Int. J. Sport Psychol., 2007; 38: 4-34

Deliberate practice and the modifiability of body and mind: toward a science of the structure and acquisition of expert and elite performance

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Some researchers in sports attribute elite performance to genetic talent. However, they do not offer complete genetic accounts that specify the causal processes involved in the activation and expression of the dormant genes in DNA during practice in the athletes' development that lead to the emergence of the distinctive physiological and anatomical attributes (innate talent). This article argues that it is possible to account for the development of elite performance among healthy children without recourse to unique talent (genetic endowment) – excepting the innate determinants of body size. This account based on the expert-performance approach shows that the distinctive characteristics of elite performers are adaptations to extended and intense practice activities that selectively activate dormant genes that all healthy children's DNA contain. The expert-performance approach has provided accounts for elite performance in several domains of expertise, such as music, ballet, chess, and medicine. This article shows how the superior performance of athletes can be captured and reproduced under laboratory conditions to discover the mechanisms mediating superior performance. The discovered mechanisms have, so far, been shown to reflect predominantly complex skills and physiological adaptations acquired over years and decades as a result of high daily levels of activities, which were specially designed to improve performance (deliberate practice). The second part of this article describes the development of expert performance in sports as an extended series of stable states of adaptation with associated physiological mechanisms that mediate performance. One section describes how frequent intense engagement in certain types of practice activities is shown to induce physiological strain which cause biochemical changes that stimulate growth and transformation of cells, which in turn leads to associated improved adaptations of physiological systems and the brain. A careful review of the published evidence on the heritability of acquisition of elite sports achievement failed to reveal reproducible evidence for any genetic constraints for attaining elite levels by healthy individuals (excluding, of course, the evidence on body size). The theoretical framework of expert performance explains individual differences in attained performance by the factors that influence the engagement in sustained extended deliberate practice, such as motivation, parental support, and access to the best training environments and teachers. Consequently, the development of expert performance will be primarily constrained by individuals' engagement in deliberate practice and the quality of the available training resources.

KEY WORDS: DNA, Genes, Performance

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Most of the non-scientific evidence for giftedness and exceptional abilities is based on extreme individual differences that seemingly defy explanation in terms of common sense views of learning and development. For example, many people think it would be impossible to explain the development and achievement of innovative scientists and outstanding athletes without assuming that they must have been born with some unspecified unique gifts and innate talents. Critics, such as Howe (1990), have pointed out that explaining the achievements of famous people, such as Mozart and Michael Jordan, by asserting that these individuals are endowed with unique innate talents is coming dangerously close to being completely circular. These talent accounts have traditionally been based on the alleged insufficiency of explanations based on learning. However, in the last two decades the potential for identifying specific genes in DNA has fueled interest in theories that explain talent in terms of individual differences at the level of the genome. Researchers have attempted to demonstrate the existence of some gene or combination of genes that highlight the uniqueness of the exceptional individual's DNA.

A complete genetic account of the development of the exceptional ability must, however, account for how these particular genes are activated and expressed during development to modify physiological and anatomical attributes, which in turn must explain the measured exceptional ability. Otherwise, the presence of unique genes might be due to a third variable only peripherally relevant to exceptional achievement, or ever worse, identified genes may be entirely unrelated to the observed achievement. All theoretical frameworks must be based on genetics, learning, and development, and must propose increasingly detailed and complete accounts of the associated development of observable behavior. These frameworks must also delineate how the development of superior achievement is mediated by both the environment and genes available to all healthy humans. More specifically, they must specify how unique environments and genes are selectively available only to those individuals with exceptional ability.

My own thoughts on exceptional ability were influenced by my family and education in Sweden, where views that genetic endowment limited the acquisition of superior performance among otherwise healthy individuals were discouraged. These views were reaffirmed by one of my first research projects on the effects of practice on memory performance. Bill Chase and I (Chase & Ericsson, 1981,1982; Ericsson, Chase, & Faloon, 1980) found that after several hundred hours of practice average college students could improve their memory for lists of rapidly presented digits from around seven digits (Miller, 1956) to over 80 presented digits – an enormous improvement

of performance corresponding to an effect size of over 70 standard deviations. Similarly large training effects on memory performance have been replicated many times with many participants in several independent laboratories (See Ericsson, 2003a, and Wilding & Valentine, 1997).

The increased memory performance observed in these studies cannot be explained by genetic differences in innate talent, because the DNA stored in the nucleus of each cell of a person is the same before and after training. There are no current claims that unique genes, which other healthy adults do not possess, are necessary to attain these levels of memory improvement. When larger groups of participants have been taught mnemonic memory strategies (related to those used by the trained students memorizing digits), and then given an opportunity for extended practice, the memory performance of motivated participants is dramatically improved (Higbee, 1997). Furthermore, Maguire, Valentine, Wilding, and Kapur (2003) found no anatomical differences in the brains of some of the world's top memorizers and a matched control group in a recent brain scanning study. Brain activation of the two groups differed during memorization, but these differences could be explained by the fact that the memory experts reported using different memory strategies that involved visualization and generation of meaningful associations. Recent reviews (Ericsson, 2003a; Ericsson, Delaney, Weaver, & Mahadevan, 2004; Wilding & Valentine, 1997) have not found any scientifically-verified evidence that would limit motivated healthy adults with appropriate instruction and training, from acquiring exceptional levels of performance for specific types of memory tasks.

In this paper I will describe how this original work led to the theoretical framework of the expert-performance approach to expertise that would permit scientists to collect evidence of reproducibly superior performance and evaluate both accounts of exceptional performance based on genetics and on acquired skills and physiological adaptations.

The Expert-Performance Approach

The empirical analysis of the mechanisms that mediate expert performance is based on three steps (Ericsson & Smith, 1991). First, the naturally observable expert performance should be captured by well-designed representative tasks that allow us to reproduce the superior performance in the laboratory. Then, the captured superior performance is analyzed with standard methodologies for tracing the mediating processes, such as latencies, eye fixations and verbal reports together with experimental procedures.

Finally once the mechanisms mediating experts' superior performance have been identified, then researchers assess if and how different types of experience and practice activities can explain the acquisition of these mechanisms and whether expert performers engaged in these activities during the development of their performance.

Capturing Superior Performance of Experts Rather than Studying Mere Behavior of Experts

In many domains it is difficult to clearly define what experts can do that less accomplished individuals cannot do. The original focus on expert-novice differences (Chi, Glaser & Rees, 1982) led investigators to search for individuals, who were perceived to be *experts*. Similarly, it was simply taken for granted that these highly experienced and knowledgeable individuals (experts) would display superior performance on relevant tasks in their respective domains. However, researchers rapidly found that "experts" with extended experience and specialized knowledge frequently did not show a performance advantage. In fact, a wide range of experts fail to exhibit a performance advantage over novices when they have been presented representative tasks under controlled conditions. For example, highly experienced psychotherapists are not more successful in treatment of patients than novice therapists (Dawes, 1994). More generally, reviews of decision making (Camerer & Johnson, 1991; Shanteau & Stewart, 1992) show that experts' decisions and forecasts, such as financial advice on investing in stocks, do not show a reliable superiority over novices and thus must not improve with additional experience. Similar absence of improvements of experienced individuals considered experts have been documented in several other areas of expertise (Choudhrey, Fletcher, & Soumerai, 2005; Ericsson, 2004; Ericsson & Lehmann, 1996).

There are, of course, many domains of expertise where experts reliably surpass the performance of beginners and novices. In some sports, such as running and swimming, the standardized task conditions remain the same regardless of the age, gender, and level of competition and the measurements are on a ratio scale, namely the shortest time to complete the distance. In other types of sports and areas of expertise, the level of complexity of the performed sequences of actions increases such as in ballet, music, gymnastics, and platform diving. In these domains it is possible to sequence many types of performances in their order of difficulty, such as single, double, triple or quadruple toe loop jumps by figure skaters. Although there is generally high agreement on detecting errors in the performance of routines,

there appears to be much less reliability in judgments of other, error-free, types of activities. For example, research in the evaluation of technically proficient performance has shown that judges of music show surprisingly low inter-judge agreements, and are influenced by irrelevant factors, such as gender, physical attractiveness, and the reputation of the performer (Gabrielsson, 1999). Similar subjective judgments by coaches may be inappropriately influenced by factors, such as fame, reputation and past performance, rather than by mechanisms that mediate current performance. More generally, researchers should seek *objective* measures of current performance, even when such measures may not capture all aspects of performance.

Particularly challenging for this approach are domains, such as chess, tennis and fencing, where each game consists of a different sequence of situations and actions. In a ground-breaking and innovative research effort on chess expertise, de Groot (1946/1978) addressed this problem by identifying challenging situations in representative games (i.e. chess positions) that required some type of action (i.e. making the next chess move). De Groot then was able to present the same game situations to all participants and could observe their cognitive processes while the chess players tried to find the best moves. If we can find chess players who are able to select consistently the best moves for arbitrary chess positions, then these players would be strong chess players almost by definition. Subsequent research has shown that this methodology of presenting representative situations and requiring generation of appropriate actions provides the best available measure of chess expertise as reflected in tournament skill ratings (Ericsson, Patel, & Kintsch, 2000; van der Maas & Wagenmakers, 2005). A similar methodology has been applied to measure superior performance in representative situations in medical diagnosis, snooker, and a wide range of other domains (Ericsson, 2004; Ericsson & Lehmann, 1996), including even *team* sports, such as soccer (see Helsen & Starkes, 1999, and Williams & Ward, 2003).

In sum, the initial goal of the expert-performance approach is to identify the essence of expertise in a domain and then design associated representative tasks that allow expert performers to reproduce their superior performance consistently under standardized conditions. Frequently, it is possible to administer the same tasks to both beginners, even children, as well as advanced experts to measure the development of performance longitudinally. It is, for example, possible to measure this in many individual sports, such as the 100-meter sprint, and other types of activities, including the selection of moves for a set of unfamiliar chess positions. In other types of domains, such as those involving team sports, it is more difficult to measure individual performance in general.

Identifying the Mechanisms that Mediate Expert Levels of Performance

Traditionally researchers have searched for any type of differences between experts and novices, such as intelligence, cognitive and perceptual abilities, and anatomical characteristics, without any explicit theoretical account for how the measured characteristics could explain the observed differences in representative performance (Ericsson, 2003a). The expert-performance approach uses a different procedure and focuses directly on the analysis of the captured superior performance. When experts' superior performance on representative tasks has been reproduced, then the next step is to identify the specific anatomical, physiological, or cognitive mechanisms that are responsible for the experts' performance advantage over less-skilled individuals on these particular types of tasks. The general research method employed during this step is to analyze the captured over-all performance in order to identify intermediate processes that make the expert performance superior to that of the less accomplished performers. Once the processes are identified then investigators design experimental tests that evaluate the causal role of the mechanisms that are proposed to account for the observed differences in performance.

The methodology for analyzing the mediating processes was developed in cognitive psychology and involves tracing the processes using analysis of latency components, eye-fixations, and concurrent and retrospective verbal reports (see Ericsson & Oliver, 1988). An analysis of the overall time to complete a task or an event illustrates how an examination of latencies can be used for motor activities. For example, one can examine the advantage of an elite sprinter over sub-elite sprinters during different phases of the event, such as the time from the sound of the starting pistol to release of force on starting block, the subsequent time to accelerate to maximum speed, and the remaining time to cross the finish line. In a similar manner, researchers can measure and examine the characteristics and reliability of putting and driving motions associated with the superior consistency of expert golfers' shots (Ericsson, 2001). Elite long-distance runners are able to run on treadmills with superior running economy – the metabolic efficiency of maintaining their race pace – in comparison to sub-elite runners (Conley & Krahenbuhl, 1980). Interviews and field experiments show that elite long-distance runners verbally report monitoring their internal states more closely and focus more on planning their race performance during competition than less accomplished runners (Baker, Côté, & Deakin, 2005; Masters & Ogles, 1998).

The most compelling scientific evidence for cognitive accounts of the expert's performance advantage comes from laboratory studies where expert performance is captured by tasks involving the generation of the most appropriate action in representative game situations (Ericsson & Smith, 1991). In his pioneering work introducing this methodology, de Groot (1946/1978) presented unfamiliar chess positions to expert and world-class chess players and asked them to select the best next move while thinking aloud. His analyses of the verbal protocols revealed that chess players first rapidly perceived and interpreted the chess position and potentially interesting moves were accessed from memory. These promising moves were then evaluated mentally by planning consequences of potential chess moves. During the phase of planning and evaluation, chess players would either select their best move among the generated set or discover new and even better moves. This account has been validated by experiments that selectively interfere with the proposed mechanisms, akin to the research on memory expertise (Ericsson et al., 2004; Ericsson & Kintsch, 1995; Ericsson, Patel, & Kintsch, 2000). As players acquire increased chess skill, they acquire better and more refined mental representations that allow them to evaluate and manipulate chess positions mentally better than less skilled players.

In a review of similar studies of experts solving representative tasks in a wide range of domains of expertise, such as medicine, computer programming, and games, Ericsson and Lehmann (1996) found a similar pattern. When superior performers in sport are presented representative tasks, verbal reports reveal how more advanced preparation, planning, reasoning, and evaluation mediate their superior performance in different domains of sport, such as snooker (Abernethy, Neal, & Konig, 1994), baseball (Nevett & French, 1997) and tennis (McPherson & Kernodle, 2003).

In most sporting events, the demand for rapid execution of highly practiced activities would seem to preclude concurrent thinking. However, even the superior speed of expert performers appears to depend primarily on acquired cognitive representations that allow performers to be prepared for execution of appropriate actions rather than better basic acuity of their sensory perceptual systems and/or faster basic speed of their motor systems (for reviews see Abernethy, 1991, Starkes & Deakin, 1984, and Williams & Ward, 2003).

The benefit of skilled preparation was first demonstrated experimentally in *typing*. By looking further ahead in the text expert typists can prepare future keystrokes in advance, moving relevant fingers toward their desired locations on the keyboard while other keys are being hit. Salthouse (1984) demonstrated experimentally that this mechanism caused superior perfor-

mance because when typists are restricted from looking ahead in the text by displaying only one word at the time on a computer screen, experts' typing speed is reduced almost to that of novice typists who do not rely on looking ahead.

The early research on the rapid reactions of athletes, such as hockey goalies, tennis players, and baseball batters, used tasks designed for predicting future outcomes from pictures and films (Abernethy, 1991). Some critics of this research (Shea & Paull, 1996) pointed out that the time taken by the athletes to generate the predictions was many times longer than the available time to emit a successful response in a corresponding real-world situation. More recent research using real-time occlusion while elite athletes execute representative tasks has been able to preserve the real-time constraints and has demonstrated experimentally that more skilled athletes use anticipatory cues to guide their motor responses (Abernethy, Gill, Parks, & Packer, 2001; Starkes, Edwards, Dissanayake, & Dunn, 1995).

Expert athletes do not simply acquire superior anticipation skills, but also acquire superior control over their motor actions. At increased levels of expertise, athletes, such as figure skaters and gymnasts, are able to perform more complex behavior, such as a triple-axel jump by figure skaters. Furthermore, expert performers acquire the ability to reproduce the same motor actions consistently. For example, expert golf players are more consistent in executing the same putt or drive than less-skilled players (Ericsson, 2001). Similarly, studies of expert musicians' representations have shown how they are able to control their performance in a flexible manner (Krampe & Ericsson, 1996).

In sum, expert performance is primarily mediated by acquired mental representations that allow the experts to anticipate courses of action, to control those aspects that are relevant to generating their superior performance, and to evaluate alternative courses of action during performance or after the completion of the competition. There are also other differences in strength, flexibility, and endurance that characterize the best performers in sports and other perceptual-motor skills.

Scientific Accounts of the Acquisition of Expert Performance and its Mediating Mechanisms

A complete scientific account of expert performance needs to be able to explain how the elite performers develop the complex cognitive mechanisms and improved physiological adaptations that mediate superior performance.

My central thesis is that experts continually engage in *deliberate practice* activities (Ericsson, 1998a; Ericsson et al., 1993; Krampe & Ericsson, 1996) that lead to refinement and maintenance of the mediating mechanisms. In contrast, less-accomplished individuals do not engage in these activities once they have reached an acceptable level. Their performance is prematurely arrested in its effortless automated form, as illustrated in the lowest arm of Figure 1. For example, after some limited period of training and experience – often less than 50 hours for most recreational activities, such as skiing, tennis, and driving a car – an acceptable level of performance is attained. As individuals' performances gradually meet task demands, the execution of the behavior is increasingly automated thus reducing conscious control and limiting those individuals' abilities to make intentional specific adjustments (Fitts & Posner, 1967). When this final automatic phase has been reached,

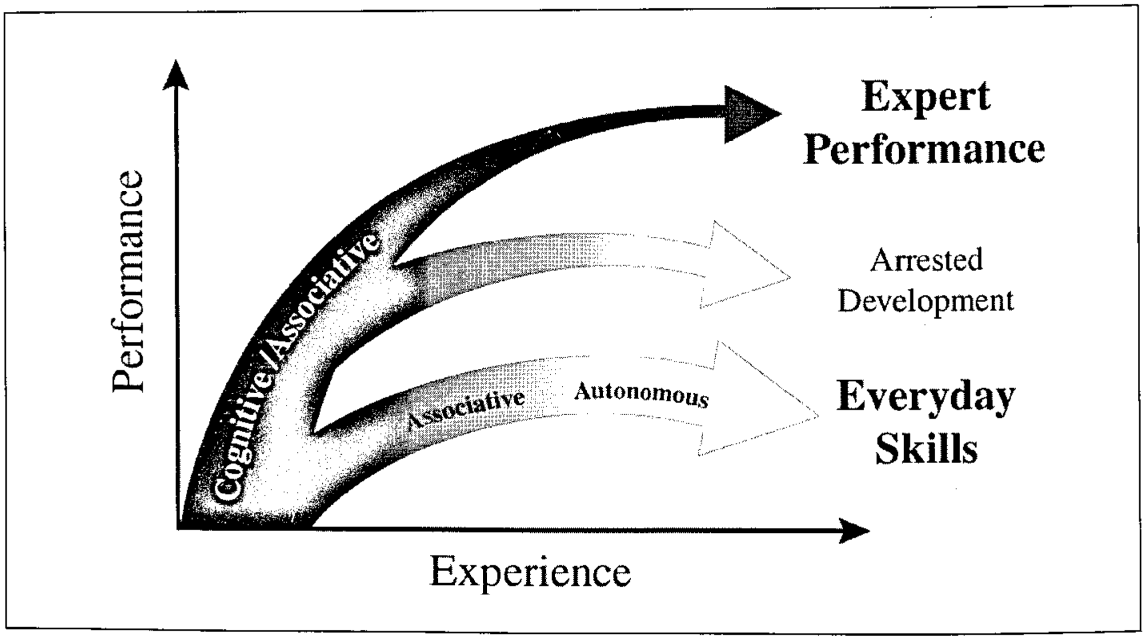

Fig. 1. - An illustration of the qualitative difference between the course of improvement of expert performance and everyday activities. The goal for everyday activities is to reach as rapidly as possible a satisfactory level that is stable and autonomous (see the gray/white plateau at the bottom of the graph). In contrast, expert performers counteract automaticity by developing increasingly complex mental representations to attain higher levels of control of their performance and will therefore remain within the "cognitive" and "associative "phases. Some experts will at some point in their career stop engaging in deliberate practice and prematurely automate of their performance. (Adapted from "The scientific study of expert levels of performance: General implications for optimal learning and creativity" by K. A. Ericsson in *High Ability Studies, 9*, p. 90. Copyright 1998 by European Council for High Ability).

further experience will not be associated with any marked improvements and the amount of accumulated experience will not be related to increases in attained level of performance (See Ericsson, 2004, and Choudrey, Fletcher, & Soumerai, 2005, for reviews in professional domains that show no change or even reductions in performance with additional experience).

The Development of Expert Performance

The expert-performance approach has shown that it is possible to measure individuals' performance independent of age and gender and thus graph the development of performance as a function of years of training (Ericsson & Lehmann, 1996), as is illustrated in Figure 2. This research has found that individuals who eventually reach an expert level of performance as adults do not start out in a domain with an already exceptional level of performance as

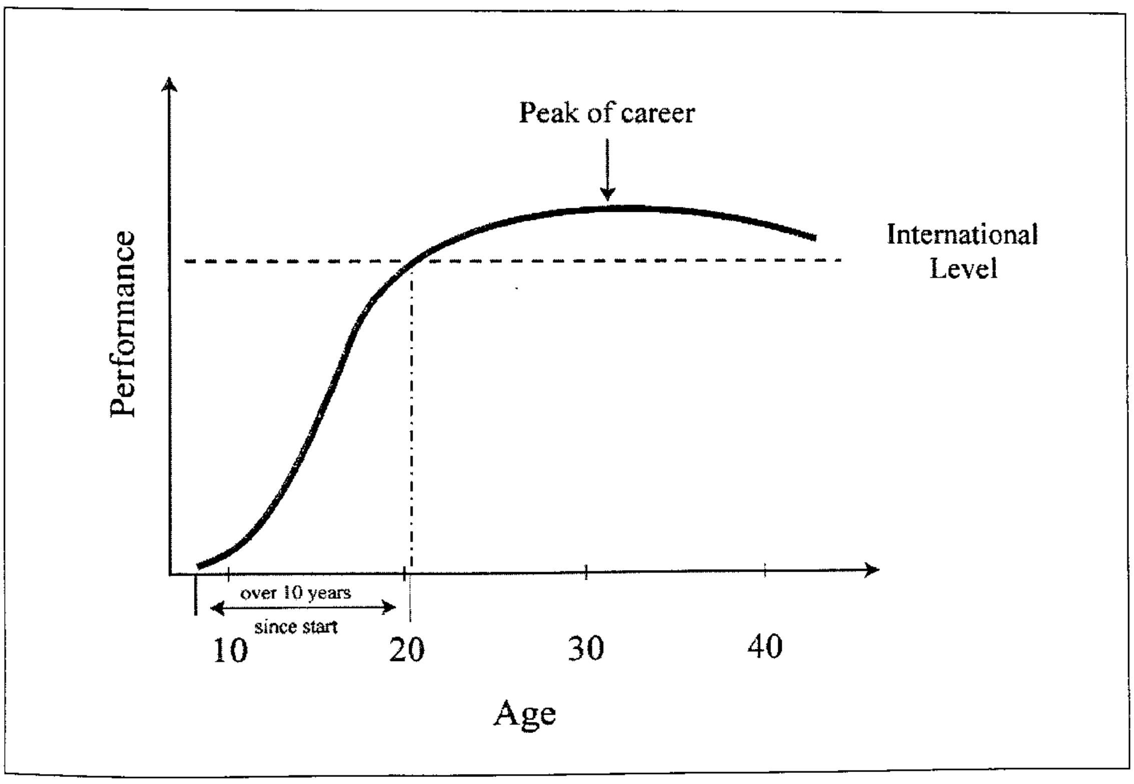

Fig. 2. - An illustration of the gradual increases in expert performance as a function of age, in domains such as chess. The international level, which is attained after more than around 10 years of involvement in the domain, is indicated by the horizontal dashed line. (From "Expertise," by K. A. Ericsson and Andreas C. Lehmann, 1999, *Encyclopedia of Creativity*. Copyright by Academic Press).

compared to their peers, when we control for the benefits of acquiring skill in other related activities (Bloom, 1985). For future elite performers, the improvement of performance continues during years and decades of actively pursuing excellence in domain-related activities. Experts' performance typically peaks when the individuals' age reaches their late 20s, 30s or early 40s – long after they have reached physical maturity at around age 18 (see Ericsson and Lehmann, 1996, for a review). In well-established domains of expertise even the most "talented" cannot reach an international level in less than around a decade of experience and intense preparation (Simon & Chase, 1973; Ericsson, Krampe, & Tesch-Römer, 1993).

Bloom and his colleagues (Bloom, 1985) showed that elite athletes and other expert performers had different developmental histories compared to their peers. The elite performers started early with supervised training and gained access to some of the best teachers and training environments. Ralf Krampe, Clemens Tesch-Römer, and I (Ericsson et al., 1993) tried to go beyond describing the necessary resources and searched for those training activities that could explain individual differences among experts with over ten years of training. Based on a review of laboratory studies of learning and skill acquisition during the last century, we found that improvement was uniformly observed when individuals were given tasks with a well-defined goal, were provided with feedback, and had ample opportunities for repetition. These deliberate efforts to increase one's performance beyond its current level involve problem solving and the search for better methods to perform the tasks. When individuals engage in a practice activity (typically designed by their teachers), with full concentration on improving some aspect of their performance, we call that activity *deliberate practice*. The requirement for *concentration on improving performance* sets deliberate practice apart from both mindless, routine performance and playful engagement as the latter two types of activities would, if anything, merely strengthen the current cognitive mechanisms rather than modify them to allow increases in the level of performance.

A prime example of deliberate practice is the expert violinists' solitary practice in which they work to master specific goals determined by their music teacher at weekly lessons. A greater amount of solitary music practice accumulated during development is associated with higher levels of attained music performance (Ericsson, 2002; Ericsson, et al., 1993). Similarly in chess, Charness and colleagues (Charness, Tuffiash, Krampe, Reingold, & Vasyukova, 2005) found that the amount of solitary chess study was the best predictor of chess skill, and when this factor was statistically controlled, there was only a very small benefit from other types of chess-playing experi-

ence, such as the number of games played in chess tournaments. Solitary study in chess has primarily involved the examination of chess games by masters, where the player attempts to anticipate the moves made by the masters for each position of the game. When the players compare their selected move against the one selected by the master they get feedback on the quality of their move. When the chess masters selected a different move then the player can analyze the position to uncover the rationale for the masters' superior move and this activity meets the criteria for deliberate practice (Ericsson et al., 1993). Similar findings have been obtained by Duffy, Baluch, and Ericsson (2004) for expert performers in dart throwing, where feedback of outcomes is immediate, and by Starkes, Deakin, Allard, Hodges, and Hayes (1996) for expert figure skaters, where feedback is successful completion of jumps and augmented by verbalized comments by the coach. Aspiring performers in these domains can use this feedback to work on weaknesses in their performance by repeating the targeted activity, first in isolation and then in increasingly complex contexts, and can observe improvements in performance within days or weeks of practice. In other domains it has been more difficult to identify individual performance measures and activities that are directly linked to feedback about improved concurrent performance (Ericsson et al., 1993). In sports, several studies have found a consistent relation between the level of competitive events (amateur, local, district, national, and international) and total amount of different types of practice activities (Helsen, Starkes & Hodges, 1998; Starkes et al., 1996, Ward, Hodges, Williams, & Starkes, 2004). In recent reviews of deliberate practice in sports (Côté, Ericsson, & Law, 2005; Ericsson, 2003c; Ward et al., 2004), several issues have been discussed that concern the methods for obtaining retrospective estimates of practice and the relations between many factors, such as effects of deliberate practice, level of skill, and observable *improvements* in reproducible performance.

Toward Detailed Causal Accounts of the Development of Expert Performance in Sports

The central assumption of the expert-performance approach is that the development of expert performance occurs gradually, through a sequence of incremental changes and refinements of the mediating mechanisms. This assumption implies that it should be possible, at least in principle, to describe the development of *each individual's performance* as an ordered sequence of specific cognitive and physiological changes to mechanisms that

ultimately generate integrated structures that explain the superior expert performance, as shown in Figure 3. This framework proposes that reliable improvements in performance have definite causes, such as developmental growth and adaptive responses to changes in the structure and intensity of practice activities. Each observable change in the structure of the mechanisms as illustrated by the transitions in Figure 3 needs to be explained. Ultimately, a complete theory should be able to account for the development and refinement of all associated biological and cognitive mechanisms that contribute to the acquisition of expert performance. The same theory should also be able to explain many of the differences in the physiological systems and anatomical features of the bodies of superior athletes who excel in various types of events.

To understand the causal mechanisms underlying the statistical correlation between reported amount of practice and levels of general performance, we need to search for causal, (preferably, biological), factors that can explain

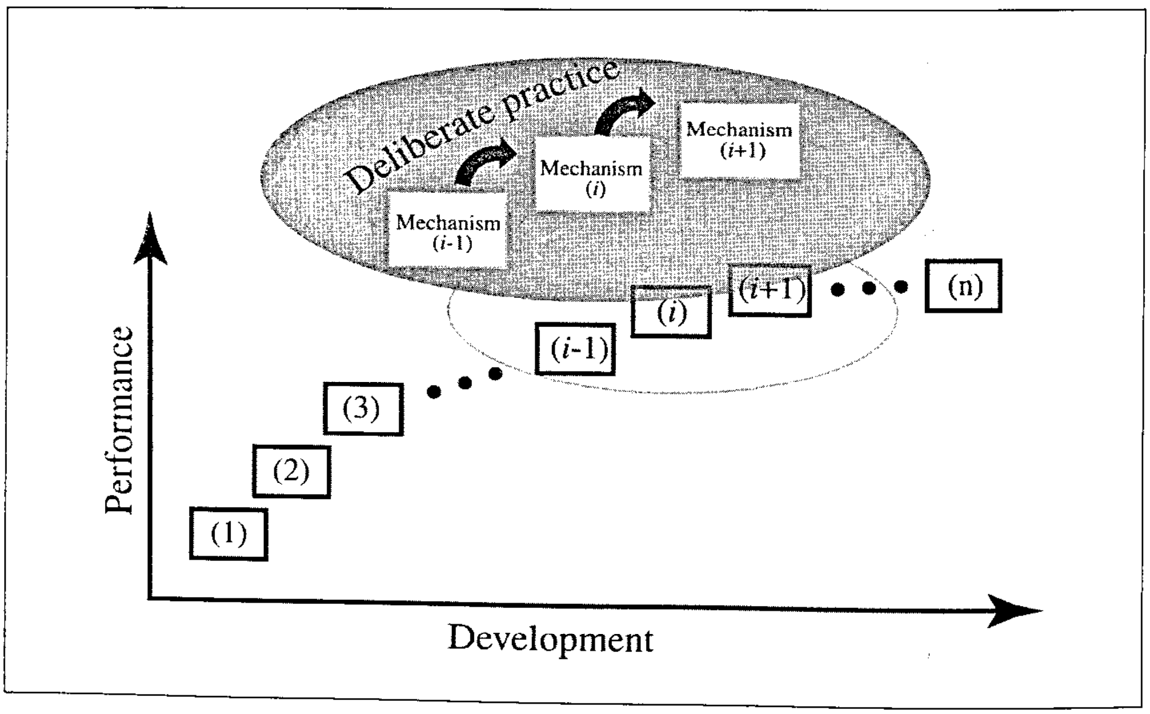

Fig. 3. - A schematic illustration of the acquisition of expert performance as a series of states with mechanisms for monitoring and guiding future improvements of specific aspects of performance (Adapted from "The development of elite performance and deliberate practice: An update from the perspective of the expert-performance approach" by K. A. Ericsson in J. L. Starkes and K. A. Ericsson (Eds.), *Expert performance in sport: Recent advances in research on sport expertise* (p. 70). Copyright 2003 by Human Kinetics).

how the specific changes of particular mechanisms are induced by engaging in particular practice activities. The key challenge for an aspiring expert performer is to avoid the arrested development associated with automaticity (see Figure 1). The developing expert performer actively counteracts the tendencies toward automaticity by deliberately constructing and seeking out training situations in which the set goal exceeds their current level of performance. In domains, such as sport, where strength, endurance or flexibility is important, the expert performers keep pushing themselves during training to go beyond their current physiological adaptations to reach new and more far-reaching changes.

The greatest advances in the development of detailed causal biological models have been made in applied physiology, where detailed accounts of changes in mediating physiological and anatomical characteristics are associated with the acquired superior performance. In the following I will discuss this research and sketch how similar accounts can be extended to changes in other mechanisms that mediate improvements in performance.

Improving the Physiological and Anatomical Mechanisms that Mediate Performance

When most healthy individuals reach adulthood they can assume that their bodies and physiological systems will remain virtually unchanged for several decades while they continue their habitual level of activity, at least until the effects of aging become noticeable. Just because the characteristics of the body remain stable does not imply the body is unable to change in response to marked alterations in peoples' lifestyles and the demands of their mental or physical activities.

The adult body has evolved to cope with short-term fluctuations in physiological demands. A fundamental role of the human body is to protect the homeostasis of its many trillions of cells, so they can survive and function within their preferred temperature range and be provided an ample supply of oxygen, water and energy. Whenever individuals engage in physical sport activities, the metabolism of their muscle fibers increases, and the supply of oxygen and energy within the muscle cells is rapidly reduced and supplies are extracted from the nearest blood vessels. To preserve homeostasis, the body activates various counter measures (negative feedback loops). For example, increased breathing rates increase oxygen concentrations and decrease carbon dioxide concentrations in the blood. In turn, the conversion of stored energy replenishes expendable energy available in the blood, and the increased rate of blood circulation distributes these commodities to the sys-

tems of the body with the greatest needs. However, when individuals deliberately push themselves beyond the zone of relative comfort (Ericsson, 2001, 2002) and engage in sustained strenuous physical activity, they will challenge the available protection of homeostasis sufficiently to induce an abnormal state for cells in some physiological systems. These states will sometimes be associated with abnormally low levels of certain vital elements and compounds, such as oxygen, and energy-related compounds (e.g., glucose, adenosine-diphosphate; ADP and adenosine-triphosphate; ATP), which lead metabolic processes to change and produce alternative biochemical products. These biochemical states will trigger the activation of some genes in the massive storage of dormant genes within the cells' DNA. The activated genes in turn will stimulate and "turn on" biochemical systems designed to cause bodily reorganization and adaptive change. Recent research shows that the biochemical response of cells to various types of strain induced by vigorous activity, such as physical exercise, is very complex. Even more directly relevant to physical exercise, over one hundred different genes are activated and expressed in mammalian muscle in response to intense physical exercise (Carson, Nettleton, & Reecy, 2001).

The nature of mechanisms that mediate change of physical characteristics is well illustrated by young active adults' difficulty in increasing their aerobic fitness by jogging and exercise of modest intensity and duration. Scientific studies show that young adults have to reach a certain threshold in the intensity of their sustained physical exercise to reliably improve their aerobic fitness (Robergs & Roberts, 1997). Specifically, young adults have to exercise at least two or three times each week for at least 30 minutes per session with a sustained heart rate that exceed 70% of their maximal level (around 140 beats per minute for a maximal heart rate of 200). Extended physical activity at these levels of intensity will cause abnormal metabolic conditions that will induce changes in cells. It is, however, not simple to induce the metabolic conditions that cause change. For example, when adults start to jog on a weekly basis one of the first challenges is to coordinate the firing of the involved muscle fibers. Once it is possible to produce coordinated sustained activity of the muscles, the limiting factors concern increasing the actions of the muscle fibers and attaining sufficient transport of blood to sustain a steady supply of oxygen and glucose. When these concentrations become too low, it will trigger biochemical activity which, in turn, stimulates the growth of new capillaries (angiogensis; Prior, Yang, & Terjung, 2004). Similarly, improvements of strength and endurance require that individuals keep engaging in a cycle of overloading some system or sub-system (i.e. increasing intensity, frequency or duration on a weekly basis), to induce a physiological adaptation. Once the new adaptation is attained, the individuals must induce

a new overload by pushing the adapted physiological systems outside the current comfort zone to trigger additional physiological growth and further adaptation (Ericsson, 2001, 2002).

Induced Changes in Elite Athletes' Physiological and Anatomical Characteristics

There are many types of physiological and anatomical characteristics that distinguish elite performers from less accomplished performers. Acquisition of these characteristics is consistent with acquired adaptations to increased demands induced by their intense and extended engagement in practice activities (See Ericsson & Lehmann, 1996, Ericsson et al., 1993, 2003b, 2003c, for reviews). For example, the larger heart sizes of endurance runners have been shown to emerge only after years of extended intense practice, and seem to grow in response to continued physiological challenge (increased intensity and duration of physical training). More recent evidence on Olympic level athletes' enlarged hearts is even more compelling. When athletes dramatically reduce or even stop training at the end of their careers their enlarged hearts eventually revert back toward average size (Pelliccia, Maron, De Luca, di Paolo, Spataro, & Culasso, 2002).

The expert-performance approach portrays the acquisition of the physiological adaptation characteristics as a sequence of adaptations where practice activities induce critical states in cells in physiological systems that trigger, as well as maintain, these adaptations. This means that adaptations cannot easily be acquired in any order and that adaptations will depend on the stage of general development of children and adolescents. Some specific practice activities appear to change anatomical characteristics in an irreversible manner during certain critical developmental periods. For example, ballet dancers' ability to turn out their feet, and the baseball pitchers' and handball players' ability to stretch back with their throwing arm are linked to stretching while practicing the associated movements when the children's bones and cartilage in joints are calcified in late childhood (Ericsson & Lehmann, 1996). Attempts by handball players to attain similar adaptations at much older ages through practice have been found to be unsuccessful and resulting in chronic shoulder pain (Pieper, 1998). There is now compelling evidence that even the development of the brain can be dramatically changed by practice with musical instruments during childhood and adolescence (Bengtsson, Nagy, Skare, Forsman, Forssberg, & Ullen, 2005; Pantev, Ross, Fujioka, Schulte, & Schultz, 2003).

According to the expert-performance approach most individual differences in elite achievement can be explained by physiological characteristics acquired through a long series of adaptations, engendered by biochemical responses to the strain induced by particular practice activities at appropriate ages or stages of physiological development. There appear to be at least three different types of reasons for why not all adults are able to attain the highest levels of achievement. First, it is possible that certain types of genes need to be part of individuals' genetic endowment (innate talent) in order to even permit the acquisition of expert performance. Second, it is possible that individuals differ in their ability to engage in the required practice intensity necessary to induce the extended series of adaptations that may take a decade or more to attain under optimal conditions. Finally, it is possible that differences related to motivational support, access to early training/instruction and availability of the best training resources lead to differences in the attained level of performance at a given age. Let me consider these three possibilities in turn.

Genetic Constraints on the Attainment of Elite Athletic Performance

Many scientists, such as Abernethy, Farrow, and Berry, (2003) and Janelle and Hillman (2003) argue that demonstrated genetic influences on the development of physical characteristics and mental abilities under typical everyday conditions imply that genetic differences (innate talents) have to similarly influence the acquisition of elite athletic performance. Although behavior geneticists have expressed support for such an extrapolation from observed heritabilities of everyday abilities to those of expert performance (Bouchard & Lykken, 1999), they also acknowledge that any generalization of heritability estimates depends directly on the similarity of environmental conditions of everyday activities to those of expert training. Any extrapolation from everyday life to expert performance is, however, questionable in light of our earlier reviewed findings that most aspects of human characteristics and abilities relevant to expert performance are highly modifiable in response to intense training activities and might even revert back to normal without maintained practice. Furthermore, the type and intensity of physical activity is different for individuals in everyday life, who are rather sedentary, and for expert performers, who train daily for several hours at very intense training levels.

Given that the research by Claude Bouchard and his colleagues on heritability of physical fitness is nearly always cited by sport psychologists (Aber-

nethy, Farrow, & Berry, 2003; Janelle & Hillman, 2003) I will briefly summarize an earlier review of that work (Ericsson, 2003c). Bouchard and his colleagues in the HERITAGE project have estimated that that over 40% of the variance in maximal oxygen uptake (VO_{2max}) is heritable (Bouchard, Simoneaum Lortie, Boulay, Marcotte, & Thibauld, 1998). Although they also argue that VO_{2max} is trainable to some degree they estimate that half of the variability of the increases in oxygen uptake in response to training is determined by heritable genetic factors (Bouchard & Lykken, 1999).

Most interestingly, the HERITAGE project did not study elite performers but examined individuals at the other extreme, namely families with individuals between ages of 17 and 65 where *everyone* in the family had been completely sedentary, that is, "no regular physical activity over the previous 3 months" (Bouchard et al., 1995, p. 723). In my review of the HERITAGE studies I raised many issues about the generalizability of their findings to elite populations (Ericsson, 2003c). I was particularly critical about their methods of assessing participants' adherence to the assigned high-level of training intensity. One point of contention was that this study reported getting virtually all their participants to comply with the assigned training regimen, whereas other studies have found rather low rates of exercise compliance, especially with sedentary participants. I suggested that some of the participants may not have trained at the assigned levels and thus a portion of the differences in improvements reflected differences in motivation/ability to sustain training at intense levels rather than differences in physiological capacity to change with a particular level of intense practice. Finally, the HERITAGE studies only examined a short-term training regimen (only around 6 weeks at 75% of max) and thus did not examine the effects of a long-term exercise regimen with intensities even approximating those of elite athletes.

In the same chapter I discussed evidence on hereditary constraints of VO_2max and other genetic constraints on athletic performance (Ericsson, 2003c). In fact, Bouchard, Lesage et al. (1986) claimed a decade earlier, based on a review of an extensive body of literature and an additional study of almost a *hundred pairs* of twins, that "a significant genetic variance has been found on dizygotic and monozygotic twin data for all variables, with the exception of $VO_{2max} \cdot kg^{-1}$ FFW *[VO_{2max}/kg controlled for fat free weight]*" (p. 645 with material in italics added). Bouchard has also acknowledged that among athletes it is quite possible to increase VO_{2max}/kg significantly even as much as 40 % with training (Prod'homme, Bouchard, Leblanc, Landry, & Fontaine, 1984). From this evidence it would appear that VO_{2max}/kg would not be a good candidate for a factor that was *constrained* by heredity. Heritability of muscle types have been similarly questioned, Bouchard and his

colleagues (Bouchard, Simoneau et al., 1986) were unable to replicate the high heritability found for the proportion of fast-twitch fibers in muscles in a famous study by Komi et al. (1977). Whereas Komi et al. (1977) estimated that the proportion of muscle fibers was virtually completely heritable (over 93%) for a sample of 31 pairs of twins, Bouchard, Simoneau et al. (1986) found no evidence for heritable factors for the same proportion with a larger sample with 61 pairs of twins and estimated the heritability to be close to 0%. There is now compelling evidence showing that the metabolic characteristics of muscle fibers can be altered in response to large changes in their level of activity induced by exercise and electric stimulation. In fact, muscle fibers can even be converted from one type of muscle fiber to another by exercise (Goldspink, 2003).

Consistent with the malleability of maximal capacity to metabolize oxygen (V_{O2} max), the differences in performance among highly accomplished long-distance athletes is better predicted by the efficiency of sub-maximal performance (running economy, Conley & Krahenbuhl, 1980), and other physiological adaptations (Coyle et al., 1991) than by VO_{2max}. In a more recent theory, St Clair Gibson and Noakes (2004) have rejected traditional models of endurance performance where it is limited by fixed and unmodifiable capacities, such as VO_{2max}, and they describe the full range of physiological, metabolic and mechanical factors that have been shown to influence endurance performance.

It is unlikely that the issues of heritable limits on expert performance will be resolved until the physical activities that induce biochemical processes that trigger gene expression and regulate synthesis of new organic compounds are better understood. Reviews show that it is rare that single genes have observable effects that benefit performance and the most observable characteristics are the result of a complex interaction of many different genes working as a system with many alternative pathways for regulating adaptations (Wahlsten, 1999). Even in cases where genetic differences appeared likely, such as for Kenyan long-distance runners, the recent evidence points to alternative accounts based on physiological differences induced by physical activity during childhood at high altitude (Larsen, Nolan, Borch, & Sondergaard, 2005; Onywera, Scott, Boit, & Pitsiladis, 2006). In a recent review of the relation between genes and elite athletic performance, McArthur and North (2005) found that there are conflicting results even for the most extensively studied gene – the polymorphism of the Angiotensin Converting Enzyme (ACE) gene. Studies with a smaller number of participants have reported genetic differences whereas studies with larger populations of more varied athletes have failed to find reliable associations

(similar to the pattern of results in the twin studies discussed earlier in this section). MacArthur and North (2005) determined that no firm conclusions can be drawn from the available evidence. Most recently, in a large study of homogenous athletes, namely Kenyan elite runners, Scott et al. (2005) failed to find any relation between ACE and performance when these elite athletes were compared to controls from the same population.

Most interestingly, research on twins has shown that attained level of expert performance is not directly determined by genetic environment and physical environment. Not even when a pair of identical twins both engage in extended practice in the same domain of sports expertise will the twins necessarily attain the same, or even a similar, level of performance (Klissouras et al., 2001). More generally, twin studies of the acquisition of elite performance are unlikely ever to resolve the issue of heritability of elite performance. The frequency of twins (even a single member of a twin pair) who attain an elite level of performance in domains of expertise is much lower than would be expected by chance. In fact, one or both members of fraternal and identical twin pairs hardly ever reach eminence in science, literature, and the arts (Ericsson, 1998b). The under-representation of twins among eminent individuals may be a consequence of how twins are reared and that deliberate practice by one or both twins may not be encouraged by their parents and other twin during childhood and adolescence due to its solitary non-social nature.

More generally, in a recent review I argued (Ericsson, 2003c) that any analysis of the attained adaptations (phenotypes) has the fundamental problem of distinguishing whether the willingness/ability to practice at the necessary exercise intensity repeatedly for extended time is lacking, on the one hand, or if the physiological response to the assigned training intensity differs between people, on the other.

The Necessity of Ability to Engage in Extended Sustained Deliberate Practice – Motivation

My colleagues and I (Ericsson et al., 1993) recognized early on the difference between genetically determined capacities (innate talent) and the ability to engage in deliberate practice: "we reject an important role for innate ability. It is quite plausible, however, that heritable individual differences might influence processes related to motivation and the original enjoyment of the activities in the domain and, even more important, affect the inevitable differences in the proclivity to engage in hard work (deliberate

practice)" (p. 399). How could one demonstrate that nearly all healthy individuals are capable of acquiring the required physiological adaptations, if they are not willing and sufficiently motivated to engage in the intense physical exercise required to produce such adaptations?

Ericsson et al. (1993) found that researchers have been able to push animals by motivational factors that would be unacceptable for treatment of humans. Random samples of animals acquire the same or similar adaptations as those observed by elite athletes when they are pushed to train intensively. More recent studies have extended these findings by using treadmills with electric shocks. For example, Iemitsu, Maeda, Miyauchi, Matsuda, and Tanaka (2005) found that the size and structure of hearts of rats can be reliably modified by genes that were expressed in response to such training. Similar studies with thoroughbred racing horses show similar physiological adaptation in response to training in jumping versus racing on flat racing tracks (Young, Rogers, & Wood, 2005). These animal studies show that even animals (in the same manner as humans) do not develop their maximal physiological potential spontaneously, but much greater physiological adaptations can be induced by designing training environments where these animals exert themselves beyond their normal comfort zone.

There is also evidence for the importance of practice activity to maintain physiological capacity. For example, if athletes are restricted to bedrest in experimental studies or, similarly, astronauts in training are confined to zero gravity for duration of weeks, their hearts and physical fitness degrades and they show characteristics similar to those of sedentary adults (Ericsson et al., 1993; Perhonen et al., 2001). Hence, physical fitness levels, especially of athletes, require continued intense exercise merely to be maintained. Research on aerobic fitness shows that to merely *maintain* their fitness levels, athletes have to engage in the same high intensity of exercise with dramatically elevated heart rate to keep their bodies' current physiological adaptations (Shephard, 1994). There is also evidence that once an adaptation is attained it is possible to reduce the duration of the weekly training time during its maintenance from the level that was originally required to attain it. However, to continue improving performance, it is necessary to maintain or increase the strain in order to keep modifying the key physiological mechanisms mediating their performance. The individuals' level of performance increases with such an approach and the demand for further effort is not reduced - if anything, the demand for effort is *increased.* I believe that the most insights will be gained from longitudinal research that identifies occasions when an athlete attains an adaptation for the first time. The deliberate practice regimen and the physiological strain required to attain an original change in

some characteristic or mechanism is likely to be quite similar across individuals. At least, this practice and strain will be much more similar then the practice required to merely maintain an already attained adaptation and change. Hence, research that compares the current practice of athletes, who already have attained an adaptation, to those who have not yet attained the same adaptation, will be much less likely to uncover the tight connections between specific types of deliberate practice and the resulting physiological adaptations.

The Necessity of Environmental Factors: Instruction, Opportunity, and Support

The expert-performance approach has found ample evidence that children and adolescents do not spontaneously engage in deliberate practice that will lead to maximal improvements in performance. Consequently, children need help to identify the appropriate training activities, to learn how to concentrate, and to find the optimal training environments. An early introduction to instruction and supervised training in the domain has been found to be associated with greater likelihood of reaching the highest levels in many different types of domains (Ericsson et al., 1993). When children start competing against each other in sport, a slight advantage in skill or maturation has been found to have great consequences for success as adult professionals. It is now established that in most sports, especially in soccer and hockey, children who have a greater relative age compared to their peers in their age cohort are more likely to become more successful as elite older players (Helsen, van Winckel, & Williams, 2005; Musch & Hay, 1999). Although the detailed mechanisms are not fully known it appears that the age advantage leads to greater probability of initial success and being perceived as more talented, which may influence treatment and access to the best training resources. A more recent study (Côté, MacDonald, Baker, & Abernethy, 2006) has shown that the population density of the community that children grow up in influence their chances of becoming a professional player in hockey, baseball, golf, and basketball in Canada and the United States. Growing up in cities with more than half a million inhabitants were associated with much lower chances of becoming a professional athlete. Similarly, the participation rates of countries in a given domain of activity are closely related to their success in international competitions, such as chess (Charness & Gerlack, 1996). The changes in athletic performance across historical time have been dramatic even in events where changes in rules and equipment

have been minimal, such as swimming and running (Ericsson & Lehmann, 1996; Schulz & Crnow, 1988). These four types of very large systematic differences at the very highest levels of performance cannot be explained by plausible differences in genetic endowment as far as I understand; therefore, they demonstrate together the very important role of environmental influences on the acquisition of elite performance.

More generally, the central claim of the expert-performance framework is that the acquisition of skilled performance can be described as a sequence of states associated with changes in the mediating mechanisms, and that these changes are induced by the engagement in selected activities designed to improve one's current performance, as is illustrated in Figure 3. At each successive state, the athlete, typically with the help of a coach, then needs to identify specific, targeted aspects of their performance (without decreasing other aspects of their performance) that can be enhanced by engaging in specific deliberate-practice activities. Consequently, expert performance requires complex integrated systems of representations for the execution, monitoring, planning and analyses of performance. Deliberate practice must therefore be designed to improve specific aspects of performance in a manner that assures that attained changes can be successfully integrated into the previously acquired structure of mechanisms that mediate representative performance. Similarly, the strain caused by a given level of physical activity on a particular physiological system will depend on the already attained level of adaptations and may activate collections of genes that sometimes have a wide range of different effects. In order to attain the benefit of any type of deliberate practice, such as strength and endurance training, it is important that the training is conducted in the appropriate context of the target activity so the desired changes occur. Hence, practice aimed at improving integrated performance cannot be performed either mindlessly or independent of the representative context for the target performance. Only by better understanding the mechanisms mediating the appropriate sequences of learning and physiological adaptations will coaches and teachers be able to guide athletes to acquire expert performance in a safe and effective manner. Expert performers need to be helped to negotiate the many constraints of daily deliberate practice and to respect the essential need for intermittent rest and daily recuperation (Ericsson, 1996; Ericsson et al., 1993), because a training load that is too large or too intense may lead to overuse injuries to bodily tissues, to fatigue that causes accidents, or to chronic fatigue and burn out.

In sum, there is no disagreement regarding the importance of genetic activity in the development of the human body and expert performance. The activation of genes is critical for developing physiological adaptations of the

body and nervous system that enable expert performance in the particular domain. So far the scientific evidence of genetic mediation suggests that all healthy individuals seem to have the critical genes required for the desired changes as part of their cells' dormant DNA. A recent review (McArthur & North, 2005) found that individual differences in attained elite performance cannot, at least currently, be explained by differential genetic endowment, barring only a few known exceptions of characteristics that directly mediate the performance, such as body-size and height (see Ericsson et al., 1993, for a discussion of the evidence for genetic control). It is entirely possible that future discoveries will uncover unique genes or combinations of genes that are associated with higher levels of expert performance, but until then we need to avoid prejudging the importance of individual differences in genetic endowment for healthy individuals. In the future when we understand the detailed biochemical processes of adaptation, we also need to understand the processes that induce the appropriate strain on the cells and the body by physical and cognitive activity as well as the individual's ability to sustain engagement in appropriate practice activities (cf. deliberate practice). These issues concerning deliberate practice are likely to lead back to the fundamental issues of differences in motivation and sustained concentration where some role of heritable differences is not controversial.

Concluding Remarks

In this article I have described how the expert-performance approach differs from approaches based on the general theories of expertise. These alternative approaches rely upon simple and generalizable learning mechanisms and suggest that further experience automatically leads to improvements as long as the aspiring individuals have the necessary innate talent. The traditional theory for skill acquisition (Fitts & Posner, 1967) aptly describes how individuals tend to automate their behavior to minimize the effort required for execution of the desired performance in most types of habitual everyday activities, such as driving a car, typing, or strenuous physical work. In direct contrast, the expert-performance approach claims that acquisition of expert performance is caused by a sequence of changes in the cognitive mechanisms mediating how the nervous system controls performance and in the physiological systems of the body that are induced by practice activities, as is illustrated in Figure 3. The focus of this framework is on reproducible improvements in performance, where observable changes in performance reflect the longitudinal development of individual

athletes. The key assumption is that reliable *improvements* in performance, especially beyond the initial proficiency, require specific causes and changes in one's behavior, that is, the structure and amount of one's deliberate practice. In contrast, research on individuals with an already attained level of performance is much more complex, because the current training may have much weaker correlations to already attained cognitive and physiological characteristics that require much less training to be maintained and would persist to some degree even without continued training, at least for some limited time. To establish a cumulative science of the acquisition of expert and elite performance, we need to develop methods for measuring performance and variability of the performance of individual athletes in order to assess when performance has been reliably improved (Hopkins & Hewson, 2001; Pyne, Trewin, & Hopkins, 2004). We need to support research where controlled attempts to increase specific aspects of performance are monitored, where training and physiological intensity are carefully documented, and where even failures to improve performance are analyzed and reported. In some cases it may be possible to show relatively uniform benefits of additional training even at the elite level (Helgerud, Engen, Wisloff, & Hoff, 2001). In other cases, it has been possible to identify observable changes associated with increases in performance during several years of intense training. In study of a three-year period of intense training Legaz and Eston (2005) found that sub-elite sprinters and long-distance runners improved their performance and that their performance increases were closely correlated with reductions in skinfold thickness (subcutaneous fat) of the lower limbs, such as skinfolds of front thighs and medial calves, but not skinfolds of the upper body. These measurable changes may provide indirect measures of the quality and intensity of deliberate practice. More generally, it will be necessary to describe the individuals' current state of adaptation in order to predict which methods of practice that will be effective in attaining improvements. I believe that the methodology of identifying changes in gene expression will be a powerful dependent variable in assessing the effectiveness of various types of training, as is illustrated by some recent studies (Coffey et al, 2006; Wittwer, Billester, Hoppeler, & Fluck, 2004). Future collaboration between cognitive, biological and genetic researchers studying the continued improvement of elite performers will be necessary to build complete models of learning and modifiability of human characteristics and abilities. In the process of developing a complete theory of expert and elite performance, it should be possible to better understand any limits on human achievement and to provide everyone with knowledge about their true potential and what it takes to reach it.

Acknowledgement

I am grateful for the financial support provided by the FSCW/Conradi Endowment Fund of Florida State University Foundation. The author wants to thank Angela Duckworth, Len Hill, Katy Nandagopal, Roy Roring III, and Paul Ward for their valuable comments on earlier drafts of this article.

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International Journal of Sport Psychology

VOL. 38 - N. 1 - JANUARY-MARCH 2007

NATURE, NURTURE AND SPORT PERFORMANCE

Special Issue Editors:
Joseph Baker and Keith Davids

EDIZIONI LUIGI POZZI - ROME

ISSN: 0047-0767

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 Printed in Rome by Arti Grafiche Tris - Published by L. Pozzi, Via Panama 68, Roma, tel. 06/855.35.48; Fax 06/855.41.05.

Autorizzazione del Tribunale di Roma n. 13404 del 24 giugno 1970 - Direttore responsabile: Luigi Pozzi - Trimestrale - sped. abb. post. - 45% - art. 2 comma 20/b L. 662/96 - Filiale di Roma

Finito di stampare nel mese di febbraio 2007 dalle Arti Grafiche Tris, s.r.l.
via delle Case Rosse, 23 - 00131 Roma