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Giftedness and evidence for reproducibly superior performance: an account based on the expert performance framework

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Giftedness researchers have long debated whether there is empirical evidence to support a distinction between giftedness and attained level of achievement. In this paper we propose a general theoretical framework that establishes scientific criteria for acceptable evidence of superior reproducible performance, which any theory of exceptional performance must explain. We review evidence for superior reproducible performance, generally emerging only after extended periods of deliberate practice that result in subsequent physiological adaptations and complex cognitive mechanisms. We also apply this framework to examine proposed evidence for innate talents. With the exception of fixed genetic factors determining body size and height, we were unable to find evidence for innate constraints to the attainment of elite achievement for healthy individuals.

Introduction

Remarkable achievements of eminent individuals have traditionally been explained by the concept of innate talent or giftedness. Some arguments for innate talent derive from the assumption that many extreme individual differences defy explanation in terms of known mechanisms for learning and development. For example, many people think explanations based on learning can never explain the development and achievements of innovative scientists and influential artists. In a recent chapter, Lykken (1998) advocated this view by quoting historian Paul Israel: 'When you see [Edison's] mind at play in his notebooks, the sheer multitude and richness of his ideas makes you recognize that there is something that can't be understood easily—that we may never be able to understand' (p. 35). He went on to assert 'I think what lies at the heart of these mysteries is genetic'. In his entry in the

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Encyclopedia of intelligence, Horowitz (1994) describes gifted individuals as having 'extraordinary ability in some area. One speaks of gifted musicians, gifted athletes, gifted linguists' (p. 491). Horowitz notes, however, that although 'colloquial and general agreement exists about who is gifted in any one of these areas, considerable disagreement arises concerning the more technical definition of giftedness and how it is to be measured' (p. 491).

In this paper we will approach the issues of gifts and innate talent a little differently. Rather than create new definitions and global theories, we apply the analytical methods of the expert performance approach and focus on the empirical evidence for reproducibly superior performance. Given that this framework differs from the traditional studies of giftedness, we will briefly sketch the development of the expert performance approach. The first author initially encountered the issues of giftedness in his studies on exceptional memory, where there is an extensive body of research on individuals with 'gifted' memory. Many years ago, Bill Chase and the first author (Ericsson *et al.*, 1980) tried to replicate an early study where several students were able to double their performance on a test of short-term memory with a few weeks of practice. They invited a college student (SF) to engage in memory practice for a few hours per week. Before the start of training SF could recall around seven presented digits—the typical performance for college students (Miller, 1956). After several hundred hours of practice he dramatically exceeded the original target of doubling his memory performance and was able to perfectly recall over 80 presented digits—an enormous improvement of performance corresponding to an effect size of over 70 standard deviations. These large training effects on memory performance have been replicated many times with many participants in several independent laboratories (see Wilding & Valentine, 1997, 2006; Ericsson, 2003a).

These studies demonstrated that individuals can increase their memory performance by orders of magnitude through training (without any changes in their DNA), and that the levels of post-training performance dramatically surpassed levels of many individuals thought to possess innately superior memory in earlier studies (Ericsson, 1985). Such findings question whether innate gifts or talents are required for an individual to reach the levels of memory skill that were initially considered extraordinary by early researchers (e.g., Luria, 1986, first published 1968). In addition, the trained students exhibited several other observable characteristics of allegedly exceptional individuals, such as flexible retrieval of the memorized information (see Ericsson & Chase, 1982). Furthermore, the encoding and retrieval mechanisms acquired by the students were investigated and experimentally validated as mediating the superior performance (Ericsson, 1988, 2004).

Currently, we are not aware of any objective evidence showing that only some rare individuals are able to improve their memory because they possess specific genes. When larger groups of participants have been taught mnemonic memory strategies (related to those used by the trained students), the memory performance of these participants is dramatically improved with extended practice (Higbee, 1997). Furthermore, in a recent brain scanning study Maguire *et al.* (2003) found no anatomical differences in the brains of some of the world's top competitive memorizers and a matched control group. Observable differences in brain activation during memorization between the two groups could be explained by the different memorization strategies that the memory experts reported using. A recent authoritative review by Wilding and Valentine (2006) concluded that 'the most striking examples of superior memory are strategy dependent' (p. 546). Moreover, Ericsson (2003a) was unable to find any reproducible evidence that would limit the ability of motivated and healthy adults to achieve exceptional levels of memory performance given access to instruction and supportive training environments.

The initial research on exceptional memory led to the proposal for the expert performance approach (Ericsson & Smith, 1991). This approach attempts to capture superior performance within a wide range of domains of expertise by reproducing it with representative tasks from the corresponding domain in the laboratory in order to identify the mediating mechanisms. In many ways the expert performance approach is quite different from the traditional approaches espousing giftedness and innate talent. Traditional approaches focus on the early detection of individuals who may possess innate gifts with the goal of providing early support in their development toward eminence as an adult. In contrast, the expert performance approach starts by identifying reproducibly superior performance and then works backwards to explain the development of the mediating mechanisms. If scientists cannot measure the reproducible performance of adult experts in a domain, there will be nothing for theories to explain.

Shortly afterwards, Ericsson *et al.* (1993) demonstrated the crucial role of deliberate practice in acquiring the associated physiological adaptations and cognitive skills that mediate expert performance levels. The same paper showed how a wide range of phenomena customarily attributed to innate talent could be given the more *parsimonious* explanation of acquisition through deliberate practice (see also Ericsson & Charness, 1994, for a more focused discussion). In an influential review Howe *et al.* (1998) questioned whether any evidence exists for innate talent as they defined it. In their response to many interesting commentaries they concluded that 'From a purely scientific standpoint, the main question raised by the target article might be a less than ideal one to address, if only because it revolves around imprecisely defined concepts' (p. 437). Commentaries frequently disputed Howe *et al*'s attempted definition—their paper probably did not resolve many of the critical issues, and it was not even cited by a large number of the many famous contributors to the recent edition of Sternberg and Davidson's (2005) *Conceptions of giftedness*. In this book's summary chapter Mayer (2005) does an impressive job of discussing the differences in opinion of the many contributors about the proper definition of giftedness and its attributes. Some contributors to the volume support an innate view of giftedness whereas other focus on the important role of the environment and practice. Some contributors focus on giftedness as potential and others on demonstrated achievement. Mayer (2005) has clear recommendations for the direction for future research and writes that 'research on giftedness will advance to the degree that it matures as a scientific field of study' (p. 447).

It is our appraisal that arguing about the correct definition of giftedness and innate talent and about global theories of the structure of giftedness (Gagné, 2005; Heller *et al.*, 2005; Renzulli, 2005; Sternberg, 2005) has not led to much progress toward the development of a science of high ability or superior performance. By applying the expert performance approach we will first focus on the reproducible evidence that any theory of giftedness, high ability or superior performance must explain. We are optimistic that there will be much more consensus if verifiable and reproducible evidence is established as the foundation for a science of superior performance, whether it is generated by researchers from a giftedness perspective, from the expert performance perspective, or from some other theoretical framework. Moreover, given that we are interested in generalizations for normal, healthy individuals, we will not include evidence from populations with individuals who have any identified and medically recognized deficits due to birth defects, accidents, diseases and known chromosomal and other well-understood genetic disorders. In this regard, we accept that individuals who have visual (e.g., blindness), auditory (e.g., deafness), mobility (e.g., quadriplegic), or other disabilities, including brain damage and related severe handicaps, will have constraints that do not permit them to compete successfully with healthy individuals in many domains. A central issue in the study of superior performance is whether some healthy individuals have an innate advantage that is necessary to attain elite levels of performance.

Our paper has four main sections and a conclusion. We start by discussing the problems with many types of evidence on high ability and high levels of performance, such as anecdotal, subjective and indirect evidence of achievements, and list criteria for reproducible scientific evidence of high ability. In the second section of the paper we describe how the development of many types of reproducibly superior performance, which we label 'expert performance', meet the criteria and how their acquisition is associated with special types of practice activities. In the third section we discuss how specific types of practice activities—qualitatively different from mere continued experience in a domain—lead to changes in physiological and cognitive characteristics. In the fourth and final section we critically examine different types of reported evidence for innate genetic endowments that have been proposed, including research on intelligence and creativity. Throughout our paper we address a number of criticisms raised against the expert performance approach by some theorists of giftedness (Gagné, 2005; Subotnik & Jarvin, 2005; Simonton, 2005; Sternberg, 1996; von Károlyi & Winner, 2005) as well as several commentators to Howe *et al*'s (1998) article. In our concluding section we discuss the implications of our findings for the future study of giftedness.

Toward criteria for reproducible evidence on giftedness and high levels of performance

In this section we will critically review characteristics of evidence cited to support claims about genius, elite achievement, and high levels of performance, namely the evidence that theories of high ability must explain. Our goal is to establish sound criteria for evidence that would form the foundation of a future science of exceptional performance and/or giftedness.

From social judgment to reproducibly superior performance

Much of the traditional evidence cited in support of genius and exceptional abilities is based on the identification of exceptional achievements, such as the discovery of a new phenomenon, the development of a new theory, the writing of classic books, the composition of innovative symphonies, and the delivery of amazing artistic performances in public. However, we argue that there are several fundamental problems for a science of superior performance when the definition of exceptional achievement is based on social criteria, such as the opinions of experts (e.g., contemporary scientists) or the general public.

First, many creative products are considered outstanding achievements based on the social judgment of an elite group of people at a given point in history. However, these judgments are inherently subjective and can change over historical time (Csikszentmihalyi, 1999). For example, many famous scientific and artistic products considered outstanding today were originally ignored, such as Bach's musical compositions (Ferguson, 1935) and Mendel's work on genetics (Hartwell *et al.*, 2004). Likewise, science and art have a long history of eventually discarding works and ideas that at one point in time were considered exceptional. Today's critics and award committees may identify a work as exceptional, but there is never a guarantee that such work will be considered exceptional in the future. A second problem is that unique innovations are generated in social contexts. It is very difficult, if not impossible, to distinguish the uniqueness of the *circumstances* of a generated idea or product from any unique *ability* of the person producing the new idea or product. For instance, there is compelling evidence from science that many discoveries are made independently by two, three, or even more scientists at around the same time (Simonton, 1984). These 'multiple discoveries' testify to the importance of having access to the appropriate knowledge. The fact that scientists and artists are socially embedded and influenced by many common factors has even led some scientists to attribute literary products to a context of interacting individuals (Stillman, 1991) rather than a single author and attribute the discovery to the zeitgeist rather any unique attributes, such as innate talent (Stein, 1991).

By relying on social judgments the contemporary scientists cannot know neither which individuals' accomplishments will fade into oblivion nor whether a given individual would have been able to generate the creative product in a different social context. But social criteria suffer even greater fundamental problems. Indeed, as we will describe in the next subsection, research has demonstrated several effects that question the validity of any approach based on subjective assessment. We will show how even experts themselves are often systematically biased or unreliable in their judgment of whether a performance is genuinely superior, raising the concern that these judgments may not accurately reflect an objective superiority that can be reliably assessed independent of historical context.

Problems with social criteria for expertise

The first problem with identifying exceptional products that might be attributed to giftedness has many similarities with an early problem in expert performance research: how can the scientist identify those who are exceptionally skilled? Many of the early studies of expertise relied on peer-nomination of well-known experts—basing their criteria on social judgments much in the same way as described above. It was simply taken for granted that peer-nominated experts and individuals with extensive job experience would display *reliably superior performance* in their respective domains. However, when the performance of these 'experts' was later measured with tasks representative of their domain, they were frequently no better than less experienced persons. For example, highly experienced psychotherapists are not more successful in their treatment of randomly assigned patients than novice therapists (Dawes, 1994). Reviews of decision-making (Camerer & Johnson, 1991; Shanteau & Stewart, 1992) show that experts' decisions and forecasts, such as financial advice on investing in stocks, are not necessarily superior to those given by novices. Expert wine-tasters are not much better than regular wine drinkers at perceptually discriminating and describing wines under blind test conditions when the identity of wine is unknown (Gawel, 1997; Valentin *et al.*, 2000). We believe that when Sternberg (1996) argued that 'much more practice [as a teacher] that has left most of us no more than ordinary as teachers' (p. 351), he had this type of professional experience in mind. Similarly, reviews have demonstrated that highly experienced individuals do not perform at a superior level compared to those with much less experience in many other areas of expertise (Ericsson & Lehmann, 1996; Ericsson, 2004). There are even examples of types of performance, such as diagnosis of heart sounds and x-rays by general physicians (Ericsson, 2004) and auditor evaluations (Bédard & Chi, 1993), that *decrease* systematically in accuracy or consistency with the length of professional experience after the end of formal training. Hence, it *cannot* be assumed that an individual with extended domain experience will demonstrate reliably superior performance.

The inherent subjectivity of social judgment is well illustrated by studies investigating subjective ratings of performance. When judges with extensive musical experience are asked to rate the musical performance of different individuals by listening to taped recordings without knowing the identity of the musician playing, they are surprisingly unable to distinguish music students with technical proficiency from professional musicians. In fact, the ratings are systematically influenced by irrelevant factors, such as gender, physical attractiveness and the reputation of the performer (Gabrielsson, 1999). Expert judges also frequently appear to make evaluations based on the reputation of the performer in domains such as gymnastics or figure skating rather than relying only on the perceptually available performance (Findley & Ste-Marie, 2004).

There is evidence that subjective factors influence expert judgment not only in artistic and athletic domains, but also in sciences. For instance, studies investigating the peer-review process reveal considerable inconsistency among referees, illustrating a large role played by chance in determining the success of a grant proposal or journal article (Cole *et al.*, 1981; Fiske & Fogg, 1990; Cicchetti, 1991). In a surprisingly large number of cases, scientists themselves disagree on which papers are good enough to warrant publication. Cole (1991) has suggested that:

> … the low levels of reliability in peer review evaluations described by Cicchetti are not an artifact of the peer-review system or of reviewer bias, but reflect the low levels of cognitive consensus that exists at the research frontier of all scientific disciplines. (Cole, 1991, p. 140)

Furthermore, evidence exists that scientists' evaluations may be biased in several ways; for instance, several studies illustrate how having prestigious reputations (Peters & Ceci, 1982), having results matching the reviewer's own beliefs (Mahoney, 1977), and even subtler details (self-citation biases: Mahoney *et al.*, 1978) may bias the judgments of reviewers (see Cicchetti, 1991, for a summary).

When experts are defined by peer nominations it is essentially impossible to eliminate the influence of social and contextual factors. However, it is possible to design conditions where only the relevant stimulus is judged, akin to investigations in psychophysics, where irrelevant cues have been eliminated and thus cannot bias the judgments. For example, it is possible to have musicians perform behind a screen (Goldin & Rouse, 2000) to eliminate biased evaluations due to gender, race and age. An even superior approach is to only focus on aspects of performance that can be measured with objective methods. Studies of music (Repp, 1999), juggling (Beek, 1989), and chess (Roring & Ericsson, submitted) discuss methods that allow scientists to study transcribed records, audio recordings, and films of public performances to assess objective characteristics of the quality of the performance. Unless it is possible to measure the reproducibly superior performance associated with giftedness in a domain by objective methods, we argue that the evidence in this domain will not meet standards of science and thus cannot be considered by a new science of high ability and exceptional performance. We want to encourage new objective methods of measurements that can establish whether findings currently based only on subjective measures are valid.

In the next sub-section, we describe how the expert performance framework limits itself to the study of reproducibly superior performance. We will describe how this has allowed us to successfully identify characteristics of elite performance in several domains. Evidence from reproducibly superior performance on representative tasks forms a basis for a science of elite achievement.

Identifying representative tasks that capture reproducibly superior performance

Ericsson and Smith (1991) proposed an 'expert performance approach'. The approach defines 'expert performance' as *reproducibly superior performance*, and it argues that the scientific study of experts' performance requires the identification of reproducible phenomena by designing standardized *representative tasks, which can capture this superior performance*. With the development of such tasks, the skill can be further analyzed using experimental methods in the laboratory. In some domains, such as most individual sports, such tasks are readily apparent because objective measurement of the athlete's performance is an integral part of fair competitions, such as in the time to run the 100-yard dash. In other domains two competitors may face each other in matches to determine who is better, resulting in a relative measure of performance, such as in tennis, fencing or chess. It is possible to aggregate results from matches to establish a rating scale, as originally developed in chess (Elo, 1978), which has more recently been extended to other domains, such as tennis. It is, however, nearly impossible from results of matches to identify the mechanisms that mediate the superior performance of the top competitors. Two chess games or two tennis games will virtually never develop in the same way and thus it may be impossible to compare different individual's behavior. Performers must be presented with the same set of situations to objectively evaluate their responses.

When de Groot (1978) initiated his studies of world-class chess players he searched for tasks that could be presented to chess players of different skill levels. He argued that the essence of winning chess games is to consistently select good moves for positions encountered during chess games. He thus selected challenging chess positions from games between chess masters and presented the same chess positions to both world-class players and club-level players, asking them to think aloud while selecting the best move. He found that the better players selected better chess moves and subsequent studies with larger populations of chess players have found that tests of move selection for pre-selected chess positions are excellent predictors of tournament performance and the chess ratings described above (Ericsson *et al.*, 2000; van der Maas & Wagenmakers, 2005). Using the method of capturing representative situations where experts excel, it has been possible to design laboratory tasks that capture the same mechanisms as those mediating competitive and professional performance in domains. For example, medical doctors have been presented with the same set of descriptions of patients and asked to make a medical diagnosis for each description, soccer players have been presented with short videos of actual soccer games with abrupt endings and asked to make predictions about what actions the player with the ball will take, and typists have been presented with the same unfamiliar texts and asked to copy as much of the text as possible within a time period of three minutes. These types of representative tasks have been found to capture expertise in medicine (Ericsson, 1996, 2004), nursing (Ericsson *et al.*, 2007), sports (Ericsson, 2003b, c), simultaneous translation of languages, (Ericsson, 2000/2001), music (Ericsson *et al.*, 1993; Ericsson, 2002) and many other domains (Ericsson, 2006a; Ericsson *et al.*, 2006).

Extending the expert performance approach to creative domains and giftedness

A central problem with identifying the exceptional achievements often associated with giftedness is that many of them require creativity and innovation, such that exceptional products reflect ideas that go beyond the current ideas in a society. However, the production of a specific innovative idea cannot be reproduced at will, and it is unlikely that a single individual could generate and develop an original innovative idea more than once. Given that the generation of many of these is unpredictable and rare (Simonton, 1999a), this natural process is virtually impossible to reproduce in a laboratory setting for scientific investigation. It will not be possible to have the same person reproduce the process by recreating the external conditions, because the regeneration will be qualitatively different from the original event. However, the expert performance approach can be adapted to research on creativity through the study of the inception and production of artistic and scientific products that can be empirically measured and elicited in controlled laboratory settings.

When a scientist or an artist generates a new idea or product for the first time, it is done within a context of commonly available knowledge. Although it would not be possible to study creativity by bringing the original creator back into this situation, it should be possible to bring other individuals, who are unaware of the creative contribution, into the same context and thus set up conditions to allow for the reproduction of the discovery. One of the most direct applications of this idea is illustrated by Qin and Simon (1990) in their research on scientific discovery. They recreated several aspects of the historical conditions in which Kepler discovered one of his laws. They then presented the situation to students, who were unaware of that discovery but had all the necessary knowledge (akin to Kepler) and examined how they were able to discover the law. In this instance, Qin and Simon found no evidence that Kepler possessed abilities beyond those of many college students. However, other studies have found initial evidence for reliably superior performance in these domains, and have invited professional artists and scientists as well as less skilled individuals to perform representative tasks under standardized conditions. In a study with a small number of faculty and graduate students Schraagen (1993) asked all the participants to design a single experiment to address a particular research issue. From an analysis of their solutions he found that only college professors researching the specific area relevant to the problem (viz., gustatory research) were able to generate an adequate design, and they performed reliably better than both college professors studying other research areas and the graduate students. However, given the limitations of this study to a single problem in a particular domain of science, this study is primarily important in demonstrating a methodology for studying research skills in science rather than supporting specific generalizable findings.

There are also some studies in which groups of artists have been given the same standardized task in artistic creation. For example, Patrick (1937) instructed professional and amateur painters to produce a drawing illustrating the same poem given to all participants, and Getzels and Csikszentmihalyi (1976) instructed skilled art students to arrange a fixed set of objects and make a drawing of it. *Blind* ratings by judges have demonstrated reliable differences between experts and novices in quality and originality of their products. Similar differences between experts and novices have been found when skilled and un-skilled poets compose poems illustrating a presented painting (Patrick, 1935).

Another approach to studying creative performance is to focus on the prerequisites for generating creative products (Ericsson, 1999). For a scientist or an artist to generate novel ideas and products, it is essential to have knowledge about all the relevant ideas and products that have already been generated, as rediscovery of someone else's already accepted ideas is not rewarded in the domain. Another prerequisite in domains involving music, painting and various forms of technical mastery, is that the individuals have the necessary tools to implement and express their ideas. Several scientists have shown that experts have greater control over their performance and excel over novices in perceptual tasks (Winner & Casey, 1992; Kozbelt, 2001). For example, Kozbelt (2001) demonstrated that expert artists outperformed novices when copying visual stimuli. Similarly, Krampe and his colleagues (Ericsson *et al.*, 1993; Krampe & Ericsson, 1996) found that expert pianists were more able to reproduce a single interpretation of a piece than amateurs and were able to execute bimanual note sequences faster than novices. In a series of studies Lehmann and Ericsson (1993, 1996) showed that trained accompanists were reliably superior in sight reading music (playing music without any opportunity for prior preparation) than soloists at the same music schools.

Some researchers, such as Subotnik and Jarvin (2005), argue that there are attributes that become more important at the highest levels of performance in art and science, which are not teachable. Subotnik and Jarvin (2005) point to intrinsic motivation ('love of communicating through music'), charisma ('ability to draw listeners to a performer') and musicality ('capability to communicate effectively through music'). Unfortunately, they do not specify if and how these abilities could be measured objectively. Earlier in this article we reviewed the difficulties that even musical judges had in distinguishing the music produced by technically proficient music students from the music of famous musicians under blind conditions. We also mentioned the problem that personal biases, such as biased rejection of female or minority musicians at auditions (Goldin & Rouse, 2000), may be legitimized by reference to lack of objective measurement of musicality and charisma. Later in this paper we will discuss how abilities related to behavior in new situations and thus requiring some degree of creativity appear to be influenced by environmental factors, such as training and deliberate practice.

Is it possible to extend the approach to evidence collected from cognitive ability tests?

The methodology of identifying a pool of representative tasks that capture the essence of superior performance appears to have parallels with the development of aptitude tests, such as tests of intelligence. In their pioneering approach Binet and Simon (1915) searched for test questions (tasks) where the correct responses would differentiate the French school children who would either succeed or fail their school examinations. It is important to note that the ability approach of Binet and Simon (1915) does not try to capture the essence of the criterial performance, namely performance on the school examinations themselves, but rather searches for any tasks and items of reasoning, memory, and other cognitive functions that correlate with and thus can predict the target performance. Later Spearman (1904, 1927) took a more theoretical approach toward measuring the basic components of thinking and invented the factor-analytic method to find groups of test items with correlated performance. Spearman was particularly interested in a generalized cognitive capacity, 'g' (cf., Jensen, 1998), and regarded many of the specific aspects of the tasks in a battery to be irrelevant. In his review Jensen (1998) argued that a diverse collection of sufficiently complex tasks, such as in most IQ tests, measure this construct and that this general ability should mediate most real-world forms of performance to some degree.

One of the goals of ability research is to uncover latent variables that measure cognitive capacities, such as 'g', by analyzing performance on a large number of test items for large representative groups of a population and then measure its relation to some other latent criterion variable measuring performance, such as teacher and job supervisor ratings. The observed correlations between particular tests and the criterion performance is often relatively low and in the 0.1 to 0.3 range, but by statistically controlling for restriction of range and lack of reliability in the criterion variable much higher correlations between the latent ability and criterion variables are estimated (see Hunter & Hunter, 1984). However, we are unaware of successful attempts to understand many of these latent variables (abilities) beyond an intuitive level—most latent variables are defined only by the specific tasks with which they correlate, tasks which are themselves typically poorly understood. In contrast, the expert performance approach focuses on the measurement of the essence of expertise in a domain and thus on the associated criterion performance and its related large reliable individual differences. The focus in the expert performance approach is on specifying the mediating mechanisms that can be assessed by process-tracing and experimental studies.

It is possible to assimilate the research on scholastic abilities within the expertise approach by changing the focus from the measurement of the latent abilities to the study of reproducible achievement by adopting its measurement (e.g., performance on scholastic achievement tests) as the gold standard. By targeting the performance on the specific forms of skill developed in school, it is possible to study how performance on these tests is influenced by different developmental histories and past engagement in various practice activities. The expert performance approach would identify individuals who perform at reliably high levels and then trace the mechanisms mediating their superior performance, to compare these mechanisms to those of students with lower achievement. Once the critical mechanisms have been established this approach would then attempt to study their origin, their possible acquisition, or whether fixed genetic factors are necessary for their emergence. For example, this approach would investigate the processes and representations mediating superior performance on mathematical examinations, and determine whether these arise from specific activities. It would subsequently assess individual differences in the quality and quantity of engagement in the appropriate mathematical activities during development as an initial attempt to understand reliable individual differences in performance. Similarly, the approach would examine the quality and quantity of reading and engagement in writing and other related activities to predict performance on verbal ability tests. In fact, there are new developments in measurement that focus on the type of training and help that individuals would need to score correctly on tests, such as the dynamic testing approach (for a review, see Sternberg & Grigorenko, 1998).

In sum, we support a science of exceptional ability and expert performance that requires a body of reproducible evidence that meets the following criteria. First, the phenomena must be observable and correspond to measurable performance. Second, the associated performance must be generated under controlled and standardized conditions in the sense that it is possible to elicit it repeatedly by presenting representative tasks. Finally, performance on the representative tasks must be reproducibly superior to motivated control groups with different amounts of experience with the task domain. The last two criteria are of utmost importance because the opportunity to reproduce the individuals' superior performance allows scientists to monitor and analyze the processes and mechanisms mediating the superior performance of an individual by applying process-tracing methods, such as recording of latencies, think-aloud reports, and eye-fixations, along with experimental methods varying the conditions and characteristics of the tasks. More generally, the expert performance approach seeks methods for measuring and describing many types of expert performance and aptitudes by objective performance standards that are independent of the social and historic context of the studied expert performance. In the next section, we discuss the development of exceptional performance from the expert performance perspective.

The developmental aspects of expert and exceptional performance

Exceptional achievements attributed to innate 'gifts' are typically thought to arise abruptly and naturally, that is, without additional training. In this section, we review how forms of achievement meeting our criteria for reproducibly superior performance have been shown to result from extended periods of incremental development in a domain. Earlier reviews (Ericsson, 1996, 2002, 2003b, 2006a, b) show that the development of performance assessed by representative tasks and competitions can be charted for individual experts from the time they are first introduced to the domain until they reach their superior expert performance, as shown in Figure 1. Barring accidents or other disruptions to the full time commitment to practice, the performance level will be monotonically improving and in domains where measurements can be made on an interval or even a ratio scale (see Ericsson, 2003d; Roring & Ericsson, submitted) the changes are incremental throughout development rather than abrupt (cf. the assumptions of the mediation of innate gifts). For many domains, skill improvement may be represented as a sequence of states (Ericsson, 2003b, 2006a, b). Each change in performance, such as a transition from one state, S[i], to another state, S[i+1], must reflect some change in cognitive or physiological mechanisms (see Figure 1). Ultimately, a complete theory must account for *all* the transitions between the different states and how some individuals attain these transitions (i.e., improvements) through either practice, experience or maturation. In other words, it might be possible to identify the

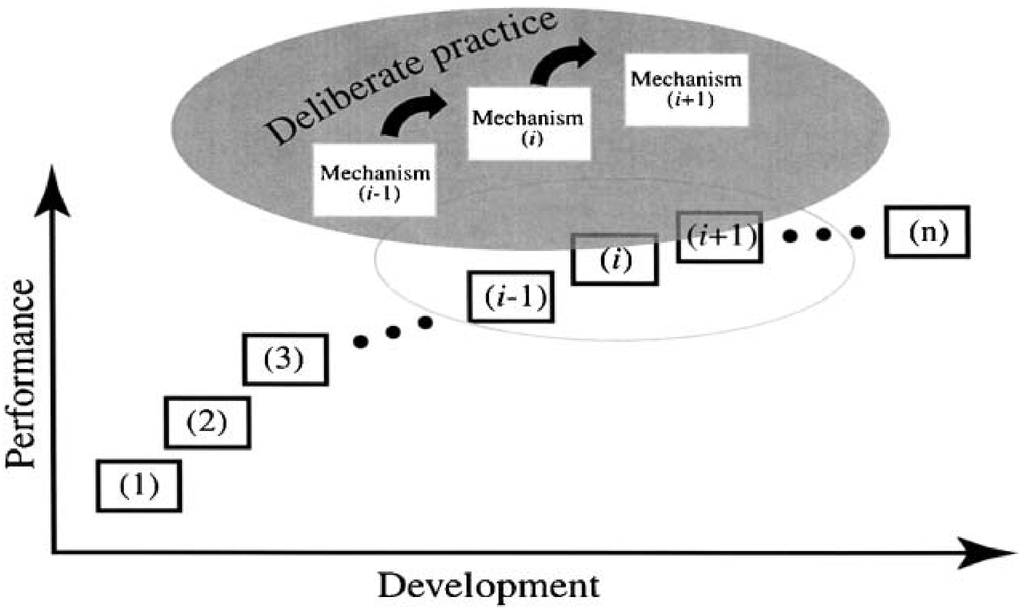

Figure 1. A schematic illustration of the acquisition of expert performance as a series of states with mechanisms for monitoring and guiding future improvements of specific aspects of performance. (Adapted from Starkes & Ericsson (Eds), 2003, *Expert performance in sport: recent advances in research on sport expertise,* p. 70. Copyright 2003 Human Kinetics.)

quantity and quality of practice necessary to transition from one state to another. If we were to find healthy individuals who fail to attain a given transition in spite of the appropriate extended training efforts, this could provide important evidence supporting the need for innate gifts to attain a performance beyond a given level. However, if we were to identify such individuals with specific difficulties we would need to know that the individual had seriously pursued the effective methods required to attain the desired change. This might further require training during certain windows during child and adolescent development, which will be discussed in more detail later in this paper. With our framework we argue that it is possible to study the sequence of necessary transitions in real-world domains where many individuals are already at advanced stages of performance. Once we understand how each stage transition is attained and, if these transitions could be demonstrably acquired without innate gifts or talents, we would argue that the skill itself requires no such gifts by induction; in contrast, if some healthy individuals could never complete a transition despite appropriate training, we would not only have more than enough evidence for innate talent, but also the opportunity to understand the nature of the gift itself through comparison with the skill transition.

This approach overcomes the need to study individuals for several decades to observe the development of high level performance. Detailed longitudinal descriptions of the development of individual experts' performance on standardized tasks for the 5–20 years of involvement in the domain are relatively rare. However, there are several findings demonstrating that the acquisition of experts' performance on representative tasks increases as a function of training. In a wide range of domains (for reviews, see Ericsson, 2004; Ericsson *et al.*, 1993; Ericsson & Lehmann, 1996) there is evidence for three general trends, illustrated in Figure 2.

First, the age at which experts typically reach the peak performance of their careers is the mid-to-late twenties for many vigorous sports, and a decade later, in the thirties and forties, for the arts and sciences and games, such as chess and music (see Roring & Charness, submitted). This extended development is illustrated in Figure 2, showing that the best individuals are able to engage in domain-relevant activities that lead to improvements in performance, *even after physical maturation and increases in height are completed at around age 18.*

Second, there is compelling evidence for the requirement of engagement in domain-related activities prior to attaining high levels of performance and that even the most 'talented' need 10 years or more of intense involvement before they reach a level where they can consistently demonstrate superior performance in international adult competitions in sports, sciences and the arts (Simon & Chase, 1973; Ericsson *et al.*, 1993; Simonton, 1997). Even in cases of famous legends, such as prodigies like Bobby Fischer, the required time to reach grandmaster status was still around nine years, and it took another two decades before Fischer played for the world championship. In many domains of expertise, most elite individuals take considerably longer than 10 years of intensive practice to win international

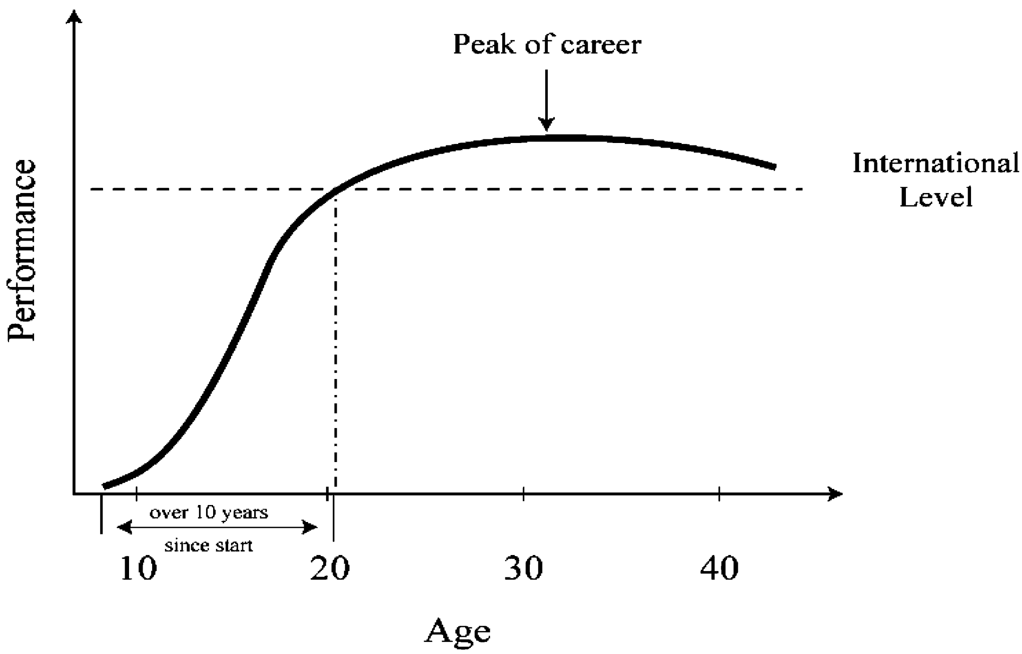

Figure 2. An illustration of the gradual increases in expert performance as a function of age, in domains such as chess. The international level, which is attained after more than around 10 years of involvement in the domain, is indicated by the horizontal dashed line. (From Ericsson & Lehmann, 1999,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

competitions consistently. Further, outstanding scientists and authors normally publish their first work at around age 25 after an extended preparation, and their best work takes an additional 10 years (Raskin, 1936).

Finally, and most generally, we are not aware of any evidence for abrupt increases in performance from one time to the next or demonstrations of high performance levels without engagement in domain-related activities, such as practice, even when the performance of child prodigies in music and chess are considered. In the fourth section of this paper we will discuss in more detail how even longitudinal assessments of the performance of prodigies is consistent with gradual improvement of performance. We will also discuss the evidence for individual differences in rate of learning proposed by researchers from the innate talent perspective. Before turning to these reviews, we will first review evidence that engaging in particular practice activities produces dramatically elevated levels of performance over an extended period of time.

Improving performance through deliberate practice

The critical role of deliberate practice in attaining expert performance was first proposed by Ericsson *et al.* (1993), who reported a study of three groups of expert musicians who differed in level of attained music performance. The first author and his colleagues (Ericsson *et al.*, 1993) examined how the expert musicians spent their daily lives by interviewing them and having them keep detailed diaries for a week. All expert musicians were found to spend about the same amount of time on all types of music related activities during the diary week—about 50–60 hours. The most striking difference was that the two most accomplished groups of expert musicians were found to spend more time (25 hours) in solitary practice than the least accomplished group, who only spent around 10 hours per week. During solitary practice the experts reported working with full concentration on improving specific aspects of their music performance—often identified by their master teacher at their weekly lessons—thus meeting the criteria for deliberate practice. The best groups of expert musicians spent around four hours every day, including weekends, in this type of solitary practice. From retrospective estimates of practice, Ericsson *et al.* (1993) calculated the number of hours of deliberate practice that five groups of musicians at different performance levels had accumulated by a given age, as is illustrated in Figure 3. By the age of 20, the most accomplished musicians had spent over 10,000 hours of practice, which is 2500 and 5000 hours more than two less accomplished groups of expert musicians or 8000 hours more than amateur pianists of the same age (Krampe & Ericsson, 1996). The same type of solitary deliberate practice has been found to be closely correlated with the attainment of expert and elite performance in a wide range of domains (for a review see Ericsson, 2006b).

Several investigators (Sternberg, 1996; Vitouch, 1998; von Károlyi & Winner, 2005) have pointed out that the above evidence is merely correlational. Sternberg (1996, p. 350) argued over 10 years ago that 'Deliberate practice may be correlated with success because it is a proxy for ability: we stop doing what we do not do well

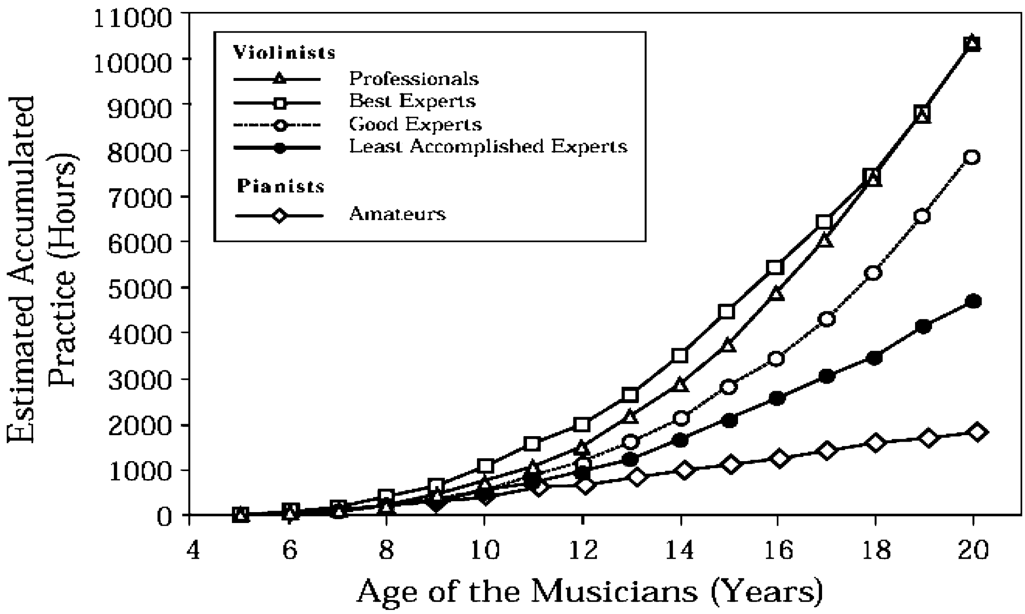

Figure 3. Estimated amount of time for solitary practice as a function of age for the middle-aged professional violinists (triangles), the best expert violinists (squares), the good expert violinists (empty circles), the least accomplished expert violinists (filled circles) and amateur pianists (diamonds). (From Ericsson *et al.*, 1993, The role of deliberate practice in the acquisition of expert performance, *Psychological Review*, 100(3), pp. 379, 384. Adapted with permission.)

and feel unrewarded for' and he even suggested practice was ineffective because 'without the ability, hours of practice can be for minimal or no rewards' (p. 349), although more recently he proposes that 'abilities are forms of developing expertise' (Sternberg, 1999, 2005, p. 343). Von Károlyi and Winner (2005, p. 378) conclude that this type of evidence 'cannot tell us whether practice causes high achievement or innate ability leads to extensive practice' (von Károlyi & Winner, 2005, p. 378). Indeed, the evidence based on retrospective estimates of practice activities is correlational in nature and restricted to the observed sample, and it cannot necessarily be generalized to the development of a random sample of healthy individuals. We are in agreement with Von Károlyi and Winner (2005) that even those considered 'talented' train and practice extensively, and this practice is necessary for the development of performance.

However, deliberate practice is a very special form of activity that differs from mere experience and mindless drill. Unlike playful engagement with peers deliberate practice is not inherently enjoyable. It also differs from successful performance in front of an audience, which is rewarded with applause, acclaim and receiving prizes. Unlike execution of already acquired skills, solitary practice is not immediately rewarded with monetary prizes or social acclaim. Deliberate practice does not involve a mere execution or repetition of already attained skills but repeated attempts to reach beyond one's current level which is associated with frequent failures. Aspiring performers therefore concentrate on improving specific aspects by engaging in practice activities designed to change and refine particular mediating mechanisms, requiring problem-solving and successive refinement with feedback. For instance, in a recent study of singers, Grape *et al.* (2003) revealed reliable differences of skill in the level of physiological and psychological indicators of concentration and effort during a singing lesson. Whereas the amateur singers experienced the lesson as self-actualization and an enjoyable release of tension, the professional singers increased their concentration and focused on improving their performance during the lesson. In their research on chess expertise, Charness and colleagues (Charness *et al.*, 1996, 2005) found that the amount of solitary chess study was the best predictor of performance during chess tournaments, and when this factor was statistically controlled, there was only a very small benefit from the number of games played in chess tournaments. Similar findings of the unique effectiveness of deliberate solitary practice have been reported by Duffy *et al.* (2004) for dart throwing. A recent study by Ward *et al.* (2004) demonstrated that elite level youth soccer players spent less time in playful activities than less skilled control participants and accrued more time spent engaged in deliberate practice. These studies involved the capture of expert performance in the laboratory and thus meet the expert performance approach criteria outlined above. Furthermore, findings from these investigations consistently demonstrate differences in the quality and intensity of practice activities (or equivalently, in the quantity of *deliberate* practice) between experts and individuals of lesser skill. Our disagreements with von Károlyi and Winner's (2005) position concerns the causes of engagement in deliberate practice. Von Károlyi and Winner (2005) assert that 'A rage to master typically accompanies high ability, and both rage to master *and high ability* must have an inborn, biological component' (p. 379, italics added). Winner (1996a, p. 274) argues that gifted children are 'intrinsically motivated to acquire skill in the domain (because the ease with which they learn)'. However, she claims that intrinsic motivation develops 'when there is a high innate ability, *as long as there is sufficient parental encouragement and support*' (Winner, 1996b, p. 146, italics added). Although Winner (1996b) assumes that high ability makes the initial acquisition of skills easier we doubt that the engagement in deliberate practice can be explained by the inherent enjoyment of the activity itself. In the third section we will show how deliberate practice is associated with frequent failures and frustrations and is not the most inherently enjoyable or 'fun' activity available, as aspiring individuals typically prefer playful interactions with friends, especially during adolescence. According to our analysis sustained deliberate practice throughout development must be motivated by the *outcomes* of continued practice, namely the improvement of different aspects of performance. Until a proposal for how this type of motivation for attaining certain levels of performance is explicated at the cognitive and physiological level it is not possible to assess which aspects might be innately endowed.

The same relation between solitary domain-related activity and high ability has been observed when examining the practice activities of gifted children and adolescents. For example, 'visually gifted' adolescents spend extended periods of time each week engaged in solitary drawing, even more than elite music students spend in music practice at comparable ages (Winner, 1996a, b; Hyllegard, 2000). Similarly, individual differences in mathematics ability can be to a large extent accounted for by differences in tutoring and involvement in math clubs or special courses in high school (Olszewski-Kubilius *et al.*, 1990). Similar interest in mathematics and involvement in gifted education are found to distinguish young adolescents who score very highly on math tests at age 13. When their subsequent development in college was tracked, they exhibited characteristics similar to graduate students at the most prestigious universities (Lubinski *et al.*, 2001). The development of eminent mathematicians (Gustin, 1985) and research neurologists (Sosniak, 1985) revealed a similar early involvement in solitary self-directed learning activities related to the target domain. In fact, winning the Westinghouse Science competition, a national scientific research project competition for high school students, is the single best predictor for winning a Nobel Prize (Berger, 1994). Similarly, the superior performance of East Asian students on international tests in mathematics and science compared to American students has been shown to correspond to increased time devoted to study activities that match the characteristics of deliberate practice (Fuligni & Stevenson, 1995). Csikszentmihalyi *et al.* (1993) found that talented teens rated studying as a negative experience (at the time they were engaging in it), although their ratings of studying were not as negative as those of average teens. In a review, Larson and Verma (1999) found evidence that studying was viewed as challenging with low intrinsic motivation across cultures in spite of the differences in the duration of engagement. The differences in studying are large—Paik *et al.* (2002) estimate that Asian students spend almost twice as much time on practice related activities during their first 18 years of life.

Empirical investigations of superior performance that adhere to the criteria outlined above demonstrate that exceptional performance does not appear suddenly or without prior training, but gradually and through sustained engagement in appropriate practice activities. This has been found in several domains, including those traditionally thought to involve gifts, especially in savants (see Ericsson & Faivre, 1988; Miller, 1999; Cowan & Carney, 2006). Furthermore, deliberate practice goes beyond mere activity in the domain. Feldman and Katzir (1998) claimed that older chess players at the Marshall Chess Club in New York City had 'not improved appreciably in decades, but they have logged two or three times the 10,000 hours of deliberate practice said to produce expert performance' (p. 414). As our review showed in this section, the hours of playing chess is not correlated with chess performance after we control for solitary chess study (deliberate practice), and although many of these individuals play frequent recreational chess, most are engaging in little, if any deliberate practice. Similarly, Winner (1996b) argues against deliberate practice by claiming that 'hard work is not sufficient, and precocious children are not mere drudges' (p. 152). As we will show in the next section deliberate practice is not mere repetition of instructed behavioral sequences, it involves problem-solving, iterative refinement, and at higher levels of skill the development of internal representations for planning, evaluating and monitoring mental representations. More generally, there are now large-scale reviews that show the relation between amount of professional experience and performance is low and even sometimes negative (Ericsson & Lehmann, 1996; Ericsson, 2004; Choudhry *et al.*, 2005) and how 'hard' the work is perceived to be does not seem to matter. In the next section, we describe the detailed role of goal-directed practice activities in producing improvements in performance by causing the targeted physiological and cognitive changes in the mediating mechanisms.

Toward a theoretical framework for causal explanation of expert performance

Investigating the existence of potential innate constraints on the acquisition of expert performance resembles the problem of whether healthy individuals could ever climb to the top of a particular mountain. The fact that many people avoid climbing the mountain does not prove that they are incapable. Some people might be afraid of heights and have realistic concerns about the risks of climbing accidents. Others might not be motivated to increase their physical fitness through training sufficiently to surpass the physiological demands necessary to complete all elements of the climb. Still others might not be willing to invest the time or the money to buy climbing equipment and take courses to develop sufficient skill in climbing—in fact, many people may not have access to the necessary instruction or training equipment. In spite of these constraints on access and motivation it should be possible to study the question of whether or not all healthy adults are equipped with the necessary genetic endowment to reach a sufficient skill and fitness level such that they would be able to climb the particular mountain if they were appropriately motivated to engage in the necessary preparation and practice.

As previously discussed, if we can show for all state transitions that healthy adults at randomly selected skill levels can improve to the level corresponding to the next state in experimental tests, then we would be able to argue by induction that healthy adults can, if motivated, acquire the skills and physiological adaptations required for the highest observed performance levels. Similarly, if we could identify some of the transitions that some people were completely unable to attain through training, then we should be able to infer individual limits (likely innate) and constraints on the acquisition of expert performance. To advance our theoretical understanding of the learning processes, we need to search for causal explanations that can reveal how the changes in the mechanisms mediating the superior expert performance can, or alternatively cannot, be attained by engaging in particular designed practice activities. Many people believe that anatomical and physiological differences are primarily determined by unmodifiable genetic factors. For them it is surprising that researchers have been quite successful in developing detailed causal models of how physiological and anatomical characteristics can be changed by the extended engagement in focused intense practice activities. Next, we briefly review this evidence before addressing the cognitive mechanisms mediating performance.

Altering the physiological and anatomical mechanisms that mediate expert performance

The human body is not a machine with pre-fabricated parts that eventually wear down with use during adulthood (Ericsson, 2003d). On the contrary, the human body consists of a complex organization of trillions of cells that developed by cell divisions from a unique single cell. Every cell in the human body contains all the genetic information necessary to generate all the different cells in the body. When people reach adulthood, natural development diminishes, but the many cells in the body retain the ability to reproduce in response to injuries and other needs to regenerate tissue. For example, adults can regenerate damage to the body following surgeries and broken bones. In fact, the body is engaged in constant regeneration to replace damaged cells in the skin and virtually all types of tissues. The human body is designed to protect its homeostasis with its preferred temperature range and desired concentration of oxygen, water and glucose in the blood stream and in all cells of the body. Whenever individuals engage in demanding physical and mental activities, the metabolism of their muscles and their nervous system increase, and the supply of oxygen and energy are dramatically reduced as the increased metabolic activity of muscles and nerves consume them at unusually high rates. To re-establish and preserve homeostasis, the body activates various counter measures (negative feedback loops), such as increased rates of breathing (to increase the oxygen levels of the blood), increased pumping action of the heart, and increased control of the vascular system (to direct additional blood to the active muscles and nerves). When individuals, however, intentionally push their bodies well beyond their comfort zone (Ericsson, 2000, 2002) and engage in sustained strenuous physical and mental activities, the normal compensatory mechanisms will not be able to maintain the regular range of homeostasis. The elevated metabolic activity will induce a strained bodily state with, for example, oxygen concentrations that are below the normal acceptable range which, in turn, leads to changes in metabolism, resulting in unique bio-chemical products. For instance, when humans engage in intense physical activity, several hundred genes are activated from their dormant state in the DNA (Carson *et al.*, 2001). The biochemical compounds and changes in metabolic processes stimulate cells in the muscles as well as in other parts of the body, such as the walls of the capillaries, to express genes in the cells' DNA that stimulate production of proteins, initiating bodily reorganization and change. When the demanding activity is stopped the generated compounds will initiate these adaptive processes as the body is restoring homeostasis during rest. To maintain sufficient concentration levels of the critical compounds long enough to complete this reorganization, people need engage in regular exercise at sufficient intensity levels. For example, it is well documented that healthy adults who engage in intense regular aerobic exercise improve their aerobic fitness (Robergs & Roberts, 1997). The type, intensity and frequency of exercise necessary for bodily adaptations will depend on current fitness level. Young non-athletes need to exercise at least twice each week for at least 30 minutes per session with a sustained heart rate that exceeds 70% of their maximal level (often around 140 beats per minute for a maximal heart rate of 200). These activity levels will lead to extreme conditions for some of the involved cells. For example, sustained activity in the muscles will lead to low levels of oxygen in the capillaries surrounding the critical muscles, which, in turn, will trigger the growth of new capillaries (angiogenesis). Similarly, improvements of strength and endurance require that individuals keep overloading (i.e., increasing intensity, frequency or duration on a weekly basis), and that they keep pushing the associated physiological systems outside the comfort zone to stimulate physiological growth and adaptation (Ericsson, 2002, 2003b, c, 2006b).

The physiological and anatomical characteristics that distinguish elite performers in domains such as sports and music have been shown to be adaptations to demands induced by their regular practice. For example, endurance runners are able to increase the pumping capacity of blood as a result of an increased size of the heart. This change emerges only after years of extended intense practice. When elite athletes eventually stop their training and engagement in intense physical exercise, the heart size reverts back toward the levels seen in non-athletes (see Ericsson, 2003d, and Ericsson & Lehmann, 1996, for reviews). Furthermore, these characteristics may even apply to the brain, as recent reviews show that the function and structure of the brain is far more adaptable than previously thought possible (Kolb & Whishaw, 1998; Gaser & Schlaug, 2003; Hill & Schneider, 2006).

In summary, individual differences in anatomical and physiological characteristics that mediate expert performance (with the exception of height and body size, Ericsson, 1990, 2006b; Ericsson *et al.*, 1993) appear on the basis of the current evidence to be the results of a long series of adaptations induced by biochemical responses to the strain induced by specific practice activities. Experimental studies with physiological and performance measures show beyond a doubt that the attainment of a higher level of functioning of physiological and performance systems in adults is enabled, if and only if, the practice intensity or duration is increased (Ericsson, 2003b, c, 2007a, b). This evidence effectively refutes some concerns about epiphenomenal correlations in these domains, namely the concern that the practice itself might not be leading to the performance improvements. The same framework can also explain why mere engagement in domain-related activities has *minimal effects* unless it overloads the physiological system sufficiently to lead to associated gene expression, which stimulates subsequent changes (improvements) of mediating systems. It is also important to recognize that there is an optimal level for straining a targeted physiological system, because if the repeated strain exceeds the systems' adaptive capacity irreparable damage to the tissue and chronic fatigue may result (Ericsson, 2000; Ericsson, 2003b, 2006b). To monitor and maintain the strain in the optimal range athletes need to exert control and sustain full concentration. Furthermore, this account of physiological change emphasizes the need for rest so that the athletes can recuperate by sleeping and napping while the body restores homeostasis, completes induced physiological transformations, and recharges metabolic reserves. In doing so, the performers can engage in deliberate practice with full concentration during the next practice session (Ericsson *et al.*, 1993).

Toward an account of the improvement of specific aspects of performance

The acquisition of most types of expert performance can be viewed as the sequential mastery of increasingly higher levels of performance through the acquisition of more complex and refined cognitive mechanisms, as is illustrated in Figure 1. For performers with a given level of skill there are some tasks that they are already able to successfully complete, such as a single rotation during a jump as an ice skater. In contrast, there are other tasks that the same performers cannot complete reliably or even at all, such as a triple or even a double rotation during the same jump. To progress to higher levels, the performers' practice needs to focus on the not-yet-attained and challenging tasks that define the desired superior level of performance. We argue that, analogous to the research on the acquisition of memory skill, the connection between attaining a new and higher level of sustained performance and the deliberate practice that led up to the associated reproducible improvement is very strong. In fact, we would challenge our critics to find reproducible evidence on improvement of adult performance that was not directly linked to practice. In the following pages we will propose how mastery of increasingly difficult tasks is gradually attained, and the essential role played by the cognitive mechanisms and representations that monitor and control the integration of complex behavior during learning.

Acquisition of increasingly difficult and complex motor activities. In many types of motor skills, such as piano and violin performance, and sports, such as gymnastics, figure skating and platform diving, teachers and coaches in the domain often agree on ranking the difficulty of movement combinations. When introduced to their domains, children are guided to mastery of the easiest movements first, and then the more advanced movements, nearly always in their order of complexity and difficulty. In all of these domains, guidance and instruction are crucial, and there is typically a close relationship between different individuals' overall achievement and the most difficult movement that they have mastered.

When aspiring performers try to learn new difficult movement sequences, their initial attempts will almost certainly be unsuccessful and eventual mastery requires changing the execution and control of their performance. Continued attempts for mastery require that the performer tries to change some specific aspects while preserving previously mastered skills by stretching performance beyond its current level. This type of deliberate practice requires full attention and complete concentration, but even with that maximal effort, repeated failures are inevitable. Nobody enjoys failing and performing activities that go beyond their current level of skill and control. Failures in some sport are particularly aversive because they often lead to falls on the ice or gym floor that can be quite painful. Indeed, even skilled, sub-elite ice skaters spend much of their limited practice time on already mastered jump-combinations rather than working on the not-yet-mastered combinations with the greater need for improvement. In contrast, more elite skaters were found to spend a higher proportion of their time compared to sub-elite skaters on jumps and other challenging activities that, while aversive, are necessary to improve performance (Deakin & Cobley, 2003). In general, more accomplished performers engage in a higher proportion of deliberate practice during which they practice aspects of their performance that have the most room for improvement contrary to Sternberg's (1996, p. 350) earlier cited argument that expert performers only engage in activities that they are already good at. For example, as skill levels of musicians increase there is a progression toward increased quality of practice, where expert musicians engage in problem-solving and rely on specialized training techniques to master greater challenges (Gruson, 1988; Chaffin & Imreh, 1997; Nielson, 1999; Ericsson, 2002).

Acquisition of superior power, control, and speed of motor activities. In many sports, such as weight-lifting, darts, swimming and running, the task in competition remains similar at all levels of performance. The major type of superiority of experts over less skilled performers involves greater strength and power (resulting from physiological and anatomical changes in the case of weight lifting). In other sports the key aspect concerns their ability to control and reproduce their actions more accurately than novices, as in the case of darts (Duffy, 2002), golf putting (Hill, 1999; Hill *et al.*, 1999), and consecutive reproduction of the same music performance (Ericsson *et al.*, 1993). In other dynamic sports, such as swimming, running and tennis, expert performers are able to initiate and complete a series of actions faster than novices. Even the superior speed of expert performers has been found to depend primarily on acquired cognitive representations that allow performers to be prepared for alternative actions rather than any general basic capacities, such as better basic acuity of the their sensory perceptual systems and/or faster basic speed of their motor systems, which do not predict expert performance (for reviews see Starkes & Deakin, 1984; Abernethy, 1991; Williams & Ward, 2003; Ward & Williams, 2005).

Strong evidence for how speed of performance can be increased through deliberate practice by refining the representations of future actions is provided by the extensive research on typing. The key finding is that expert typists have acquired mental representations to allow them to look further ahead in the text while typing in order to prepare for future key strokes in advance (as shown by high speed filming of anticipatory movement of the fingers of typists). Typists are able to type at their normal speed for years without increasing it. They are, however, also able to increase their speed of typing beyond their normal speed by pushing themselves for as long as they can maintain full concentration, which is typically between 15–30 minutes per day in the beginning of training (Dvorak *et al.*, 1936). While they push themselves to type at a faster speed— usually around 10–20% faster than their normal speed— typists uncover keystroke combinations that are comparatively slow and poorly executed. This type of practice allows identification and subsequent correction of weaker components that will allow gradual speed-up of performance during an extended series of practice sessions. More generally, deliberate practice in many different domains involves finding methods to push performance beyond its normal comfortable level by maximal concentration—even if that higher level of performance can be maintained only for short time without errors.

Improvement in the selection of actions in representative situations. In order to improve one's ability to select actions, it is necessary to set up practice tasks where the trainees' selected actions can be evaluated by comparisons against gold standards, such as the best possible action or the action taken by expert performers with the highest performance index. In chess, aspiring expert performers typically solve this problem by studying published games between very strong chess players. These aspiring players examine these games one move at a time to determine if they can generate a move that will match the corresponding move originally selected by the masters for that particular position. If the chess master's move differed from their own selection, it might imply that their planning and evaluation must have overlooked some aspect of the position. With sufficient time for planning, greater than could devoted during a tournament game, a weaker player may match the move selections of a better player, given that even the best chess players show improved play when given more time, as illustrated by their making more mistakes under time pressure (viz., in speed chess: Chabris & Hearst, 2003). With more chess study, individuals refine their representations and can access or generate the same information faster. Serious chess players spend as much as four hours every day engaged in this type of solitary study of chess games (Ericsson *et al.*, 1993; Charness *et al.*, 1996, 2005; Ericsson, 1996).

In a review of research on musicians, chess players, actors and many other individuals with exceptional abilities, Ericsson and Kintsch (1995) found that expert performers acquire memory skills based on mechanisms of long-term working memory (LTWM) that allowed them to expand their working memory to facilitate planning, reasoning, evaluation and other demanding activities within their domain of expertise. Ericsson and Kintsch (1995) found that the same type of acquired mechanisms that mediated working memory in expert performance (Ericsson *et al.*, 2000) could also explain superior working memory for regular adults, such as the expanded working memory used during comprehension of texts and books. Similarly, Ward and Williams (2003) demonstrated that as soccer players acquire better control and can execute several alternative actions, they develop more sophisticated representations of game situations, which improves their subsequent ability to select actions. There is also evidence from studies of other sports, such as baseball and tennis, that superior performance is linked to more refined representations of game situations (see McPherson & Kernodle, 2003). Studies of visual artists have also revealed that the best-rated products generated in constrained experimental situations are associated with more complex generation processes where more alternative ideas are generated and explored before the final one is selected (Getzels & Csikszentmihalyi, 1976; Kozbelt, 2003). The superior ability to generate and evaluate alternative products parallel the results found in chess.

In summary, investigations from the expert performance approach have demonstrated that engagement in deliberate practice enables not only the acquisition of complex movements, but also improves the speed at which these moves are executed. Furthermore, a wealth of evidence from several domains supports the notion that expert performers acquire memory skills based on mechanisms of

LTWM, which allows them to access appropriate superior moves and, if time permits, generate and consider multiple alternatives. Moreover, the psychological and physiological demands of deliberate practice limit the time that performers can devote without a break. These limits also constrain the daily practice amounts, where even experts need sleep and rest in order to recuperate prior to the next training sessions (Ericsson, 2006b; Ericsson *et al.*, 1993). Even though many giftedness researchers agree that practice is necessary for the attainment of superior performance, several claim that innate limiting factors exist (see Schneider, 1993; Detterman & Ruthsatz, 2001; Heller *et al.*, 2005). In the next section, we review evidence for potential limits to the attainment of superior performance and the implications of this evidence.

A critical review of the proposed evidence for unmodifiable mediating mechanisms of expert performance

The proposed framework provides a method to describe the types of training needed to achieve cognitive and physiological changes mediating improved performance. We believe that this knowledge accumulation of effective training techniques must be pursued in tandem with any investigations of modifiability, where desired changes might not be attained in spite of persistent efforts. In the following subsection, we will discuss in more detail a few reported abilities that seem very difficult to attain through practice as well as the current evidence for a fixed innate endowment that constrains the upper limits of performance.

Developmental windows: when performance is difficult to improve

There are examples of abilities that adults find difficult to learn. For example, adult immigrants often have great difficulties attaining the language of the host country to the level that they are perceived to be native speakers. In some cases the difficulties are particularly salient, such as native Japanese being unable to perceive the difference between the English phonemes ‘l’ and ‘r’ (Miyawaki *et al.*, 1975; Iverson *et al.*, 2003). Notably, recent research shows that the ‘l’ versus ‘r’ distinction can be acquired with well-designed training activities using immediate feedback, which is rarely available in natural language interactions (McClelland *et al.*, 2002). Originally, it was generally believed that the brain was only able to acquire a new language during childhood while the brain was developing (Lenneberg, 1967), and that acquisition of complete language mastery of a new language, especially pronunciation, at older ages was not possible. Although a critical period for effective mastery pronunciation may exist, recent research has uncovered evidence that questions such firm limits and emphasizes the constraints involving extensive training necessary to achieve language mastery. This work further highlights the difficulties of doing so for adults who engage in full time work and family life (Bongaerts, 1999). It may be easier to acquire native language pronunciation as a child, but it is not impossible for an adult; however, it may be nearly impossible for adults without sufficient time for language learning and development activities, especially as acquiring native pronunciation may be particularly difficult after childhood.

There are other types of expertise that benefit from anatomical changes, where practice can change the course of development in a potentially irreversible manner during certain critical developmental periods. For example, ballet dancers' ability to turn out their feet, and baseball pitchers' ability to stretch back with their throwing arm are linked to practice overload at around 8- to 11-years-of-age, when the children's bones are in the process of being calcified (Ericsson & Lehmann, 1996). More generally, early and extended training has been shown to change the cortical mapping of the brain area controlling fingers of string players (Elbert *et al.*, 1995) and the flexibility of fingers (Ericsson & Lehmann, 1996). Also interesting is the recent finding that intense music practice influences the development of myelin around nerves in critical brain regions. The development of white matter (myelin) occurs in different brain regions at different ages (Bengtsson *et al.*, 2005). Even the famous ability to name musical notes in isolation—'the gift for perfect pitch' (Simonton, 2005, p. 312)—is linked to a very early developmental window of opportunity. It is most easily acquired between ages 3 and 5 years during early music instruction, when children encode stimuli in absolute terms (Levitin & Rogers, 2005). At older ages music students encode musical tones in relation to other tones and thus acquire relative pitch, finding it far more difficult to acquire absolute pitch. Importantly, these differences in adult abilities are explained with critical periods, rather than with genetic differences between individuals. There are interesting examples of late starters, who attempt to attain the physical adaptations of the early starters but are not able to do so and where the training of the late-starting adults may lead to injuries (Pieper, 1998).

There is also considerable evidence that correct fundamental technique is more easily acquired at younger ages when there is no need to overcome interfering habits. For example, when young children start working with music teachers, they start to work on simple music pieces. Easy music pieces of low to medium difficulty levels can be played with a wide range of playing styles, so there is no inherent need to acquire sound fundamental technique. However, when the students progress and attempt to master more advanced and difficult pieces that require higher speed and more expressive control, the quality of fundamental technique becomes the limiting factor for performance. The music students with flawed fundamentals may at this point have reached a firm limit, unless they take off a year or two to focus on relearning the fundamentals correctly and then re-acquire the complex skills on that base. Interestingly, recent investigations have observed neurological differences between students with flawed fundamentals and those possessing proper techniques (for a review, see Pascual-Leon, 2001). The importance of acquiring fundamental posture and movement patterns has also been demonstrated in some sports. For example, Law *et al.* (2007) found that world-class rhythmic gymnasts started their careers by studying classical ballet, a technically demanding form of dance, as children. In contrast, rhythmic gymnasts at the national level started with less structured dance activities, such as playful gymnastics.

These studies demonstrate that methods of practice, particularly during the beginning phase of development, might lead to different performance asymptotes. Although these findings suggest that there are possible limits to performance, these explanations are not genetically based. These types of limits on further development may be circumvented with appropriate practice activities before critical developmental periods, and early training and access to resources such as knowledgeable coaches can enable motivated students to excel. Indeed, it is likely that children who were initially perceived by their teachers as 'talented' may have been encouraged to invest more effort to acquire the appropriate fundamental techniques during the initial phase and thus were able to build sound skills on these fundamentals.

Recent research on general skills in reading has found that fundamental skills, such as phonological awareness, appear to be prerequisites for normal development. If interventions are made to assure acquisition of these skills then normal reading development can be attained even for at-risk children. Akin to the findings demonstrating that intense music practice influences the development of white matter, recent research suggests that there is a relationship between reading ability and the development of white matter in children (Deutsch *et al.*, 2005). In both children and adults, white matter structure in the left temporal–parietal region of the brain is correlated with multiple aspects of reading performance. Preliminary results from Deutsch and colleagues (2005) suggest that this effect strengthens over time, with increased reading experience.

Analogous to the relearning of fundamentals (e.g., in music), many types of skills can be surprisingly difficult or impossible to attain by adolescents and adults, because of several factors—none of which are based on genetic advantages or disadvantages. The natural environment often does not provide the suitable practice situations with contrastive stimuli, feedback, and opportunities for refinement through repetition. Moreover, the window of susceptibility of practice-induced anatomical change occurs during childhood in many cases. Finally, people often underestimate the amount time required for learning even for children and in particular relearning of incompatible skills. Importantly, the limitations discussed are due to a lack of appropriate practice activities during developmental critical periods rather than innate performance restrictions.

In search of evidence for innate abilities and upper limits of superior performance

Many researchers and teachers interested in innate talent have searched for evidence of giftedness in early childhood before any training and relevant practice has been initiated. Much of this 'evidence' is anecdotal and based on retrospective reports. For example, Scheinfeld (1939) claimed that virtually all famous musicians had shown reported evidence of music talent prior to any training in music. However, a closer examination of his evidence for innate talents shows that it does not reflect any reproducible performance but rather signs of interest, such as 'response to violins at concert' (p. 239) (Yehudi Menuhin at 18 months) or producing song-like sounds before speaking (Arthur Rubinstein at 18 months). Moreover, Howe *et al.* (1995) collected retrospective interviews from parents of adolescents with widely differing music achievement and found that subsequent music performance is unrelated to the frequency of reported talents and the age of their first reported appearance. Other examples of frequently recounted evidence cannot be independently verified. For example, the popular childhood anecdotes about Gauss' mathematical genius were first reported by Gauss himself as an old man. These and other anecdotal reports nearly always lack independent verification and are therefore not even considered in modern biographies of Gauss (Bühler, 1981). Howe *et al.* (1998) give several examples of initial claims about sudden appearances of abilities that after investigation show a gradual development consistent with normal skill acquisition (see also Treffert, 1989, for the rejection of the sudden inexplicable emergence of music skill of a famous savant). Although even modern researchers such as Gagné (1998) argue that we need to trust experienced teachers' judgments, such as the famous music professor Dorothy DeLay's subsequent recall of her initial impression of Sarah Chang, we argue that such evidence is not based on reproducible observable performance but on anecdotes that typically cannot be verified and in particular replicated under controlled test conditions. Such evidence is of little value to scientists and will not contribute to sound empirical foundations.

In many domains children start training at very young ages. In the last hundred years children (with the help of their parents) have been training in perceptual-motor skills, such swimming, music and dance, at ages as young as 3 and 4 years (Ericsson *et al.*, 1993). Reviews of talent identification in children, especially young children, have shown consistent failures in the identification of future outstanding performers in music and sports (Ericsson & Lehmann, 1996). In fact, research on the efforts to identify talents in young athletes show that the selection is systematically biased by factors unrelated to innate talents. For example, professional athletes in soccer and ice hockey are born much more frequently (three–six times) in some months of the year than in others (Boucher & Mutimer, 1994). The factors causing this 'birth-date' or 'relative age' effect are due to the grouping of young children together in age cohorts, such as children born between 1 January and 31 December. At the age children start participating in sports, this means that some 6-year olds will be competing with 5-year-olds. Coaches who do not know the children's birth dates tend to perceive the oldest and most physically mature children within an age cohort as the most talented. The older children appearing more talented are given access to better training resources that, in turn, accelerate their development. A recent review by Musch and Hay (1999) has more or less conclusively linked the birth-date effect to the *relative age* of children competing within the same age cohort. The most compelling evidence comes from a recent study (Helsen *et al.*, 2000) that has analyzed a natural experiment, where the dates defining the age cohorts were changed from 1 August through 31 July to 1 January through 31 December. Within a single year the more mature children in the new cohorts, born from January to

March, became the most highly selected among the younger cohorts of soccer players. In sum, these findings show that the coaches' bias for children with older relative ages leads to several consequences that change the treatment and opportunities for practice of these children and adolescents, which have long-lasting implications so as to increase the frequency of these athletes becoming professionals and even representatives for the country's national team in the World Cup (Richardson & Stratton, 1999). Although it is not yet clear what specific cues coaches use during this identification process, the early search for talent has powerful discriminatory effects when it selectively identifies more mature children as being more 'innately talented'.

In addition to citing early signs of talent and the sudden emergence of abilities, proponents of innate talent also cite the existence of individual differences in the limits of attainable performance as evidence of genetic differences (Galton, 1876; Gottfredson, 1997; 2004; Detterman & Ruthsatz, 2001; Ilies *et al.*, 2006). For example, there is a large body of evidence from occupational psychology that has related individual differences in job performance to tested cognitive abilities, which is often assumed to reflect fundamental fixed capacities (see Gottfredson, 2004). However, reviews from the expert performance approach suggest that typical job performance may not be limited by actual capacities. In fact, Ericsson *et al.* (1993) found that the stable levels of performance of office workers do not reflect the maximal levels that these individuals are capable of attaining. For instance, when people were motivated to improve performance to attain a promotion, they were often able increase their performance, such as typing speed, beyond its prior level by a substantial amount. Like recreational engagement in athletics or music, many individuals in different jobs are most likely unmotivated to improve once they reach a level of performance that is acceptable. Moreover, our review of laboratory studies of learning and skill acquisition during the last century showed that improvement of performance was uniformly observed when the participants were given well-defined tasks, were provided with feedback, and had ample opportunities and motivation to gradually refine their performance by repetition (Ericsson *et al.*, 1993). These deliberate efforts to increase one's performance beyond its current level require concentration and involve problem-solving and finding better methods to perform the tasks. Most college students are able to keep improving on a task as long as the training sessions were limited to around an hour—the time that college students maintain concentration during lectures and tests in college (for a review, see Ericsson *et al.*, 1993). More generally, engaging in an activity with the primary goal of improving some aspect of performance is a prerequisite of effective improvement. Mere experience in a job (beyond the limited period of initial mastery) does not lead to large improvements without an individual engaging in some form of specific training activity (i.e., deliberate practice), as discussed above.

In summary, we are unable to find empirical support for the sudden emergence of high levels of performance that meets our criteria. Our reviewed evidence favors a gradual development of these abilities. Furthermore, while proponents of innate talent may cite upper limits of ability as evidence of genetic predisposition, reviews from the expert performance approach suggests that these upper-limits may not reflect innate limits, as motivated individuals are often able to improve their performance by engaging in deliberate practice.

Prodigies and gifted students

Another group of proposed exceptions to the expert performance framework are prodigies, namely children who attain a performance only seen in much older children or even adults. Notably, there are only comparatively few prodigies, such as Mozart, Picasso and Yehudi Menuhin, who continued their success into adulthood—most prodigies do not live up to expectations (Barlow, 1952; Bamberger, 1986; Freeman, 2000; Goldsmith, 2000). In a recent critique of the expert performance account von Károlyi and Winner (2005) argued that 'extreme precocity makes its appearance prior to practice and training' (p. 378), citing examples such as 'Garett, who read at 18 months … a skill typically learned in school at age 6' (p. 378) and 'Amy, who did algebra for fun at age 4' (p. 378). There are many other similar examples from a variety of other domains, but we question the assertion that these individuals 'come ''hard-wired'' with both interest *and ability* in particular domains' (p. 378, italics added). It is difficult to imagine how a child could be 'hard-wired' to read a particular language, such as English, or to solve algebra problems using formal rules and modern mathematical symbols; instead, an explanation based on earlier onset of acquisition is more plausible. We would welcome rigorous studies that carefully document and monitor the environmental conditions of such suddenly emerging precocious activities along with independent measurement of the alleged abilities using the process-tracing and experimental methods of the expert performance approach. Without this type of scientific documentation, we prefer an alternative explanation of these findings, namely that these abilities emerged as the result of practice or training that was part of the child's early environment (e.g., parental support). In fact, Winner's (1996a, b) own research supports the claim that prodigies often spend substantial amounts of time engrossed in their respective fields, determined with a 'rage to master' the skills required to excel (see also Hyllegard, 2000). Even biographies of very eminent individuals reveal that these individuals engaged in immense amounts of practice and their technique developed over time. In a review of musical prodigies, Lehmann (1997) noted that all had a live-in teacher, which would ensure that each of them had access to specialized instruction and encouragement to engage in the amount of practice required to maintain superior levels of performance.

Although the current evidence does not, according to our assessment, support the claim that abilities or skills are 'hard-wired', the possibility of genetic differences in the motivational factors required for extended deliberate practice has always been considered to be plausible based on the review of the available evidence (Ericsson *et al.*, 1993). This view is consistent with Winner's (1996a, b) proposal for a 'rage to master', namely that 'some passion, some rage to master, must drive children to devote uncounted hours to understanding a domain' (von Károlyi & Winner, 2005, p. 379). An acceptance of the importance of innate determinants of motivation would not change our argument that training and deliberate practice are the principal causes of exceptional performance. Still, as children mature, it becomes increasingly important to maintain motivation, particularly when prodigies become adolescents and adults. At that age it is no longer sufficient for them to perform at a level that is impressive for a child. These individuals need to engage in effortful practice activities in order to improve their performance to be able to maintain their performance advantages compared to their peers and develop skills to allow them to make creative contributions to their domain of expertise at the final phase of expertise development (Ericsson *et al.*, 1993). Jeanne Bamberger (1982) has referred to this period in a young prodigy's life as 'mid-life crisis'. It is a crucial period during which the once prodigious individual can choose to continue to excel or fall by the wayside. Biographies of the few successful prodigies reveal that these individuals took measures to ensure that they gained the knowledge and experience necessary to perpetuate their superiority. For example, as a young musician, Mozart traveled to cities with advanced music culture in order to work with eminent contemporaries and improve his own musical abilities (Lehmann, 1997).

Similar to prodigies, gifted students show unusual performance for their age, typically in academic domains. Many studies use academic achievement to define giftedness (Hoover & Feldhusen, 1990; Shore, 2000), others use various cut-off scores on tests such as the IQ test (Hollingworth, 1942; Gottfried *et al.*, 1994) and the Scholastic Aptitude Test (SAT) (Stanley *et. al.*, 1974; Jarosewich & Stocking, 2003). Still others rely on social criteria, such as teacher nominations (Kammer, 1984; for a review, see Konstantopoulous *et al.*, 2001). Authorities in the gifted field agree that the lack of consensus on how to define the gifted student, and the problems with the identification process (e.g., a large amount of false negatives) are major concerns (Gagné, 1991; Feldhusen & Jarwan, 1993; Pfeiffer, 2003). Of particular concern are the results of investigations of the 'underachieving-gifted' students, who were once identified as gifted (by standards that are highly variable) but are not performing according to their purported potential. For example, the National Commission on Excellence in Education (1983) reported that up to half of all gifted students were not performing up to their expected abilities, i.e., academic performance at the top 3–5% of students (US Commissioner of Education, 1972). Similarly, Johnson (1981) reported that 45% of gifted students in Iowa had GPAs lower than a C. There have been proposals for a wealth of strategies (similar to those offered to underachieving non-gifted students) to 'rehabilitate' gifted students who are underachieving (Gallagher, 1991; Schultz, 2002). While some researchers would emphasize the importance of potential for achievement rather than actual accomplishments, other researchers reject the notion of gifted underachievers (see Cross & Coleman, 2005) contending that conceptions of giftedness should be based on performance. Borland (2005) even questions the value of the giftedness label in general. The most effective method for accommodating gifted students appear to be to advance them to a higher grade commensurate with their level of achievement in the particular subject, such as mathematics (Charlton *et al.*, 2002) or more generally (Borland *et al.*, 2002; Rogers, 2002). In general, remediation interventions and acceleration programs designed for gifted students can be offered to *all students based on actual achievements*, which should be closely monitored and frequently assessed. Interestingly, Ma (2005) found that early acceleration in mathematics benefited regular students even more than gifted and honors students. All students should receive challenges and feedback appropriate to their own current level of performance.

In sum, we found no rigorous evidence for the sudden emergence of superior abilities in both prodigies and gifted students. Both prodigies and gifted students must engage in substantial amounts of practice to keep improving and maintaining their advantage in their respective domains. Interestingly, it is clear from studies of ‘underachieving gifted’ and prodigies facing ‘mid-life crises’ that these individuals may lose their motivation (cf. rage to master) to engage in appropriate training activities. From our survey of the research it seems that prodigies and ‘gifted’ individuals are similar in their path toward high levels of performance (Feldman, 1986) but their rate of progression is argued to be faster than normal. In the next subsection we will discuss individual differences in the rate of learning and rate of development of performance.

Individual differences in rates of learning

Stable individual differences in domain-specific performance have not been demonstrated before the child is exposed to activities in a related domain. However, one key argument often made in favor of innate accounts is that gifted individuals learn at faster rates than their less gifted peers. For instance, Simonton (2005) argues that perspectives similar to ours ‘run into numerous empirical and theoretical problems’ (p. 318). He claims that ‘the extreme environmentalist position fails to account for the exceptional rates at which highly gifted individuals can acquire mastery of a chosen domain’ (p. 318). While stable individual differences in rates of learning (improvement of performance) in certain domains unquestionably exist, they are associated with differences in the type of practice activities and the nature of the students’ concentration and engagement. From retrospective interviews of international-level performers in several domains, such as sports, arts, mathematics and neurology, Bloom and his colleagues (Bloom, 1985) showed that future elite performers engage in activities that differ systematically from those of recreational amateurs. Amateurs in sports, such as tennis, golf and jogging, acquire an acceptable level of performance and then merely maintain that level for decades as is illustrated in the lowest performance trajectory in Figure 4. The single most important differences between these amateurs and the three groups of elite performers is that the future elite performers seek out teachers and coaches and engage in supervised training, whereas the amateurs rarely engage in similar types of practice. According to Bloom (1985) the international-level

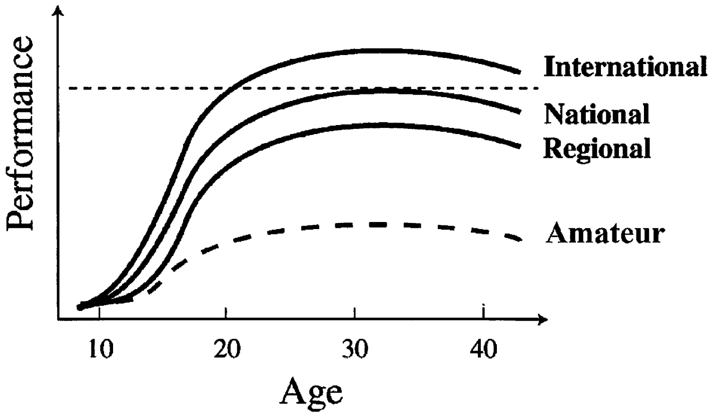

Figure 4. Performance development as a function of age for different level of attained achievement

performers did not show any evidence that would meet our criteria for clearly superior performance before the start of training. Their superior performance emerged as the result of training. More generally, research is increasingly questioning claims that some highly talented individuals can attain high levels of performance in a domain without concentration and deliberate practice. Even the well-known fact that allegedly more 'talented' children improve faster in the beginning of their music development appears to be in large part due to the fact that these children spend more time in practice each week (Sloboda *et al.*, 1996) rather than naturally learning faster per unit of time. In fact, one of the primary studies cited by Simonton (2005) concerned Lubinski *et al.*'s (2001) longitudinal study of students defined as 'profoundly gifted' based on scores in the math and/or verbal SAT's at early ages. Lubinski *et al.* (2001) noted that 'An overwhelming majority of participants (95%) took advantage of various forms of academic acceleration in high school or earlier to tailor their education to create a better match to their needs' (p. 720) and that:

> ... high-math participants preferred math/science courses, whereas high-verbal participants were more likely to prefer humanities courses... with respect to undergraduate majors, the specific disciplines that the participants chose appear to have been a function of both gender and ability profile. (Lubinski *et al.*, 2001, p. 721)

Clearly, these individuals actively sought out environments and learning experiences that matched their interests and supported their continued development in the domain.

Individual differences in basic learning rates are challenging to study, because individuals differ substantially in their background knowledge and in the structure of the skills and strategies that they bring to bear in learning situations in the laboratory. These differences in prior knowledge and skills influence the selection of initial strategies in tasks that in turn often account for much of the variance in how much is learned (Ericsson & Simon, 1993). In laboratory experiments on memory, participants often learn wordlists, showing reliable individual differences in memory performance, which are associated with strategies in processing. Nonetheless after practice with mnemonics, individuals with average initial memory performance can dramatically improve and even surpass the individuals who initially performed at the upper end of the distribution (Ericsson, 1985, 2003a). These findings show clearly that the rate of learning in memory tasks depends on strategies and accessible knowledge and thus does not generalize across all domains of knowledge and activity.

More generally, as skill increases, the strategies, learned procedures, and other mastered techniques are often fundamentally different from the changes observed from relatively brief practice sessions in the laboratory, and differences in learning rates observed there may only reflect learning rate differences in making the early transitions in the acquisition process of expert memory skill (Ericsson & Kintsch, 1995). The acquisition of expert performance described in Figure 1 as a sequence of states S[i], where the transition between any two states, such as S[i] and S[i+1], corresponds to a change in the critical aspects of performance, e.g., learning. The modification of the mediating cognitive mechanisms and physiological adaptations associated with each transition differs and will typically require engagement in different types of deliberate practice activities. Consequently, the processes mediating learning differ qualitatively as a function of the level of acquired skill (Ericsson, 2006b), which makes the concept of 'rate of learning' confounded with differences in already acquired skill and with the particular changes necessary for improving the targeted aspects of performance.

Heritable general abilities and cognitive capacities

Behavioral geneticists argue that most cognitive abilities and physical characteristics are determined in part by genetic factors and typically around half of the variance in individual differences is heritable, that is, attributable to genetic factors (Plomin *et al.*, 1990). However, despite frequent confusions of the term, heritability does not imply immutability or unchangeability (see Vogel & Motulsky, 1997). When people think of genetic influences (cf. Galton, 1979, originally published 1869) they often think of height, which most agree cannot be increased by training (see Ericsson *et al.*, 1993, for a review of the overwhelming evidence that height and body size are primarily controlled by genes in affluent cultures without any shortage of food). There are other characteristics such as weight and body mass, which have high heritabilities (Speakman, 2004) yet can be externally controlled by diet and vigorous exercise. If individuals reduced their intake of calories below the level that they expend by, for example, increasing their physical exercise and reducing the calories ingested consistently, *any* individual will eventually reduce their weight. Our argument is that observed heritabilities for cognitive tasks in a similar manner do not reflect upper-bounds of functioning (limits on attainable performance) when we are addressing these issues within the domain of general psychology. Our review shows that the attainable performance has so far not been found to be limited by attributes, such as height, eye color and facial features, which do not change in response to training, but other attributes that are responsive to sustained training as outlined in the third section of this paper. Finally, reviews show that it is rare that single genes have observable effects that enhance functioning (Vogel & Motulsky, 1997). This contrasts with the fact that there are many mutations (errors in single genes) that cause diseases or even lethal effects. A recent review (McArthur & North, 2005) found that individual differences in attained elite performance in sports *cannot*, at least currently, be explained by differential genetic endowment. Most observable characteristics related to behavior are the result of a complex interaction of many different genes working as a system with many different pathways for attaining the same type of adaptation (Wahlsten, 1999).

Many aptitude tests attempt to measure cognitive capacities that are general in nature. Given that expert performance tends to be highly domain specific (see Helsen & Starkes, 1999), it is possible that a general ability could represent some form of genetic talent. Notably, whether such a general ability exists is still disputed. Some researchers claim that the evidence for a general cognitive ability, the 'g' factor, is overwhelming given findings from factor analyses of the well-replicated finding of positive manifold (Jensen, 1998; Carroll, 2003). These researchers claim that IQ scores, for instance, largely reflect such a factor. However, other researchers have disagreed with this interpretation, arguing that positive manifold may reflect whatever circumstances or influences that lead some individuals to acquire more of the skills measured in typical IQ tests. Indeed, many researchers have suggested that schooling plays a large causal role in influencing IQ scores (Ceci, 1991), and it is plausible that educational advantages lead some individuals to acquire a broader range of skills than others, leading to the observed positive manifold. Similar to heritability, the arguments for a *g* factor are primarily correlational and thus cannot distinguish a unitary ability from a composite of autonomous skills (cf. Howe, 1997).

Moreover, even if IQ were to measure a latent general ability, there is surprisingly little evidence that these tests are predictive of individual differences in expert performance, such as in chess and music (Ericsson & Lehmann, 1996). In fact, with the exception of height and body size (Ericsson, 2006b), there are no generally accepted limits for attaining elite performance in sports that cannot be influenced by deliberate training (Ericsson, 2003b, c). Although some studies of elite scientists, mathematicians, artists and writers have repeatedly claimed that these individuals must possess extraordinarily high levels of intelligence (Cox, 1926; Roe, 1953), these studies do not use objective criteria. In her study Cox (1926) had raters try to assign IQ scores to famous geniuses of the past, though many problems with this approach emerge that are similar to non-blind ratings of performers in other domains (see Gould, 1981, for a critique), and no actual IQ tests could be administered as the geniuses were long deceased. Moreover, Simonton (1976) argued that the correlation between ranked eminence and rated IQ was an artifact of low reliability. In a subsequent study, Roe (1952, 1953) administered a newly constructed test of aptitudes of living eminent scientists and Roe (1953, p. 164) found that 'eminent scientists are on the average higher than the general run of those that get Ph.D.s, but, and this is very important, some of them are not as high as the average Ph.D.'. Roe selected scientists using the peer-based subjective criteria we previously argued against considering; notably, Roe's test appears to have at least partially measured skills needed by scientists (e.g., mathematics). More recent biographies show that some very famous eminent scientists' IQ scores, such as Richard Feynman's score of 123 in high school (Gribbin & Gribbin, 1997; see also Gleick, 1993), are not much higher than that of most graduate students and is around the mean for most groups of professionals (Schmidt & Hunter, 2004).

More importantly for our review is that we have found no studies that have demonstrated that IQ is predictive of achievement in domains where reliable, superior performance has been collected meeting our earlier criteria. Even studies using the subjective method of peer ratings (as we critically reviewed in the first section) found no significant Wechsler IQ differences between a more productive, creative group of female mathematicians as compared to a control group of other female mathematicians (Helson, 1971). In a study of creative artists, MacKinnon (1962) found that 'Among creative artists who have a mean score of 113 on the Terman Concept Mastery Test (1956), individual scores range widely from 39 to 179' (p. 487). As another example, Masunaga and Horn (2001) found no differences between the highest level expert Go players and lower level experts in their performance on cognitive ability measures. In chess, some evidence for IQ correlations have been found with child players with low levels of skill (Horgan & Morgan, 1990; Frydman & Lynn, 1992), but studies of high rated (adult) players have not found correlations significantly different from zero (Djakow *et al.*, 1927; Doll & Mayr, 1987; Grabner *et al.*, 2006). Studies have also shown that memory experts (Ericsson, 1985; Maguire *et al.*, 2003; Parker *et al.*, 2006) are not distinguished by consistently superior IQ scores. In general, IQ tends to correlate with performance at very low skill levels, and is not significant for individuals reaching high levels of performance after extended deliberate practice, which supports other findings that IQ has increasingly less, even no reliable, predictive power after many years of experience (see Hulin *et al.*, 1990). Also, given that there are examples of individuals with average or below average IQ scores that reach the highest levels of achievement (see Doll & Mayr, 1987), a high IQ does not appear to be necessary for attaining elite levels of performance.

In the commentaries to Howe *et al.*'s (1998) review article, researchers cited studies allegedly showing a correlation between IQ and expert performance; for example, Detterman *et al.* (1998) cite two studies to support their claim that 'there is no doubt that attainment in even very specific abilities such as music is influenced by general ability' (p. 412). However, the cited study by Lynn *et al.* (1989) and another by Phillips (1976), are not studies of high ability in music. Both studies administered musical tests that, to the best of our knowledge, have never been shown to predict future elite music performance (Shuter-Dyson, 1982). In a subsequent dissertation, Ruthsatz (2001), one of the authors of the Detterman *et al.* (1998) commentary, found that IQ was not predictive of the audition performances of college orchestra musicians and that accumulated practice was the sole reliable predictor (Ruthsatz, 2001). In fact, this interesting dissertation did find IQ correlations with less skilled high school students (although their music performance was based on potentially-biased, non-blind ratings), which may be in line with the previously discussed findings of decline in IQ score prediction with increasing levels of skill. Moreover, this author raises an important point, namely that the college orchestra musicians have above average IQ scores; however, the finding that these expert musicians have above average IQ scores is probably at least partially a selection artifact. In other words, to be member of a college orchestra (or, similarly, to become a scientist, mathematician, or artist), individuals must be admitted to college, which typically requires a high score on standardized tests, which are known to be highly correlated with IQ tests. These types of selection problems could extend to several domains other than music, especially domains, such as science and medicine, where a doctorate is a virtual prerequisite for an independent career. Ultimately, though, we have little knowledge of whether individuals, who did not meet the college selection criteria, would have succeeded if given appropriate access to training and other resources, and more research is needed. However, the finding that performers have above average IQ scores does not prove that IQ would begin to predict elite domain performance if individuals with average IQ scores were included in the sample.

Overall, the general finding from expertise and expert performance is that IQ does not predict higher levels of achievement among participants within those skill domains. Moreover, for virtually all domains evidence exists that individuals with average or even below average IQ scores can achieve extremely high levels of performance (see Doll & Mayr, 1987; see also Roe, 1953). Generally, we agree with Ziegler's (2005) view that Gardner's (1983) multiple intelligence and other conceptions of intelligence, such as a general latent factor, lack explanatory power given that:

> … neither the multiplication of intelligence nor its enhancement through additional psychological variables was able to procure more than a partial clarification of what gifts or talents 'really' were and what role they played in the emergence of achievement excellence. (Ziegler, 2005, p. 412)

Without knowing what the IQ test measures, we stand to gain little scientific understanding from knowing whether it correlates with achievement. Renzulli (2005) articulated the problem well in writing that the 'concerns about the historical difficulty of defining and measuring intelligence [highlights] the even larger problem of isolating a unitary definition of giftedness' (p. 252).

Another potential general ability that may be linked to high ability and elite achievement is creativity. However, studies correlating scores on creativity tests to real-world creative achievement have generally failed to find reliable relationships. Most real-world forms of creative achievement have not yet been successfully measured by objective methods, so research has relied on subjective judgments. Studies of subjective ratings of creativity of individuals have had difficulty finding any relations to typical creativity tests, such as divergent thinking (see Wallach, 1970; Gough, 1976). Furthermore, that different types of creativity tests do not even show reliable correlations with each other (see Davis & Belcher, 1971) has raised doubts about a general creativity factor. Research on insight problems by Burke and Maier (1965) has not found a relation to IQ and other creativity tests and subsequent studies by Raaheim (1988) found low or negligible relations between IQ and problem-solving on insight problems and other real life problems. Our review has failed to uncover any valid evidence that creativity tests either correlate with objectively measured eminence, measure a general creative capacity, or measure something unmodifiable or innate. Interestingly, some heritability estimates for creativity tests are not reliably different from zero (Pezzullo *et al.*, 1972; Reznikoff *et al.*, 1973).

Several theorists of genius and high ability have noted some curious findings. The children with the highest abilities do not grow up to become eminent (for a review see Freeman, 2000). Gardner (1993) argued that eminent individuals often have an unusual developmental history and individuals with highest ability in the domain were unlikely to produce innovations. Lykken (1998) and Simonton (1999b) argued that exceptional performance is not predictable from similarity with other family members and thus cannot be accounted for by simple independent genes. Instead they have proposed that the interaction of a unique combination of genes in a supportive environment lead to emergence of eminence. More recent research has shown, however, expert performance is no direct consequence of the same genetic endowment and environment. When identical twins engage in extended practice in the same domain the twins' performance will not always be the same—in some cases it will differ significantly. For example, Klissouras *et al.* (2001) report an instance when one identical twin reached world class level whereas the other twin only reached a reliably lower level. Klissouras *et al.* (2001) explain the differences in attained performance in terms of motivation to train, essentially the engagement in deliberate practice (Ericsson, in press b). More importantly, Bouchard and Lykken (1999) found a much lower probability of attaining the highest levels of performance for both fraternal and identical twins. This striking under-representation of eminent twins, where either one or both members of identical and fraternal twin pairs reach elite levels, makes it virtually impossible to estimate heritability for eminent achievement (Ericsson, 1998). Similarly, the lack of appropriate twin data makes it essentially impossible to evaluate Simonton's (2005) claims about the critical role of unique combinations of genes with empirical methods.

Evidence against innate capacities and upper limits

A common *misconception* of the expert performance framework is that this approach *denies* the possibility that differences in innate talent could ever be able to explain individual differences in attainable performance. The expert performance framework merely requires that valid evidence for innate talents must be presented and reviewed before it is accepted. This framework has long acknowledged the possibility that individual genetic differences might causally explain individual differences in elite achievement. However, according to recent reviews (Ericsson, in press a, b) no evidence currently exists, with the exception of height and body size (Ericsson *et al.*, 1993; Ericsson, 2006b). In our review of the improvements in performance by individuals over their career we presented several findings that are not easily reconciled with the innate, fixed talent assertions. While none of these conclusively proves that innate talent does not limit attainable performance of healthy individuals, they provide challenges for the view of innate talents and their associated ideas of fixed upper limits for performance. Although these findings have already been mentioned earlier in different parts of the paper; however, we present them as a unit here.

First, there is compelling evidence that engagement in domain-related activities is required for high levels of performance and that even individuals who might be the most 'talented' need around 10 years of intense involvement before they reach a level where they can consistently win at open adult competitions in sports, sciences and the arts (Simon & Chase, 1973; Ericsson *et al.*, 1993). Hence, the popular idea that some individuals enter a domain and rapidly reach high levels of performance with little effort is false. Effortful training is required for all individuals, even those who might have gifts. In fact, evidence indicates that the most successful individuals engaged in the most deliberate practice, which is a more parsimonious explanation than one that adds an innate talent factor.

Second, the age at which experts typically reach their peak career performance is the mid-to- late twenties for many vigorous sports, and a decade later, in the thirties and forties, for the arts and sciences and games, such as world championship chess and world class musical performance (Ericsson & Lehmann, 1996; Roring & Charness, submitted). This continued, extended development implies that the best individuals are able to engage in domain-relevant activities that lead to improvements in performance, even when physical maturation and increases in height are completed at around age 18. Thus, if development from childhood to maturity reflects fixed capacities reaching their final levels, the finding that high-level performance continues to improve implies that such fixed capacities do not terminate growth toward the upper limits of ability. Indeed, that growth and improvement occur after maturity implies that developmental capacities must certainly not be the sole causal agent and may be less relevant to improvement than is often assumed.

Third and finally, we have extensive evidence for large improvements in the highest levels of performance that have occurred during the last decades and centuries. There are several domains where the competitive conditions and the tasks have remained intact for centuries, and when there are minimal changes in the equipment and rules, any observed changes in performance over the course of a century can likely be explained by changes (improvement) in the type and quantity of training. This is because evolutionary changes involving the emergence of new genes that increase fitness and adaptation take thousands of years and could not explain a dramatic increase in the highest performance levels occurring over the last century. We already know of several examples of this finding from very different domains.

For instance, music pieces that were believed to be unplayable a century ago or only playable by a single elite performer, such as the violinist Paganini, are now frequently standard repertoire for students graduating from music academies (Lehmann & Ericsson, 1998)—thus indicating a dramatic increase in the level of technical proficiency. In the last century many music pieces were rated for their difficulty level expressed as the number of years of music study that would be typically required for a student to be able to perform it well at its recommended tempo. Using this information Lehmann and Ericsson (1998) collected evidence about how old the music prodigies of the past, such as Mozart, were when they gave public performance of pieces of a given difficulty levels. Surprisingly, modern prodigies were much younger when they performed such complex pieces than Mozart had been. In this regard Mozart may be rather unremarkable compared to modern prodigies!

Some of the most striking improvements in the level of performance over historical time are found in sports, where today's world records may be as much as 50% superior to those a century ago (Schulz & Curnow, 1988). The elite performance for events such as the marathon and swimming have changed so much that the gold medal winners of the early Olympic Games would barely meet the standards for amateur athletes, such as entry in the Boston Marathon, and admittance to high school teams in swimming. In these sports there have been large increases in the intensity and daily duration of practice (for a review, see Ericsson *et al.*, 1993; also see Ericsson, 1990, 2003a, b)

In technical domains, such as diving, figure skating, and gymnastics, the difficulty levels of routines have changed and many of the available triple and quadruple jumps in figure skating were not even considered a few decades ago. The change in technical standards becomes even more apparent if one considers that after the IVth Olympic Games in 1908, officials almost prohibited the double somersault in dives because they believed that these dives were dangerous and no human would ever be able to control them. Today *triple* somersault dives are standard among elite divers. Even in intellectual activities, such as chess, Roring and Ericsson (submitted) demonstrated that the early world champion contenders a century ago played chess at a level that is two to three standard deviations below today's typical professional grandmaster chess player.

The historical increases in performance, especially at the elite level, show unequivocally that for most tasks it is possible for a very large number of individuals, through extended training, to match and even surpass the performance levels of the most elite individuals of the past. Hence, if differences in genes constrain the upper limit on attainable performance, how can today's serious amateurs match the performance of earlier elite performers? Notably, for some domains, it could be argued that the chances that the 'super-talented' become involved in the domain have increased due to increased popularity of a domain and that although the population gene-pool may be invariant, the gene-pool of future expert performers in a given domain is not. However, it should be noted that some of the historic increases have occurred in domains that may not have experienced increases in popularity, such as in some athletic domains. Given that majority of researchers accept the critical role of deliberate practice and that many domains have also demonstrated an improved access to quality training resources (Gobet *et al.*, 2002) as well as increased amount of practice due to younger starting ages (see Roring & Ericsson, submitted) we believe that historic improvements in performance are unlikely to require additional explanation in terms of innate talent.

Concluding remarks

The first part of our paper used the theoretical expert performance framework to establish criteria for building a body of evidence for a science of exceptional superior performance. We then described the accumulated evidence on reproducible superior performance within the expert performance framework and described the mechanisms that have been found to mediate the acquisition of performance through training and deliberate practice. In the fourth and final section we discussed a number of phenomena related to exceptional superior performance that had been cited in support of innate talent and as a refutation of acquired performance. We found no rigorous reproducible evidence that innate abilities, excepting height and body size, prevent healthy individuals from attaining expert levels of performance.

Although we have attempted to identify all the relevant evidence it is very likely that we have overlooked important studies. It is, therefore, our hope that commentaries on this paper will help us and all the other researchers of exceptional superior performance to identify the complete body of reproducible evidence that any general scientific account of reproducible exceptional performance needs to explain. Only when the new evidence is identified and scrutinized will it be possible to evaluate the type and diversity of mechanisms that are necessary to give a satisfactory and parsimonious account. To summarize, the studies we would argue are most likely to provide evidence for innate influences would examine a sample of healthy motivated individuals engaging in activities designed to improve their performance in a domain (deliberate practice) with an objective metric of reliably superior performance (e.g., a representative task). The demonstration of large, *reliable* individual differences in the attainable levels of performance *after* engagement in appropriate amounts and types of deliberate practice would give us new insights into the existence of individual differences in limits that constrain performance for motivated healthy individuals.

As we have pointed out, the focus on reproducible performance is consistent with many researchers' concerns about the validity and the usefulness of concepts of latent giftedness, and we argue for a shift toward a focus on observable achievements (Borland, 2005; Walberg & Paik, 2005; Ziegler, 2005). Similarly, we and other researchers (Ziegler, 2005) are critical of theories of giftedness expressed in terms of other latent capacities, such as intelligence, creativity and motivation, which have similarly been found difficult to measure and define in a consensually acceptable manner. The expert performance approach avoids the problems of latent capacities by capturing and analyzing the observed target performance of individuals, namely their reproducibly superior performance in the particular domains. In explaining this performance it is possible to account for its acquisition by an analysis of the associated learning activities, such as deliberate practice. These practice activities are, at least in principle, observable. It is even possible to analyze the detailed structure of the learning processes by collecting process-tracing data, such as concurrent and retrospective reports. Perhaps even more importantly, the expert performance approach does not have to measure an elusive latent variable corresponding to motivation that is correlated with performance. In this framework, it is possible to measure the relevant aspects of motivation indirectly, namely by measuring the quantity and quality of practice that is the duration of deliberate practice. There are also other factors that are prerequisites for engagement in deliberate practice that should be possible to observe and study, namely the necessary concentration and effort required for extended sustained daily deliberate practice. Similarly, there are numerous other factors, such as access to the best training environments, to monetary resources, and to motivational support, that will facilitate the development of expert performance.

In many ways the expert performance approach is antithetical to the traditional giftedness and innate talent approach. The traditional approach focuses on early detection of innately gifted individuals with the goal of giving early support to the development of future eminent adults. Our review suggests that the emphasis on early detection, especially before we know if significant innate talents are essential for the attainment of expert performance, has not led to the accumulation of a firm base of reproducible evidence. It is essential that we first know which particular innate talents are necessary attributes of expert and elite performers in each domain of expertise. In contrast, the expert performance approach takes as its starting point the reproducibly superior performance of adults or adolescents. If we cannot even measure the reproducible performance of mature experts in a given domain, there would be nothing to explain, at least not for a theory of high ability and exceptional performance. When we are able to capture the reproducible performance and assess its mediating mechanisms then we are in a position to work backwards to uncover the mechanisms that are responsible for the associated target performance. By working backwards we should eventually be able to assess whether or not the superior performance is significantly limited by innate talent and gifts. The current evidence suggests that innate factors constraining the acquisition of expert performance are currently restricted to height and body size, but future evidence may change this list.

Talent accounts for achievement have traditionally been based on the presumed *in*sufficiency of other accounts based on learning. However, in the last few decades it has become possible to develop genetic accounts based on the identification of genes in DNA. In developing this paper we have found it interesting that the identification of unique genes able to explain the exceptionally *superior* performance of 'gifted' individuals has been remarkably unsuccessful. More importantly, upon finding any such genes, a complete genetic account of the development of the exceptional ability must ultimately explain how these particular unique genes are activated and expressed during development to modify the physiological and anatomical attributes that account for the measured exceptional ability. All theoretical frameworks must be based on genetics, learning, and development and propose increasingly detailed and complete accounts of the associated development of observable behavior. These frameworks must describe how the development of performance is mediated by activities, environments, and those genes common to all healthy humans, and how unique activities, environments, and genes are selectively available only to those individuals with exceptional ability. We believe there are many reasons for investigators of giftedness, high ability, and expert performance to adopt a common empirical framework, where adult skills might be described as a sequence of acquired states of measurable levels of mastery. With such a framework it would be possible to cumulate knowledge within and between domains of expertise as well as identify empirical findings that could be submitted to replication and experimental investigation. A deeper understanding of human potential and how it can or cannot be attained by motivated efforts to improve should be a central goal for future research.

The progress of science is closely linked to the accumulation of base of reproducible evidence. We hope that the proponents of innate talent are challenged to identify any existing evidence on suddenly appearing reproducible abilities and other abilities that are necessary for attaining expert and elite levels of performance, particularly those that cannot be improved and acquired through training. The first author recalls a famous scientist who explained over a decade ago that he had always thought that evidence for innate gifts was so obvious that it did not need any rigorously collected and analyzed evidence to support it. However, when he went to identify this overwhelming evidence he discovered that it was much harder to find than he had thought. The sooner that we can share a common body of valid reproducible evidence the faster our theorizing will develop to provide a comprehensive account of the fascinating domain of exceptional performance.

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