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# The Role of Deliberate Practice in the Acquisition of Expert Performance

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The theoretical framework presented in this article explains expert performance as the end result of individuals' prolonged efforts to improve performance while negotiating motivational and external constraints. In most domains of expertise, individuals begin in their childhood a regimen of effortful activities (deliberate practice) designed to optimize improvement. Individual differences, even among elite performers, are closely related to assessed amounts of deliberate practice. Many characteristics once believed to reflect innate talent are actually the result of intense practice extended for a minimum of 10 years. Analysis of expert performance provides unique evidence on the potential and limits of extreme environmental adaptation and learning.

Our civilization has always recognized exceptional individuals, whose performance in sports, the arts, and science is vastly superior to that of the rest of the population. Speculations on the causes of these individuals' extraordinary abilities and performance are as old as the first records of their achievements. Early accounts commonly attribute these individuals' outstanding performance to divine intervention, such as the influence of the stars or organs in their bodies, or to special gifts (Murray, 1989). As science progressed, these explanations became less acceptable. Contemporary accounts assert that the characteristics responsible for exceptional performance are innate and are genetically transmitted.

The simplicity of these accounts is attractive, but more is needed. A truly scientific account of exceptional performance must completely describe both the development leading to exceptional performance and the genetic and acquired characteristics that mediate it. This account must specify the critical differences between exceptional and ordinary performers. It must also show that any postulated genetic differences can be hereditary and are plausible from an evolutionary perspective. Theoreticians in behavioral genetics (Plomin, DeFries, & McClearn, 1990) now argue that this is a very challenging task because observed behavior is the result of interactions between environmental factors and genes during the extended period of development. Therefore, to better understand expert and exceptional performance, we must require that the account specify the different environmental factors that could selectively promote and facilitate the achievement of such performance. In addition, recent research on expert performance and expertise (Chi, Glaser, & Farr, 1988; Ericsson & Smith, 1991a) has shown that important characteristics of experts' superior performance are acquired through experience and that the effect of practice on performance is larger than earlier believed possible. For this reason, an account of exceptional performance must specify the environmental circumstances, such as the duration and structure of activities, and necessary minimal biological attributes that lead to the acquisition of such characteristics and a corresponding level of performance.

An account that explains how a majority of individuals can attain a given level of expert performance might seem inherently unable to explain the exceptional performance of only a small number of individuals. However, if such an empirical account could be empirically supported, then the extreme characteristics of experts could be viewed as having been acquired through learning and adaptation, and studies of expert performance could provide unique insights into the possibilities and limits of change in cognitive capacities and bodily functions. In this article we propose a theoretical framework that explains expert performance in terms of acquired characteristics resulting from extended deliberate practice and that limits the role of innate (inherited) characteristics to general levels of activity and emotionality. We provide empirical support from two new studies and from already published evidence on expert performance in many different domains.

## Brief Historical Background

Sir Francis Galton was the first scientist to investigate the possibility that excellence in diverse fields and domains has a common set of causes. He found that eminent individuals in the British Isles were more likely to have close relatives who were also eminent—although not necessarily in the same domain—than to have distant relatives who were eminent. He concluded that eminence, that is, exceptional performance in a

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field, must be transmitted from parents to their offspring. Galton (1869/1979) argued that eminence was a virtually inevitable consequence of inherited "natural ability," which was the conjunction of three types of elements:

> By natural ability, I mean those qualities of intellect and disposition, which urge and qualify a man to perform acts that lead to reputation. I do not mean capacity without zeal, nor zeal without capacity, nor even a combination of both of them, without an adequate power of doing a great deal of very laborious work. (p. 37)
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> If a man is gifted with vast intellectual ability, eagerness to work, and power of working, I cannot comprehend how such a man should be repressed. (p. 39)

Galton readily acknowledged the importance of physiological exercises for improvement in motor performance and drew a direct analogy to improvement of mental powers through studying and education. In his view, hereditary factors determine the limit of the attainable performance for a given individual:

> So long as he is a novice, he perhaps flatters himself there is hardly an assignable limit to the education of his muscles; but the daily gain is soon discovered to diminish, and at last it vanishes altogether. His maximum performance becomes a rigidly determinate quantity. (Galton, 1869/1979, p. 15)

Even a hundred years later, Galton's conceptualization of eminent performance as reflecting a higher level of ultimate performance determined primarily by innate capacities (talent) is still the modal view among people outside genetics and behavioral genetics. Genetic influences are still incorrectly viewed as deterministic factors that lead to unmodifiable consequences determining the structure of the human body and its nervous system (Plomin, 1991). Galton's recognition of the interaction between environmental and genetic factors is clearly shown in his tri-part definition of natural ability as innate capacity, zeal, and power to do very laborious work. The last two factors are also likely to have a genetic component as we argue later in this article. Nonetheless, the study of eminent performance subsequent to Galton has given far less emphasis to zeal and power to do very laborious work and has focused primarily on genetic influences on structure and capacities. Everyone agrees that the shared characteristics of the human body and its nervous system are due to shared genes. Similarly, the successful identification of genetic factors influencing individual differences in height and other physical characteristics has inspired researchers to search for genetic mechanisms regulating individual differences in mental capacities. Hence the focus of research on talent has been on finding similar basic structural differences in the nervous system that might mediate stable differences in expert performance.

## Natural Abilities and Other Stable Characteristics

If genetic factors rigidly determine maximal performance, it is reasonable to assume that these genetic factors cannot be influenced by practice and training and hence remain stable across time. Early genetic research showed that many physical and anatomical attributes, such as height and facial features, are largely determined by hereditary factors. In many sports the height of elite athletes is systematically different from that of the normal population. Greater height is an obvious advantage in basketball, high jumping, and most sports emphasizing strength. Shorter height is an advantage in gymnastics. Differences in height were found to discriminate well among male athletes of different events at the Olympic games in Montreal, although the average height of all athletes did not differ from that of a control group of students (Carter, Ross, Aubrey, Hebbelinck, & Borms, 1982). Elite athletes also differ in the size of their muscles, such as arm girth, and in the amount of fat measured by skin folds. Endurance athletes have a much higher aerobic ability, larger hearts, more capillaries supplying blood to muscles, and a higher percentage of slow-twitch muscle fibers (Ericsson, 1990). Until quite recently researchers commonly believed that percentages of muscle fiber types and aerobic power "are more than 90% determined by heredity for males and females" (Brown & Mahoney, 1984, p. 609). Some researchers have therefore reasoned by analogy that basic general characteristics of the nervous system, such as speed of neural transmission and memory capacities, have a genetic origin and cannot be changed through training and practice.

Early efforts to find stable individual differences in neural transmission speed with simple response time (RT) and other basic capacities were remarkably unsuccessful (Guilford, 1967). Binet (Varon, 1935) started out using tests of basic perceptual and cognitive capacities to measure IQ, but found large practice effects, which were later documented by Gibson (1969). Binet eventually developed successful IQ tests derived from tests measuring comprehension, knowledge, and acquired skills. Because IQ reflects both environmental and genetic factors, recent research has challenged its interpretation and relation to successful performance outside the school environment (Ceci, 1990; Howe, 1990). The relation of IQ to exceptional performance is rather weak in many domains, including music (Shuter-Dyson, 1982) and chess (Doll & Mayr, 1987). For scientists, engineers, and medical doctors that complete the required education and training, the correlations between ability measures and occupational success are only around 0.2, accounting for only 4% of the variance (Baird, 1985). More generally, prediction of occupational success from psychometric tests has not been very successful (Tyler, 1965). In a review of more than one hundred studies, Ghiselli (1966) found the average correlation between success-on-the-job measuring and aptitude-test scores to be 0.19. Aptitude tests can predict performance immediately after training with an average correlation of 0.3, but the correlation between performance after training and final performance on the job is only about 0.2 (Ghiselli, 1966). Reviews of subsequent research (Baird, 1985; Linn, 1982) have reported very similar correlation estimates. When corrections were made for the restriction of range of these samples and for unreliability of performance measures, Hunter and Hunter (1984) found that only cognitive ability emerged as a useful predictor with an average adjusted correlation of 0.5 with early job performance. However, a recent review (Hulin, Henry, & Noon, 1990) has shown that with increased experience on the job the predictive validities of ability tests for performance decrease over time by an average correlation of 0.6 (after corrections for restrictions of range and unreliability of performance measures). This implies that ability tests can predict early performance on a job, whereas final performance is poorly predicted. Even for a well-defined skill, such as typing, with relatively unselect groups of subjects, numerous efforts to predict the attained performance from pretraining aptitude tests have failed (Clem, 1955). Striking differences between eminent individuals (experts) and less accomplished individuals are found, not surprisingly, when their current performance in the field of expertise is compared (Ericsson & Smith, 1991b); experts are faster and more accurate than less accomplished individuals. However, experts' superior speed in their domain of expertise does not transfer to general tests of speed, such as simple RT, or to general tests of perception (Starkes, 1987; Starkes & Deakin, 1984). Similarly, experts' memory for representative stimuli from their domain is vastly superior to that of lesser experts, especially for briefly presented stimuli. But when tested on randomly rearranged versions of representative stimuli from their domain presented with short exposures or on materials outside their domain, the memory of experts is no better than that of ordinary individuals.

The domain-specific nature of experts' superior performance implies that acquired knowledge and skill are important to attainment of expert performance. We can cite only two abilities that investigators have argued directly reflect genetic factors. Some successful musicians can recognize a musical note in isolation by its pitch (perfect pitch). Championship-level typists can tap their fingers faster than normal (Book, 1924; Keele & Hawkins, 1982). Although we claim that genetic factors have little direct impact on ultimate adult performance, a plausible role for hereditary factors is in the developmental history of an individual. Superior performance by very young children without prior instruction may suggest exceptional promise, leading to the early onset of training. This in turn leads to a consistently greater accumulation of practice (and hence, by our framework, performance) relative to later-starting individuals. In the General Discussion section we consider this potential indirect role of innate talent at length, concluding instead that unique environmental conditions and parental support, rather than talent, may be the important factors determining the initial onset of training and ultimate performance.

In summary, the search for stable heritable characteristics that could predict or at least account for the superior performance of eminent individuals has been surprisingly unsuccessful. The best evidence for the effect of heritable characteristics comes from several types of sports, for which anatomical characteristics such as height systematically differ for elite performers compared with the average population. The belief that the striking differences between expert performers and less accomplished performers reflect innate abilities (talent) is so strong that the failure to identify the specific talents necessary for expert performance in a given domain is viewed, at most, as a temporary problem until the relevant talents are discovered. The conviction in the importance of talent appears to be based on the insufficiency of alternative hypotheses to explain the exceptional nature of expert performance. If one agrees with Galton's plausible claim that the improvements resulting from experience and practice occur during limited time until a stable maximal level of performance is attained, the factors limiting further improvement must be fixed and unmodifiable by environmental factors. The most likely source of such unmodifiable factors is genetic. However, this argument is only valid if the associated assumptions can be verified empirically.

In the following two sections we examine the assumption that with extensive experience in a domain a maximal level of performance is automatically reached and that the period of improvement has a relatively limited duration, especially for talented individuals.

### *Does Practice and Experience Inevitably Lead to Maximal Performance?*

The view that merely engaging in a sufficient amount of practice, regardless of the structure of that practice, leads to maximal performance has a long and contested history. In their classic studies of Morse Code operators, Bryan and Harter (1897, 1899) identified plateaus in skill acquisition, when for long periods subjects seemed unable to attain further improvements. However, with extended efforts, subjects could restructure their skill to overcome plateaus. Keller (1958) later showed that these plateaus in Morse Code reception were not an inevitable characteristic of skill acquisition, but could be avoided by different and better training methods. Nonetheless, Bryan and Harter (1897, 1899) had clearly shown that with mere repetition, improvement of performance was often arrested at less than maximal levels, and further improvement required effortful reorganization of the skill. Even very experienced Morse Code operators could be encouraged to dramatically increase their performance through deliberate efforts when further improvements were required for promotions and external rewards (Bryan & Harter, 1897).

More generally, Thorndike (1921) observed that adults perform at a level far from their maximal level even for tasks they frequently carry out. For instance, adults tend to write more slowly and illegibly than they are capable of doing. Likewise, adults (including clerks with many years of frequent daily experience) add numbers far more slowly than they can when they are doing their best. Thorndike (1921, p. 178) accounts for these curious observations with the following comment: "It is that we have too many other improvements to make, or do not know how to direct our practice, or do not really care enough about improving, or some mixture of these three conditions." In support of this claim, he reported several laboratory studies and a study of experienced typesetters by Aschaffenburg (1896), which showed gradual improvements of up to 25% as a result of continued testing. Kitson (as described in Book & Norvell, 1922) found that during a 20-week period, typesetters with around 10 years of experience gradually improved their job performance between 58% and 97% in response to a bonus system rewarding higher performance. Dvorak, Merrick, Dealey, and Ford (1936) reported substantial improvements in experienced typists as a result of deliberate efforts.

Because performance in sports, especially, has been measured under standardized conditions, and the best performance has been recorded at world, national, district, and club levels, it can be clearly demonstrated that performance has continually improved during this entire century. Schulz and Curnow (1988) found that throughout the history of the Olympic Games, the best performance for all events has improved—in some cases by more than 50%. It is generally recognized that some of these improvements are due to equipment and rule changes, but improvements are great even in events with minor changes, such as running and swimming. Increases in duration, intensity, and structure of training appear to play a major role. The fastest time for the marathon in the 1896 Olympic Games was just a minute faster than the required entry time in large marathon races such as the Boston Marathon (Ericsson, 1990). The fastest rate of typing in the World Championship in typing increased from 82 words per minute in 1904 to 147 words per minute in 1923—an improvement of 80% (Book, 1925a). Even in music there is evidence for improved skill. 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 this concerto part of the standard repertory. The improvement in music training is so great that according to Roth (1982) the violin virtuoso Paganini "would indeed cut a sorry figure if placed upon the modern concert stage" (p. 23).

In virtually all domains, insights and knowledge are steadily accumulating and the criteria for eminent as well as expert performance undergo continuous change. To reach the status of an expert in a domain it is sufficient to master the existing knowledge and techniques. To make an eminent achievement one must first achieve the level of an expert and then in addition surpass the achievements of already recognized eminent people and make innovative contributions to the domain. In sum, the belief that a sufficient amount of experience or practice leads to maximal performance appears incorrect.

### *Preparation Time Required for Attainment of Exceptional Performance*

There is a relatively widespread conception that if individuals are innately talented, they can easily and rapidly achieve an exceptional level of performance once they have acquired basic skills and knowledge. Biographical material disproves this notion. In their classic study of expertise in chess, Simon and Chase (1973) observed that nobody had attained the level of an international chess master (grandmaster) "with less than about a decade's intense preparation with the game" (p. 402). Simon and Chase estimated that the amount of knowledge a chess master has acquired is comparable in size to the vocabulary of an adult native speaker of English. It takes normal individuals approximately a decade to acquire this vocabulary. Similarly, Krogius (1976) showed that the time between chess players' first learning the rules of chess and attaining international chess master status was 11.7 years for those who learned chess rules late (after age 11) and even longer for those who started early, that is, 16.5 years. If only well-established domains with a large number of active individuals are considered we know of only a small number of exceptions to the general rule that individuals require 10 or more years of preparation to attain international-level performance. The exceptions in this century, such as the famous chess players, Bobby Fischer and Salo Flohr, were only a year shy of the prerequisite 10 years of preparation (Krogius, 1976).

J. R. Hayes (1981) confirmed that 10 years' experience is necessary in another domain, musical composition. He calculated an average of about 20 years from the time individuals started to study music until they first composed an outstanding piece of music. According to Hayes, this long preparation period is necessary because "the composer must know the timbres of the various instruments and the sound, look, and feel of chords and key structures" (p. 209). Most important, Hayes showed that the 10 or more years of necessary experience was not an artifact. Because musicians start very early, insufficient development may restrict their ability to compose before attaining adulthood. Those who started at ages younger than 6 years did not write their first eminent composition until 16.5 years later; those who started between ages 6 and 9 and older than 10 years of age required 22 and 21.5 years, respectively, to compose their first distinguished work. Simon and Chase's (1973) "10-year rule" is supported by data from a wide range of domains: music (Sosniak, 1985), mathematics (Gustin, 1985), tennis (Monsaas, 1985), swimming (Kalinowski, 1985), and long-distance running (Wallingford, 1975).

Long periods of necessary preparation can also be inferred for writers and scientists, although the starting point of their careers is more difficult to determine. Scientists have reported that they made a career decision during their middle or late teens, whereas they most often published a truly major contribution one or two decades later (Lehmann, 1953). Raskin (1936), who analyzed the 120 most important scientists and 123 most famous poets and authors in the 19th century, found that the average age at which scientists published their first work was 25.2; poets and authors published their first work at the average age of 24.2. Moreover, many years of preparation preceded first publication. The average ages at which the same individuals produced their greatest work were 35.4 for scientists and 34.3 for poets and authors. That is, on average, more than 10 years elapsed between these scientists' and authors' first work and their best work. In many other domains, the highest level of expert performance is displayed by individuals with more than 10 years of experience: evaluation of livestock (Phelps & Shanteau, 1978), diagnosis of X-rays (Lesgold, 1984), and medical diagnosis (Patel & Groen, 1991). This evidence is consistent with Galton's (1869/1979) claim that motivation and perseverance are necessary for attainment of eminent performance.

Our review has also shown that the maximal level of performance for individuals in a given domain is not attained automatically as function of extended experience, but the level of performance can be increased even by highly experienced individuals as a result of deliberate efforts to improve. Hence, stable levels of performance after extended experience are not rigidly limited by unmodifiable, possibly innate, factors, but can be further increased by deliberate efforts. We have shown that expert performance is acquired slowly over a very long time as a result of practice and that the highest levels of performance and achievement appear to require at least around 10 years of intense prior preparation. However the relation between acquired performance and the amount of practice and experience was found to be weak to moderate in the earlier review. We propose that the reason for this comparatively weak relation is that the current definition of practice is vague. If we are to improve our understanding of the environmental influences mediated through participation in different activities, we must analyze the types of activities commonly called practice.

## The Role of Deliberate Practice

In this section we characterize deliberate practice—those activities that have been found most effective in improving performance. We then contrast deliberate practice with activities that tend to occur more frequently in various domains. Finally, we propose a theoretical framework that explains how expert performance can be attained through deliberate practice.

### *Characteristics of Deliberate Practice*

The basic skills required for living in a culture are acquired by virtually all children as part of normal social interaction with a minimum of instruction. In contrast, the skills of reading, writing, and arithmetic have been explicitly taught in schools by teachers with assigned activities of, for example, copying of presented material, for more than 3 thousand years (Eby & Arrowood, 1940). We want to distinguish activities invented with the primary purpose of attaining and improving skills from other types of everyday activities, in which learning may be an indirect result. On the basis of several thousand years of education, along with more recent laboratory research on learning and skill acquisition, a number of conditions for optimal learning and improvement of performance have been uncovered (Bower & Hilgard, 1981; Gagné, 1970). The most cited condition concerns the subjects' motivation to attend to the task and exert effort to improve their performance. In addition, the design of the task should take into account the preexisting knowledge of the learners so that the task can be correctly understood after a brief period of instruction. The subjects should receive immediate informative feedback and knowledge of results of their performance. The subjects should repeatedly perform the same or similar tasks.

When these conditions are met, practice improves accuracy and speed of performance on cognitive, perceptual, and motor tasks (Fitts & Posner, 1967; Gibson, 1969; Welford, 1968). Tasks used in laboratory studies of learning that are designed to focus on the accuracy of performance clearly display the relevant cues and the relevant feedback. Studies focusing on speed of performance tend to use easy tasks, where highly accurate performance is rapidly attained, and subjects are instructed to increase the speed of performance while maintaining the high level of accuracy. Under these conditions subjects' performance improves monotonically as a function of the amount of practice according to the power law (J. R. Anderson, 1982; Newell & Rosenbloom, 1981). In the absence of adequate feedback, efficient learning is impossible and improvement only minimal even for highly motivated subjects. Hence mere repetition of an activity will not automatically lead to improvement in, especially, accuracy of performance (Trowbridge & Cason, 1932).

When laboratory training is extended over longer time periods, studies show that providing a motivated individual with repeated exposure to a task does not ensure that the highest levels of performance will be attained. Assessment of subjects' methods shows that inadequate strategies often account for the lack of improvement. For example, in their study on the effects of practice on digit span, Chase and Ericsson (1981) found a subject who kept rehearsing the digits whose performance showed only minimal improvement. In contrast, all subjects who used preexisting knowledge to encode the presented digits improved dramatically. One subject who discovered how to use efficient retrieval structures increased his performance by over 1000%. Recent reviews of exceptional memory performance (Ericsson, 1985, 1988) show that a small set of general methods underlie such performance. After being instructed to use adequate strategies, subjects have attained exceptional levels of memory performance after extended practice (Baltes & Kliegl, 1992; Kliegl, Smith, & Baltes, 1989; 1990).

Early investigators of extended skill acquisition in typing (Book, 1925b; Dvorak et al., 1936) and other perceptual-motor skills (Kao, 1937) carefully monitored improvements in performance and collected verbal reports on subjects' cognitive processes. These studies revealed subjects' active search for methods to improve performance and found that changes in methods could often be related to clear improvements. Other studies (Chase & Ericsson, 1981; VanLehn, 1991) have also shown that subjects actively try out different methods and refine methods in response to errors and violated expectations. The critical importance of a correct method or strategy has also been demonstrated in date calculation (Addis & O. A. Parsons, as described in Ericsson & Faivre, 1988), mental multiplication (Chase & Ericsson, 1982; Staszewski, 1988), absolute judgment of colors and pitches (for a review see Ericsson & Faivre, 1988), motor skills (Norman, 1976), and methods of work (R. H. Seashore, 1939).

The inability of some subjects to discover new methods has sometimes been interpreted as evidence for basic cognitive or perceptual deficits, especially for performance of seemingly simple tasks. However, specific instruction or the generation of new methods can eventually enhance improvement temporarily arrested at suboptimal levels. As the complexity of a desired skill increases beyond the simple structure of most laboratory tasks, the logically possible methods to correctly and incorrectly perform the task by subjects increase as well. To assure effective learning, subjects ideally should be given explicit instructions about the best method and be supervised by a teacher to allow individualized diagnosis of errors, informative feedback, and remedial part training. The instructor has to organize the sequence of appropriate training tasks and monitor improvement to decide when transitions to more complex and challenging tasks are appropriate. Although it is possible to generate curricula and use group instruction, it is generally recognized that individualized supervision by a teacher is superior. Research in education reviewed by Bloom (1984) shows that when students are randomly assigned to instruction by a tutor or to conventional teaching, tutoring yields better performance by two standard deviations—the average tutored student performed at the 98th percentile of students taught with the conventional method. Interestingly, the correlation between prior achievement and achievement on the current course was reduced and corresponded to only about 6% of the variance for the tutored subjects as compared with around 36% for students taught with conventional methods. More generally, improved instruction appears to benefit subjects with lower cognitive ability more than high-ability subjects thus lowering the earlier discussed correlation between cognitive ability and early performance seen under standard training conditions.

Most contemporary domains of expertise have evolved over centuries from activities originally centered around playful interaction with learning through active participation. As the levels of performance in the domain increased in skill and complexity, methods to explicitly instruct and train individuals were developed. In all major domains there has been a steady accumulation of knowledge about the best methods to attain a high level of performance and the associated practice activities leading to this performance. Full-time teachers and coaches are available for hire and supervise the personalized training of individuals at different levels of performance starting with beginners. Throughout development toward expert performance, the teachers and coaches instruct the individuals to engage in practice activities that maximize improvement. Given the cost of individualized instruction, the teacher designs practice activities that the individual can engage in between meetings with the teacher. We call these practice activities *deliberate practice* and distinguish them from other activities, such as playful interaction, paid work, and observation of others, that individuals can pursue in the domain.

### *Comparison of Deliberate Practice to Other Types of Domain-Related Activities*

Consider three general types of activities, namely, work, play, and deliberate practice. Work includes public performance, competitions, services rendered for pay, and other activities directly motivated by external rewards. Play includes activities that have no explicit goal and that are inherently enjoyable. Deliberate practice includes activities that have been specially designed to improve the current level of performance. The goals, costs, and rewards of these three types of activities differ, as does the frequency with which individuals pursue them.

Public performance and competitions are constrained in time; these activities as well as rendering a service for pay require that individuals give their best performance at a given time. The distinction between work and training (deliberate practice) is generally recognized. Individuals given a new job are often given some period of apprenticeship or supervised activity during which they are supposed to acquire an acceptable level of reliable performance. Thereafter individuals are expected to give their best performance in work activities and hence individuals rely on previously well-entrenched methods rather than exploring alternative methods with unknown reliability. The costs of mistakes or failures to meet deadlines are generally great, which discourages learning and acquisition of new and possibly better methods during the time of work. For example, highly experienced users of computer software applications are found to use a small set of commands, thus avoiding the learning of a larger set of more efficient commands (see Ashworth, 1992, for a review). Although work activities offer some opportunities for learning, they are far from optimal. In contrast, deliberate practice would allow for repeated experiences in which the individual can attend to the critical aspects of the situation and incrementally improve her or his performance in response to knowledge of results, feedback, or both from a teacher. Let us briefly illustrate the differences between work and deliberate practice. During a 3-hr baseball game, a batter may get only 5–15 pitches (perhaps one or two relevant to a particular weakness), whereas during optimal practice of the same duration, a batter working with a dedicated pitcher has several hundred batting opportunities, where this weakness can be systematically explored (T. Williams, 1988).

The external rewards of work activities include social recognition and, most important, money in the form of prizes and pay, which enables performers to sustain a living. In play and deliberate practice, external rewards are almost completely lacking. The goal of play is the activity itself, and the inherent enjoyment of it is evident in children who spontaneously play for extended periods of time. Recent analyses of inherent enjoyment in adults reveal an enjoyable state of "flow," in which individuals are completely immersed in an activity (Csikszentmihalyi, 1990). Similarly, analyses of reported "peak experiences" in sports reveal an enjoyable state of effortless mastery and execution of an activity (Ravizza, 1984). This state of diffused attention is almost antithetical to focused attention required by deliberate practice to maximize feedback and information about corrective action.

In contrast to play, deliberate practice is a highly structured activity, the explicit goal of which is to improve performance. Specific tasks are invented to overcome weaknesses, and performance is carefully monitored to provide cues for ways to improve it further. We claim that deliberate practice requires effort and is not inherently enjoyable. Individuals are motivated to practice because practice improves performance. In addition, engaging in deliberate practice generates no immediate monetary rewards and generates costs associated with access to teachers and training environments. Thus, an understanding of the long-term consequences of deliberate practice is important.

## Theoretical Framework for the Acquisition of Expert Performance

We now outline a framework within which we can explain how differential levels of performance are attained as a function of deliberate practice. Our basic assumption—the "monotonic benefits assumption"—is that the amount of time an individual is engaged in deliberate practice activities is monotonically related to that individual's acquired performance. This assumption can be tested empirically. It follows from this assumption that individuals should attempt to maximize the amount of time they spend on deliberate practice to reach expert performance.

However, maximization of deliberate practice is neither short-lived nor simple. It extends over a period of at least 10 years and involves optimization within several constraints. First, deliberate practice requires available time and energy for the individual as well as access to teachers, training material, and training facilities (the resource constraint). If the individual is a child or adolescent, someone in the individual's environment must be willing to pay for training material and the time of professional teachers, as well as for transportation to and from training facilities and competitions.

Second, engagement in deliberate practice is not inherently motivating. Performers consider it instrumental in achieving further improvements in performance (the motivational constraint). The lack of inherent reward or enjoyment in practice as distinct from the enjoyment of the result (improvement) is consistent with the fact that individuals in a domain rarely initiate practice spontaneously.

Finally, deliberate practice is an effortful activity that can be sustained only for a limited time each day during extended periods without leading to exhaustion (effort constraint). To maximize gains from long-term practice, individuals must avoid exhaustion and must limit practice to an amount from which they can completely recover on a daily or weekly basis.

### *Attaining Expert Performance*

Considering the cost of pursuing expert-level performance and the small number of individuals who, out of millions of children exposed to such domains as sports and music, can make a living as professionals, it seems remarkable that individuals get started and are encouraged to continue. From many interviews with international-level performers in several domains, Bloom (1985b) found that these individuals start out as children by engaging in playful activities in the domain. After some period of playful and enjoyable experience they reveal "talent" or promise. At this point parents typically suggest the start of instruction by a teacher and limited amounts of deliberate practice. The parents support their children in acquiring regular habits of practice and teach their children about the instrumental value of deliberate practice by noticing improvements in performance. With increased experience and deliberate practice, individuals' performance in the domain reflects an inseparable combination of practice and innate talent. We rely on Bloom's (1985b) characterization of the period of preparation in three phases, which are illustrated in Figure 1.

The first phase begins with an individual's introduction to activities in the domain and ends with the start of instruction and deliberate practice. The second phase consists of an extended period of preparation and ends with the individual's commitment to pursue activities in the domain on a full-time basis. The third phase consists of full-time commitment to improving performance and ends when the individual either can make a living as a professional performer in the domain or terminates full-time engagement in the activity. During all three phases the individual requires support from external sources, such as parents, teachers, and educational institutions. This framework needs to be extended with a fourth phase to accommodate eminent performance. During this fourth phase the individuals go beyond the knowledge of their teachers to make a unique innovative contribution to their domain.

To be complete, our theoretical framework must show how individuals negotiate the various constraints on deliberate practice during that first decade of preparation necessary for attaining international-level performance. There are several methodological problems involved in demonstrating the relevant processes. During the decade or two leading to adult expert performance, many aspects of training and evaluation change. In the beginning, a child's performance is compared with that of other children of the same age in the local neighborhood. At the start of participation in competitions, the reference group consists of other trained individuals of similar ages from a larger area. Success at these earlier stages may eventually lead to participation in competitions at a national and international level. At increased levels of performance, the practice activities obviously change and so do the criteria of evaluation. In the performance of music, children and adolescents are judged principally on their technical proficiency. Expert adult performers, however, are judged on their interpretation and ability to express emotions through music (Sloboda, 1991). The inability of many child prodigies in music to succeed as adult musicians (Bamberger, 1986; Barlow, 1952) is often attributed to difficulties making this transition—possibly resulting from inappropriate training and instruction during the early and middle phases of music training. To become outstanding musicians at the international level, individuals have to contribute unique interpretations of music (Roth, 1982). Similar considerations may explain why mathematical prodigies can fail as adult mathematicians. The lack of overlap in the performance of precocious children and adult scientists in mathematics is even clearer than in music: Superior ability in mental addition

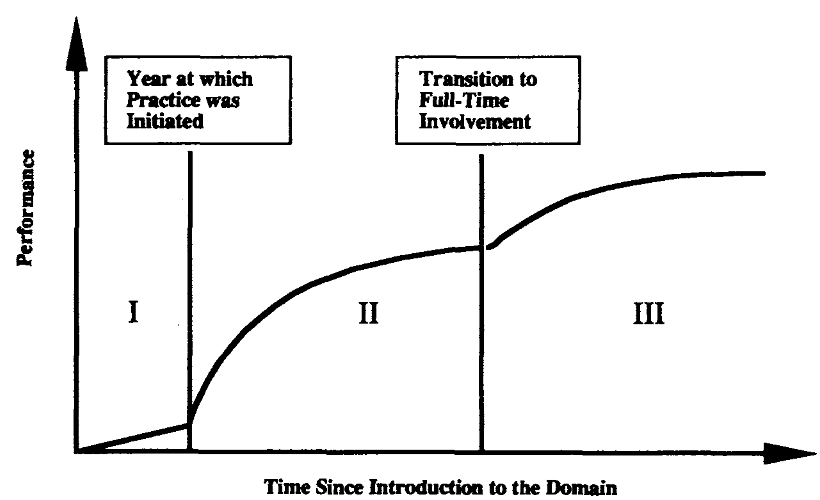


*Figure 1.* Three phases of development toward adult expertise.

and multiplication demonstrate efficiency in the mechanics of mathematics, whereas major adult contributions in mathematics reflect insights into the structure of mathematical problems and domains. The criteria for eminent performance goes beyond expert mastery of available knowledge and skills and requires an important and innovative contribution to the domain. An eminent musician can contribute new techniques and distinct interpretations of existing music, and eminent chess players discover new variants of chess openings and advance the knowledge of chess. In the arts and sciences, eminent achievements involve contributions of new ideas, theories, and methods.

In most domains it is impossible to assess retrospectively the cognitive aspects of the development of precocious exceptional performers. Precocious painters may be an exception (see J. Radford's, 1990, review). Pariser (1987) analyzed drawings completed by Klee, Toulouse-Lautrec, and Picasso until age 20, and concluded that these three "gifted" individuals encountered and mastered problems in graphic development in ways similar to those of the "less-gifted" (p. 53). Their juvenile drawings include "a fair number of awkward, flawed and *unexceptional* drawings" (Pariser, 1987, p. 65), suggesting that instruction and practice strongly affected even these three exceptional artists. The age at which eminent individuals attain their best performance is much later in their 20s and 30s (Lehmann, 1953). In fact any significant achievements in literature, music composition, visual arts, and most other domains before age 16 are exceedingly rare (Barlow, 1952). (Judit Polgar and Bobbie Fischer attained the level of international grandmasters in chess at age 15; we discuss their developmental history later.) The methodology we applied in our studies takes these considerations into account as we demonstrate later. At this point we must further specify the constraints inherent in the attainment of exceptional performance.

### *Resource Constraint*

International-level performers often receive their first exposure to their domain between the ages of 3 and 8. Obviously, their parents are responsible for providing this early access. Parents and guardians, in encouraging the childrens' activity and monitoring performance, make possible the discovery of early signs of "talent" and promise. The parents' interest is also critical in aiding children's transition to deliberate practice and providing facilities for practice, such as musical instruments for musicians, tennis courts for tennis players, and ice arenas for skaters. Bloom (1985a) and his colleagues show that transportation for young individuals to and from practice, meetings with the teachers, and competitions can almost completely occupy parents' free time, and the direct economic costs of sustaining these activities are substantial. The parents' costs for a national-level swimmer is estimated by Chambliss (1988) to exceed 5 thousand dollars per year. In many cases, the family is even willing to move to a location close to the best training facilities offering year-round opportunities for practice. These extraordinary commitments by parents are probably based on the belief that their children are somehow special and particularly likely to succeed. Bloom (1985b) found that there seems to be at least one central person in a promising child's near environment who firmly believes, as the child develops, that the child is special, that is, talented in the domain. This person's belief prevails even though Bloom (1985b) found no evidence that, during the early phases, the individual exhibited any clear evidence of prowess. However, Bloom (1985b) found that only one child per family was considered special. This is perhaps the best empirical evidence that each family's available resources are limited.

### *Effort Constraint*

The central claim of our framework is that the level of performance an individual attains is directly related to the amount of deliberate practice. Hence, individuals seeking to maximize their performance within some time period should maximize the amount of deliberate practice they engage in during that period. When this time period extends over months and years, it is clear that maximization of an effortful activity is not simple and that the traditional research on learning, which is limited to a few sessions, provides little guidance. In this section, we review evidence showing that the duration of effective daily practice that can be sustained for long periods is limited, and that according to teachers and training instructions, it is necessary to maintain full attention during the entire period of deliberate practice. We then discuss some consequences of increasing practice activity beyond its optimal duration and finally consider evidence that through training the daily duration of deliberate practice can be slowly increased over extended periods of time.

The limited duration of practice is the best evidence of the effort it requires. When individuals, especially children, start practicing in a given domain, the amount of practice is an hour or less per day (Bloom, 1985b). Similarly, laboratory studies of extended practice limit practice to about 1 hr for 3–5 days a week (e.g., Chase & Ericsson, 1982; Schneider & Shiffrin, 1977; Seibel, 1963). A number of training studies in real life have compared the efficiency of practice durations ranging from 1–8 hr per day. These studies show essentially no benefit from durations exceeding 4 hr per day and reduced benefits from practice exceeding 2 hr (Welford, 1968; Woodworth & Schlosberg, 1954). Many studies of the acquisition of typing skill (Baddeley & Longman, 1978; Dvorak et al., 1936) and other perceptual–motor skills (Henshaw & Holman, 1930) indicate that the effective duration of deliberate practice may be closer to 1 hr per day. Pirolli and J. R. Anderson (1985) found no increased learning from doubling the number of training trials per session in their extended training study. The findings of these studies can be generalized to situations in which training is extended over long periods of time such as weeks, months, and years.

The goal of deliberate practice is improved performance, and detailed analyses of the musicians' activities during practice sessions in music (Gruson, 1988; Miklaszewski, 1989) reveal careful monitoring and problem solving by the musicians to attain the desired improvements. C. E. Seashore (1938/1967), the pioneering researcher in music psychology, claimed, "Many a student becomes disgusted with music because he cannot learn by dull drudgery. The command to rest is fully as important as to work in effective learning" (pp. 154–155). Both Auer (1921), the famous violin teacher, and C. E. Seashore (1938/1967) recommended that practice periods be limited to less than 1 hr with ample rest in between. A necessary precondition for practice, according to Auer (1921), is that the individual be fully attentive to his playing so that he or she will notice areas of potential improvement and avoid errors. Auer (1921) believes that practice without such concentration is even detrimental to improvement of performance. On the basis of an extended study of Olympic swimmers, Chambliss (1988, 1989) argued that the secret of attaining excellence is to always maintain close attention to every detail of performance "each one done correctly, time and again, until excellence in every detail becomes a firmly ingrained habit" (1989, p. 85).

Deliberate practice aimed at improving strength and endurance in sports clearly shows the importance of near maximal effort during practice and the resulting fatigue. Physical activity and exercise produce no benefit unless they are sufficiently intense. Untrained adults must attain a minimum heart rate of around 140 beats per minute or 70% of their maximal heart rate for an extended time at least three times a week to see improvements (Lamb, 1984). However, elite athletes train at much higher intensities to improve their performance. Athletes train to maximize their performance in a specific event. In endurance events, such as marathon running, most of the training consists of running at the highest speed an athlete can maintain for extended periods. Improvements resulting from training appear to be more a function of intensity (as close to maximum as possible) than of the total distance covered (Maughan, 1990). In sprint events, where runners expend maximal effort for a short time, strength training is essential (P. F. Radford, 1990). Near maximal efforts with a 3-s duration produce the most efficient results for strength training (Klausen, 1990). Obviously such near-maximal training can be sustained only for limited periods even if these periods are interspersed with periods of rest. Other objective indicators of the intensity of athletic training include measurements of metabolic rate during the activity (MacLaren, 1990). Athletes need to consume many more calories than do normal adults simply to sustain their regular training program (Maughan, 1990). Costill et al. (1988) found that some swimmers experienced chronic muscular fatigue because their intake of calories was insufficient to accommodate a recent increase in training activity. The exhausting effects of regular training are also evidenced by the standard practice of reducing the training level several days before a competition (Maughan, 1990; P. F. Radford, 1990).

Under the assumption that practice draws on limited physical and mental resources, one would expect that the level of practice an individual can sustain for long periods of time is limited by the individual's ability to recover and thereby maintain a steady state from day to day. After the individual has slowly adapted to a constant level of practice, increases ought to be possible. In contrast, if an individual cannot recover each day from a given level of practice, sustaining that level will lead to exhaustion and mental fatigue. The risk of physical injury and chronic maladaptation will increase "runner's knee," shin splints, and Achilles tendonitis for athletes (Subotnick, 1977) and sores, tendonitis, and muscle spasms for musicians (Caldron et al., 1986). Inability to recover from the stress of training, which is viewed as necessary for improvement in sports, can lead to "staleness," "overtraining," and eventually "burnout." These states are characterized not only by physical fatigue and soreness but also by motivational problems such as lack of enthusiasm and even unwillingness to continue with a sport (Silva, 1990). The only known effective treatment for these conditions "consists of rest, and in some cases, complete abstention from training and sporting activities may be necessary" (Hackney, Pearman, & Novack, 1990, p. 30).

Early in this century, considerable research was directed toward the subjective experience of mental fatigue and its consequences for performance. On the one hand, efforts to demonstrate decline in performance, even after consecutive days of mental multiplication for 12 hr per day, have been remarkably unsuccessful (Arai, 1912; Huxtable, White, & McCartor, 1946). On the other hand, the subjective feelings of discomfort and aversion often become so strong that continuing these experiments beyond 4 days would seem very difficult, if not impossible. The best data on sustained intellectual activity comes from financially independent authors. While completing a novel famous authors tend to write only for 4 hr during the morning, leaving the rest of the day for rest and recuperation (Cowley, 1959; Plimpton, 1977). Hence successful authors, who can control their work habits and are motivated to optimize their productivity, limit their most important intellectual activity to a fixed daily amount when working on projects requiring long periods of time to complete.

When individuals start with deliberate practice in a domain, the initial duration of weekly practice is limited (Bloom, 1985b). Given that most future international-level performers start at early ages, these brief durations are consistent with the short duration (10–20 min per session) of long-term training programs with children (see Howe, 1990, for a review). Consistent with the idea of slow adaptation to the demands of extended practice, individuals beginning to practice are encouraged to adopt a regular weekly schedule with practice periods of relatively fixed duration (Bloom, 1985b). After extended time with an acceptable practice level, individuals adapt their bodies and lives and can slowly and gradually increase the level of practice. Too rapid increases in the intensity of practice lead to "overuse and overtraining," which occur frequently in sports (Hackney et al., 1990; Silva, 1990) and even in music (Fry, 1986; Newmark & Lederman, 1987). Bailey and Martin (1988) report many instances of successful 9- to 11-year-old children increasing their training to very high levels, only to experience motivational burnout and quit the domain altogether.

In summary, disregard of the effort constraint on deliberate practice leads to injury and even failure. In the short term, optimal deliberate practice maintains equilibrium between effort and recovery. In the long term, it negotiates the effort constraint by slow, regular increases in amounts of practice that allow for adaptation to increased demands.

### *Motivational Constraint*

A premise of our theoretical framework is that deliberate practice is not inherently enjoyable and that individuals are motivated to engage in it by its instrumental value in improving performance. Hence, interested individuals need to be engaging in the activity and motivated to improve performance before they begin deliberate practice. Bloom (1985b) found evidence supporting this implication. His interviews with international-level performers showed that parents typically initiated deliberate practice after allowing their children several months of playful engagement in the domain and after noticing that their children expressed interest and showed signs of promise. The social reactions of parents and other individuals in the immediate environment must be very important in establishing this original motivation.

At the start of deliberate practice, parents help their child keep a regular daily practice schedule and point out the instrumental value of practice for improved performance (Bloom, 1985b). With increased experience and the aid of teachers and coaches, the developing individual is able to internalize methods for assessing improvement and can thus concurrently monitor the effects of practice. As individuals get more involved in the activities of a domain, competitions and public performances provide short-term goals for specific improvements. At this point the motivation to practice becomes so closely connected to the goal of becoming an expert performer and so integrated with the individual's daily life that motivation to practice, per se, cannot be easily assessed.

Certain naturally occurring events and changes illuminate the relation between practice and performance. Activities in many domains, especially sports, are seasonal because most scheduled competitions occur during a single season of the year. If individuals enjoyed deliberate practice, they ought to practice at a uniformly high level all year. Instead, athletes train much harder during the preseason period and during the season itself; during the off season they often reduce the level of training dramatically (Reilly, 1990a; Reilly & Secher, 1990). Many individuals who have practiced for a long period of time give up their aspirations to compete and excel in an activity. Without the goal of improving performance, the motivation to engage in practice vanishes. Kaminski, Mayer, and Ruoff (1984) found that many elite adolescents who decided to stop competing remained active in the domain but virtually stopped engaging in practice.

Some individuals have had to terminate their professional careers for reasons unrelated to their ability to perform. In a longitudinal study of visual artists, Getzels and Csikszentmihalyi (1976) found that most artists were drawn to painting because it allowed social isolation. However, aspiring painters have to promote social relations with art dealers, art critics, and buyers to gain notoriety, increase the demand for their art, and generate sufficient sales for full-time artistic activity. Failure to do so forced many of the best artists to take another job unrelated to painting. Once these artists could no longer commit sufficient time and energy to maintain and improve their performance they stopped painting completely because they could not accept performing at a lower level. This finding shows that the activity of painting as such is not inherently motivating but rather the act of producing art that satisfies the artists' subjective criteria for quality.

### *Implications for Empirical Studies*

Applied to an individual, our theoretical framework made three types of predictions: (a) predictions about the developmental history; (b) predictions about current levels and habits of practice; and (c) predictions about experts' evaluations regarding the nature and role of deliberate practice activities that are relevant throughout development.

Our framework made two important predictions about an individual's development history. First, the past amount of deliberate practice is directly related to the individual's current performance. More specifically, expert performance is not reached with less than 10 years of deliberate practice. Second, deliberate practice starts at low levels and increases slowly over time. These predictions can be best tested in domains of expertise that are relatively independent of the traditional school system and where deliberate practice can be easily identified and measured. It is important that the domain has qualified teachers who guide individuals in learning basic skills correctly and direct them toward optimal practice activities. Music is one such domain, and in the current studies we chose to study individuals who perform at very high levels on a particular instrument. To study individuals who had completed the 10-year period of preparation and had made a commitment to music as a profession, we contacted the Music Academy in West Berlin. This academy has an international reputation for its training program for violinists. Violinists in this program were asked to provide retrospective reports on their levels of deliberate practice over the years before they entered the academy so that we might test our predictions.

Next, our framework made several predictions regarding the current level and related habits in elite performers. First, the highest improvement of performance, and indirectly the highest attained performance, is associated with the largest weekly amounts of deliberate practice. We predicted that elite performers practice at a constant level from day to day to maximize improvement over extended periods of time. Furthermore, the daily periods of deliberate practice should be of limited duration with rest periods in between. In domains with weekly competitions, stability and equilibrium should occur over longer time periods such as a week. The extremely effortful nature of competition, normally on the weekend, would lead to a reduced load and duration after and just before the competitions.

To obtain information about music performers' current practice patterns, we asked them to keep diaries. By collecting detailed diaries by these individuals, we could assess the duration and regularity of different types of activities, in particular those activities judged to constitute deliberate practice. Drawing on earlier research on time budgeting (Juster & Stafford, 1985; Szalai, 1972), we had individuals record at the end of the day all extended activities with their start and end times. By recalling already completed activities, individuals who maintain this diary report should minimize any biasing influence on the frequency and duration of any activity during the day. Furthermore, the instruction to recall the complete sequence of extended activities during the entire day avoids the bias of focusing on a single activity. This type of diary report is consistent with Ericsson and Simon's (1984) criteria for valid and unbiased verbal reports of cognitive processes. This technique is preferable to an alternative in which subjects are instructed to keep a selective diary for occurrences of specific problem behaviors, such as drinking and smoking; the keeping of such a diary appears to reduce the frequency of these behaviors and thus yields biased estimates (Hodgson & Miller, 1982).

Large-scale studies have evaluated the accuracy and convergent validity of diary reports by comparing subjects' diary estimates with estimates derived from random time sampling (Robinson, 1985). The diaries were found to underreport activities of very short duration, such as brief social interactions and phone calls, a result that is to be expected with diaries focusing on extended activities. More important for our purposes, the diary estimates for extended activities were found to be quite consistent with the results derived from more labor-intensive methods.

Most of the research using diaries with reported temporal sequences of activities has been conducted primarily in sociological and economic studies to estimate and project the use of time in representative national populations (Juster & Stafford, 1985; Szalai, 1972). The goal of this research has been to derive general categories of activities that allow investigators to reliably classify any one of the reported activities into one of a limited number of categories. At the highest level, the activities can be grouped into categories, such as sleep, work, and leisure. In studying the daily lives of expert performers, we can draw on this previously developed classification for general activities, but we must supplement it with an analysis of the activities relevant to the particular domain of expertise under investigation.

As to the third point, our framework made predictions about the qualities of various domain-related activities, such as deliberate practice. We predicted that deliberate practice would be rated very high on relevance for performance, high on effort, and comparatively low on inherent enjoyment. We could evaluate ratings by expert individuals to determine the extent to which deliberate practice is perceived to have these attributes.

The central prediction from our framework was that the adult elite performance, even among individuals with more than 10 years of practice, is related to the amount of deliberate practice. This prediction contradicts Galton's (1869/1979) modal view outlined earlier that eminent performance reflects primarily innate talent after sufficient practice and that, by implication, practice and elite performance are not related. However, often talent is contrasted with practice, where the best individuals are assumed to practice less than individuals with inferior performance. Finally, plausible alternative hypotheses also suggest that the most talented individuals would practice more. These hypotheses imply a high correlation between innate talent and practice. Because our studies were not designed to address the last possibility, we do not consider it except in the General Discussion section.

Study 1 compared the current and past levels of practice in three groups, elite violinists judged to have promise for careers as international soloists and two groups of less accomplished expert violinists. Study 2 replicated the results of the first by comparing expert and amateur pianists. In addition, it related estimates of the amount of prior practice to current performance on a wide range of musical and nonmusical tasks for all pianists.

## Study 1

We assessed current and past levels of deliberate practice in three groups of elite, adult violinists whose current performance differed. First we identified the activities constituting deliberate practice. We then determined the duration and organization of deliberate practice and contrasted them for the three groups.

### *Method*

#### *Subjects*

The music professors at the Music Academy of West Berlin (Hochschule der Kuenste) nominated violin students who had the potential for careers as international soloists. Out of 14 students nominated, 3 were not fluent in German and 1 was pregnant. The remaining 10 students agreed to participate in the study and are called "the best violinists." The music professors also nominated a large number of good violinists in the same department. From these subjects, we selected 10 violinists, "the good violinists," by matching their sex and age to those of the best violinists. Similarly, we recruited 10 students specializing in the violin from a different department (music education) in the academy, which has lower admissions standards. Again, we matched these students' sex and age to those of the violinists in the best group. We call the students from the department of music education the "music teachers" because teaching is the most likely future profession for this group. To obtain additional data on the developmental history of outstanding violinists, we interviewed 10 middle-aged violinists who belong to two symphony orchestras in West Berlin with international reputations, the Berlin Philharmonic Orchestra and the Radio Symphony Orchestra (RSO). According to the professors at the music academy, the most likely professional career for the best young violinists is to perform as a member of one of the best symphony orchestras in Germany.

#### *Procedure*

The data-collection procedures for the best and good violinists and the music teachers were identical. The first part of the procedure for the middle-aged violinists, from which data are reported, was the same as for the three groups of young violinists.

Each young violinist was interviewed during three sessions. During the first session biographical information was obtained including the start of practice, sequence of music teachers, and participation in competitions. The subjects were then asked to estimate how many hours per week they had practiced alone with the violin for each year since they had started to practice.

Each subject was then given instructions about a taxonomy of activities. Ten categories of *everyday activities* were presented, each with a general label and description and a listing of frequent examples. From extensive pilot work, 12 categories of *musical activities* were identified and similarly presented. Musical and everyday activities are listed in Table 1. For those subjects playing other instruments besides the violin, the eight musical categories for playing an instrument were split into activities involving the violin and activities involving all other instruments. After presentation of the taxonomy, subjects were asked to estimate how much time they spent on each type of activity during the most recent typical week. Subjects were also asked to rate each of the activities on three dimensions using a scale from 0–10. First they were asked to rate the relevance of the activity to improving performance on the violin. Next they were asked to rate the effort required to perform the activity. Finally, they were asked to rate how enjoyable the activity was without considering their evaluation of the result of the activity. (For example, it is possible to enjoy the result of having cleaned one's house without enjoying the activity of cleaning.)

During the second session, subjects answered questions about practice and concentration. They also recalled all activities they had engaged in during the previous day. For this recall they used a specially

Table 1
*Mean Relevance, Effort, and Pleasure Ratings for 12 Music-Related and 10 Everyday Activities Collapsed Over Three Groups of Young Expert Violinists*

| Activities | Relevance | Effort | Pleasure |
|---|---|---|---|
| Music related | | | |
| Practice (alone) | 9.82 H | 8.00 H | 7.23 |
| Practice (with others) | 8.73 H | 6.97 H | 7.57 |
| Playing for fun (alone) | 5.67 | 3.27 L | 8.33 H |
| Playing for fun (with others) | 6.67 | 3.93 | 8.60 H |
| Taking lessons | 9.63 H | 8.60 H | 7.67 |
| Giving lessons | 7.03 | 7.51 H[a] | 6.79[a] |
| Solo performance | 9.03 H | 9.80 H | 7.28[a] |
| Group performance | 7.67 H | 8.14 H[a] | 8.07 H |
| Listening to music | 8.33 H | 4.38[a] | 8.38 H |
| Music theory | 7.63 H | 6.37 H | 6.07 |
| Professional conversation | 6.50 | 4.33 | 6.40 |
| Organization and preparation | 2.90 L | 4.70 | 1.53 L |
| Everyday | | | |
| Household chores | 1.80 L | 2.23 L | 3.63 L |
| Child care | 2.64 L[b] | 6.14[b] | 6.43[b] |
| Shopping | 0.77 L | 2.80 L | 3.97 L |
| Work (not music related) | 1.79 L[b] | 5.56[c] | 3.74 L[c] |
| Body care and health | 4.90 | 1.43 L | 5.23 |
| Sleep | 8.17 H | 0.47 L | 7.70 |
| Education (not music) | 4.52[a] | 5.45[a] | 7.17[a] |
| Committee work | 1.93 L[a] | 5.55[a] | 5.07[a] |
| Leisure | 6.30 | 3.00 L | 8.93 H |
| Sports | 6.07 | 2.67 L | 7.07 |
| Grand mean | 5.89 | 5.03 | 6.52 |

*Note.* $N = 30$, unless shown with a superscript. (Some subjects could not make their ratings because of a lack of familiarity with the activity in question.) The grand means over all activities and information about the significant deviation from the grand mean is given based on post hoc analyses using Bonferroni's method. The statistical test is conservative as the grand mean includes the ratings for the particular activity in the respective comparison. H = significantly higher than grand mean; L = significantly lower than grand mean.
[a] $N = 29$. [b] $N = 28$. [c] $N = 27$.

designed diary sheet that divided the 24-hr day into ninety-six 15-minute intervals. Use of the sheet ensured that the start and end of recalled activities covered the entire 24-hr day. After completing the recall, subjects were asked to encode the activities using the 30 categories in the taxonomy. Following the second session, subjects kept a diary using the provided sheets for a full 7-day week. Subjects were given envelopes addressed to the investigators and sent in their diaries after each day. Before returning for the third and final interview session, the subjects, working from copies of their diaries, encoded each activity according to the taxonomy. Subjects were encouraged to identify the primary category for each activity but they were allowed to use more than one category to encode mixtures of activities, such as a professional discussion during lunch. At the beginning of the third interview session, subjects were allowed to ask any questions they had about their encoding. During the remaining part of the session the interviewer asked questions about the subjects' developmental life goals and engaged in general debriefing.

## *Results*

Our analyses focus on young violinists' allocation of time for relevant preparatory activities as revealed by their diaries and retrospective estimates of practice during their development. In preparation for this analysis, we briefly describe the biographic data and other data relevant to systematic differences in the violin performance of the three groups of young violinists and analyze each group's ratings of everyday and musical activities regarding relevance, effort, and enjoyment.

The three groups of subjects were selected such that the performance of the best violinists should be better than that of the good violinists, whose performance in turn should be better than that of the music teachers. In the following statistical analyses, the hypothesized differences between the three groups of violinists are represented by two orthogonal contrasts. The first contrast refers to the average difference between the best and the good violinists. The second orthogonal contrast compares the average of the best and good violinists (referred to as the soloist students) to that of the music teachers. In statistical analyses that include the developmental history of middle-aged professional violinists, the data from this group are contrasted with those of the group of the best young violinists.

### *Biographic Information*

All three groups of young violinists consisted of 7 women and 3 men. The middle-aged professional violinists were all men. The ages of the young subjects were successfully matched, and no reliable differences in age were found. The mean age of young violinists was 23.1 years old. The mean age of the professional violinists was 50.5 years old.

The biographic histories of the four groups of subjects with respect to violin playing are remarkably similar and show no systematic differences between groups. The age when they began practice was 7.9 years old and essentially coincided with the age of starting systematic lessons, which was 8.0-years-old. The age at which they first decided to become musicians was 14.9 years old. The average number of music teachers who had taught them was 4.1, and the average number of musical instruments that they had studied beyond the violin was 1.8.

The best indicator of violin performance, besides the evaluation of the music professors, is success at open competitions. A statistical analysis of the number of successful entries in violin competitions confirmed systematic differences in performance among the three groups of young violinists. The frequencies for the best and good violinists were reliably different, 2.9 vs. 0.6; $F(1, 27) = 19.35$, $p < .01$. The average frequency of the best and good violinists differed from that for the music teachers, 1.8 vs. 0.2; $F(1, 27) = 11.78$, $p < .01$. The same pattern of results emerged when the proportion of successful entries from all participations was analyzed. The young violinists were also asked to estimate in minutes of playing time how much music they could perform from memory without preparation. The best violinists reported an average of 128.9 min, which is longer than the 79.1 min reported by the good violinists, $F(1, 27) = 4.07$, $p < .05$. The average playing times for the best and good violinists were longer than that of the music teachers, 104.0 vs. 42.27; $F(1, 27) = 8.23$, $p < .015$.

In sum, all four groups had a similar musical background, and by the age of 23 (the mean age of the young violinists), all 40 subjects had spent at least 10 years practicing the violin.

### *Ratings of Everyday and Musical Activities*

In analyzing the ratings of relevance to improving violin performance, effort, and enjoyment of the everyday and musical activities, our primary goal was to identify a smaller set of activities rated critical to improvement of violin performance by all young violinists. Analyses of each set of ratings for the 22 activities for the three groups of young violinists revealed no profile differences, that is, interactions between group and ratings of activities, which could account for differences in their actual allocation of time to different types of activities. We therefore collapsed the further analyses of differences in ratings between various activities across the three groups of young violinists. For each type of rating (relevance, effort, and enjoyment) we compared the mean rating across all activities with the mean rating of that activity. The significance of differences was determined from adjusted alpha levels ($\alpha^* = \alpha/22 = 0.0023$). The mean ratings and information about significant differences are given in Table 1.

As shown in Table 1, subjects reliably rated 7 of the 12 musical activities as more relevant than the overall mean. Consistent with our theoretical assumption, 27 of the 30 violinists gave "practice alone" the highest relevance rating. In contrast, playing alone for fun, which an observer would have difficulty discriminating from practice alone, received a much lower relevance rating. Out of the 10 everyday activities, only sleep was rated as reliably more relevant to improving one's violin performance than the grand mean, and 5 activities were rated reliably less relevant. Many of the activities with the highest relevance ratings are constrained by external factors and resources. For example, the duration of taking lessons and public performance alone and in a group cannot easily be increased at the will of the subject. Similarly, practice in groups is to a lesser degree constrained. After these additional criteria are applied, there remain four relevant activities of which the violinists can easily control the duration: practice alone, music theory, listening to music, and sleep.

The ratings of effort associated with different activities show that six of the eight activities judged to be highly relevant to performance improvement are also judged to require reliably more effort than the average activity. The two exceptions are listening to music and, not surprisingly, sleep, which is judged reliably less effortful than the average activity. The ratings of inherent pleasure show that only two of the eight highly relevant activities—listening to music and group performance—are also judged to be reliably more pleasurable than the average activity.

In sum, all three groups seem to have the same conception of the relevance of different activities for improvement of violin performance, and all three similarly evaluate the inherent enjoyment and effort associated with different activities. We now turn to the analysis of the time each group allocated to different activities and, in particular, to activities judged to be highly relevant for improving violin performance.

### *Diaries*

From the detailed diaries with encoded activities, the total time a violinist spent during the week on any one of the activity categories can be calculated by simple addition. Most of the encoded activities were described by a single category, such as exclusive categories like sleep and practice; but some activities, such as a professional discussion over dinner, were given multiple encodings. When activities were given multiple encodings, the time of the activity was split equally among the associated categories.

When the duration of all music-related activities was summed across the diary week, the average number of hours per week was 50.6, and no reliable differences between the groups were found. Of the eight activities judged to be highly relevant to improvement of violin performance, only two had an average duration across all three groups exceeding 5 hr per week. These two activities were practice alone (19.3 hr per week) and sleep (58.2 hr per week).

*Practice alone.* In agreement with our theoretical framework, violinists rated practice alone as the most important activity related to improvement of violin performance. Practice alone is a particularly interesting activity because the violinists themselves control its duration and distribution during the week. In contrast, most other activities judged to improve violin performance, such as public solo performance and taking lessons, are highly constrained by external factors. We analyzed the total duration of practice alone for the three groups and then examined the distribution of practice alone during the week.

During the diary week, the average duration of the violinists' practice alone with the violin did not differ for the two best groups and averaged 24.3 hr of practice. This average was reliably greater than that for the music teachers who practiced 9.3 hr per week, $F(1, 27) = 44.05$, $p < .001$. As the first step in analyzing the distribution of practice, we analyzed the daily amount of practice as a function of the day of the week for the three groups. No main effect or interaction of the day of the week was observed, and only the contrast found earlier between the two best groups and the music teachers was reliable. The two best groups practiced alone for 3.5 hr per day and the music teachers for 1.3 hr per day for each day of the week including the weekend. As the second step, we assessed the frequency of practice as a function of time of day. The frequency distributions across all weekdays shown in Figure 2 suggest a preference by the two best groups for practicing alone before lunch, whereas no corresponding pattern is observed for the music teachers.

For statistical analyses, the percentage of time each violinist spent practicing alone was calculated for the five 2-hr intervals from 10:00 am to 8:00 pm for each day of the week. An analysis of variance (ANOVA) revealed no main effects or interactions involving the day of the week and no systematic differences between the two best groups. The two best groups spent a greater proportion of time on practice alone than the music teachers did, $F(1, 27) = 59.11$, $p < .001$, and this difference interacted with the time of day, $F(4, 108) = 2.94$, $p < .05$. A post hoc analysis showed that the time music teachers practiced alone was distributed uniformly across the day, whereas the two best groups had elevated levels of practice between 10:00 am and 2:00 pm. This interaction and the main effect of time of day, $F(4, 108) = 6.09$, $p < .001$, are shown in Figure 3.

Consistent with the rated effortfulness of practice alone, the

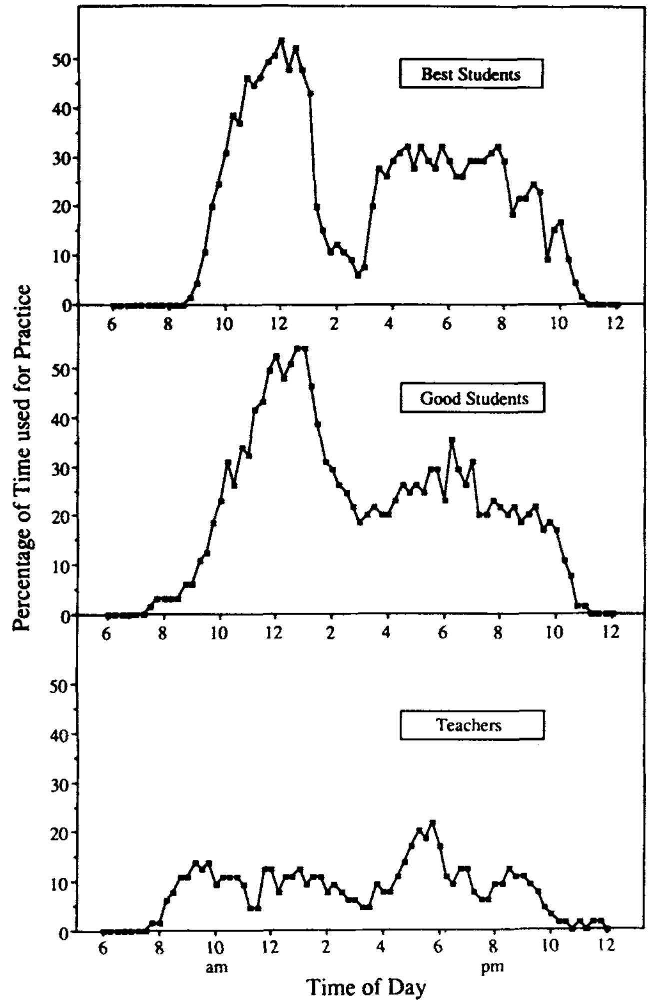


*Figure 2.* Proportion of time spent practicing along with the violin as a function of time of day for the best violinists (top panel), the good violinists (middle panel), and the music teachers (bottom panel).

duration of sustained practice is limited. Most interestingly, the duration of practice sessions is very similar to other estimates of optimal practice duration reviewed in this article. The mean duration of practice sessions during the diary week did not differ during that week and averaged 80 min with no reliable differences among groups. Hence, the differences in amount of practice reflected differences in the number of practice sessions. The two best groups did not differ reliably and had an average of 19.5 sessions per week, a number that was reliably more than the average of 7.1 sessions per week for the music teachers, $F(1, 27) = 22.40$, $p < .001$.

The differences in practice alone between the two best groups and the music teachers might be due to very different curricula in the two departments at the Academy. However, a careful comparison revealed only minor differences between the two departments' training requirements in music. The music teachers had additional requirements consisting of pedagogical aspects of music education, but these requirements corresponded to less than 5 hr during the diary week. This increased time requirement for the music teachers was for the most part balanced out by the longer duration of activities relating to public performance by the two best groups.

*Sleep.* The high relevance of sleep for improving violin performance must be indirect and related to the need to recover from effortful activities such as practice. Consistent with the ratings, sleep is the least effortful of the activities and thus constitutes the purest form of rest. The weekly amount of sleep during the diary week did not differ for the two best groups and averaged 60.0 hr. This average was reliably longer than that for the music teachers, which was 54.6 hr, $F(1, 27) = 5.02$, $p < .05$. Hence the two best groups, who practice more, also sleep reliably longer.

An ANOVA of the amount of sleep as a function of day of the week for the three groups showed no main effect or interaction with day of the week. The average amount of sleep per day was 8.6 hr for the two best groups and was reliably longer than 7.8 hr of sleep for the music teachers. Large-scale diary studies from several different countries show that adults sleep on average 8 hr per day (Converse, 1972) and that adults sleep about 1 to $1\frac{1}{2}$ hr more on the weekend than they do during the work week (Robinson, Converse, & Szalai, 1972). Laboratory studies show that the amount of sleep differs as a function of age (Roffwarg, Muzio, & Dement, 1966). A recent study by Robinson, Andreyenkov, and Patrushev (1988) shows that adults between 18 and 29 years of age sleep around 7.7–7.9 hr per day, a finding that is remarkably consistent with our estimate for the music teachers. The distribution of the frequency of sleeping as a function of the time of the day is shown in Figure 4 for the three groups.

The two best groups appear to sleep more during the afternoon. The duration of sleep episodes separated from nighttime sleep by at least 1 hr from 9:00 am to 9:00 pm was not reliably different for the two best groups and averaged 2.8 hr per week. This average differed reliably from that of the music teachers, $F(1, 27) = 5.92$, $p < .05$, who napped only 0.9 hr per week. The two best groups did not take longer naps to compensate for deficits in nighttime sleep because, when napping was subtracted from the total sleep time, the mean for the two best

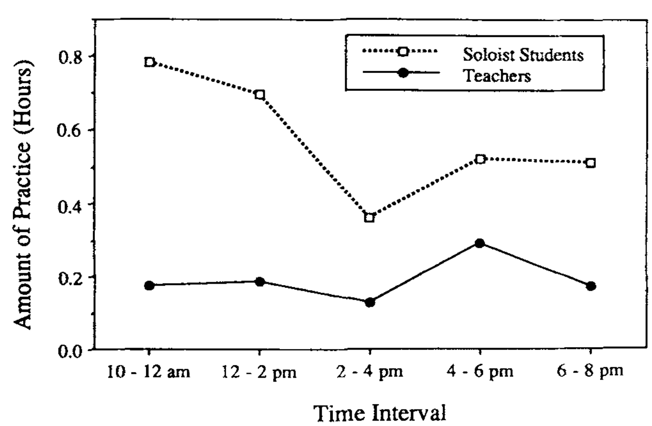


*Figure 3.* Proportion of time spent practicing alone with the violin as a function of five 2-hr intervals for the music teachers (solid line) and the average of the best and the good (soloist) violinists (dashed line).

groups was higher than that of the music teachers, although the difference was no longer reliable.

An analysis of napping as a function of day of the week for the three groups showed no main effect of weekday, but did show a significant interaction between day of the week and the contrast between the two best groups and the music teachers, $F(6, 162) = 2.22$, $p < .05$, which is illustrated in Figure 5.

The overall pattern in Figure 5 suggests that the amount of napping is uniformly low for the music teachers, whereas the amount of napping for the best and good violinists is elevated at the beginning of the work week and reaches its lowest levels during the weekend. Further analysis revealed that the primary source of the interaction reflects differences between the weekend and the five weekdays. An ANOVA of the amount of napping for the three groups revealed a reliable difference between the weekend and the work week, $F(1, 27) = 4.29$, $p < .05$, and an interaction with the difference between the best and good violinists and the music teachers, $F(1, 27) = 12.06$, $p < .005$. Given our general argument for recovery from practice through rest and the result that levels of napping decreased over weekends whereas the amount of practice did not, we looked for alternative sources of rest that could moderate the amount of napping required over the weekend. Of the other activities rated high on restfulness, that is, rated low on effortfulness, leisure has the longest weekly duration during the diary week, with 28.2 hr per week. Thus, we now consider the role of leisure activity in providing recovery from practice.

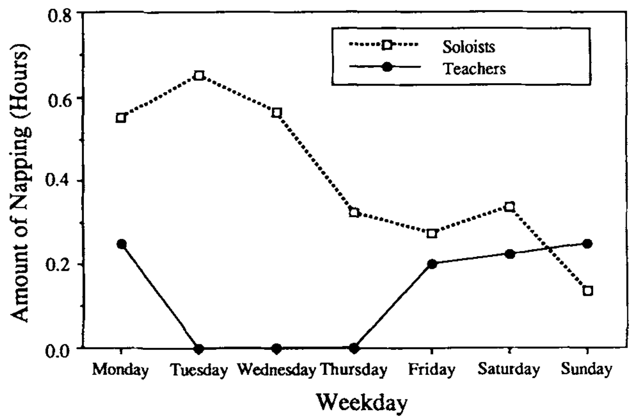


*Figure 5.* Amount of napping as a function of the day of week for the music teachers (solid line) and the average for the best and good (soloist) violinists (dashed line).

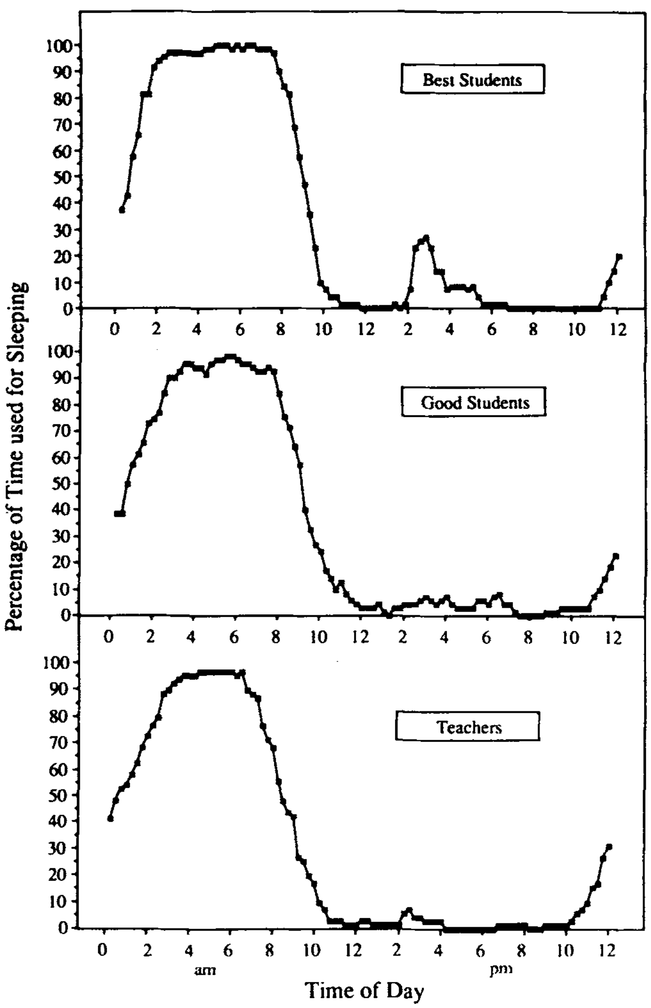


*Figure 4.* Proportion of time used for sleeping as a function of time of day for the best violinists (top panel), the good violinists (middle panel), and the music teachers (bottom panel).

*Leisure.* We performed an ANOVA of the daily amount of leisure activities as a function of the day of the week for the three groups. The best violinists spent 3.5 hr per day on leisure, which is reliably less than the 4.7 hr for the good violinists, $F(1, 27) = 4.27$, $p < .05$. The average for the best and good violinists was 4.1 hr of leisure per day, which is not reliably different from the mean for the music teachers (4.0 hr). In comparison, other adults aged 18–29 are estimated to spend around 5.2 hr a day on leisure activities—defined as Robinson et al.'s (1988) estimate of free time with sports and education excluded. An ANOVA of the leisure time as a function of the day of the week for the three groups of violinists revealed no reliable interactions, but a reliable main effect of weekday was observed, $F(6, 162) = 5.59$, $p < .001$, and is shown in Figure 6.

A post hoc analysis using Bonferroni's $t$ tests showed that out of the 21 possible paired comparisons, only 9 reached significance. All 9 involved comparing a weekday to either Saturday or Sunday, a finding that implies that leisure time is reliably elevated during the weekend. This pattern is consistent with the hypothesis that activities other than sleep can provide necessary rest. The finding that the best violinists spend less time for leisure is important because leisure is judged to be the most enjoyable of all activities, as reflected by the ratings of inherent pleasure in Table 1. For all young violinists there is a reliable negative correlation between amount of leisure time and amount of time on music-related activities, $r(28) = -0.37$, $p < .05$.

### *Estimates of Weekly Duration of Various Activities*

It is possible that some of the results found with the time-consuming method of collecting and analyzing diaries could have

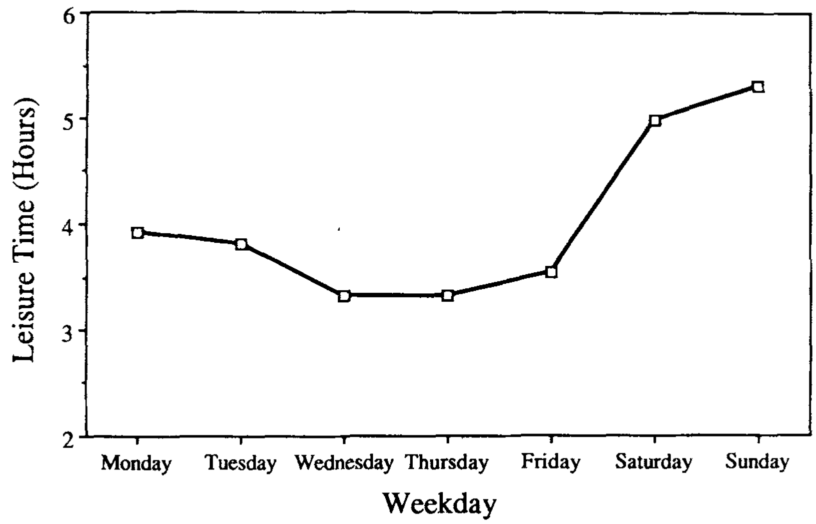


*Figure 6.* Average amount of leisure time for all young violinists as a function of the day of week.

been obtained with more efficient methods. In this section we analyze the time these students estimated spending on the different activities during a current week as well as their retrospective estimates for the time they practiced alone earlier in their career. We first consider the estimates for a current typical week, which the violinists made prior to the diary week. Estimates for practice alone are reported, then the estimates for sleep and leisure.

Our analysis of the diaries showed that the violinists maintained practice alone with the violin at a stable level across the entire week. We therefore expected that they could accurately estimate the amount of weekly practice on the basis of their daily practice. An ANOVA of the estimated weekly amount of practice revealed no reliable differences between the two best groups of violinists, who estimated 29.8 hr of practice alone. The two best groups were found to estimate a reliably greater amount of practice than the music teachers did, 29.8 vs. 13.4; $F(1, 27) = 38.68$, $p < .001$. A repeated-measures ANOVA, including the estimates for the current week and the diary data, revealed that the estimates for the current week were reliably higher by 5.2 hr than the amount assessed from the diaries, $F(1, 27) = 15.39$, $p < .001$, and that this overestimate did not differ across the three groups. The two measures of practice alone were highly correlated for all young violinists, $r(28) = 0.74$, $p < .001$.

A closer analysis revealed that 85% of the best two groups and 50% of the music teachers expressed their estimated weekly amount of practice during the typical week as a daily amount multiplied by 7 days or as an integer value that was an exact multiple of seven. Debriefing interviews suggested that the estimates for a typical week reflected a level of daily practice to which the violinists aspired rather than the level they actually attained. Hence estimates of weekly practice appear to be valid, albeit biased, indicators of actual practice, and the bias does not differ among the three groups.

The estimates of sleep during a typical week revealed no differences between the best and good violinists, but a reliably higher average for the best and good than the mean for the music teachers, $F(1, 27) = 5.42$, $p < .05$. A repeated-measures ANOVA for estimated sleep and sleep assessed by the diary revealed no differences between the best and the good violinists, but a reliable main effect for the contrast between the best and good violinists and the music teachers, $F(1, 27) = 7.21$, $p < .05$. The estimates indicated 3.5 hr of sleep less per week than the diary measure, $F(1, 27) = 10.19$, $p < .005$, and there were no reliable interactions with the group contrasts. The correlation between estimated sleep and sleep assessed through the diaries was reliable, $r(28) = 0.49$, $p < .01$. Most of the violinists (83%) estimated their weekly sleep as a multiple of seven.

The estimated amount of leisure revealed a different pattern of results than that assessed from the diaries. An ANOVA uncovered no differences between the best and the good violinists, but reliably lower estimates for the music teachers than the average for the best and good violinists, $F(1, 27) = 5.25$, $p < .05$. A repeated-measures ANOVA for the estimated amount of leisure and the amounts derived from the diaries found no reliable main differences between groups. The estimated amount of leisure was 7.4 hr lower than that derived from the diaries, $F(1, 27) = 13.46$, $p < .001$, and the interaction of the difference between the best vs. the good violinists was reliable, $F(1, 27) = 6.66$, $p < .05$. The estimated amounts of leisure and the amounts of leisure assessed from the diaries are shown for all three groups in Figure 7.

The best violinists, who spent the least amount of time on leisure, made estimates closely matching the amounts measured for the diary week. The estimates of the other two groups are much lower than the leisure time measured for the diary week. Not surprisingly, the correlation between estimates and diary assessments was low, $r(28) = .082$, $p > .05$. Only half of the subjects estimated the weekly leisure time as a multiple of seven.

In sum, the violinists could give reasonably accurate estimates of the weekly duration of stable, habitual activities, such as sleep and amount of practice alone. All subjects, except those

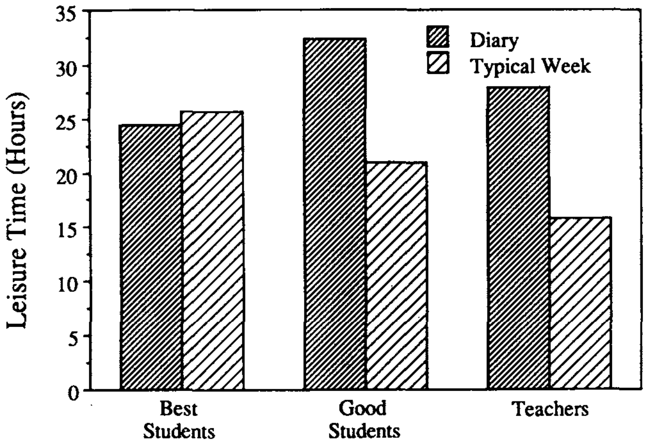


*Figure 7.* Amount of leisure time recorded for diary week and estimated for a typical week for the three groups of young violinists.

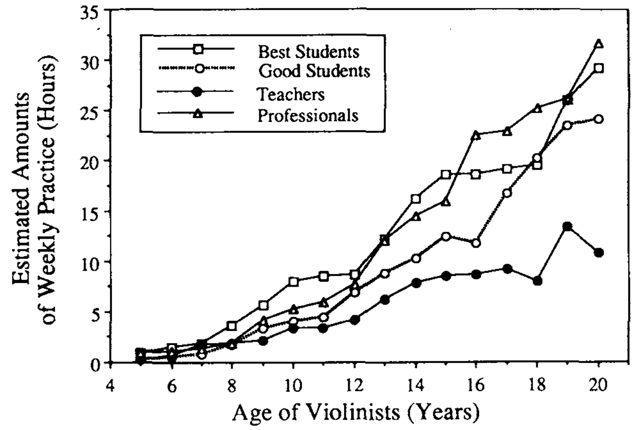


*Figure 8.* Estimated amount of time for practice alone with the violin as a function of age for the middle-aged (professional) violinists (△), the best violinists (□), the good violinists (○), and the music teachers (●).

in the best group, were very inaccurate in their estimates of spontaneous activities such as leisure time.

### *Retrospective Estimates of Practice During Musical Development*

Our findings on practice alone imply that subjects should be able to accurately report not just their current level of practice, but past levels of practice as well. Practice alone is viewed as the most important activity for improvement of violin performance, and its daily amount is remarkably stable. The effortful nature of practice suggests that subjects monitor its duration carefully and hence should be able to estimate it even after long retention intervals. Our earlier analyses showed that concurrent estimates of weekly duration of practice alone are highly correlated with the durations recorded in the diaries. These retrospective estimates are likely to have a larger error component, but they should not be systematically biased. The one caveat is that subjects might report the level of practice to which they aspired rather than the actual amount. However, the correlation between aspired and actual amounts appears to be quite high for all three groups of young violinists. In addition, the widely held view that very talented musicians need to practice less than other musicians would yield a bias in the opposite direction of what the skill-acquisition framework predicts; namely, the best or "most talented" violinists would be inclined to underestimate their past amount of practice to support their beliefs that they are very talented.

At the end of the extended biographical interview, all of our subjects estimated the average number of hours of practice alone with the violin per week for each year since they had started playing the violin. Figure 8 illustrates that for all four groups the reported amount of practice increases monotonically from the start of practice until the age of 20.

The theoretically most interesting index of amount of practice is the total amount of practice accumulated at a given age. The weekly estimates of practice alone can easily be converted to estimated yearly amounts by multiplication of the number of weeks in a year. The number of hours of practice accumulated by a violinist at a given age can be easily calculated by adding the yearly estimates at and below that age. The average number of hours of accumulated practice for each of the four groups is shown in Figure 9 as a function of age.

To avoid any confounding influences from the activities at the music academy, we statistically analyzed the amount of practice the young violinists had accumulated by age 18. At this age, the best young violinists had accumulated an average of 7,410 hr of practice, which is reliably different from 5,301 hr, the average number of hours accumulated by the good violinists, $F(1, 27) = 4.59$, $p < .05$. The average of the best two groups was reliably different from that of the music teachers, who had accumulated 3,420 hr of practice by age 18, $F(1, 27) = 11.86$, $p < .01$. Hence, there is complete correspondence between the skill level of the groups and their average accumulation of practice time alone with the violin.

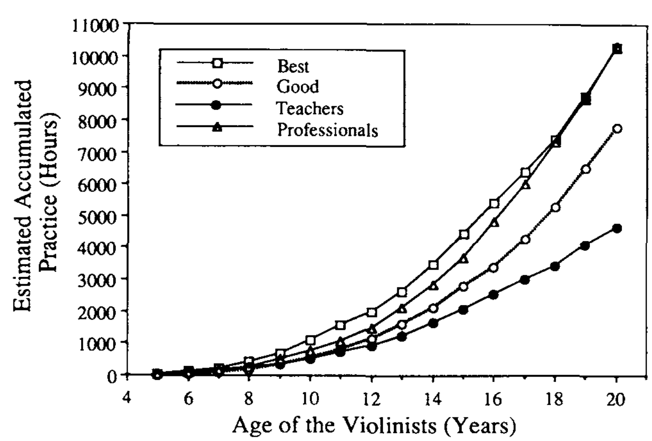


*Figure 9.* Accumulated amount of practice alone (on the basis of estimates of weekly practice) as a function of age for the middle-aged violinists (△), the best violinists (□), the good violinists (○), and the music teachers (●).

A further test of the relation between performance and practice is provided from the amount of practice accumulated by the professional middle-aged violinists at age 18. The average for middle-aged violinists is 7,336 hr, which is so close to the average of 7,410 hr for the best young violinists, that the difference is not statistically significant. Presumably the middle-aged violinists were selected by international-level orchestras because they had the same skill level in early adulthood as the best young violinists currently have. The high degree of correspondence between these two groups' retrospective estimates of practice alone during their music development thus supports the validity of these estimates.

## *Summary of Results of Study 1*

Confirming our theoretical framework, the violinists in all groups rated practice alone as the most relevant activity for improving violin performance. Among all the activities rated highly relevant, practice alone is unique: A violinist can extend its duration at will because no external resources, such as availability of teachers or audiences, are involved. An analysis of the week-long diaries showed that the two best groups of young violinists did not differ from each other in their amount of practice alone with the violin, but they practiced almost three times longer than the music teachers. The violinists were able to estimate their weekly practice, and their estimates were highly correlated with the calculated durations from the diary week. From retrospective estimates of weekly practice during their musical development, the amount of accumulated estimated practice alone by age 18 was calculated. The accumulated amount of practice for the best young violinists was indistinguishable from that of professional middle-aged violinists belonging to international-level orchestras. This finding was expected because the most likely professional career for the best violinists is membership in a first-rate orchestra. The good violinists had accumulated fewer hours of practice alone by age 18, but reliably more than the music teachers had.

Beyond the internal consistency of the retrospective estimates of practice alone, it is possible to compare the weekly estimates from our study to concurrent estimates of amounts of practice by young award-winning musicians from two German studies (Kaminski et al., 1984; Ruoff, 1981). These musicians are biographically similar to the violinists in our best group and were assessed with a diary procedure at two different ages. At age 13 the award-winning musicians practiced 13.7 hr per week (Ruoff, 1981), an amount close to the 12.2 hr estimated by our best group and higher than the 8.8 and 6.2 hr per week estimated by the good and music teacher groups, respectively. At age 17, the practice of the award-winning musicians averaged 15.5 hr per week (Kaminski et al., 1984) compared with the 19.2, 16.8, and 9.1 hr per week estimated by the best, good, and music teacher groups. The agreement between the estimates of our best violinists and the award-winning violinists' diary data is reasonably close and is consistent with the hypothesis that the best violinists practice more than the good violinists during early adolescence and more than the music teachers during their entire developmental period. In a recent study Sloboda and Howe (1991) interviewed more than 40 students (aged 10–18) in a music school, where about half of the students were superior to school standards. They found no reliable difference in the estimated amount of daily practice between their two groups of superior and average musicians. The difference between the results and our own can be explained by the more select samples of musicians studied by us and Kaminski et al. (1984). Consistent with this interpretation, the estimated amount of daily practice for their subjects was only half that of our subjects' estimates for the comparable age period. Furthermore, only a fraction (14%) of Sloboda and Howe's (1991) subjects were totally self-motivated to practice, which raises some issues as to whether the practice of most of their subjects meets the criteria for deliberate practice.

Consistent with our theoretical framework, the violinists rated practice alone as requiring effort. The analysis of the diaries revealed that uninterrupted sessions of practice alone were limited to a duration between 1 and 1.5 hr, a finding that is consistent with extended laboratory studies on practice. For the two best groups practice was systematically distributed during the day and was particularly high in the late morning. Two findings provide intriguing evidence of the effortful character of practice. First, violinists rated sleep as highly relevant for improvement of violin performance. Second, the analysis indicated that the violinists napped to recover from practice. The two best groups of violinists with the highest levels of practice were found to nap more in the afternoon than did the group of music teachers. Furthermore, the duration of napping decreased during the weekend, when ample time for relaxing activities such as leisure was available. Another study provides similar findings. World-class musicians interviewed by Samuel (1987) rated practice as extremely important, especially during development. A majority of these subjects (65%) judged sleep as important, and many musicians reported taking afternoon naps, especially before a public performance.

The diary-based analyses of the amount and distribution of practice showed clear differences between the music teachers and the two best groups, but no difference between the two best groups. The two more accomplished groups differed in the accumulated amount of estimated practice, and the best group spent less time on leisure than the good group did during the diary week. Most interestingly, the subjects in the best group were able to estimate quite accurately the time they allocated to leisure, whereas the good violinists underestimated their leisure time during the diary week by more than 11 hr. With our finding that, compared with the good violinists, the best violinists tended to spend more time on music-related activities, these results suggest that our most accomplished subjects show a greater involvement in music and organize their time better, especially their leisure time.

It is important to note that our study shows only that the amount and distribution of practice is related to the level of performance of adult musicians. In fact, many additional factors consistent with the skill-acquisition framework could attenuate the differences among our three groups. Sosniak (1985) found that international-level pianists had spent considerable efforts to seek out the very best musical teachers during their musical development. Furthermore, it is likely that an analysis of the detailed activities during practice alone would reveal qualitative differences between violinists at different advanced levels of performance (Gruson, 1988; Miklaszewski, 1989).

## Study 2

The purpose of the second study was to extend the findings from the violinists to another domain of expertise and, most important, to obtain experimental measures of performance in skill-related tasks that could then be related to measures of current and accumulated practice. To determine whether the previous findings could be replicated for subjects with more extreme differences in proficiency than the violinists had, we compared a group of young expert pianists with a group of amateur pianists. The data reported in this study are from a larger investigation including two more groups, one of elderly professional pianists and another group of elderly amateur pianists. Recent research on expert piano performance (McKenzie, Nelson-Schultz, & Wills, 1983; Palmer, 1989; Shaffer, 1981; Sloboda, 1983) has shown that it is possible to record the sequence of piano keystrokes and analyze motor skills differentiating pianists at different levels of performance. In his dissertation Krampe (1991) designed a battery of tasks ranging from nonmusical tasks, such as choice reaction time, to actual performances of a musical piece to study four groups of expert vs. amateur and younger vs. older pianists. Unfortunately, we could not find a large group of young pianists who met the selection criteria used for the best violinists in Study 1. Instead, we recruited a sample of expert pianists from the Music Academy of Berlin according to selection criteria similar to the good violinists in Study 1. The amateur pianists were matched for sex and equated for mean age with the expert pianists.

As with Study 1 we first provide biographical data, then the report of the 1-week diary and retrospective estimates of past practice. We report on the battery of nonmusical and musical tasks and finally relate the performance on the musical tasks to our estimates of accumulated practice. Our main prediction was that we would be able to predict differences in proficiency in the skill-related tasks at least as well from our measures of accumulated practice as from the differences in the pianists' level of expertise.

### Method

#### Subjects

Twelve expert pianists (8 men and 4 women) and 12 amateurs (7 men and 5 women) equated for mean age (24.3 years) participated in the study. The expert pianists were students in advanced soloist classes at the "Hochschule der Kuenste," a Berlin music academy. All expert pianists were students but had already started to perform in public concerts. Fifteen amateurs recruited through newspaper and campus ads were students in academic or vocational training programs. To make the amateurs comparable to the experts, we specified that the amateurs had to play classical music and be able to successfully play a piece by Bach used in the musical performance task. Three amateurs failed this criterion. The estimates of practice alone during early development were also collected from two age-matched samples of 12 older experts and 12 amateur pianists with the average age of 59.8 years.

#### Apparatus

An electronic keyboard (Yamaha CB-300 Clavinova) and a MacII computer were used for monitoring experiments and collecting data for all tasks except for the digit-symbol substitution test. That test was administered in the paper-and-pencil version.

#### Procedure

Data were collected during two sessions separated by 7–12 days. During the first session subjects participated in an abbreviated version of the interview in Study 1. They provided detailed biographical information and estimated the average amount they had practiced alone every week for each year of their lives since they started practicing. Then followed the first experiment, the *complex movement coordination task,* which challenged the speed and accuracy of subjects' bimanual movement coordination. The task was to play a series of nine keystrokes either with one hand or simultaneously with both hands. Each finger was assigned to one of five adjacent, white keys on the piano; no lateral movements were required. We manipulated the complexity of hand coordination by having subjects perform either with *single hands* (left or right), *mirror image movements* for both hands, or *different movements* for opposite hands. The tasks were presented as strings of nine numbers, each number indicating which finger of a given hand was to be used in performance. A display with the relevant task information appeared on the computer screen and remained for subjects' inspection during performance. Motor demands were identical across tasks: the same series were used for the left and right hands; bimanual tasks were generated by combining the single-hand tasks. Conditions were tested in ascending order of complexity. Instructions encouraged the subjects to play accurately and rapidly while maintaining a steady tempo. The single-hand condition consisted of two series of keystrokes for each hand; the two bimanual conditions involved playing two different series each. In addition to warm-up, each task consisted of an initial block of 6 and a second block of 12 practice trials. During the second block of practice trials, subjects received graphic feedback on accuracy, speed, and the timing of single keystrokes (steadiness). Only the data from the third block of 6 trials were used in the analysis. Following the first experiment toward the end of Session 1, subjects were introduced to the diary procedure. The introduction, recording of daily activities during a 7-day period between Sessions 1 and 2, and coding of activities were identical to the procedures described for Study 1. Session 2 started with the debriefing for the diary procedure. The *musical performance task,* following debriefing for the diary procedure in Session 2, required subjects to give three successive performances of the Prelude No. 1 in C-major ("Wohltemperiertes Klavier") by J. S. Bach. Subjects were given up to 15 min of practice to work out an interpretation and then attempted to replicate this interpretation three times while being as consistent as possible across performances. Musicians consider the piece to be technically very simple; at the same time it leaves room for musical interpretation. All subjects were able to perform the piece fluently except for the two amateurs, who were not included in the analyses for this reason. Force and onset–offset times for single keystrokes were recorded with the apparatus described previously; high-speed tape recordings were also generated for later evaluation. Following the musical performance task, subjects completed a paper-and-pencil version of the *Digit-Symbol Substitution Test* (DS), a subtest of the WAIS that is considered a measure of general perceptuo-motor speed. A *two-choice reaction time task* (CRT) required speeded responses of pressing either one of two assigned keys on the piano keyboard. Both tasks are often used to measure cognitive–motor speed. Three *finger tapping tasks* involving their right, left, and alternate forefingers, respectively, were used as measures of simple motor efficiency. Following an auditory start signal subjects had to tap as fast as they could for 15 s. Tasks were terminated by an auditory signal.

### Results

#### Biographic Background

All experts had more than 14 years of playing experience; amateurs had between 5 and 20 years of experience. Amateurs had started with piano instruction at an average age of 9.9 years and were reliably older than expert pianists, who started at 5.8 years of age, $F(1, 22) = 7.00$, $p < .02$. On average experts had received 19.1 years of formal instruction from 4.7 teachers. In comparison, the amateurs had received 9.9 years of instruction and had studied with 3 different teachers on average. The differences in years of formal instruction, $F(1, 22) = 29.36$, $p < .001$, and number of teachers, $F(1, 22) = 10.00$, $p < .01$, were significant. All of the expert subjects and 50% of the amateur subjects were receiving formal instruction at the time of investigation. All but one expert subject had participated in open competitions ($M = 3.6$, $SE = .73$); only two amateur subjects had ever participated in a competition at a local level. Whereas amateur subjects were more likely to play at least one additional instrument ($M = 1.25$, $SE = .22$), this was the exception for expert pianists ($M = .25$, $SE = .18$); this difference was reliable, $F(1, 22) = 12.57$, $p < .01$, and illustrates the experts' focus on improvement on their main instrument.

### *Diaries*

The experts spent a total of 56.75 hr on music-related activities during the diary week. In comparison, the amateurs spent only 7.02 hr, $F(1, 22) = 348$, $p < .001$. As in Study 1, we analyzed the amount and distribution of practice alone, the most relevant activity for improvement in the skill, and also examined data on sleep and leisure time.

*Practice alone.* During diary week, the experts spent 26.71 hr in solo practice at the piano; the amateurs spent 1.88 hr. This difference was, of course, significant, $F(1, 22) = 93.98$, $p < .001$. An analysis of the amount of practice as a function of weekday had to be limited to the experts because the amateurs did not practice at all on most days. No reliable difference between weekdays was found. Figure 10 shows the distribution of practice activities across the time of the day averaged across weekdays.

To analyze the distribution of practice across time of the day, we computed the amount of practice during five intervals as described in Study 1. This analysis was also restricted to the data on the expert pianists. It revealed no interaction between

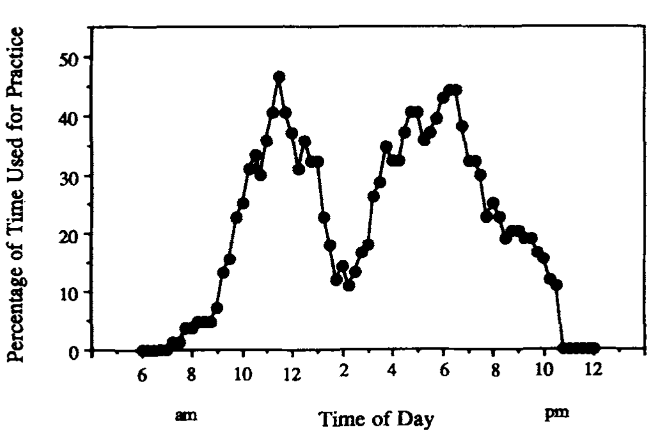


*Figure 10.* Proportion of time spent on practicing alone at the piano for the expert pianists.

weekday and interval and no main effect for weekday. The effect of interval did not reach significance, $F(4, 44) = 2.57$, $p < .052$. An analysis of the length of practice sessions showed that the experts practiced longer (87.90 min) than the amateurs (46.00 min), $F(1, 20) = 15.25$, $p < .001$. These average durations are probably overestimates as shorter breaks (< 15 min) between consecutive sessions were probably not recorded in the diaries.

*Sleep.* The weekly amount of sleep did not differ for the experts and the amateurs and averaged 56.86 hr per week. A repeated measures ANOVA revealed a main effect of weekday, $F(6, 132) = 4.01$, $p < .002$, which did not interact with skill level. To locate the effect, we performed pairwise $t$ tests contrasting the mean of each day with the means of other days. Six out of 42 possible comparisons were significant, all involving contrasts between a working day and either Saturday or Sunday. These results indicate that both groups of pianists tended to sleep longer during the weekend ($M = 8.68$ hr) than during the working week ($M = 7.91$ hr). The average duration of napping was only 0.63 hr per week and did not reliably differ between the two groups.

*Leisure.* A repeated measures ANOVA was performed on the amount of leisure time for each day during the diary week. The amount of leisure time, 4.66 hr per day, did not differ for experts and amateurs. As in Study 1, however, we obtained a significant effect of weekday, $F(6, 132) = 11.04$, $p < .001$. Eleven out of 21 post hoc comparisons were significant, and 8 of these involved contrasting a working day with a weekend day. Subjects considerably increased their leisure time during the weekend days ($M = 6.22$ hr) compared with the working week ($M = 4.05$ hr).

### *Retrospective Estimates of Practice During Musical Development*

To determine how good our subjects were at estimating how long they practiced each week we compared the measures obtained from the diaries with the estimate for the current year. A repeated measures ANOVA with type of assessment as a within-subjects factor yielded a main effect of type of assessment, $F(1, 22) = 4.81$, $p < .05$, and a main effect of skill level, $F(1, 22) = 350$, $p < .001$, but no interaction. Both experts and amateurs overestimated their amount of practice during the diary week by an average of 5.2 hr, in agreement with the results of Study 1.

Figure 11 shows the average amount of weekly practice as estimated by amateur and expert subjects as a function of age until age 20, the age of the youngest subject. Although expert subjects show the same linear increase in the amount of practice that was found for the violinists, there is little change in amateurs' training level after the mean starting age (9.9 years). Following the procedure in Study 1, we calculated the average amount of practice accumulated by a given age for each group (see Figure 12). At the age of 18 the expert pianists had accumulated 7,606 hr of practice, which is reliably different from the 1,606 hr of practice accumulated by the amateurs, $F(1, 22) = 26.29$, $p < .001$. The estimated amount of practice accumulated by age 18 for the group of older expert pianists did not differ from that of the younger experts, $F(1, 22) = 1.74$, $p > .20$. Similarly, the accumulated amount of practice for the older ama-

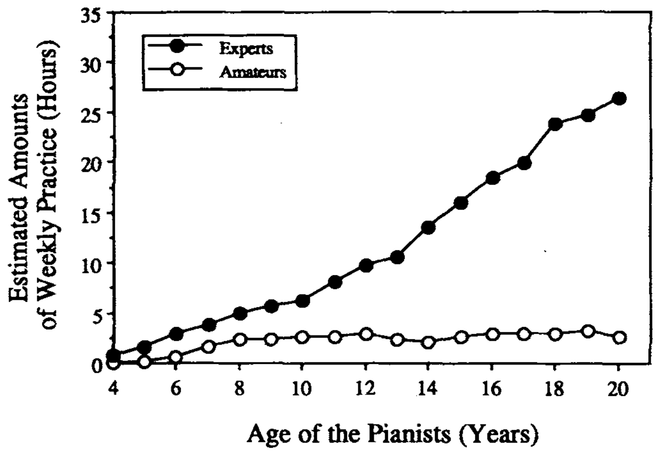


*Figure 11.* Estimated amount of time for practice alone at the piano as a function of age for expert pianists and amateur pianists.

teurs did not reliably differ from that of the younger amateurs, $F(1, 22) = .83$, $p > .35$.

## *Performance on Tasks Unrelated to Music*

Performance in the two nonmusic tasks, the DS and the CRT tasks, did not distinguish between experts and amateurs. Only three subjects made errors on the DS. The mean digit-symbol score was 69.0 and did not differ for the two groups, $F(1, 22) = 1.18$, $p > .25$.[1] The mean error rate in the CRT was 4.2% with no differences between groups. The mean reaction time was 422 ms; again, differences between groups were not significant, $F(1, 22) = 1.09$, $p > .30$. These results confirm the assumption that domain-specific mechanisms, rather than more general cognitive–motor abilities, are responsible for experts' superior performance. The findings are in line with earlier proposals by Lashley (1951) and Shaffer (1982), who suggested that integrated complex representations rather than rapid serial processing govern speed and fluency in a complex motor skill.

## *Music Performance: Validation of Differences in Piano Performance*

Two measures were derived from the musical performance task: expert ratings on the musical quality of the interpretation and the consistency of dynamic changes applied across the three successive performances of the piece. Three expert raters evaluated tape recordings of the second interpretation separately for each subject. The evaluation consisted of seven scales ranging from 0 to 10. The reliability of the rating instrument was very high (Cronbach's alpha = .94 for both groups; $\alpha = .94$ for amateurs, $\alpha = .79$ for experts, on the basis of all 21 items). Ratings were collapsed across scales and averaged for the three raters. The average rating for expert pianists' performance was 6.4 ($SE = .21$) compared with 4.7 ($SE = .42$) for the amateur group. The expert raters' overall evaluation of musical performance was reliably higher for the expert pianists, $F(1, 22) = 12.74$, $p < .01$.

Thirty-two bars were used for statistical analyses of computer recordings of keystrokes. The average force pianists applied to the 16 keystrokes in each bar was computed, and three Pearson correlation coefficients corresponding to the similarity between the three successive performances were calculated. The average Pearson $r$ was .695 for the amateurs and .866 for the expert pianists. Single correlation coefficients were $z$ transformed and submitted to a repeated measures ANOVA. The analysis yielded a main effect of skill level, $F(1, 22) = 11.95$, $p < .01$, indicating that experts were more consistent in expressing dynamic changes in terms of loudness than amateurs. This main effect was not dependent on which two of the three performances were compared.

## *Performance in Skill-Related Tasks*

Tests of homogeneity of variances revealed that the mean latencies between successive keystrokes (interstroke latencies) were not normally distributed within skill groups. We therefore analyzed the interstroke latencies for the simple tapping tasks and the three conditions of the complex movement coordination experiment by log-transforming the latencies at the level of single intervals.[2]

*Simple tapping tasks.* Interstroke intervals from the three tapping tasks were analyzed with a repeated measures ANOVA with two orthogonal contrasts comparing left vs. right forefinger tapping and single vs. alternate finger tapping. Both within-subjects contrasts were significant, indicating that right-index tapping was faster than left-index finger tapping, $F(1, 22) = 21.63$, $p < .001$, and alternate tapping was faster than single forefinger tapping, $F(1, 22) = 476$, $p < .001$. The second contrast showed a reliable interaction with skill level, $F(1, 22) = 8.19$, $p < .01$, indicating that expert pianists' increase in speed when the task allowed overlapping of movements between alternate fingers was proportionally larger than for the amateurs as shown in Figure 13. The overall effect of skill level was reliable, $F(1, 22) = 26.63$, $p < .001$; experts were faster on each of these tasks than amateurs.

*Complex movement coordination tasks.* Performance on single hand tasks was averaged for left and right hands, and the mean log-interstroke latencies were calculated for the last block of six criterion trials on each condition. A repeated measures ANOVA was performed, contrasting single-hand performance

[1] There are no available German norms for this specific version of the digit-symbol substitution test. Two recent studies at the Max Planck Institute for Human Development and Education in Berlin show that the mean performance of groups of subjects with comparable age and educational background range between 59 and 66. Hence, the performance of the two groups of expert and amateur pianists is comparable although somewhat higher.

[2] After log transformation the data approached a normal distribution, where the mean and median coincide. The common procedure of analyzing the median of observed latencies will hence give similar results but entails somewhat less statistical power. An analysis based on medians gave the exact same results as those reported below with one exception. Namely, interaction between skill level and alternate finger tapping was not reliable. The correlation between the medians and the averages of the log-transformed latencies ranged from .94 to .99 with an average of .98.

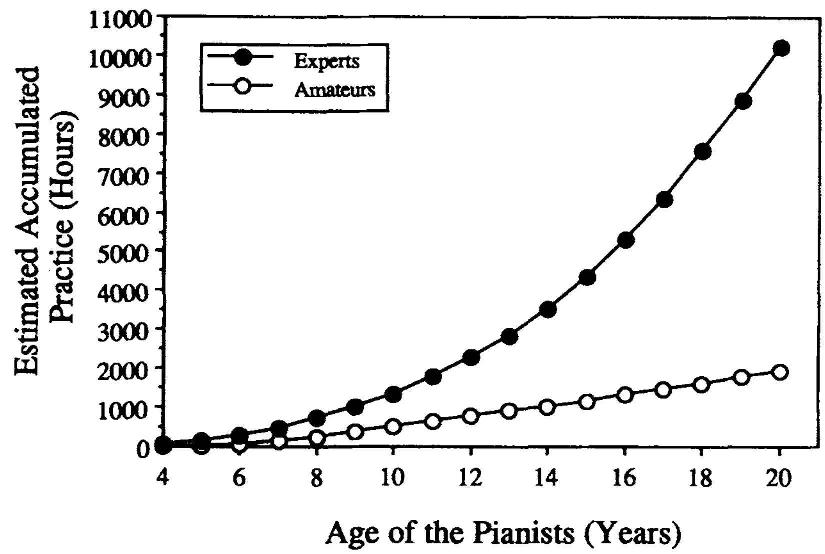


*Figure 12.* Accumulated amount of practice alone (on the basis of estimates of weekly practice) as a function of age for expert pianists and amateur pianists.

with the two bimanual tasks and comparing the two bimanual conditions, namely, mirror-image movements and different movements in opposite hands. Both contrasts were significant indicating that the complexity manipulation acted as predicted: Single-hand movements were faster than the average of the two bimanual tasks, $F(1, 22) = 92.34$, $p < .001$, and different movements in opposite hands were slower compared to mirror-image movements in both hands, $F(1, 22) = 53.39$, $p < .001$. The second contrast showed a reliable interaction with skill level, $F(1, 22) = 5.91$, $p < .05$. This indicates that the complexity of bimanual coordination impaired the amateurs' performance more than the experts' performance. The main effect of skill level was significant, $F(1, 22) = 65.98$, $p < .001$. The main effect and the interaction are illustrated in Figure 14.

### *Relation Between Accumulated Practice and Performance in Skill-Related Tasks*

One premise of our theoretical framework is that performance increases monotonically according to the power law (J. R. Anderson, 1982; Newell & Rosenbloom, 1981). Accumulated practice was thus log-transformed prior to analyses. A hierarchical regression approach was used on all measures of performance in skill-related tasks. The skill-level factor was

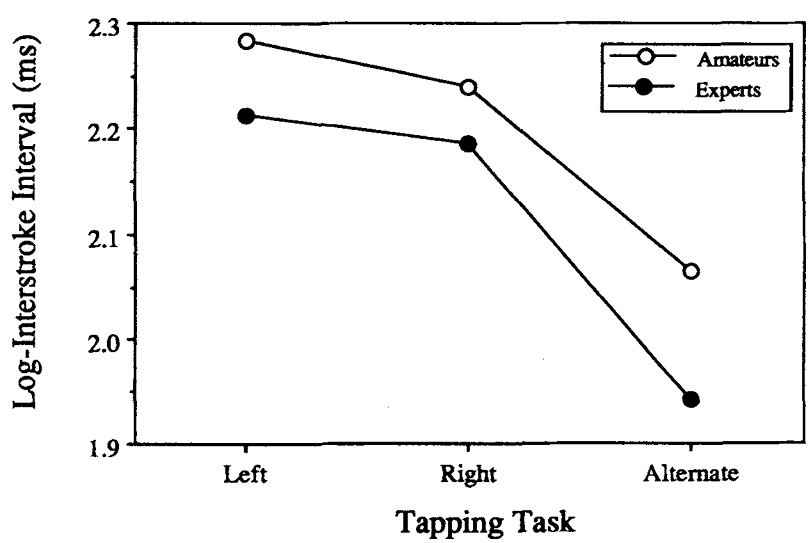


*Figure 13.* Mean log-interstroke latency (in ms) as a function of task complexity in three simple finger tapping tasks for expert and amateur pianists.

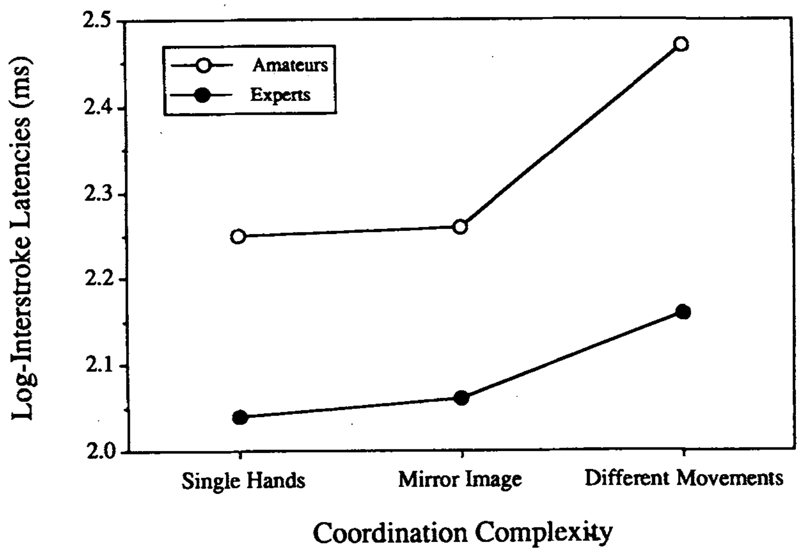


*Figure 14.* Mean log-interstroke latency (in ms) as a function of coordination complexity in three conditions of the complex movement coordination experiment for expert and amateur pianists.

entered first. Then accumulated practice (log values) was entered as a second step so that we could determine whether this variable could predict within-group interindividual variation that the skill factor could not capture. As a third step, the skill level factor was removed from the regression equation so that we could determine the degree to which accumulated practice alone could account for task performance. Table 2 gives the $R^2$ (amount of variance explained) associated with the successive implementation of the three regression models and the significance levels for the relevant $F$ tests.

The table illustrates two major findings. First, expert pianists had a clear advantage in all measures of skill-related performance; all $R^2$s in the first row are significant. Second, accumulated practice could account for the skill difference as well as the skill factor could; there was no significant reduction in variance explained when skill level was removed from the equation for any of the variables (3rd row). Furthermore, accumulated practice accounted for additional variance within groups for the complex movement coordination tasks when added to the skill-level factor. Inspection of the beta weights revealed that the relation was in the predicted direction: Those subjects who had practiced more did better in the experiments even when skill level was statistically controlled for. Figure 15 illustrates the relation between accumulated amounts of practice and performance for the three conditions of the complex movement coordination experiment.

To determine whether the additional variance accounted for by accumulated practice was merely reflecting differences in current practice intensity, we performed a separate set of control analyses. Current amount of practice (the number of hours practiced during the diary week) was entered prior to accumulated practice into the regression equations for each variable listed in Table 2. The emerging pattern of results was as reported before. This analysis shows that the effects of accumu-

Table 2
*Performance in Skill-Related Tasks as Accounted for by Skill Level and Accumulated Amounts of Practice in Study 2 ($R^2$s and Significance of F Change)*

| | Simple tapping | | | Complex movement coordination | | |
|---|---|---|---|---|---|---|
| | Right | Left | Alternate | Single-hand movements | Mirror-image movements | Different movements |
| Skill level only | .55*** | .43*** | .47*** | .74*** | .67*** | .66*** |
| $R^2$ added with accumulated practice | .02 | .02 | .06 | .05* | .09** | .08* |
| $R^2$ removed with skill level | .04 | .03 | .01 | .04 | .01 | .01 |
| Accumulated practice only | .53*** | .42*** | .52*** | .75*** | .75*** | .73*** |

* $p < .05$. ** $p < .01$. *** $p < .001$.

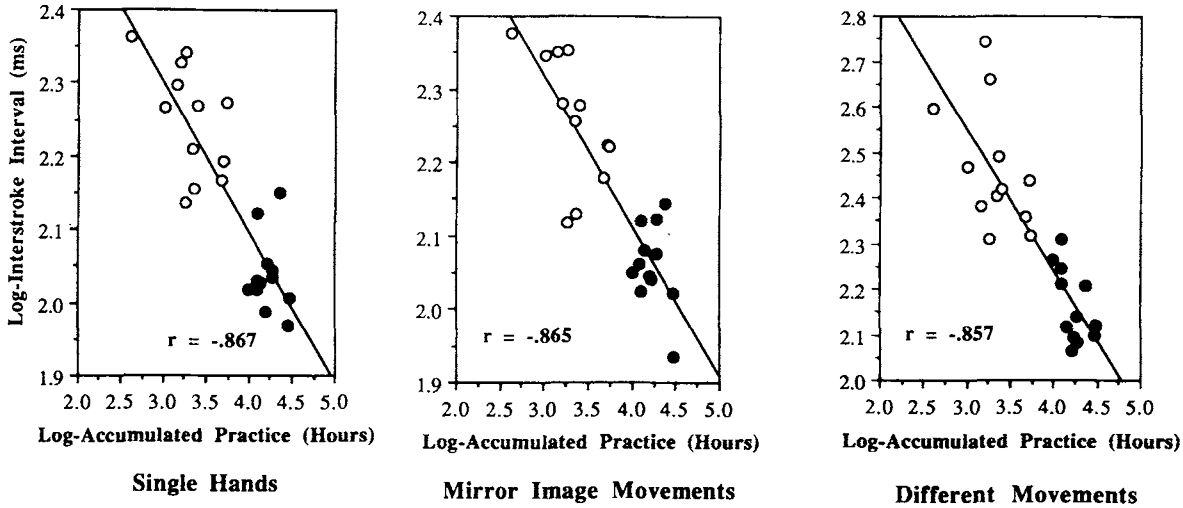


*Figure 15.* Individual mean log-interstroke intervals for the three conditions of the complex movement coordination experiment as a function of accumulated practice (log-means) for amateur (○) and expert pianists (●).

lated practice remain predictive of current performance even if the impact of current level of training is statistically controlled for.

Another question in this context was whether general motor ability would predict interindividual differences in task performance once the effects of past practice were partialed out as implied by Keele and Hawkins (1982). To test this claim, we entered each of the simple tapping measures to the regression equations for the three complex tasks as predicted by accumulated practice. In no case did any of the three variables add significant variance to the model. This analysis shows that the interindividual differences in performance in simple motor tasks do not predict performance differences in similar but inherently more complex tasks once the effects of prior practice are accounted for.

## *Summary of Results of Study 2*

Consistent with our predictions, we found large differences in the histories of deliberate practice for expert pianists and amateurs. At no point during development did the two groups accumulate comparable amounts of practice, or, as we would infer, attain comparable levels of performance. The expert pianists started on the average 4 years earlier than the amateurs. Their average amount of practice increased each year until it attained its current high level, whereas the amateurs maintained their early levels until adulthood. The current amount of practice assessed from the diaries is more than 10 times higher for the experts than for the amateurs. Even the average length of their practice sessions differed. During the diary week experts were fully engaged in music and spent close to 60 hr on music-related activities. Their practice was evenly distributed across the entire week, and the length of practice sessions was limited, in accord with our theoretical expectations. We found no differences in the weekly allocation of restful activities, such as sleep and leisure, between the expert pianists and the amateurs, who also were students in domains other than music. For both groups the amount of sleep and leisure increased during the weekend, the pattern normally seen in studies of samples of the general population (Robinson et al., 1972). It is difficult to assess the influence of the musical instrument on the differences between the expert pianists and the two best groups of expert violinists. In the next section we discuss differences in starting ages between the two groups. However, in most important respects the pattern of results is remarkably consistent for the expert pianists and violinists.

We initially proposed three levels of investigation to decompose the complex skill of playing the piano: efficiency of peripheral motor functions, coordination of complex bimanual movements, and the ability to consistently vary movement parameters in expressive musical performance. Findings from all experimental tasks designed to test these components were in line with our predictions: The data revealed considerable differences between experts and amateurs. The differences between skill groups increased with the hypothesized level of task complexity in the simple finger tapping tasks as well as in the more complex movement coordination tasks. Clearly experts can overcome the processing constraints in the more difficult task conditions. These constraints seem to arise mostly from requirements for bimanual coordination and have been documented for untrained subjects in earlier studies (Kelso, Southard, & Goodman, 1979; Klapp, 1979). Shaffer (1981) demonstrated that expert pianists show superior abilities for independent timing of movements in opposite hands. Our results are also in line with findings for a skill that in several ways is related to playing the piano, namely typing. A recurrent finding has been that expert typists' speed advantage is most pronounced for rapidly alternating keystrokes between hands (Gentner, 1988; Salthouse, 1984; Shaffer, 1976), whereas the differences for repetitive movements of the same finger are normally the smallest.

The skill advantage in our study was limited to those tasks that presumably reflect components of skilled performance; no skill differences were apparent in the two far transfer tasks. Interindividual differences in skill-related tasks could be predicted from accumulated amounts of practice, as predicted, even when current levels of training were statistically controlled for. Predictions that were based on the power law model of practice were as good as those based on the skill level factor; predictability was even reliably better for the complex movement coordination tasks that were designed to maximize performance differences supposedly underlying the skill.

Although our study does not directly disconfirm the assertions that general cognitive–motor abilities account for performance in a complex skill (e.g., Keele & Hawkins, 1982), it is hard to see how our findings could be reconciled with those accounts. The absence of skill effects in the two far transfer tasks is not in line with these explanations. Furthermore, the regression analyses reported here support the notion that skills (even simple tapping skills) are gradually acquired rather than inherited as stable cognitive–motor dispositions.

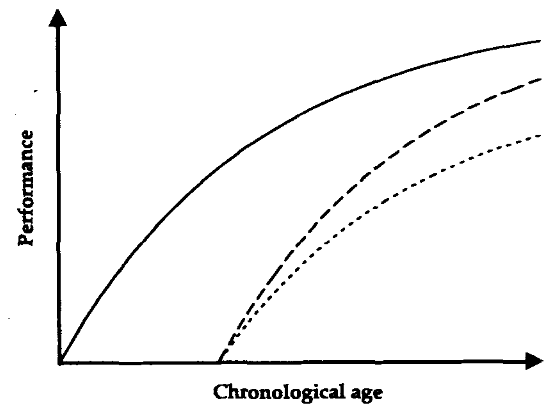


*Figure 16.* Three schematic relations between chronological age and performance. (The solid line shows the performance associated with an early starting age and a high level of practice. The line with long dashes shows performance for an equally high level of practice but with a later starting age. Finally, the dotted line shows the performance associated with the same late starting age and a lower level of practice.)

## The Framework Applied to Several Domains of Expertise

The central thesis of our framework is that expert performance is the result of an extended process of skill acquisition mediated by large, but not excessive daily amounts of deliberate practice. In the domain of music, we showed that individual differences in adult levels of performance were correlated with the past and current amount of deliberate practice at a given age, in particular the age of 18, when performers in music are normally selected for higher levels of professional training. Because our methodology for assessing the current and past amounts of deliberate practice is new, we further explicate the relation between performance and deliberate practice by considering research findings in music and other domains of expertise.

Our framework predicts a monotonic relation between the current level of performance and the accumulated amount of deliberate practice for individuals attaining expert performance. The general shape of this relation is illustrated by the solid line in Figure 16. It is relatively rare that domains of expertise have a univariate performance variable that quantifies the performance for individuals at different ages and levels of performance. The best examples are individual track and field events in sports, for which the performance of any individual can be measured. Particularly in sports, but in other domains as well, developmental and maturational factors are known to influence performance as a function of age. For example, age-related changes in height may directly or indirectly influence performance in certain sports. For these reasons in virtually all domains individuals are grouped by age for external evaluation and competitions. Consequently, many studies report performance as a function of age. If performance is graphed as a function of age, where the first data point corresponds to an individual's introduction to the domain and start of deliberate practice, we expect a monotonic relation similar to the solid line in Figure 16, although the exact functional form of the curve is not important.

To evaluate acquired musical skills, J. G. Watkins (1942) designed a test to assess the level of performance of a musical piece by 151 cornet players who had had from 1 to 10 years of prior practice. Music performance was related to the number of years of practice by a functional form very similar to the solid line in Figure 16. Longitudinal studies of elite performers found that their recorded performance at younger ages shows monotonic improvement even well after the age of 18 when physical maturation is completed. Curves for the personal best performance on an event as a function of age and training for elite performers (see Ericsson, 1990, for some examples) have roughly the shape shown by the solid line in Figure 16 until a contestant attains the highest performance of his or her career. The rating system in chess has properties of an interval scale, and Elo (1978) found that the earlier chess ratings increased in a similar manner as a function of age well through their twenties for three groups of elite chess players.

When we consider the evidence for the 10-year rule of preparation to attain international-level performance, even when individuals started during adolescence and adulthood, a rather continuous acquisition of expert performance is implicated. Evidence for the accumulated effects of deliberate practice on expert performance is clearer when we examine mediating skill components, such as increases in amount of accessible knowledge, where the acquisition process is well established in laboratory studies. Differences in expert performance have been successfully related to tests measuring the amount of relevant knowledge and procedures in chess (Pfau & Murphy, 1988), mathematics (Webb, 1975), and sports (French & Thomas, 1987). The organization and accessibility of knowledge has also been shown to distinguish individuals at different levels of expertise in physics (Chi, Glaser, & Rees, 1982), medicine (Feltovich, Johnson, Moller, & Swanson, 1984; P. E. Johnson et al., 1981), and social science (Voss, Greene, Post, & Penner, 1983).

Unlike the rapid decay of acquired knowledge seen in laboratory studies, repeated application and use of knowledge over extended periods leads to remarkably good retention of the knowledge even after years or decades of disuse. Bahrick and Hall (1991) found considerable retention of knowledge of mathematics for content from a successive sequence of courses with the exception of the most advanced mathematics course taken. Similarly, once an individual has acquired a reasonably high level of skill, it is possible for that individual to attain an above-average performance or even regain the original performance after a brief period of retraining. A moderate level of acquired skill in typing (Baddeley & Longman, 1978; Hill, 1934, 1957; Hill, Rejall, & Thorndike, 1913), language (Bahrick, 1984), and other domains (Farr, 1987) appears to decay slowly and can be rapidly reacquired.

The demonstrations of retained skill without recent practice as well as of regaining a considerable level of skill with limited current practice are relevant to our framework for a couple of reasons. First, such demonstrations might appear to show a complete dissociation of current practice and performance. Given that acquired skill resulting from prior accumulated practice cannot be observed, it could easily be incorrectly attributed to native talent. Second, the relatively small amount of practice required to maintain or regain a previously acquired level of nonelite performance is quite different from the massive amount of practice required originally to attain that level or improve even more. Furthermore, elite performers rarely experience problems from long periods of inactivity because once they take up systematic practice they continue practicing at a uniformly high level, and we assume that the amount of deliberate practice necessary to specifically maintain earlier attained levels of performance is negligible for active young experts.

Our framework postulates that individual differences in performance at a given age are a function of acquired characteristics, which in turn are directly related to the accumulated amounts of deliberate practice. Given the earlier reviewed evidence for the stability of daily and weekly amounts of practice, it is possible to approximate the accumulated amount of practice on the basis of weekly estimates. There are two sources of individual differences. First is the number of years of deliberate practice, which is a linear function of starting age. In the General Discussion we discuss the possibility that assessed talent prior to practice is the cause for initiating practice early. Second, individual differences in the weekly amount of practice at a given time will influence the rate of increase of accumulated practice and the current level of performance. Current performance and current level of practice are determined concurrently and the direction of causality cannot be determined on temporal grounds. In the following review of evidence on weekly amounts of practice, we discuss additional evidence on the direction of causality.

### *Relation Between Starting Age and Performance*

During childhood and adolescence the performance of an individual is evaluated by comparison to those of other individuals of the same age. An individual starting at an earlier age would have accumulated more deliberate practice and thus have acquired a higher level of performance. An individual exhibiting a higher performance at any age would be more likely to be given resources and support by the environment. The dashed line in Figure 16 illustrates performance as a function of age for an individual who starts practicing later in life than the individual represented by the solid line. In this ideal case, the dashed line is simply shifted to the right, which gives the individual with the earlier starting age a higher performance level at all ages. Even in a more realistic case, where the performance level of individuals starting later would initially increase faster, the advantage of an early start would remain. In many different domains elite performers tend to start deliberate practice and instruction at remarkably young ages. In this section we consider the starting ages of music performers, athletes, and chess players. Information about world-class and eminent performers will also be included as their development is assumed to match or surpass the top-level expert performers.

A discussion of music performers requires a separate review for different instruments. Consistent with the observation that it is more difficult for a child to play a normal-sized violin than a piano, we found that our four groups of expert violinists were older when they started than were the expert pianists, $F(1, 40) = 9.60$, $p < .01$. This comparison is shown in Table 3. Although we found no statistically reliable differences among the starting ages of the different groups of adult violinists, these violinists started almost 3 years later than a group of the best solo violinists of the 20th century (Heizmann, Krampe, & Ericsson, 1993), $F(1, 41) = 18.88$, $p < .001$. Only those 13 violinists who had had a solo career for more than 20 years and were mentioned by both Roth (1982, 1987) and Schwarz (1983), three main reference books, as internationally famous violinists born in the 20th century were included in this group of outstanding performers. Expert pianists in Study 2 started instruction at nearly the same age as the age given by Sosniak (1985) for pianists who win international competitions, which is similar to internationally famous pianists from the 20th century (Heizmann et al., 1993). Expert pianists in their fifties and sixties (Krampe, 1991) had a starting age of 7.8 years, which was considerably older than for the young experts in Study 2 and the famous pianists. The starting ages for amateur pianists are reliably older, as we reported in Study 2. It appears necessary for professional musicians to start earlier than most of the amateurs in the same domain. The large sample of elite music performers studied by Manturzewska (1990) contained no individual who had started later than age nine.

In sports, the time at which an individual first engages in the activity is much less closely linked to the start of deliberate practice than to the start of competition in an event after the individual joins a team. Table 3 summarizes data on starting ages for athletes at different levels of performance in swimming, gymnastics, running, and tennis.

Chess differs from music and sports in that chess is not normally studied under the close supervision of professional teachers and coaches who direct daily practice activities. Even in chess, however, some critical events and indicators enable us to assess players' early exposure and occupation with the game. To be able to play chess, a beginner must receive an explanation of the rules, and a chess board has to be available. Hence the starting age for playing chess is fairly distinct and can be easily reported, especially by chess players. Krogius (1976) presented biographical data on world-famous chess masters born in the 19th and 20th centuries. The oldest starting age among Krogius' grand masters was 17. For chess players born in this cen-

Table 3
*Starting Ages for Performers at Various Levels in Different Domains of Expertise*

| Domain | Amateurs | Regional | National | International | Highest |
|---|---|---|---|---|---|
| Music | | | | | |
| Violin | | | 7.7[a] | | 5.0[b] |
| Piano | 9.9[c] | | 5.8[c] | ≈ 6.0[d] | 5.8[b] |
| Chess | | | | | |
| Starting age | | | 10.3[e] | 7.25[e] | 9.75[f] |
| Joining club | | | 13.8[e] | 10.5[e] | |
| Sports | | | | | |
| Gymnastics | | 9.7[g] | 8.2[g] | | |
| Running | | | 10.5[h] | | |
| Tennis | | | | 6.5[i] | |
| Swimming | | | 9.6[g] | 7.0[j] | |

[a] Study 1. [b] Heizmann, Krampe, and Ericsson, 1993. [c] Study 2. [d] Sosniak, 1985. [e] Doll and Mayr, 1987. [f] Krogius, 1976. [g] Kaminski et al., 1984. [h] Sack, 1980. [i] Monsaas, 1985. [j] Kalinowski, 1985.

tury, the oldest starting age is 14, and the mean starting age is 9 years. We found that in Krogius' data, the starting age is closely correlated, $r(38) = 0.48$, $p < .001$, with the age of players' first achievement of an international level of performance. According to Mayr (1989), a small sample of contemporary grand masters reported starting at about 7 years of age, a finding that suggests a historical trend toward younger starting ages. The starting age for a larger sample of chess masters was 10.5 years of age. The age at which contemporary grand masters joined a chess club is reliably younger than the age for contemporary national-level chess masters in Mayr's sample (Ericsson, Tesch-Römer, & Krampe, 1990).

Consistent with our hypothesis, we find that the higher the level of attained elite performance, the earlier the age of first exposure as well as the age of starting deliberate practice. In some domains such as music and ballet, it is generally found that elite performers have started well before the age when most children first gain access to training.

### *Weekly Amount of Practice and Performance During the Development of Elite Performance*

Once individuals have started with deliberate practice, additional differences in accumulated practice can be due to individual differences in the weekly amount of deliberate practice at the same ages. The dashed line in Figure 16 illustrates a case with a higher level of weekly practice, which would give an individual a uniform advantage compared with the individual with the same starting age but with less weekly practice (dotted line). This case is similar to the differences in weekly practice intensity between the four groups of violinists in Study 1.

In our review of practice in the domain of music, we found evidence for the claim that deliberate practice is a specific type of music-related activity, which is judged to be most relevant for improvement of music performance, effortful, and less inherently enjoyable than leisure and several other music-related activities. Individual differences in the amount of deliberate practice in music at the same ages were found to correlate with current and future music performance, even sometimes in the absence of reliable differences in the overall amount of time spent on music-related activities. Given that the distinction between deliberate practice and other domain-related activities is new, it is difficult to find available data relating performance and weekly amounts of deliberate practice. We review available evidence on indicators of deliberate practice in sports, where coaches supervise training and also in chess, where individuals are assumed to acquire their skill without explicit guidance.

On the basis of interviews and questionnaires, future elite performers have been found to spend a large amount of time per week on their domain even at a young age: 20 hr per week by tennis players around age 13 (Monsaas, 1985) and 24–30 hr per week by swimmers around age 11 (Kalinowski, 1985). Given that these childrens' and adolescents' activities are for the most part supervised by coaches, it can be inferred that a significant portion of this time is spent in deliberate practice. Better estimates of current levels of practice have been obtained by Kaminski et al. (1984) who used a diary procedure to assess the duration of actual practice for national-level swimmers, ice-skaters, and gymnasts at ages 15–16. These athletes practiced about 16 hr per week, almost 3 hr more than the athletes below the national level practiced. These pure estimates of practice cannot be directly compared with the retrospective estimates for the international-level athletes (Kalinowski, 1985; Monsaas, 1985), but they appear to be considerably lower. On the basis of the questionnaire responses from a large sample of male runners, 17–18 years old, Sack (1975) estimated the frequency of training during a week for runners at different levels of performance. Runners at the national level trained 4.9 times per week; runners at regional and local levels trained 4.2 and 3.2 times per week, respectively. Apart from the number of participations at national championships, the best predictor of the subjects' best running performance was the frequency of training ($r = .56$). Questionnaire items referring to motivation (e.g., "regular training" and "training during holidays") were reliably correlated with both frequency of practice and performance. The performance of adult marathon runners in a race can be predicted with high accuracy from the regularity and amount of practice during the 9 weeks preceding the race (Hagan, Smith, & Gettman, 1981). The length of training runs and the total distance covered per week accounted for nearly half of the variance in actual running times on the marathon. Even better evidence for the relation between performance and amount of practice comes from recommended training schedules for different levels of competitive runners (Glover & Schuder, 1988). Championship competitors not only take more time practicing and cover longer running distances than advanced and basic competitors, but they spend proportionally more time on training directed at improving endurance and speed, such as interval training and fartlek. An analysis of the training schedules of the world's best long-distance runners shows that they uniformly put a major emphasis on speed work (Noakes, 1991), which is typically completely absent in the training of recreational runners. A recent interview study (Sachs, 1991) of conditions inducing the enjoyable state called "runners' high" showed the importance of a comfortable pace during an extended run and the absence of any strain to run fast, which seems to preclude deliberate practice.

Unfortunately, we did not find any systematic data on the amount of time elite chess players spend playing and studying chess. There are, however, some unique data available about improved competence in chess as a function of age (Elo, 1978). With the Elo Rating System, it is possible to assess the chess skills of young chess players with the same interval scale used for adults. By analyzing the development of chess skills in many individuals who reached world class, international level, and national level, Elo (1978) found that at 11–12 years of age, differences in chess playing ability were relatively small. At that age, all three groups of subjects played at the level of average adult chess players. Large improvements in ability were observed for the players during adolescence (12–18 years of age). From the ages of 18–22, improvements started leveling off and differences in ability between the three groups remained relatively unchanged. These results are unique within the three domains considered in this article because musical performance is not rated on an age-independent scale, and physical growth during adolescence seriously confounds available measures of performance in sports.

Even less information is available on the way full-time chess players allocate their time to chess-related activities. Charness (1991) estimates that the actual time spent playing chess games at tournaments, chess clubs, and private games constitutes only a fraction of the time available to chess players and that they give more time to individual study and analysis of chess positions and published chess games. In informal interviews, chess masters report spending around 4 hr a day analyzing published chess games of master-level players. Selecting the next moves in such games provides an informative learning situation in which players compare their own moves against those selected in an actual game. A failure to select the move made by the chess masters forces the chess players to analyze the chess position more carefully to uncover the reasons for that move selection. There exists also a large body of chess literature in which world-class chess players explicitly comment on their games and encyclopedias documenting the accumulated wisdom on various types of chess openings and middle-game tactics and strategies. An examination of biographies of world-class chess players (Karpov & Roshal, 1980; Korchnoi, 1978) shows, contrary to common belief that chess players develop their chess skills independently, that these elite players have worked closely with individuals (other more advanced players, often chess masters) who explicitly taught them about chess and introduced them to the literature on chess. Of particular interest are Bobby Fischer and Judit Polgar, who attained their international grand master status at the youngest recorded age, namely age 15. Bobby Fischer learned the rules of chess at age 6 and in the same year he started studying his first book of chess games (F. Brady, 1973). As a result of his mother's initiative, at age 7 Bobby got in touch with the president of the Brooklyn Chess Club, who tutored Bobby on a weekly schedule for several years and actively supported Bobby's chess career. At age 12 Bobby joined the Manhattan Chess Club, which was one of the strongest in the world. Around that time he started close interactions with the strong chess master Jack Collins several times a week and got free access to Collins' outstanding library of chess books. From that point Bobby started collecting chess books, and in 1973 he had about 400 books and thousands of magazines and journals (F. Brady, 1973). According to Brady (1973), Bobby Fischer became the best educated chess theoretician in modern times. Judit Polgar was tutored in chess by her father from age 4 (J. Radford, 1990) or, at least, age 5 (McFadden, 1992) and carefully coached by her father. Judit did not attend regular school and was allowed to spend all the time with her parents, who were both teachers.

Consistent with our framework, we find that elite performers spend much time on deliberate practice and, in those cases in which amount of weekly deliberate practice has been recorded, high level of performance is associated with higher levels of deliberate practice at the same age. Another striking, but not surprising, finding is that the amount of weekly practice for individuals maintaining regular practice increases with age, accumulated practice, and performance. Given the early starting ages and the high level of practice of the expert performers the available data do not allow an analysis of the independent and interactional effects of those variables. Furthermore, the structure of training programs in virtually any domain adapts the deliberate practice activities to suit the level of current performance. Increased complexity and proficiency of acquired skills and characteristics leads to increased performance and allows for engagement in more challenging deliberate practice activities for a longer period of time. This would be particularly clear for domains with endurance activities, such as long-distance running. In our framework we expect that increased level of acquired skill and performance would increase the maximal level of deliberate practice that can be sustained over extended periods of time without exhaustion.

In our framework accumulated deliberate practice causes acquired skill and characteristics, which in turn cause performance, and some of these characteristics increase the maximal amounts of possible practice. It is, of course, possible that non-acquired factors, such as innate talent, might influence performance directly. A performance advantage resulting from such factors can allow individuals, essentially by definition, to complete the same activities (including deliberate practice) for longer times with the same amount of effort. Although this mechanism provides an account for individual differences in work-related activities, where the goal is to maximize the amount produced, we believe that it cannot be extended to deliberate practice for the following reasons: The goal of deliberate practice is not "doing more of the same." Rather, it involves engaging with full concentration in a special activity to improve one's performance. As deliberate practice is not inherently enjoyable, there doesn't seem to be any reason for engaging in it or prolonging its duration unless the individuals and their teachers believe that their performance improves as a result. Many other domain-related activities are judged to more enjoyable than deliberate practice and they should be preferred. Hence, there doesn't seem to be any reason for engaging in deliberate practice, and especially prolonging its duration, unless the individuals and their teachers believe that their performance improves as a result.

Further evidence against the hypothesis that higher levels of performance cause an elevated level of deliberate practice is found for adult elite performers. The general level of deliberate practice has been increased in many domains in the recent past. For example, the training distances in swimming were almost doubled in preparation for Olympic Games in 1972 (Kalinowski, 1985). The steady improvement of world records in sports is generally recognized to reflect more practice and, in particular, the faster improvement of world records for women is believed to be due to disproportionate increase in the levels of training for women (Wells, 1991). In Study 1 we found differences in accumulated practice but no differences in the current levels of deliberate practice for the best and the good expert violinists. The daily amount of around 4 hr of deliberate practice was also found for the expert pianists, raising the possibility of a more general limit on the maximal amount of deliberate practice that can be sustained over extended time without exhaustion.

### *Maximal Levels of Deliberate Practice Sustained Over Extended Periods*

According to our framework, elite performers attempt to maximize the improvement of performance all through their development and, thus, should reach in adulthood the highest stable levels of deliberate practice that they can sustain without exhaustion. During adolescence, the daily lives of future elite performers are quite constrained by school activities. In spite of this, Kaminski et al. (1984) found that young elite performers in music and various types of sports, such as gymnastics, swimming, and ice-skating, spent more than 15 hr on weekly practice. Furthermore, this amount did not differ systematically across domains. When expert performers make a full-time commitment to the domain, our studies showed that they spend between 50 and 60 hr per week on domain-related activities. Less than half of that time (about 25 hr per week) is spent on deliberate practice, and this time is distributed across the entire week in practice sessions of limited duration. Our analyses of rest and relaxation were consistent with our claim that these individuals had attained a level of deliberate practice limited not by available time but by available resources for effortful practice.

A similar pattern holds true for professional athletes. Elite long-distance runners usually run twice a day and cover distances from 65 to 140 miles every week of the year (Hagan et al., 1981; Wallingford, 1975). From published reports in the magazine *Runner's World* on the weekly practice schedules of professional long-distance runners who are in complete control of the duration and distribution of practice, it is clear that the vast majority of runners practice every day except for days during the weekend with competitions. A normal day of practice consists of a session before lunch and a more strenuous session in the afternoon. The duration of a training session is about 45–90 min and the daily total of deliberate practice amounts to 2–3 hr. The total time including preparation, warm-up, massage, and so forth, is considerably longer. Similar estimates are reported for other types of sports, such as swimming (Reilly, 1990b) and cycling (Burke, Faria, & White, 1990). Athletes' pursuit of most other types of sports is characterized by maximal efforts to train without inducing exhaustion and burnout (Reilly & Secher, 1990). Similar to musicians, the amount of deliberate practice is not limited by available time; professional athletes spend their "free" time on recuperation and relaxing activities. Olympic athletes sleep for close to 8 hr and in addition take a half-hour nap each day (Coleman, 1986). Many elite runners take a nap between daily workouts (Glover & Schuder, 1988). The complete focus on a single domain by elite performers in music and sports is further evidence that their efforts to reach their highest performance in that domain are maximal.

Studies of international-level performers have included artists and scientists as well as athletes and musicians. The studies reported in a book edited by Bloom (1985a) show several clear parallels between the development of artists and scientists on the one hand and that of athletes and musicians on the other. Years of intensive preparation under the supervision of a master invariably precede the attainment of international recognition. Consistent with the data on athletes and musicians, eminent scientists are completely absorbed in their vocation so "as to seriously limit all other activity" (Roe, 1953, p. 49). The degree of commitment has been quantified in a couple of sources (Bruner, 1983; J. R. Hayes, 1981) to suggest that scientists must work 80 hr per week for an extended time to have a chance of reaching an international level in their field. Although our theoretical framework supports the full commitment to the domain it takes issue with the implication that one should maximize the number of hours of any domain-related activity. Instead we suggest that one should identify those activities that are most likely to result in the desired achievements.

In science an eminent achievement nearly always corresponds to a new theory or idea presented in the written publication of a persuasive argument. The deliberate activities that are necessary for producing such a rare result consist of focused and extended work developing and refining generated theoretical solutions to selected general problems. We believe that during the process of writing scientists develop and externalize their arguments. The written products can be successively criticized and improved by the scientists themselves, even after long delays, and also easily shared with other scientists for evaluation and comments. The writing of expert authors on new topics is deliberate and constitutes an extended knowledge-transforming process, quite unlike the less effortful knowledge-telling approach used by novice writers (Scardemalia & Bereiter, 1991). In support of the importance of writing as an activity, Simonton (1988) found that eminent scientists produce a much larger number of publications than other scientists. It is clear from biographies of famous scientists that the time the individual spends thinking, mostly in the context of writing papers and books, appears to be the most relevant as well as demanding activity. Biographies report that famous scientists such as C. Darwin, (F. Darwin, 1888), Pavlov (Babkin, 1949), Hans Selye (Selye, 1964), and Skinner (Skinner, 1983) adhered to a rigid daily schedule where the first major activity of each morning involved writing for a couple of hours. In a large questionnaire study of science and engineering faculty, Kellogg (1986) found that writing on articles occurred most frequently before lunch and that limiting writing sessions to a duration of 1–2 hr was related to higher reported productivity. Many scientists involved in laboratory studies, teaching, and administration must cope with external constraints on their time that may partially determine how they schedule writing and thinking. In this regard, it is particularly interesting to examine the way in which famous authors allocate their time. These authors often retreat when they are ready to write a book and make writing their sole purpose. Almost without exception, they tend to schedule 3–4 hr of writing every morning and to spend the rest of the day on walking, correspondence, napping, and other less demanding activities (Cowley, 1959; Plimpton, 1977).

Further evidence that elite performers try to maximize the effectiveness of their deliberate activities is found in their preference for engaging in them at a certain time of day. The preferred time of day for deliberate activities differs across domains. Scientists and authors consistently chose to use mornings for demanding writing, and athletes prefer afternoons for their most strenuous practice sessions. Research on the effects of the time of day (Folkard & Monk, 1985) shows that simple perceptual–motor performance is enhanced in the afternoon and early evening, whereas intellectually demanding activities are enhanced in the morning. Systematic studies confirm that performance of elite athletes is reliably higher in the afternoon and evening than in the morning (Winget, DeRoshia, & Holley, 1985).

Across several different types of domains, elite performers are found to engage in similarly high levels of selected activities, such as deliberate practice. The complete focus on the domain provides most of these individuals with much available time, yet the time for deliberate practice occupies only a fraction of that time, with clear preferences about the best time of day. The amount of time they spend on practice and other highly relevant activities appears to be limited by how long the demanding activity can be continued with sustained benefits rather than by the available time.

### *An Account of Individual Differences in Elite Performance in Terms of Deliberate Practice*

In our framework we distinguish between two types of elite performance: expert and eminent performance. Expert performance reflects the mastery of the available knowledge or current performance standards and relates to skills that master teachers and coaches know how to train. Eminent performance requires that the individual go beyond the available knowledge in the domain to produce a unique contribution to the domain, hence it is, by definition, not directly instructable. Our framework proposes that the probability of making eminent contributions is related to the amount of deliberate efforts directed toward that goal.

Our framework makes stronger claims for the acquisition of expert performance. We argue that expertise and expert performance are the result of extensive engagement in relevant practice activities supervised by teachers and coaches and that individual differences in ultimate performance can largely be accounted for by differential amounts of past and current levels of practice. Across many domains of expertise, a remarkably consistent pattern emerges: The best individuals start practice at earlier ages and maintain a higher level of daily practice. Moreover, estimates indicate that at any given age the best individuals in quite different domains, such as sports and music, spend similar amounts of time on deliberate practice. In virtually all domains, there is evidence that the most important activity—practice, thinking, or writing—requires considerable effort and is scheduled for a fixed period during the day. For those exceptional individuals who sustain this regular activity for months and years, its duration is limited to 2–4 h a day, which is a fraction of their time awake.

Contrary to the popular "talent" view that asserts that differences in practice and experience cannot account for differences in expert performance, we have shown that the amount of a specific type of activity (deliberate practice) is consistently correlated with a wide range of performance including expert-level performance, when appropriate developmental differences (age) are controlled. Because of the high costs to the individuals and their environments of engaging in high levels of deliberate practice and the overlap in characteristics of deliberate practice and other known effective training situations, one can infer that high levels of deliberate practice are necessary to attain expert level performance. Our theoretical framework can also provide a sufficient account of the major facts about the nature and scarcity of exceptional performance. Our account does not depend on scarcity of innate ability (talent) and hence agrees better with the earlier reviewed findings of poor predictability of final performance by ability tests.

We attribute the dramatic differences in performance between experts and amateurs–novices to similarly large differences in the recorded amounts of deliberate practice. Furthermore, we can account for stable individual differences in performance among individuals actively involved in deliberate practice with reference to the monotonic relation between accumulated amount of deliberate practice and current level of performance. The individuals who start early and practice at the higher levels will have a higher level of performance throughout development (the solid line in Figure 16) than those who practice equally hard but start later (line with long dashes). The differences in performance between subjects with the same starting age but differing levels of practice are shown in Figure 16, where the line with long dashes shows the performance associated with a high level of practice and the dotted line a lower level of practice.

Figure 16 illustrates how our framework can account for many common observations about skill acquisition and stable individual differences in performance. Individuals with a later starting age for deliberate practice will experience rapid initial improvements and may feel that they will in a few years attain the level of individuals with earlier starting ages and thus higher performance at comparable ages. However, because the rate of improvements with practice decreases and becomes less perceptible, the difference between the two groups remains distinct, and an attribution of greater talent for the group with earlier starting ages is natural. In the current system with age-matched evaluation of performance, it is impossible for an individual with less accumulated practice at some age to catch up with the best individuals, who have started earlier and maintain maximal levels of deliberate practice not leading to exhaustion. As noted earlier, the amount of possible practice appears to slowly increase with accumulated practice and skill. Hence, individuals intent on catching up may suddenly increase the amount of deliberate practice to the level or even above the level of the best performers. Within months these individuals are likely to encounter overuse injuries and exhaustion and may terminate their engagement in the domain convinced that the best performers are qualitatively different. Furthermore, the difference in accumulated deliberate practice in late adolescence for the good and best violinists is remarkably large and to eliminate this difference the good violinists would have to practice an additional 5 h per week beyond their current optimal level of weekly practice for more than 8 full years.

The problem of overcoming differences in skill resulting from accumulated practice is further amplified by the continuous selection of individuals because of the costs associated with the maintenance of deliberate practice. In all domains there is only a small number of positions in which individuals can freely continue their efforts to attain eminent performance without severe occupational constraints. Prior to that, the best training environments with master teachers and coaches carefully select the individuals with the best performance in late adolescence. Institutions providing grants and master teachers have strong restrictions on the maximum age of applicants. From the start of training, the individual and his or her teachers and parents constantly monitor and compare the current performance to that of other individuals of the same age in the domain to assess whether the costs in time, effort, and money associated with sustaining high levels of deliberate practice are warranted. A high level of performance, whether it is due to acquired skill or to innate talent, will always be the best predictor of future performance and will therefore attract motivational support and necessary resources. The majority of individuals in the domain are not provided these resources because of their lower current performance at the relevant ages with lost opportunities for further development.

In addition, our theoretical framework can easily account for changing levels of performance in different historical times and in different cultures by corresponding differences in the encouragement and availability of deliberate practice. Wells (1991) attributed the big differences in athletic performance between men and women, which are currently decreasing as a function of changing sex-role expectations, to differential "opportunities for participation at an early age and the availability of expert coaching" (p. 49).

In summary, our framework can account for a wider range of empirical characteristics of exceptional performance than the talent view. Although we are reluctant to accept individual differences in innate abilities (talent) and any important role of these differences in determining expert performance, we do not rule out the importance of individual differences in general. In fact, within our framework we would expect that several "personality" factors, such as individual differences in activity levels and emotionality may differentially predispose individuals toward deliberate practice as well as allow these individuals to sustain very high levels of it for extended periods. We now turn toward a reevaluation of the evidence linking expert performance and innate abilities and characteristics reviewed in the introduction. Once individuals have started deliberate practice, it is virtually impossible to distinguish the role of natural ability (innate talent) from that of acquired characteristics and skill in their current level of performance. This is particularly true as the effects of extended practice, especially at young ages, are much more far reaching than commonly believed possible. In the General Discussion we review evidence on the possibility that early signs of natural ability (talent) are the cause of especially early start of practice, as well as the reverse possibility that characteristics assumed to reflect innate talent are the result of deliberate practice.

## General Discussion

In a couple of respects our findings and those from the literature we reviewed are consistent with two of the three factors Galton (1869/1979) thought necessary for attaining eminent performance. The necessity for 10 years of preparation is clearly consistent with Galton's requirement of motivation and perseverance. The quantified role of deliberate practice corresponds nicely with Galton's prerequisite of "adequate power of doing a great deal of very laborious work" (p. 37). Although both of these factors could be plausible loci for heritable differences, Galton and subsequent researchers in genetics have emphasized that a third factor, namely, innate ability, is the major source of heritable differences that determine eminent performance.

The best information about the innate attributes characterizing the best performers can be gained by careful examination and analysis of critical attributes that distinguish these individuals from less successful individuals. Because innate differences have traditionally been viewed as impossible to modify, researchers have been interested primarily in innate differences that can be detected in children at very early ages and thus aid parents, teachers, and coaches in guiding these children into the domain appropriate to their talents. Selecting a domain is more difficult if, as Galton believed, general talents predispose a child for eminence in almost any domain. If there is such a thing as a general talent, availability and the child's early interest in a domain would govern the selection of a domain for early start of practice. Both the hypotheses of general and domain-specific talents would predict that a child would exhibit signs of talent after a short period of exposure to the domain. This raises the possibility that talent revealed early provides the environmental support and motivation for the early start of practice and the high levels of deliberate practice observed while individuals are attaining expert performance. According to this hypothesis, early talent is the cause of increased practice, and the correlation between practice and elite performance is confounded by differences in initial talent.

In the following discussion we reexamine the evidence, cited in the introduction to this article, for the role of innate differences in the attainment of expert performance. The dichotomy between characteristics that can be modified and those that cannot may not be valid when we examine the effects of over

10,000 h of deliberate practice extended over more than a decade. We first consider the possibility that many of the physical characteristics of elite performers are the result of adaptation to many years of intense training and are not a direct expression of genes. We then discuss the abilities and characteristics displayed by children and "idiot savants" and consider whether these abilities are acquired through normal learning and adaptation. We discuss the relation between early performance and late performance in the acquisition of skill and expert performance, and we review evidence on the qualitative differences that emerge with extensive practice. We review evidence for the role of early talent and parent–offspring relations in acquired performance. Finally, we offer an alternative account in terms of "perceived talent" and predisposition to deliberate practice.

### *Distinct Physical Characteristics of Elite Performers*

Perhaps the most commonly cited evidence for innate talent is that elite athletes in many types of events have unique physical advantages. The physical and anatomical differences between elite athletes and less successful athletes or even normal adults are often simply assumed to reflect pure genetic factors. However, some of these differences may not be innate but instead may be the result of physiological adaptations to extremely intense practice extended over many years. If these characteristics are purely genetic, it should be possible to demonstrate that they are inherited and that they are manifest in the absence of any special environmental influences. Ideally, it should be possible to specify the biochemical mechanisms that control the emergence of these characteristics.

Height is an excellent example of a characteristic for which the genetic mechanism has clearly been demonstrated. It is well-known that genetic factors closely determine height in industrialized countries with adequate nutritional support (Wilson, 1986). In developing countries such as Mexico (Malina & Bouchard, 1991), the average height of well-nourished individuals can be as much as 7 inches higher than the average height of undernourished individuals. The age at which the highest increases in height are observed during development also appears to be genetically determined (Malina & Bouchard, 1991). Environmentally induced differences in the height of newborn monozygotic twins disappear during development (Wilson, 1986). Moreover, the primary method of altering height, except for reduction by surgery, consists of supplementary injections of growth hormone during development. All of this persuasive evidence compels us to attribute adult height primarily to genetic factors when nutritional requirements are met.

One might assume that all or most morphological characteristics of the bodies of adults are similarly determined primarily by genetic factors. Studies comparing elite athletes to other athletes and nonathletes have revealed systematic differences in sizes of hearts, lungs, bones, and muscles; proportions of slow-twitch and fast-twitch muscles; amount of fat; number of capillaries supplying blood to muscles; as well as in aerobic power and ability. Many of these differences were originally believed to be almost completely determined by genetic factors in the normal population of adults. Considerable empirical work has shown, however, that these differences have only a moderate genetic component (Bouchard, 1986). In a recent study Fagard, Bielen, and Amery (1991) found reasonably high genetic components for maximal aerobic and anaerobic power even when differences in the amount of exercise and other life-style factors were controlled. However when testing was made at submaximal levels—more comparable to normal activity levels—the amount of exercise and other life-style factors accounted for all systematic variance. This result suggests that many physiological characteristics are the result of adaptation to a level of daily activity.

For older sedentary adults, additional scheduled walks improve aerobic ability, whereas young adults require sustained training at around 75% of maximal heart rate to realize improvements (Ericsson, 1990; Haskell, 1989). Extended exercise programs show that aerobic ability is not fixed but can be dramatically changed. After a year of exercise, adults can increase their aerobic activity up to 35% and in some instances up to 50% (Haskell, 1989). However, to reach the aerobic ability of elite endurance athletes, average nonathletes would have to increase their aerobic ability by 75%. In Haskell's (1989) view, this fact supports the role of genetic factors; but Haskell's inference is based on extrapolation from training programs for fully developed adults, programs that last a fraction of the duration known to be required to attain expert-level performance in sports.

Detailed examinations of the anatomical changes resulting from intense exercise reveal that the human body is remarkably adaptable. The number of capillaries supplying blood to muscle fibers changes after a few weeks of practice (Salmons & Henriksson, 1981). Increased numbers of mitochondria, as well as other biochemical changes, which increase the efficiency of metabolic processes, result from extended exercise (C. Williams, 1990). Even the characteristics of muscle fibers can be changed, namely from fast-twitch to slow-twitch and vice versa. Although this conversion of muscle fibers has been documented in animal research (Salmons & Henriksson, 1981), a review by Howald (1982) showed that the fiber conversion demonstrated in animals can be generalized to human skeletal muscles. There is good evidence that environmental conditions can influence the volume of the lungs. Greksa (1988) examined individuals of the same ethnic and racial background who at various ages moved from locations at sea-level to a location at over 10,000 feet. He found that the younger the age at the time of the move to high altitude, the larger the lung capacity and the depth of chest.

The best evidence linking intensive training directly to observed changes in heart size comes from longitudinal studies of young athletes attaining expert performance and of older athletes terminating their careers and practice regimens. Elovianio and Sundberg (1983) found that elite long-distance runners acquired greater aerobic power and larger heart volumes during a 5-year period of training but showed no initial superiority at age 14. Rost (1987) found during a longitudinal study of children from age 8 to 11 that heart volumes increased much more in young swimmers than in nontrained children (control). It appears that at least 1 year of intense training is required before the size of a human heart begins to change. Similarly, once athletes terminate their training the increased heart sizes remain, but in the absence of exercise the heart volume regresses to within normal range over a 10-year period; Rost (1987) reports a volume reduction of 42% in one case. Howald (1982) reports case studies of top athletes who were forced to stop or reduce training because of injuries. Drastic decrements in the percentage of their slow-twitch fibers occurred within 6 months to 1 year.

Because most sports involve only some of the muscles in the body, it is possible to contrast these intensively trained muscles with other muscles in the same athletes. Tesch and Karlsson (1985) examined the size and frequency of fast- and slow-twitch fibers in the muscles of different types of elite athletes as well as of students serving as control subjects. They found that differences in the percentage of slow-twitch fibers in elite athletes' muscles occur only for muscles specifically trained for a sport (legs in runners and back muscles in kayakers), with no differences for untrained muscles.

Some physiological changes, such as heart enlargements, require years of increasingly intense practice to emerge and take years to regress once training is stopped. For example, Eriksson, Engström, Karlberg, Saltin, and Thorén (1971) found that swimmers' aerobic ability decreased by 29% five years after training had stopped. The increased lungs and hearts of these swimmers had not changed yet. Other changes are gained and lost more rapidly. For example, aerobic power in bicyclists (Burke et al., 1990) increases over 50% during the competitive season every year. Female gymnasts reduce the proportion of their body fat from average levels by 50% during the competitive season (Reilly & Secher, 1990). Within a week of no training, swimmers lose on average 50% of the respiratory capacity of their muscles (Reilly, 1990b), but regaining this capacity takes considerably longer during retraining.

In sum, most anatomical characteristics, unlike height, are remarkably adaptable to intense physical activity extended over long periods of time. Detailed biochemical mechanisms mediating the transformation of the phenotype of muscle fibers in response to intense physical activity (Booth, 1989) and general mechanisms for influence of environmental factors on developmental outcomes are now being proposed and evaluated (Gottlieb, 1992). Many extreme physical characteristics in elite athletes are the result of the same adaptive processes that determine similar characteristics in the normal population, and the extreme differences in these attributes correspond to the equally extreme differences in the amount and intensity of practice between these two groups.

A reasonable objection to the generalizability of the effects of training for all adults can be made on the basis of the large dropout rate for adults from exercise programs (Martin & Dubbert, 1985). It is apparently not possible to motivate all people to engage in regular exercise. Research on the effects of extended exercise in animals has demonstrated that intensive exercise results in conversion of muscle fibers (Pette, 1984) and enlargement of hearts (Harpur, 1980). The primary method for motivating animals to exercise vigorously is punishment, for example, running on a treadmill with a slope to avoid a bar giving electric shock or swimming with or without additional weights. However, similar but less pronounced effects have been attained from animals that voluntarily run in a wheel compared with those in a sedentary condition (Harpur, 1980). Recent research has shown activity-specific physiological changes resulting from extended practice also in the central nervous system. After difficult acrobatic training an increased number of synapses in the cerebellar cortex were found for rats, but not for rats engaged in extensive physical exercise, which instead exhibited a greater density of blood vessels in the same area (Black, Isaacs, Anderson, Alcantara, & Greenough, 1990). Replications of the adaptive changes with animals under controlled conditions are likely to be the best obtainable evidence on generalizability given the problems of motivating random samples of humans.

### *Early Demonstrated Abilities Assumed to Reflect Innate Talent*

In the introduction we mentioned several abilities demonstrated by children and idiot savants that have been thought to reflect innate talents and predispositions. In this section we consider one of these abilities, perfect pitch, in detail. We also briefly discuss other abilities of idiot savants and some of the anatomical characteristics of ballet dancers and swimmers.

Perfect pitch (or absolute pitch), the ability to identify isolated musical tones, is considered a sign of musical talent. Often future elite musicians and musical savants exhibit perfect pitch at an early age. Qualitatively different processes mediate the performance of individuals with perfect pitch and that of musicians who lack it. Individuals with absolute pitch tend to confuse tones with the same location in different subscales but not tones having the smallest difference in fundamental frequencies. For example, an untrained subject might confuse C with B, whereas a subject with perfect pitch would confuse C in one octave with C in a different octave (Ward & Burns, 1982). Several empirical findings suggest that perfect pitch is an acquired skill. Individuals with "perfect pitch" differ in their ability to judge pitches and perform best when judging pitches generated with the instrument they play. As the tests of ability to recognize pitch get harder, as they do when artificially generated sinus tones are used, for example, fewer and fewer subjects pass the tests (Oakes, 1955). In addition, adults can acquire perfect pitch after extended training. P. T. Brady (1970) demonstrated that he was able to acquire perfect pitch by an intriguing training procedure, which involved learning to identify a single tone. Brady reported that once developed, the identification task required little effort and that he did not have to practice purposefully to maintain the skill. No decrement in performance was reported after 6 months, and only a slight decrement was reported after 13 years (Costall, 1985). Finally, recent research (Cohen & Baird, 1990) provides evidence that normal children, especially before age 5, more easily recognize notes individually (absolute pitch) before they perceive notes as part of larger musical structures (relative pitch). These findings suggest that subjects with absolute pitch acquire the necessary skill as children and then simply maintain it for the rest of their lives (Miyazaki, 1990). Young children's acquisition of absolute pitch is intriguingly similar to the ease with which they learn a second language (J. S. Johnson & Newport, 1989), and with Japanese subjects learning to make the difficult distinction between [r] and [l] in English (Yamada, 1991).

The importance of early practice and experience for adult ability is similarly found in swimming and ballet. Ballet training must start before dancers reach age 11 to gain the necessary flexibility of joints. Stress induced during extensive training at young ages appears necessary for dancers to gain the necessary "turn out" in the different positions of demi-plie at adult ages (DiTullio et al., 1989; A. Watkins, Woodhull-McNeal, Clarkson, & Ebbeling, 1989). Dancers apparently acquire flexibility through early training as shown by a longitudinal study (Klemp & Charlton, 1989). In a large group of club swimmers (aged 8–17) the only physical measures discriminating this group from a matched control group of other types of athletes were ankle and shoulder flexibility (Poppleton & Salmoni, 1991). Statistically controlling for age, these two measures of flexibility were the best predictors of the swimmers' speed; however, no measure of current or past practice was included in the analysis. Consistent with the hypothesis that increased flexibility is acquired through extended swimming, it is common that elite swimmers have weak ankles, which are particularly susceptible to injury (Chambliss, 1988).

Certain exceptional abilities in idiot savants have been taken as evidence that innate talent accounts for exceptional performance. Given the low general level of these individuals' intellectual functioning, it has seemed plausible that exceptional memory for some types of material and exceptional perceptual abilities, such as perfect pitch, reflect inherited basic capacities. But recent research has shown that these exceptional abilities are more consistent with acquired skill than with innate talents (Howe, 1990). Often these individuals' performance on tasks measuring their abilities is exceptional only compared with their general level of functioning, which is otherwise low (Ericsson & Faivre, 1988). On the other hand, college students' performance on these tasks can be dramatically improved. Training studies for memory for numbers (Chase & Ericsson, 1982), date calculation (Addis & O. A. Parsons, unpublished and described in Ericsson & Faivre, 1988), and mental calculation (Staszewski, 1988) have shown that within weeks, college students can attain levels of performance outside the range of normal adult performance. Careful examination of idiot savants and other individuals with exceptional abilities suggests that they rely on mechanisms similar to those used by trained students, and that these individuals have had access to necessary information and opportunity to practice prior to the first public demonstration of their abilities (Ericsson & Faivre, 1988; Howe, 1990).

The only exceptional performance that has not been matched in a training study is certain individuals' immediate memory for music they have not heard previously. However, even in this case, recent studies refute the possibility that this memory performance reflects some basic, superior memory capacity (Charness, Clifton, & MacDonald, 1988; Sloboda, 1991). Superior memory is limited to music of familiar structure and does not transfer to modern atonal music (Sloboda, Hermelin, & O'Connor, 1985). This finding is consistent with one from all other instances of exceptional memory (Ericsson, 1985), namely, that knowledge mediates superior performance. In addition, Judd (1988; see Treffert, 1989, for additional references to blind musical savants) has pointed out that most of the musical savants with superior memory for music were blind. The only way they could learn new pieces of music was to memorize them by listening to them. Thus blindness provided the prerequisite motivation to acquire this memory skill. With extended practice, their memory performance for music increased and reached exceptional levels.

In summary, exceptional abilities observed in children and idiot savants are consistent with all the characteristics of acquired skills. Most of them can be easily acquired by adults through known training methods, although some of them may be more easily acquired during childhood. The motivational factors that lead children and idiot savants to focus their time and energy on activities that improve performance are still poorly understood.

### *General Difficulties of Predicting Ultimate Performance From Initial Performance: Qualitative Differences Acquired Through Extended Practice*

In the introduction we briefly reviewed the difficulties of predicting the level of expert performance individuals attain after extended practice. Bound up with the notion of innate talents, which are revealed during early performance, is the notion that the same fixed components determine both early performance and the final level of performance and thus enable observers to identify and select future exceptional performers as well as to predict their final achievement after practice. In this section we briefly review the literature on individual differences in performance as a function of practice in studies of skill acquisition. We then review some findings on the nature of individual differences in expert performance.

Extensive research on skill acquisition with college students and more representative samples, such as military recruits, shows that performance on a wide range of tasks improves monotonically as a function of many hours of practice. Current theories (J. R. Anderson, 1982; Fitts, 1964; Fitts & Posner, 1967) propose that initial performance is mediated by sequential processes, which with additional practice are transformed into a single direct (automatic) retrieval of the correct response from memory. This radical change in processing makes it difficult to identify any locus for individual differences in innate talent that could influence initial superiority as well as superior final performance. The most successful attempts to relate individual differences in ability to individual differences in performance have dealt with short-term skill acquisition. Evidence from these studies suggests that performance during the initial, middle, and final phase of skill acquisition is correlated with different types of abilities in each phase (Ackerman, 1988), initial performance being correlated with general cognitive abilities and final performance with perceptual–motor abilities. This evidence is consistent with the current theories of skill acquisition. With several hours of practice, cognitive differences are essentially eliminated, giving way to the more "basic" differences in components associated with perception and motor production. Because, however, the perceptual and motor systems show great adaptability in response to extended practice (a phenomenon discussed earlier in this article), it may be inappropriate to generalize the findings from relatively simple tasks involving 2–20 h of practice to expert performance acquired during a 10-year period of intense preparation.

Two general findings concerning individual differences in high levels of performance imply that expert performance and initial performance do not have a common basis. First, most individual differences related to levels of elite performance are due to the amount and organization of knowledge, which everyone agrees must have been acquired. Finally, memory performance for briefly presented stimuli relevant to a given domain differs as a function of the level of performance in those domains (Chase & Simon, 1973; for a review see Ericsson and Smith, 1991b), but does not generalize to scrambled versions of the same stimuli. Hence experts' superior memory performance must be mediated by knowledge about the domain, knowledge that enables them to encode meaningful relations between the elements of the stimuli.

The second general finding is that expert performers have acquired skills that enable them to circumvent general memory and processing limits. Chase and Simon (1973) originally attributed experts' superior memory to chunking in short-term memory. This account has been revised, and the exceptional memory of experts has been shown to reflect rapid storage in long-term memory (Charness, 1976; Frey & Adesman, 1976; Lane & Robertson, 1979). Building on Chase and Ericsson's (1982) skilled memory theory, Ericsson and Staszewski (1989) concluded that experts acquire memory skill enabling them to rapidly access relevant information in an extended working memory that relies on storage in long-term memory. This acquired memory skill underlies experts' superior ability to plan and evaluate potential sequences of moves in chess (Charness, 1981, 1989), sequences of card exchanges in bridge (Charness, 1989), and alternative diagnoses in medicine (Patel & Groen, 1991). The most important implication of these acquired memory skills is that they enable experts to circumvent the limited storage capacity of short-term memory. Thus these skills eliminate any restrictive influence of individual differences in this basic capacity (Ericsson & Smith, 1991b).

In tasks involving motor performance, experts can similarly circumvent basic limits of sequential processes (Salthouse, 1991). It is plausible that after extended practice, the ultimate reaction time on a simple task depends on the speed of the neural and motor components of the response process in a simple reaction. However, individual differences in simple reaction time are essentially unrelated to expert performance (Starkes & Deakin, 1984). Furthermore, the speed of motor processes is faster than would be expected from a sequence of simple reactions. Expert typists can type at great speed because they prepare several typing responses in advance of the next typing response, a finding which Gentner (1988) documented by high-speed filming of experts' finger movements on the keyboard. Monitoring of expert typists' eye fixations reveals that they look ahead in the text to be typed, and the extent to which they do so is strongly correlated with their typing speed (Butsch, 1932). Experimental manipulations of the number of characters that are displayed in advance (preview) show that a certain preview is necessary for maximal typing speed. Reduction of preview below that amount decreases typing speed, and without preview, expert typists type at speeds comparable to those of novices (Salthouse, 1984). Experts' typing speed becomes constrained by several new factors, such as the need to use the same finger in consecutive key strokes and independence of movements between and within hands. Similarly, when expert pianists prepare a musical piece for public performance, they spend considerable time determining how to hit keys with different fingers and thereby minimize such constraints on movement.

The ability to anticipate future events and thus prepare actions in advance is critical in many domains of expertise, particularly in sports. Abernathy and Russel (1987) showed tennis players pictures of an opponent in different phases of preparing to serve. They found that with increasing levels of expertise, tennis players can use advance cues, such as location of arms and racquet, to predict where the tennis ball will hit in the service area. Shown pictures of an attacking field-hockey player preparing a shot, national-level field-hockey players can predict where the ball will go even before the attacking player's club has made contact with the ball (Starkes, 1987). The important implication of this research is that experts can circumvent any basic limits on the serial motor processes constraining a novice by using advance cues to prepare movements.

In summary, research on skill acquisition indicates that performance in the initial phases of practice is determined by characteristics quite different from those that determine performance during later phases. Considering that expert performance is acquired during a decade of intense preparation, the evidence suggests that relevant practice activities during development lead to far greater changes in basic perceptual and motor abilities than previously thought. What distinguishes expert performers is mostly more and better organized knowledge, which had to have been acquired. Most important, recent research on expertise shows that experts can acquire cognitive skills enabling them to circumvent the limits of short-term memory capacity and serial reaction time. This research rules out the hypothesis that individual differences in those functions will influence and constrain final adult performance and is consistent with the low predictability of performance by ability tests after extended relevant experience (Hulin et al., 1990). Finally, because the criteria for expert performance in most domains change as a function of age and level of performance, it appears unlikely that the study of early performance will reveal fixed elements that determine the level of final adult performance.

### *The Role of Perceived Talent, Motivation, and Predisposition for Practice*

From our search for immutable characteristics corresponding to innate talent, we conclude that individuals acquire virtually all of the distinguishing characteristics of expert performers through relevant activities (deliberate practice). At least one characteristic, height, cannot be acquired. However, even height is imperfectly related to expert performance, and adult height has a correlation of only around 0.8 with height at ages younger than 17 to 18 (Malina & Bouchard, 1991), when decisions to start practice are made. Apparently no valid information on innate talent is available during an individual's initial exposure to the domain. In spite of this, assessments of talent and decisions to initiate deliberate practice are as a rule made during this period (Bloom, 1985b). The perception that a child is talented is unquestionably real, and such perceptions motivate parents to provide the time and money to support deliberate practice as well as to encourage their children in a particular domain. In the normal case (Bloom, 1985b), the child enjoys the activities in the domain and is superior in these activities to other children of the same age in the same neighborhood. Whether enjoyment precedes superior performance or vice versa is not known. In either case, perceived talent and enjoyment of the activities of a domain are ideal preconditions for initiating the effortful but valuable activity of deliberate practice. Our framework differs from a view that is based on innate talent in that we emphasize the motivation and enjoyment necessary to start and maintain deliberate practice and the motivation of parents and coaches to support the individuals without assuming that the initial superior performance reflects immutable characteristics (innate talent).

In this section we show that our framework not only explains the facts but also gives a better account of them than a framework that is based on innate talent. First, we examine detailed descriptions of observed talent (Scheinfeld, 1939), and we then argue that expert performers' familial relations can be accounted for by shared environment. The central argument is first that the perception that an individual is talented, that is, innately equipped and predestined for success in a domain, leads to the early start of deliberate practice. Second, the individual attains an elite level of adult performance by maintaining a high level of practice. Note that the perception of innate talents will be relatively immune to disconfirming evidence so long as the talents are kept general and unspecified. As a result such a perception can continue to bolster an individual throughout his or her development.

The classic studies of innate talent emphasized that talent is observed very early before the start of deliberate practice. Scheinfeld (1939) found that the age at which talent is first noticed is quite young for truly outstanding musicians—an average of 4.9 years of age. Scheinfeld's descriptions suggest that "talent" means promise rather than objective evidence of unusual capacity. For example, "unusual response to music" at age 3 (p. 238) and "playing violin with two sticks" at age 4 (p. 239) would not be impressive in children at older ages. Examples of talent for the oldest ages (6–7 years) in Scheinfeld's review nearly always involve absolute pitch. These accounts are consistent with Bloom's (1985b) interviews with parents and teachers of international-level performers; Bloom found that the level of talent exhibited by these individuals was only unusual compared with that of other children of a similar age in the immediate environment. We find this evidence more consistent with demonstrated interest and enjoyment of a domain than with any superior, innate advantage involving fixed capacities.

To identify these early expressions of interest it is critical that adults closely observe their children and are willing to support this interest and provide access to deliberate practice. The importance of the early environment is clearly evident in our finding that children who become elite performers are first exposed to a domain and start practice at remarkably young ages. At these young ages it is more plausible that parents' perception of innate talent, not objective evidence, leads to the start of practice. In fact, evidence of talent does not precede most instances of very early start of practice. Many parents of precocious children were convinced of the great importance of very early systematic training and attribute the remarkable abilities of their children to the training and not to inherent talent. Howe (1990) reviewed the education of John Stuart Mill, Norbert Wiener, and William Sidis. An outstanding feature of these early educational efforts was the total elimination of inherently enjoyable activities such as play and social interaction with other children. This feature is consistent with our assertion that deliberate practice is not inherently enjoyable. More recently, a Hungarian educator, Polgar, announced a similar educational experiment with his daughters involving early and focused training in chess (J. Radford, 1990). All three daughters developed into highly skilled chess players (ranked first, second, and sixth in the world among women chess players in 1992) and the youngest daughter, Judith, recently became the youngest grand master ever in chess (McFadden, 1992). Given the biological relation between parent and children, these cases clearly do not rule out hereditary influences, but they do show that the level of performance can be dramatically accelerated through systematic training initiated prior to evidence of talent.

Better evidence for our framework would go beyond showing improvement from practice without knowledge of talent and show that individuals with negative talent, for example, a disability, have attained great performance through practice. No theory of expert performance would give individuals with disabilities an advantage or even opportunity compared with normal individuals. Individuals with disabilities have nevertheless attained international-level performance and even won Olympic medals. The gold medal winner at Melbourne in hammer throwing was born with a paralyzed left arm and devised new training techniques to overcome the disadvantage of his disability (Jokl, 1958). The first female to win three Olympic gold medals in the same games, Wilma Rudolph, lost the use of her left leg at the age of 4 and after intense treatment and practice was able to walk without braces and reinforced shoes by age 11 (Ladd, 1988). In these cases subnormal performance seems to have motivated the individuals' start to deliberate practice as a means of reaching normal functioning and then to continue practice to reach elite levels. Several athletes have experienced severe injuries, but were able to overcome these disabilities and win Olympic medals for their performance (Jokl, 1964). One suffered amputation of the arm used to hold the pistol in shooting. Another, a rider, contracted polio and lost control of her legs. These examples indicate that training can compensate for disabilities and has a greater impact than often believed possible.

The fact that children who later attain expert performance share their early environment with their parents would seem a satisfactory explanation of familial relations to expert performance. The most often cited examples of families of gifted musicians are from early music, Johann Sebastian Bach's family tree being the most striking (Rowley, 1988; Scheinfeld, 1939). In those times before the advent of professional music teachers, the transmission of knowledge and skills from parent to child was natural and did not presuppose any genetic transmission of innate talent. Similarly, nobody would argue that bilingual children who speak a foreign language have innate abilities for speaking that particular language. Obviously they have acquired that language through social interaction with their parents or grandparents. Similarly, it is likely that in many cases parents transmit to their children a substantial amount of knowledge and motivation in skilled activities in a domain. In a recent study in behavioral genetics, Coon and Carey (1989) compared the music performance of identical and fraternal twins and found that the environmental correlations were always higher than the genetic ones. (Whether the same findings would emerge if the study were restricted to expert musical performance is unknown; given the low frequency of expert musicians, an appropriate study of twins would be nearly impossible to conduct.) Similarly, de Garay, Levine, and Carter (1974) interviewed more than 1,200 athletes attending the 1968 Olympic games in Mexico City and found no meaningful familial resemblance in reported physical or motor abilities between these athletes and their families compared with a reference group.

In summary, our review has uncovered essentially no support for fixed innate characteristics that would correspond to general or specific natural ability and, in fact, has uncovered findings inconsistent with such models. At the same time we recognize that parents and teachers who perceive talent in their children and pupils are motivated to provide them with instruction and social support. We also recognize that being told by parents and teachers that they are talented, that is, genetically endowed with unusual gifts, most likely increases motivation, boosts self-confidence, and protects young performers against doubts about eventual success during the ups and downs of the extended preparation. A famous violin teacher, Galamian (1962), discusses the importance of giving praise to build self-confidence, but warns against too much praise as it causes "them to relax their efforts (p. 106)." Too much recognition at young ages may lead young musicians to consider themselves as special individuals—not just musicians—deserving of treatment as prima donnas in all aspects of everyday life (Gelber, 1990). Research in social psychology on interpersonal expectation and self-fulfilling prophesies confirms these effects in the laboratory and in everyday settings (Darley & Fazio, 1980; Rosenthal & Rubin, 1978). The important influence of parents' expectations on their children's performance, interest, and self-judgments of ability in a domain has been demonstrated for large random samples in the general population. Children's and adolescents' perception of their own ability in mathematics is influenced by their parents' beliefs about their abilities, even when past performance and effort are statistically controlled for (Parsons, Adler, & Kaczala, 1982). The parents' beliefs in gender differences in talent in mathematics and English influence their perception of their children's abilities more than is warranted given the objective differences in performance between boys and girls for these two subjects (Eccles, Jacobs & Harold, 1990). Recent studies have uncovered pathways by which the parents' beliefs influence children's beliefs in their own abilities as well as their performance. Harold, Eccles, Yoon, Aberbach, and Freedman-Doan (1991) have shown how the child's gender influences the parents' perception of the child's ability in sports and music, which in turn influences the frequency of opportunities for relevant activities provided by parents for their children in the corresponding domain. Eccles and Harold (1991) have linked the influence of gender on the child's self-concept in English, mathematics, and sports and the influence of self-concept on how much free time is spent on activities in the corresponding domain. Hence, parental beliefs and expectations can influence the children's relevant experiences directly by offering opportunities or indirectly by strengthening motivation and self-confidence for a given activity. In addition, laboratory studies, where amount of experience is equated, show that implicit theories of stability of abilities are an important aspect of individuals' self-concept and greatly influence future learning goals and reactions to failure (Dweck & Leggett, 1988).

Returning to Galton's framework, we reject any important role for innate ability. It is quite plausible, however, that heritable individual differences might influence processes related to motivation and the original enjoyment of the activities in the domain and, even more important, affect the inevitable differences in the capacity to engage in hard work (deliberate practice). In this review we have already pointed out the motivational problems associated with persuading adults to start and maintain exercise programs and with getting children to start and maintain deliberate practice. Individual differences in emotionality and general level of activity are also likely influences on the capacity to engage in sustained practice as well as on the preference or dislike for this type of isolated activity. Moderate heritabilities have been estimated for these differences (Plomin et al., 1990) and for self-reported interest in especially artistic activities (Grotevant, Scarr, & Weinberg, 1977). Although we are not aware of any controlled human studies relating activity levels and emotionality to deliberate practice and attained level of expert performance, the relation between productivity and eminence (Simonton, 1984) is at least consistent with such a relation. In addition, Cox (1926) estimated IQ from early achievements documented in biographies of the hundred most eminent men of recent centuries but concluded that "high but not the highest intelligence, combined with the greatest degree of persistence, will achieve greater eminence than the highest degree of intelligence with somewhat less persistence" (p. 187). The pattern of results from animal studies is remarkably consistent with the importance of such relations and interesting from an evolutionary perspective. Early behavioral geneticists were able to selectively breed strains of rats that performed differently on specific learning tasks (McClearn, 1962). Contrary to expectation, the superior learning ability of these rats was specific to the parameters of the task, such as types of relevant cues (visual vs. spatial) and types of motivation (hunger vs. escape from water). Furthermore, "bright" and "dull" rats differed in either emotionality or activity or both (McClearn, 1962). In a classic study, Scott and Fuller (1965) examined the characteristics and test performance of several breeds of dogs and found that the only general factor was emotion. Rather than viewing the emotional and activity factors as variables confounding pure learning factors, K. J. Hayes (1962) proposed viewing them as integral and necessary prerequisites for learning and acquired skill in animals as well as humans. Future research will tell whether individual differences in factors related to individuals' motivation to practice can account for any heritable influences in attained levels of performance.

## Conclusion

People believe that because expert performance is qualitatively different from normal performance the expert performer must be endowed with characteristics qualitatively different from those of normal adults. This view has discouraged scientists from systematically examining expert performers and accounting for their performance in terms of the laws and principles of general psychology. We agree that expert performance is qualitatively different from normal performance and even that expert performers have characteristics and abilities that are qualitatively different from or at least outside the range of those of normal adults. However, we deny that these differences are immutable, that is, due to innate talent. Only a few exceptions, most notably height, are genetically prescribed. Instead, we argue that the differences between expert performers and normal adults reflect a life-long period of deliberate effort to improve performance in a specific domain.

Most of our scientific knowledge about improvement and change comes from laboratory studies of training and practice that lasted hours, days, and occasionally weeks and months. In addition, there is a growing body of data on the heritabilities of various abilities and characteristics estimated for twins and parents and their offspring sampled from the general population (Plomin et al., 1990). Although behavioral geneticists carefully point out that their heritability estimates are valid only for the limited range of practice and skill in the normal environment of the adults studied, it is often incorrectly assumed by lay people that these estimates can be directly extended to extreme manipulations of environmental conditions, such as extended deliberate practice. Most important, the effects of short-term training cannot be readily extended to the effects of orders of magnitude more practice.

A promising direction for research on the effects of extended activities is to identify activities relevant to some goal and to assess the amount of time individuals allocate to these activities. Recent research has shown that the amount of time individuals spend reading as assessed by diaries is related to memory for prose even when education and vocabulary are partialed out (Rice, Meyer, & Miller, 1988). The estimated amount of reading is also related to reading ability and, most interestingly, increases in reading ability (R. C. Anderson, Wilson, & Fielding, 1988). Research on physical fitness has a long tradition of measuring daily physical activity and exercise, and we have cited the study in which Fagard et al. (1991) assessed the influence of both genetic factors and regular activity on aerobic and anaerobic abilities. It would be ideal to plot the interaction of genetic and environmental factors in longitudinal studies across the entire life span (Rutter, 1989). Within this context, we view the study of elite performers as particularly interesting because from early ages their lives appear to maximize the influence of environmental activities (deliberate practice) improving a specific type of performance. In a rare study Schneider, Bös, and Rieder (1993) included environmental factors along with physical characteristics and motivational characteristics of individuals in a longitudinal study of elite tennis players. Consistent with our framework they found that tennis performance at ages 11 and 17 was primarily determined by parental support and in particular motivation and tennis-specific skills, where the level of these skills in turn are mainly attributable to assessed levels of motivation and concentration.

We view elite performance as the product of a decade or more of maximal efforts to improve performance in a domain through an optimal distribution of deliberate practice. This view provides us with unique insights into the potential for and limits to modifying the human body and mind. Many anatomical characteristics, traditionally believed to be fixed, can adapt and change in response to intense practice sustained for years. Substantial change and learning can occur even during childhood, when some changes, such as in certain perceptual–motor abilities, might be even easier to attain than during adulthood. Untrained adults can overcome limits on speed and processing capacity by acquiring new cognitive skills that circumvent these limits by qualitatively different processes. Further research on the capacities and characteristics of expert performance will give us a much deeper understanding of the full range of possible adaptations and methods for circumventing limits (Ericsson & Smith, 1991a).

It does not follow from the rejection of innate limits on acquired performance that everyone can easily attain high levels of skill. Contemporary elite performers have overcome a number of constraints. They have obtained early access to instructors, maintained high levels of deliberate practice throughout development, received continued parental and environmental support, and avoided disease and injury. When one considers in addition the prerequisite motivation necessary to engage in deliberate practice every day for years and decades, when most children and adolescents of similar ages engage in play and leisure, the real constraints on the acquisition of expert performance become apparent. The commitment to deliberate practice distinguishes the expert performer from the vast majority of children and adults who seem to have remarkable difficulty meeting the much lower demands on practice in schools, adult education, and in physical exercise programs.

We believe that a more careful analysis of the lives of future elite performers will tell us how motivation is promoted and sustained. It is also entirely plausible that such a detailed analysis will reveal environmental conditions as well as heritable individual differences that predispose individuals to engage in deliberate practice during extended periods and facilitate motivating them. Our empirical studies have already shown that experts carefully schedule deliberate practice and limit its duration to avoid exhaustion and burnout. By viewing expert performers not simply as domain-specific experts but as experts in maintaining high levels of practice and improving performance, we are likely to uncover valuable information about the optimal conditions for learning and education.

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