and depth of search increase as a function of chess expertise to a given point (the level of chess experts); thereafter, no further systematic differences were found (Charness, 1989). That the very best chess players still differ in their ability to find and selectively explore the most promising moves suggests that the structure of their internal representation of chess positions differs.

The central importance of experts' representation of solutions is revealed by verbal reports in other domains

Figure 1
Chess Position Presented to Players With Instruction to Select Best Next Move by White (Top Panel)



Note. Think-aloud protocols of a good club player (chess rating = 1657) and a chess expert (chess rating = 2004) collected by Charness (1981a) are shown in bottom panel to illustrate differences in evaluation and planning for one specific move, P-c5 (white pawn from c4 to c5), the best move for this position. Reported considerations for other potential moves have been omitted. The chess expert considers more alternative move sequences, some of them to a greater depth than the club player does. (From "Search in Chess: Age and Skill Differences" by N. Charness, 1981, *Journal of Experimental Psychology: Human Perception and Performance, 7*, p. 469. Copyright 1981 by American Psychological Association.)

such as physics and medical diagnosis. When novices in physics solve a problem, they typically start with the question that asks for, say, a velocity; then they try to recall formulas for calculating velocities and then construct step by step a sequence of formulas by reasoning backward from the goal to the information given in the problem. In contrast, more experienced subjects proceed by forward reasoning. As they read the description of the problem situation, an integrated representation is generated and updated, so when they finally encounter the question in the problem text, they simply retrieve a solution plan from memory (Larkin, McDermott, Simon, & Simon, 1980). This finding suggests that experts form an immediate representation of the problem that systematically cues their knowledge, whereas novices do not have this kind of orderly and efficient access to their knowledge. Similarly, medical experts comprehend and integrate the information they receive about patients to find the correct diagnosis by reasoning forward, whereas less accomplished practitioners tend to generate plausible diagnoses that aid their search for confirming and disconfirming evidence (Patel & Groen, 1991).

Experts' internal representation of the relevant information about the situation is critical to their ability to reason, to plan out, and to evaluate consequences of possible actions. Approximately 100 years ago Binet was intrigued by some chess players' claims that they could visualize chess positions clearly when they played chess games without a visible chessboard (blindfold chess). Binet (1894) and subsequently Luria (1968) studied individuals with exceptional memory abilities, who claimed to visualize as a mental image the information presented to them. These claims, if substantiated, would imply that some individuals have a sensory-based memory akin to a photographic memory, making them qualitatively different from the vast majority of human adults. To gain understanding of these processes and capacities, investigators have turned to tests of perception and memory.

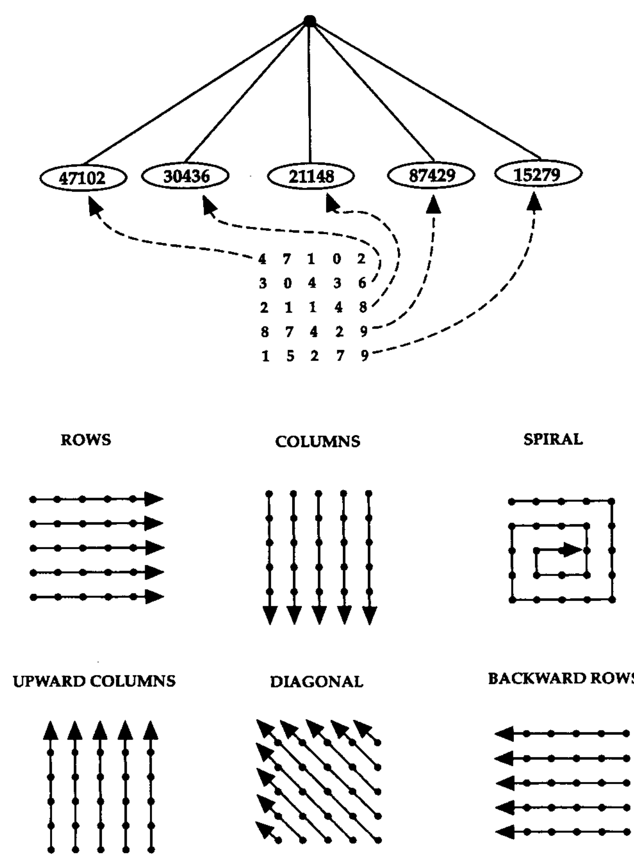
Immediate Memory of Perceived Situations

To study subjects' immediate perception of chess positions, de Groot (1946/1978) restricted the presentation to 2–15 seconds and then removed the chess position from view. Even after such a brief exposure, the best chess players were able to describe the structure of the chess position and could reproduce the locations of all the chess pieces almost perfectly. Weaker chess players' memory was much worse, and generally the amount of information chess players could recall was found to be a function of skill. In a classic study Chase and Simon (1973) studied subjects' memory for briefly presented chess positions and replicated de Groot's findings under controlled conditions. To the same subjects Chase and Simon also presented chess positions with randomly rearranged chess pieces. Memory for these scrambled positions was uniformly poor and did not differ as a function of skill. This finding has been frequently replicated and shows that the superior memory for briefly presented chess positions in not due to any general memory ability, such as photographic memory, but depends critically on subjects' ability to perceive meaningful patterns and relations between chess pieces. Originally Chase and Simon proposed that experts' superior short-term memory for chess positions was due to their ability to recognize configurations of chess pieces on the basis of their knowledge of vast numbers of specific patterns of pieces. With greater knowledge of more complex and larger configurations of chess pieces (chunks), an expert could recall more individual chess pieces with the same number of chunks. Hence Chase and Simon could account for very large individual differences in memory for chess positions within the limits of the capacity of normal short-term memory (STM), which is approximately seven chunks (Miller, 1956).

The Chase–Simon theory has been very influential. It gives an elegant account of experts' superior memory only for representative stimuli from their domain, and not even for randomly rearranged versions of the same stimuli (see Ericsson & J. Smith, 1991a, for a summary of the various domains of expertise in which this finding has been demonstrated). At that time Chase and Simon (1973) believed that storage of new information in long-term memory (LTM) was quite time consuming and that memory for briefly presented information could be maintained only in STM for experts and nonexperts alike. However, subsequent research by Chase and Ericsson (1982) on the effects of practice on a specific task measuring the capacity of STM has shown that through extended practice (more than 200 hours), it is possible for subjects to improve performance by more than 1,000%. These improvements are not mediated by increasingly larger chunks in STM but reflect the acquisition of memory skills that enable subjects to store information in LTM and thereby circumvent the capacity constraint of STM. Hence with extensive practice it is possible to attain skills that lead to qualitative, not simply quantitative, differences in memory performance for a specific type of presented information.

From experimental analyses of their trained subjects and from a review of data on other individuals with exceptional memory, Chase and Ericsson (1982; Ericsson, 1985) extracted several general findings of skilled memory that apply to all subjects. Exceptional memory is nearly always restricted to one type of material, frequently random sequences of digits. The convergence of acquired memory skills and alleged exceptional memory was demonstrated when the trained subjects performed tasks given previously to "exceptional" subjects. Figure 2 (middle panel) shows a matrix that Binet presented visually to his subjects. Below the matrix are several orders in which the same subjects were asked to recall the numbers from the matrix that they memorized. Ericsson and Chase

Figure 2
25-Digit Matrix Used by Binet to Test Memory Experts



Note. Binet asked subjects to repeat entire matrix in various orders shown at bottom or to repeat individual rows as five-digit numbers. Top shows trained subjects' representation of matrix as a sequence of rows, with all digits in a row stored together in an integrated memory encoding.

(1982) found that their subjects matched or surpassed the exceptional subjects both in the speed of initial memorization and in the speed of subsequent recall. A detailed analysis contrasting the speed for different orders of recall showed the same pattern in trained and exceptional subjects, both of whom recalled by rows faster than by columns. Consistent with their acquired memory skill, the trained subjects encoded each row of the matrix as a group by relying on their extensive knowledge of facts relevant to numbers. They then associated a cue corresponding to the spatial location of each row with a retrieval structure illustrated in the top panel of Figure 2. To recall numbers in flexible order, subjects retrieved the relevant row using the corresponding retrieval cue and then extracted the desired next digit or digits. The high correlation between the recall times predicted from this method and the recall times observed for both exceptional and trained subjects imply that these groups have a similar memory representation. When the biographical background of individuals exhibiting exceptional memory performance was examined, Ericsson (1985, 1988) found evidence for extended experience and practice with related memory tasks. Hence, these exceptional individuals and the trained college students should be viewed as expert performers on these laboratory tasks, where the same type of memory skills has been acquired during extended prior experience.

Acquired memory skill (skilled memory theory, Ericsson & Staszewski, 1989; and long-term working memory, Ericsson & Kintsch, 1994) accounts well even for the superior memory of experts. In many types of expert performance, research has shown that working memory is essentially unaffected by interruptions, during which the experts are forced to engage in an unrelated activity designed to eliminate any continued storage of information in STM. After the interruption and after a brief delay involving recall and reactivation of relevant information stored in LTM, experts can resume activity without decrements in performance. Storage in LTM is further evidenced by experts' ability to recall relevant information about the task even when they are unexpectedly asked for recall after the task has been completed. The amount recalled is found to increase as a function of the level of expert performance in chess (Charness, 1991).

The critical aspect of experts' working memory is not the amount of information stored per se but rather how the information is stored and indexed in LTM. In support of this claim, several cases have been reported in which nonexperts have been able to match the amount of domain-specific information recalled by experts, but without attaining the expert's sophisticated representation of the information. After 50 hours of training on memory for presented chess positions, a college student with minimal knowledge of chess was able to match the performance of chess masters (Ericcson & Harris, 1990). However, an analysis of how the chess position was encoded revealed that the trained subject focused on perceptually salient patterns in the periphery of the chessboard, whereas the chess master attended to the central aspects critical to the selection of the next moves (Ericsson & Harris, 1990). When told explicitly to memorize presented medical information, medical students match or even surpass medical experts (Patel & Groen, 1991; Schmidt & Boshuizen, 1993). However, the medical experts are more able than medical students to identify and recall the important pieces of presented information. Medical experts also encode more general clinical findings, which are sufficient for reasoning about the case but not specific enough to recall or reconstruct the detailed facts presented about the medical patient (Boshuizen & Schmidt, 1992; Groen & Patel, 1988).

Experts acquire skill in memory to meet specific demands of encoding and accessibility in specific activities in a given domain. For this reason their skill does not transfer from one domain to another. The demands for storage of intermediate products in mental calculation differ from the demands of blindfold chess, wherein the chess master must be able not simply to access the current position but also to plan and accurately select the best chess moves. The acquisition of memory skill in a domain is integrated with the acquisition of skill in organizing acquired knowledge and refining of procedures and strategies, and it allows experts to circumvent limits on working memory imposed by the limited capacity of STM.

Perceptual–Motor Skill in Expert Performance

In many domains it is critical that experts respond not just accurately but also rapidly in dynamically changing situations. A skilled performer needs to be able to perceive and encode the current situation as well as to select and execute an action or a series of actions rapidly. In laboratory studies of skill acquisition, investigators have been able to demonstrate an increase in the speed of perceptual–motor reactions as a direct function of practice. With extensive amounts of practice, subjects are able to evoke automatically the correct reaction to familiar stimulus situations. This analysis of perceived situations and automatically evoked responses is central to our understanding of skilled performance, yet it seems to be insufficient to account for the speeds observed in many types of expert performance. The time it takes to respond to a stimulus even after extensive training is often between 0.5 and 1.0 seconds, which is too slow to account for a return of a hard tennis serve, a goalie's catching a hockey puck, and fluent motor activities in typing and music.

The standard paradigm in laboratory psychology relies on independent trials in which the occurrence of the presented stimulus, which the subject does not control, defines the beginning of a trial. In contrast, in the perceptual environment in everyday life, expert performance is continuous and changing, and experts must be able to recognize if and when a particular action is required. Most important, it is possible for the expert to analyze the current situation and thereby anticipate future events. Research on the return of a tennis serve shows that experts do not wait until they can see the ball approaching them. Instead they carefully study the action of the server's racquet and are able to predict approximately where in the service area the tennis ball will land even before the server has hit the ball. Abernethy (1991) has recently reviewed the critical role of anticipation in expert performance in many racquet sports. Similarly, expert typists are looking well ahead at the text they are typing in any particular instant. The difference between the text visually fixated and the letters typed in a given instant (eye–hand span) increases with the typists' typing speed. High-speed filming of the movements of expert typists' fingers shows that their fingers are simultaneously moved toward the relevant keys well ahead of when they are actually struck. The largest differences in speed between expert and novice typists are found for successive keystrokes made with fingers of different hands because the corresponding movements can overlap completely after extended typing practice. When the typing situation is artificially changed to eliminate looking ahead at the text to be typed, the speed advantage of expert typists is virtually eliminated (Salthouse, 1991a). Similar findings relating the amount of looking ahead and speed of performance apply to reading aloud (Levin & Addis, 1979) and sight-reading in music (Sloboda, 1985).

In summary, by successfully anticipating future events and skillfully coordinating overlapping movements, the expert performer is able to circumvent potential limits on basic elements of serial reactions.

General Comments on the Structure of Expert Performance

Recent studies of expert performance have questioned the talent-based view that expert performance becomes increasingly dependent on unmodifiable innate components. Although these studies have revealed how beginners acquire complex cognitive structures and skills that circumvent the basic limits confronting them, researchers have not uncovered some simple strategies that would allow nonexperts to rapidly acquire expert performance, except in a few isolated case, such as the sexing of chickens (Biederman & Shiffrar, 1987). Analyses of exceptional performance, such as exceptional memory and absolute pitch, have shown how it differs from the performance of beginners and how beginners can acquire skill through instruction in the correct general strategy and corresponding training procedures (Howe, 1990). However, to attain exceptional levels of performance, subjects must in addition undergo a very long period of active learning, during which they refine and improve their skill, ideally under the supervision of a teacher or coach. In the following section we describe the particular activities (deliberate practice) that appear to be necessary to attain these improvements (Ericsson, Krampe, & Tesch-Römer, 1993).

By acquiring new methods and skills, expert performers are able to circumvent basic, most likely physiological, limits imposed on serial reactions and working memory. The traditional distinction between physiological (unmodifiable physical) and cognitive (modifiable mental) factors that influence performance does not seem valid in studies of expert performance. For the purposes of the typical one-hour experiment in psychology, changes in physiological factors might be negligible; but once we consider extended activities, physiological adaptations and changes are not just likely but virtually inevitable. Hence we also consider the possibility that most of the physiological attributes that distinguish experts are not innately determined characteristics but rather the results of extended, intense practice.

Acquisition of Expert Performance

A relatively uncontroversial assertion is that attaining an expert level of performance in a domain requires mastery of all of the relevant knowledge and prerequisite skills. Our analysis has shown that the central mechanisms mediating the superior performance of experts are acquired; therefore acquisition of relevant knowledge and skills may be the major limiting factor in attaining expert performance. Some of the strongest evidence for this claim comes from a historical description of how domains of expertise evolved with increased specialization within each domain. To measure the duration of the acquisition process, we analyze the length of time it takes for the best individuals to attain the highest levels of performance within a domain. Finally we specify the type of practice that seems to be necessary to acquire expert performance in a domain.

Evolution of Domains of Expertise and the Emergence of Specialization

Most domains of expertise today have a fairly long history of continued development. The knowledge in natural science and calculus that represented the cutting edge of mathematics a few centuries ago and that only the experts of that time were able to master is today taught in high school and college (Feldman, 1980). Many experts today are struggling to master the developments in a small subarea of one of the many natural sciences. Before the 20th century it was common for musicians to compose and play their own music; since then, distinct career patterns have emerged for composers, solo performers, accompanists, teachers, and conductors. When Tchaikovsky asked two of the greatest violinists of his day to play his violin concerto, they refused, deeming the score unplayable (Platt, 1966). Today, elite violinists consider the concerto part of their standard repertory. The improvement in music training has been so considerable that according to Roth (1982), the virtuoso Paganini "would indeed cut a sorry figure if placed upon the modern concert stage" (p. 23). Paganini's techniques and Tchaikovsky's concerto were deemed impossible until other musicians figured out how to master and describe them so that students could learn them as well. Almost 100 years ago the first Olympic Games were held, and results on standardized events were recorded. Since then records for events have been continuously broken and improved. For example, the winning time for the first Olympic Marathon is comparable to the current qualifying time for the Boston Marathon, attained by many thousands of amateur runners every year. Today amateur athletes cannot successfully compete with individuals training full time, and training methods for specific events are continuously refined by professional coaches and trainers.

In all major domains there has been a steady accumulation of knowledge about the domain and about the skills and techniques that mediate superior performance. This accumulated experience is documented and regularly updated in books, encyclopedias, and instructional material written by masters and professional teachers in the domain. During the last centuries the levels of performance have increased, in some domains dramatically so. To attain the highest level of performance possible in this decade, it is necessary both to specialize and to engage in the activity full time.

Minimum Period of Attainment of Expert Performance

Another measure of the complexity of a domain is the length of time it takes an individual to master it and attain a very high level of performance or make outstanding achievements. Of particular interest is how fast the most "talented" or best performers can attain an international level of performance. In their classic study on chess, Simon and Chase (1973) argued that a 10-year period of intense preparation is necessary to reach the level of an international chess master and suggested similar requirements in other domains. In a review of subsequent research, Ericsson, Krampe, and Tesch-Römer (1993) showed that the 10-year rule is remarkably accurate, although there are at least some exceptions. However, even those exceptions, such as Bobby Fischer, who started playing chess very early and attained an international level at age 15, are only about a year shy of the 10-year requirement. Winning international competitions in sports, arts, and science appears to require at least 10 years of preparation and typically substantially longer. In the sciences and some of the arts, such as literature, the necessary preparation overlaps so much with regular education that it is often difficult to determine a precise starting point. However, when the time interval between scientists' and authors' first accepted publication and their most valued publication is measured, it averages more than 10 years and implies an even longer preparation period (Raskin, 1936). Even for the most successful ("talented") individuals, the major domains of expertise are sufficiently complex that mastery of them requires approximately 10 years of essentially full-time preparation, which corresponds to several thousands of hours of practice.

Practice Activities to Attain Expert Performance

In almost every domain, methods for instruction and efficient training have developed in parallel with the accumulation of relevant knowledge and techniques. For many sports and performance arts in particular, professional teachers and coaches monitor training programs tailored to the needs of individuals ranging from beginners to experts. The training activities are designed to improve specific aspects of performance through repetition and successive refinement. To receive maximal benefit from feedback, individuals have to monitor their training with full concentration, which is effortful and limits the duration of daily training. Ericsson, Krampe, and Tesch-Römer (1993) referred to individualized training on tasks selected by a qualified teacher as deliberate practice. They argued that the amount of this type of practice should be closely related to the level of acquired performance.

From surveys of the kinds of activities individuals engage in for the popular domains, such as tennis and golf, it is clear that the vast majority of active individuals spend very little if any time on deliberate practice. Once amateurs have attained an acceptable level of performance, their primary goal becomes inherent enjoyment of the activity, and most of their time is spent on playful interaction. The most enjoyable states of play are characterized as flow (Csikszentmihalyi, 1990), when the individual is absorbed in effortless engagement in a continuously changing situation. During play even individuals who desire to improve their performance do not encounter the same or similar situations on a frequent and predictable basis. For example, a tennis player wanting to improve a weakness, such as a backhand volley, might encounter a relevant situation only once per game. In contrast, a tennis coach would give that individual many hundreds of opportunities to improve and refine that type of shot during a training session.

Work, another type of activity, refers to public performances, competitions, and other performances motivated by external social and monetary rewards. Although work activities offer some opportunities for learning, they are far from optimal. In work activities, the goal is to generate a quality product reliably. In several domains, such as performance arts and sports, there is a clear distinction between training before a performance and the performance itself. During the performance itself, opportunities for learning and improvements are minimal, although the problems encountered can be addressed during training following the performance. Most occupations and professional domains pay individuals to generate efficiently services and products of consistently high quality. To give their best performance in work activities, individuals rely on previously well-entrenched methods rather than exploring new methods with unknown reliability. In summary, deliberate practice is an effortful activity motivated by the goal of improving performance. Unlike play, deliberate practice is not inherently motivating; and unlike work, it does not lead to immediate social and monetary rewards (Ericsson, Krampe, & Tesch-Römer, 1993).

Individualized training of students, who begin as very young children under the supervision of professional teachers and coaches, is a relatively recent trend in most major domains. It was only in 1756, for example, that Wolfgang Amadeus Mozart's father published the first book in German on teaching students to play the violin. Before organized education became the norm, people acquired skill through apprenticeship, working as adolescents with a skilled performer, frequently one of their parents. Recently there has been a lot of interest in this type of learning environment within the framework of situated cognition (Lave, 1988; Lave & Wenger, 1991). A significant element of apprenticeship is the imitation of skilled performers and careful study and copying of their work. In the arts the study and imitation of masterpieces has a long history. For example, Benjamin Franklin (1788/1986) described in his autobiography how he tried to learn to write in a clear and logical fashion. He would read through a passage in a good book to understand it rather than memorize it and then try to reproduce its structure and content. Then he would compare his reproduction with the original to identify differences. By repeated application of this cycle of study, reproduction, and comparison with a well-structured original, Franklin argued that he acquired his skill in organizing thoughts for speaking and writing.

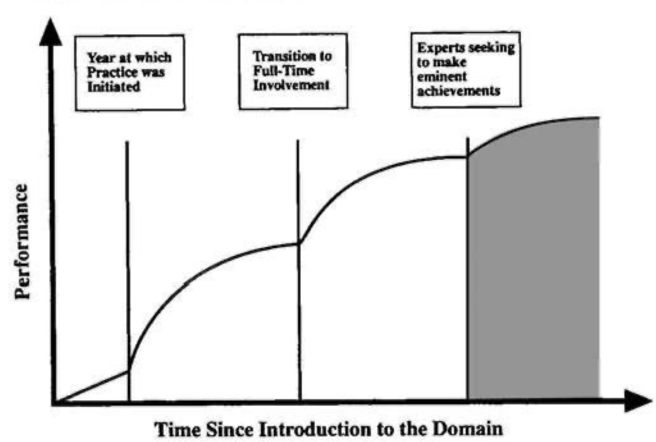
With the advent of audio and video recording, which have opened new possibilities for repeated study of master artists' performance, reproduction and comparison have been extended to allow individualized study and improvement of performance. This general method is central to achieving expert performance in chess. Advanced chess players spend as many as four hours a day studying published games between international chess masters (Forbes, 1992). The effective component of this type of study is predicting the chess master's next move without looking ahead. If the prediction is wrong, the advanced player examines the chess position more deeply to identify the reasons for the chess master's move. The activity of planning and extended evaluation of chess games is likely to improve a player's ability to internally represent chess positions, a memory skill that we discussed earlier in this article. This form of self-directed study has most of the characteristics of deliberate practice, but it is probably not as effective as individualized study guided by a skilled teacher. It is interesting to note that most of the recent world champions in chess were at one time tutored by chess masters (Ericsson, Krampe, & Tesch-Römer, 1993).

Deliberate practice differs from other domain-related activities because it provides optimal opportunities for learning and skill acquisition. If the regular activities in a domain did not offer accurate and preferably immediate feedback or opportunities for corrected repetitions, improvements in performance with further experience would not be expected from learning theory. Most amateurs and employees spend a very small amount of time on deliberate efforts to improve their performance, once it has reached an acceptable level. Under these conditions only weak relations between amount of experience and performance would be predicted, which is consistent with the empirical data. Recent research has explored the question whether deliberate practice can account for the attainment of elite performance levels and for individual differences among expert-level performers. According to the framework proposed by Ericsson, Krampe, and Tesch-Römer (1993), the primary mechanism creating expert-level performance in a domain is deliberate practice.

Acquiring Elite Performance

Why do individuals even begin to engage in deliberate practice, when this activity is not inherently enjoyable? From many interviews, Bloom (1985) found that international-level performers in several domains start out as children by engaging in playful activities in the domain (see Phase 1 in Figure 3). After a period of playful and enjoyable experience they reveal "talent" or promise. At this point parents typically suggest that their children take lessons from a teacher and engage in limited amounts of deliberate practice. The parents help their children acquire regular habits of practice and teach them that this activity has instrumental value by noticing improvements in performance. The next phase (Bloom, 1985) is an extended period of preparation and ends with the individual's commitment to pursue activities in the domain on a full-time basis. During this period the daily amounts of deliberate practice are increased, and more advanced teachers and training facilities are sought out. Occasionally parents even move to a different region of the country to provide their children with the best training environment. In the next phase, the individual makes a full-time commitment to improving performance. This phase ends when the individual either can make a living as a professional performer in the domain or terminates full-time engagement in the activity. Bloom (1985) found that during this phase nearly all of the individuals who ultimately reach an international level performance work with master teachers who either themselves had reached that level or had previously trained other individuals to that level. All through their development, international-level performers are provided with the best teachers for their cur-

Figure 3
Three Phases of Development of Expert Performance Followed by a Qualitatively Different Phase of Efforts to Attain Eminent Achievements



Note. From "Can We Create Gifted People?" by K. A. Ericsson, R. Th. Krampe, and S. Heizmann in *The Origins and Development of High Ability* (pp. 222–249), 1993, Chichester, England: Wiley. Copyright 1993 by Ciba Foundation. Adapted by permission.

rent level of performance and engage in a great amount of deliberate practice.

The dilemma in most domains of expertise is that millions of young individuals enter these domains with aspirations to reach the highest levels of performance, but by definition only a very small number can succeed. Given the low probability of ultimate success, parents and coaches have been very much interested in identifying these select individuals as early as possible and giving them encouragement, support, and the best learning opportunities. The consistent failures to identify specific "talents" in children is not surprising when one considers the qualitative changes occurring during the long period of development. In many domains international performers start practice at age 4 to 6, when it is unclear what kind of objective evidence of talent and promise they could possibly display. Available descriptions suggest that children this young display interest and motivation to practice rather than exceptional performance. Once deliberate practice has begun, the primary measure of acquired skill and talent is the current level of performance compared with that of other children of comparable ages in the neighborhood. Only later at age 10 to 12 do the children typically start participating in competitions, where their performance is compared with that of other successful children from a larger geographical area. As performance level and age increase, the criteria for evaluating performance also change. In the arts and sciences, technical proficiency is no longer enough, and adult criteria of abstract understanding and artistic expression are applied.

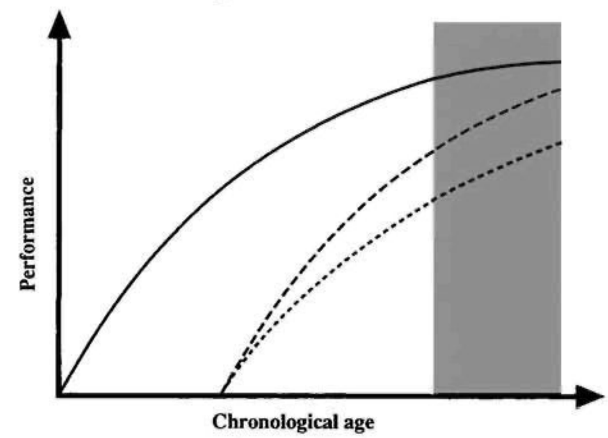
During the first three phases of development, individuals master the knowledge and skills that master teachers and coaches know how to convey. To achieve the highest level (eminent performance), individuals must enter a fourth phase, going beyond the available knowledge in the domain to produce a unique contribution to the domain. Eminent scientists make major discoveries and propose new theories that permanently change the concepts and knowledge in the domain. Similarly eminent artists generate new techniques and interpretations that extend the boundaries for future art. The process of generating innovations differs from the acquisition of expertise and mastery. Major innovations by definition go beyond anything even the master teachers know and could possibly teach. Furthermore, innovations are rare, and it is unusual that eminent individuals make more than a single major innovation during their entire lives. Unlike consistently superior expert performance, innovation occurs so infrequently and unpredictably that the likelihood of its ever being captured in the laboratory is small. However, it is still possible through retrospective analysis of concurrent records, such as notebooks and diaries (Gruber, 1981; D. B. Wallace & Gruber, 1989), to reconstruct the processes leading up to major discoveries. Once the context of a particular discovery has been identified, it is possible to reconstruct the situation and study how other naive subjects with the necessary knowledge can uncover the original discovery (Qin & Simon, 1990). Let us now turn back to expert performance, which we consider both reproducible and instructable.

Individual Differences in Expert Performance

Biographies of international-level performers indicate that a long period of intense, supervised practice preceded their achievements. The simple assumption that these levels of deliberate practice are necessary accounts for the fact that the vast majority of active individuals who prematurely stop practicing never reach the highest levels of performance. However, in most major domains a relatively large number of individuals continue deliberate practice and thus meet the criterion of necessity. Within this group striking individual differences in adult performance nonetheless remain.

Ericsson, Krampe, and Tesch-Römer (1993) hypothesized that differences in the amount of deliberate practice could account for even the individual differences among the select group of people who continue a regimen of deliberate practice. The main assumption, which they called the *monotonic benefits assumption*, is that individuals' performances are a monotonic function of the amount of deliberate practice accumulated since these individuals began deliberate practice in a domain. The accumulated amount of deliberate practice and the level of performance an individual achieves at a given age is thus a function of the starting age for practice and the weekly amount of practice during the intervening years. This function is illustrated in Figure 4. The second curve

Figure 4
Relations Between Age and Performance



Note. Late period involving selection to the best music academies has been shaded. Solid line: performance associated with early starting age and high level of practice. Dashed line: performance for equally high level of practice but later starting age. Dotted line: performance associated with the same late starting age but lower level of practice. The slope of the dashed line appears steeper than that of the solid line. However, the horizontal distance between these two curves is constant. From "Can We Create Gifted People?" by K. A. Ericsson, R. Th. Krampe, and S. Heizmann in *The Origins and Development of High Ability* (pp. 222–249), 1993, Chichester, England: Wiley. Copyright 1993 by Ciba Foundation. Adapted by permission.

has been simply moved horizontally to reflect a later starting age, and the third curve reflects in addition a lower weekly rate of practice.

To evaluate these predictions empirically, it is necessary to measure the amount of time individuals spend on various activities, in particular deliberate practice. One way of doing so, which is to have them keep detailed diaries, has a fairly long tradition in studies of time budgeting in sociology (Juster & Stafford, 1985). In most domains with teachers and coaches, deliberate practice is regularly scheduled on a daily basis, and advanced performers can accurately estimate their current and past amounts of practice as well as their starting ages and other characteristics of their practice history.

In a comprehensive review of studies comparing starting ages and amount of weekly practice for international, national, and regional-level performers in many different domains, Ericsson, Krampe, and Tesch-Römer (1993) found that performers who reached higher levels tended to start practicing as many as from two to five years earlier than did less accomplished performers. Individuals who attained higher levels of performance often spent more time on deliberate practice than did less accomplished individuals, even when there was no difference in the total time both groups spent on domain-related activities. Differences in the amount of deliberate practice accumulated during their development differentiated groups of expert performers at various current levels of performance. The three graphs in Figure 4 illustrate how simple differences in starting ages and weekly amounts of practice can yield very stable differences in amounts of training and performance levels.

Everyone recognizes that maturational factors affect performance. For this reason competitions are nearly always structured by groups of contestants with the same ages. By the time individuals approach their middle to late teens (the shaded area in Figure 4) and are applying for scholarships and admission to the studios of master teachers and the best training environments, large differences in past practice and acquired skill are already present. Ericsson, Krampe, and Tesch-Römer (1993) found that by age 20, the top-level violinists in their study had practiced an average of more than 10,000 hours, approximately 2,500 hours more than the next most accomplished group of expert violinists and 5,000 hours more than the group who performed at the lowest expert level.

In summary, evidence from a wide range of domains shows that the top-level experts have spent a very large amount of time improving their performance and that the total amount accumulated during development is several years of additional full-time practice more than that of other less accomplished performers. This difference is roughly equivalent to the difference between freshmen and seniors in a highly competitive college. In these environments, where the best opportunities for further development are offered only to the individuals with the best current performance, it may be difficult for individuals with less prior practice and lower levels of performance even to secure situations in which they can practice full time. It is virtually impossible for them to catch up with the best performers because those performers maintain their lead through continuous practice at optimal levels.

Structure of Practice in the Daily Lives of Elite Performers

From analyses of diaries and other sources of biographical material, Ericsson, Krampe, and Tesch-Römer (1993) concluded that expert performers design their lives to optimize their engagement in deliberate practice. Expert musicians in their study spent approximately four hours a day—every day including weekends—on deliberate practice. Practice sessions were approximately one hour long, followed by a period of rest. Performers practiced most frequently during the morning, when independent research indicates that individuals have the highest capacity for complex, demanding activity during the day (Folkard & Monk, 1985). All the expert musicians reported on the importance of sleep and rest in maintaining their high levels of daily practice. The expert musicians in the two best groups, who practiced longer each day, slept more than those in the least accomplished group and also slept more than other reference groups of subjects of comparable age. The additional sleep was primarily from an afternoon nap. Expert subjects maximize the amount of time they can spend on deliberate practice when they can fully focus on their training goals without fatigue. Many master teachers and coaches consider practice while fatigued and unfocused not only wasteful but even harmful to sustained improvements.

Focused, effortful practice of limited duration has been found to be important in a wide range of domains of expertise. Interestingly the estimated amount of deliberate practice that individuals can sustain for extended periods of time does not seem to vary across domains and is close to four hours a day (Ericsson, Krampe, & Tesch-Römer, 1993).

The effort and intensity of deliberate practice is most readily observable for perceptual-motor behavior in sports and performance arts. One goal of most of the practice activities is to push the limits of performance to higher levels by, for example, stretching in ballet, or repeated maximal efforts until exhaustion during interval training in running and weight lifting. It is well-known that intense exercise increases endurance and the size of muscles. However, recent research in sports physiology has shown that anatomical changes in response to extended intense exercise are more far-reaching than commonly believed. Within a few weeks of vigorous training, the number of capillaries supplying blood to the trained muscles increases. Longitudinal studies show that after years of "elite-level" endurance training, the heart adapts and increases in size to values outside the normal range for healthy adults. The metabolism and general characteristics of muscle fibers also change—from slow-twitch to fast-twitch or vice versa. Most interestingly these changes are limited only to those muscles that are trained and critical to the particular sports event for which the athlete is preparing. Many of these changes appear to increase when practice overlaps with the body's development during childhood and adolescence. For example the flexibility required for elite performance in ballet requires that dancers begin practicing before age 10 or 11. With the exception of height, the characteristics that differentiate elite athletes and performance artists from less accomplished performers in the same domains appear to reflect the successful adaptations of the body to intense practice activities extended over many years (Ericsson, Krampe, & Tesch-Römer, 1993).

These physiological adaptations are not unique to expert performers. Similar but smaller changes are found for individuals who train at less intense levels. Similar extreme adaptations are seen in individuals living under extreme environmental conditions, such as at very high altitudes, or coping with diseases, such as partial blockages of the blood supply to the heart. Many occupation-specific problems that expert performers experience in middle age also seem to result from related types of (mal)adaptive processes.

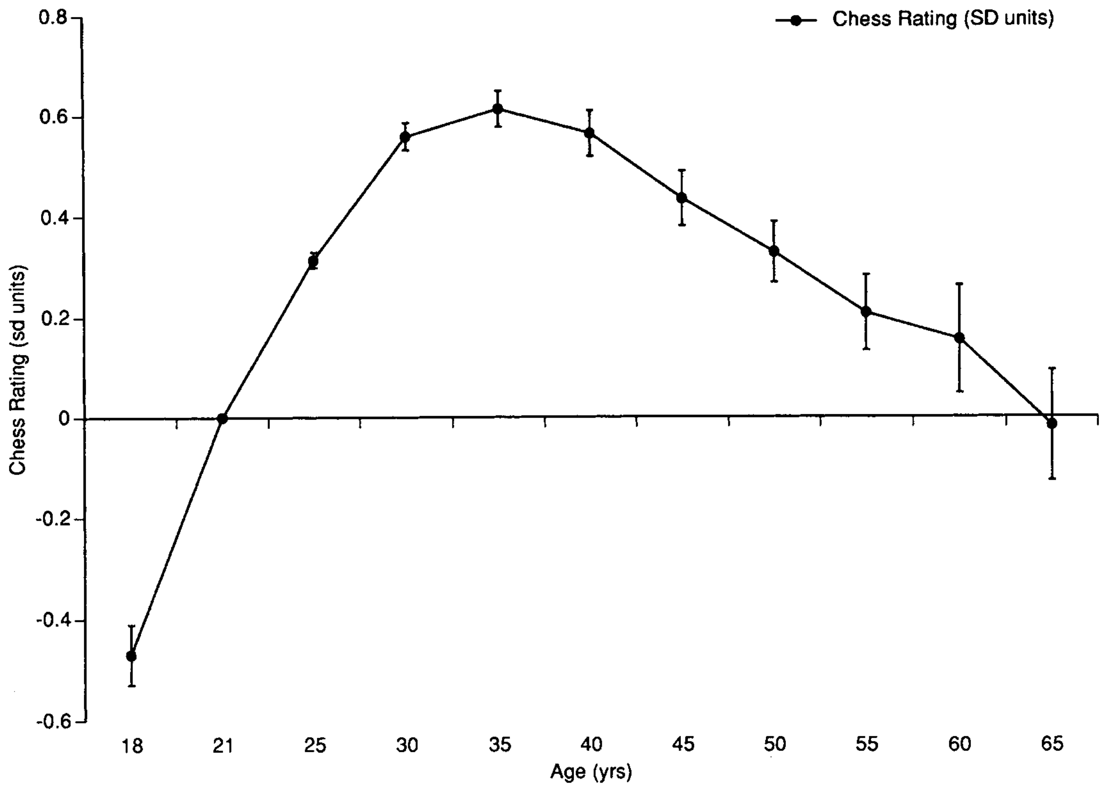
It is becoming increasingly clear that maximizing the intensity and duration of training is not necessarily good. Expert performers have a constant problem with avoiding strains and injuries and allowing the body enough time to adapt and recuperate. Even in the absence of physical injuries, an increasing number of athletes and musicians overtrain and do not allow themselves enough rest to maintain a stable equilibrium from day to day. Sustained overtraining leads to burnout, for which the only known remedy is to terminate practice completely for long periods. It appears that top-level adult experts practice at the highest possible level that can be sustained for extended periods without burnout or injury. Hence, it may be extremely difficult to consistently practice harder and improve faster than these individuals already do.

Expert Performance From a Life Span Perspective

Elite performers in most domains are engaged essentially full time from childhood and adolescence to late adulthood. The study of expert performers therefore offers a unique perspective on life span development and especially on the effects of aging. Many studies have examined the performance of experts as a function of age or of the ages when experts attained their best performance or their highest achievement. It is extremely rare for performers to attain their best performance before reaching adulthood, but it is not necessarily the case that performance continues to improve in those who keep exercising their skills across the life span. Rather, a peak age for performance seems to fall in the 20s, 30s, and 40s, as Lehman (1953) first noted. The age distributions for peak performance in vigorous sports are remarkably narrow and centered in the 20s with systematic differences between different types of sports (Schulz & Curnow, 1988). In vigorous sports it is rare for elite athletes above age 30 to reach their personal best or even in many cases remain competitive with younger colleagues. Although less pronounced, similar age distributions centered somewhere in the 30s are found for fine motor skills and even predominantly cognitive activities, such as chess, science, and the arts. Simonton (1988a) has argued that the relative decline with age may be slight and may be attributable to the fact that total creative output for artists and scientists declines, although the probability of achieving an outstanding performance remains constant. Thus the frequency of producing an outstanding work declines with age. Perhaps the best evidence for decline with age is Elo's (1965) analysis of the careers of grand master chess players. As seen in Figure 5 (from Charness & Bosman, 1990), there is a peak for chess players in their 30s, although performance at 63 years of age is no worse than that at 21 years. The peak age for creative achievement differs considerably between domains. In pure mathematics, theoretical physics, and lyric poetry, the peak ages for contributions occur in the late 20s and early 30s. In novel writing, history, and philosophy, the peaks are less pronounced and occur in the 40s and early 50s (Simonton, 1988a). Even within domains the peak age for performance seems to vary systematically with the types of demands placed on the performer. In international-level tournament chess, individuals typically play chess games for four to five hours daily for more than a week. Furthermore, tournament chess makes strong demands on working memory and, to some extent, on speed of processing, when players attempt to choose the best move by searching through the problem space of possible moves. On average, a tournament chess player has approximately three minutes to consider each move (when normal time controls are used). In "postal chess," players have several days to make a move. Because deliberation times are longer and the players can use external memory to maintain the results of analysis, ascension to the world postal chess championship occurs much later, near 46 years of age as compared with 30 years of age for tournament chess (Charness & Bosman, 1990).

To researchers on aging, the decline in expert performance in old age, which in many domains is often relatively slight, is less interesting than expert performers' ability to maintain a very high level of performance during ages when beginners and less accomplished performers display clear effects of aging. A common hypothesis related to the notion of innate talent is that experts generally age more slowly than other performers, and thus no observable impairments would be expected. However, this hypothesis is not consistent with recent research on expert performance in chess (Charness, 1981b), typing (Bosman, 1993; Salthouse, 1984), and music (Krampe, 1994). The superior performance of older experts is found to be restricted to relevant tasks in their domains of expertise. For unrelated psychometric tasks and some tasks related to occupational activities, normal age-related decline is observed (Salthouse, 1991b).

Figure 5
Grand Master Performance by Age



Note. Chess ratings scaled in standard deviation units, with performance at age 21 for each individual set to zero (data from Elo, 1965). Averaged scores across grand masters shown with standard error bars. From "Expertise and Aging: Life in the Lab" (p. 358) by N. Charness and E. A. Bosman in *Aging and Cognition: Knowledge Organization and Utilization,* T. H. Hess (Ed.), 1990, Amsterdam: Elsevier. Copyright 1990 by Elsevier. Adapted by permission.

The mediating mechanisms in younger and older experts' performance have been examined in laboratory studies developed under the expert performance approach. In typing, older experts who type at the same speed as younger experts are found to have larger eye-hand spans that permit older experts to compensate through advance preparation (Bosman, 1993; Salthouse, 1984). Older chess experts' ability to select the best chess move is associated with less planning than that of younger experts at an equivalent skill level. This suggests that older chess experts compensate through more extensive knowledge of chess (Charness, 1981a). Comparisons of older and younger expert pianists' ability to perform simple and complex sequences of key strokes requiring bimanual coordination reveal no or small differences, whereas the same comparisons between older and younger amateur pianists reveal clear decrements with age that increase with the complexity of the tasks (Krampe, 1994). Such age effects require greater diversity in the models proposed to explain expertise. It is now evident that at least in typing and chess, two individuals at the same level of skill can achieve their performance through mechanisms with different structure. Although it is convenient to collapse a measure of expertise onto a unidimensional scale (such as chess rating or net words per minute for typing), this is an oversimplification that may obscure individual differences in the underlying processes the mediate same-level performance.

The Role of Deliberate Practice

In the previous sections we described the evidence for the necessity of deliberate practice for initially acquiring expert performance. The maintenance of expert performance could be due to the unique structure of the mechanisms acquired in expert performance or to a level of deliberate practice maintained during adulthood or both.

The most marked age-related decline is generally observed in perceptual–motor performance displayed in many types of sports. High levels of practice are necessary to attain the physiological adaptations that are found in expert performers, and the effects of practice appear to be particularly large when intense practice overlaps with physical development during childhood and adolescence. Most of these adaptations require that practice is maintained; if not, the changes revert to normal values, although for some anatomical changes many years of no practice appear necessary before the reversion is completed. Hence, much of the age-related decline in performance may reflect the reduction or termination of practice. Studies of master athletes show that older athletes do not practice at the same intensity as the best young athletes. When older master athletes are compared with young athletes training at a similar level, many physiological measurements do not differ between them. However, at least some physiological functions, such as maximal heart rate, show an age-related decline independent of past or current practice. In summary, the ability to retain superior performance in sports appears to depend critically on maintaining practice during adulthood (Ericsson, 1990).

Evidence on the role of early and maintained practice in retaining cognitive aspects of expertise is much less extensive. Takeuchi and Hulse's (1993) recent review of absolute (perfect) pitch shows that children can easily acquire this ability at around the ages of three to five. Acquisition of the same ability during adulthood is very difficult and time consuming. Some other abilities, such as the acquisition of second languages (especially accents and pronunciation), appear easier to acquire at young rather than adult ages. Whether early acquisition of abilities, per se, translates into better retention into old age is currently not known.

Virtually by definition expert performers remain highly active in their domains of expertise. With increasing age, they typically reduce their intensive work schedules, a change in life style that is consistent with the decrease observed in their productivity (Simonton, 1988a). Roe (1953) found that eminent scientists reduce their level of work during evenings and weekends. Information about the distribution of time among different types of activities and especially the amount of time spent on maintaining and improving performance is essentially lacking. However, Krampe (1994) collected both diaries and retrospective estimates of past practice for older expert pianists. Consistent with the lack of performance differences between younger and older pianists in tasks relevant to piano playing, Krampe found that the older experts still practiced approximately 10 hours a week and spent more than 40 additional hours a week on other music-related activities. In addition he found that individual differences in performance among older pianists could be predicted well by the amount of practice during the past 10 years. Whether a reduction in practice by older chess players and typists accounts for the differences between younger and older experts in these fields cannot currently be answered, given the lack of longitudinal data on performance and practice.

The study of expert performance over the life span of the performers is needed. This perspective is quite likely to provide new insights into the plasticity of the structure of human performance as a function of different developmental phases. Through investigation of focused sustained practice, it may be possible to determine which aspects can and, at least with the current training methods, cannot be modified to enhance current and future performance. Of particular practical and theoretical interest are those factors that enable experts to retain and maintain superior performance into old age.

Summary and Conclusion

The differences in performance between experts and beginners are the largest that have been reliably reproduced with healthy, normal adults under controlled test conditions. From the life-long efforts of expert performers who continuously strive to improve and reach their best performance, one can infer that expert performance represents the highest performance possible, given current knowledge and training methods in the domain. Individuals' acquisition of expert performance is thus a naturally occurring experiment for identifying the limits of human performance. It is hard to imagine better empirical evidence on maximal performance except for one critical flaw. As children, future international-level performers are not randomly assigned to their training condition. Hence one cannot rule out the possibility that there is something different about those individuals who ultimately reach expert-level performance.

Nevertheless the traditional view of talent, which concludes that successful individuals have special innate abilities and basic capacities, is not consistent with the reviewed evidence. Efforts to specify and measure characteristics of talent that allow early identification and successful prediction of adult performance have failed. Differences between expert and less accomplished performers reflect acquired knowledge and skills or physiological adaptations effected by training, with the only confirmed exception being height.

More plausible loci of individual differences are factors that predispose individuals toward engaging in deliberate practice and enable them to sustain high levels of practice for many years. Differences in these factors clearly have, in part, an environmental origin and can be modified as the level of practice is slowly increased with further experience. However, some of these factors, such as preferred activity level and temperament, may have a large genetic component. Furthermore, there may need to be a good fit between such predisposing factors and the task environment (along the lines of Thomas & Chess's, 1984, temperament–environment fit model) for expert-level performance to develop.

For a long time the study of exceptional and expert performance has been considered outside the scope of general psychology because such performance has been attributed to innate characteristics possessed by outstanding individuals. A better explanation is that expert performance reflects extreme adaptations, accomplished through life-long effort, to demands in restricted, well-defined domains. By capturing and examining the performance of experts in a given domain, researchers have identified adaptive changes with physiological components as well as the acquisition of domain-specific skills that circumvent basic limits on speed and memory. Experts with different teachers and training histories attain their superior performance after many years of continued effort by acquiring skills and making adaptations with the same general structure. These findings imply that in each domain, there is only a limited number of ways in which individuals can make large improvements in performance. When mediating mechanisms of the same type are found in experts in very different domains that have evolved independently from each other, an account of this structure based on shared training methods is highly unlikely.

There is no reason to believe that changes in the structure of human performance and skill are restricted to the traditional domains of expertise. Similar changes should be expected in many everyday activities, such as thinking, comprehension, and problem solving, studied in general psychology. However, people acquire everyday skills under less structured conditions that lack strict and generalizable criteria for evaluation. These conditions also vary among individuals because of their specific living situations. In contrast, stable expert performance is typically restricted to standardized situations in a domain. Hence, the criteria for expert performance offer a shared goal for individuals in a domain that directs and constrains their life-long efforts to attain their maximal performance. Even when scientific investigators' ultimate goal is to describe and understand everyday skills, they are more likely to succeed by studying expert performance than by examining everyday skills because the former is acquired under much more controlled and better understood conditions and achieved at higher levels of proficiency in a specific domain.

We believe that studies of the acquisition and structure of expert performance offer unique evidence on many general theoretical and applied issues in psychology. Extended deliberate practice gives near maximal values on the possible effects of environmental variables (in interaction with developmental variables) relevant to theoretical claims for invariant cognitive capacities and general laws of performance. We will significantly advance our knowledge of the interaction between environment and development by observing the effects of training during the early development of expert performers and the effects of maintaining training for older experts in late adulthood. The study of expert performance complements cross-cultural studies of environmental influences on thinking and cognition. The relation between language and thinking, traditionally restricted to comparisons between different languages (Hunt & Agnoli, 1991), should be particularly suitable for study in the context of expertise, where domain-specific names, concepts, and knowledge are explicated in training manuals and books and subjects with differing levels of mastery of the vocabulary and where "language" of the domain can be easily found.

For applied psychologists the study of expert performers and their master teachers and coaches offers a nearly untapped reservoir of knowledge about optimal training and specific training methods that has been accumulated in many domains for a long time. Across very different domains of expert performance, Ericsson, Krampe, and Tesch-Römer (1993) uncovered evidence for intriguing invariances in the duration and daily scheduling of practice activities. Further efforts to investigate training and development of training methods and to derive principles that generalize across domains should be particularly fruitful. Most important, a better understanding of social and other factors that motivate and sustain future expert performers at an optimal level of deliberate practice should have direct relevance to motivational problems in education, especially in our school system.

In conclusion, an analysis of the acquired characteristics and skills of expert performers as well as their developmental history and training methods will provide us with general insights into the structure and limits of human adaptations.

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