The Psychology of Abilities, Competencies, and Expertise

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The search within the social sciences for stable, invariant, and quantifiable attributes of living organisms closely parallels historic investigations in the hard sciences in search of characteristics of physical phenomena. The revolutionary advances in physics in the sixteenth through eighteenth centuries allowed scientists to develop lawful relations between characteristics of objects such as weight, size, and velocity with their subsequent "behavior" (trajectories) under specified physical conditions (for example, collisions between objects). Similarly, psychology, when it emerged as an independent science in the nineteenth century, approached its own quest to uncover laws of perception and memory under the guidance of pioneering scientists such as Hermann Ebbinghaus, with comparable scientific methods. Psychology's focus was not, however, on the characteristics of physical objects, but on the search for invariant processes and attributes of individuals that could be quantified and used to predict human behavior and achievement. These same theoretical frameworks were subsequently extended to describe individual differences in ability, and finally used to predict performance in schools and other everyday settings.

In this chapter I review the search for general ability and basic capacities. I begin by briefly sketching the history of the study of individual differences and the methods pioneering investigators employed to develop theoretical conceptions of ability and capacity. Most important,
I discuss the historical arguments for the existence of ability and capacity efforts to measure these quantities, and proposals for the biological mechanisms mediating the effects of ability and capacity on performance. I document how the study of extreme expressions of ability viewed by pioneering investigators (such as Franz Joseph Gall [1751828] and Sir Francis Gallon [1822-1911]) as the most promising source to find empirical evidence for the existence of underlying capacities. It was found that even the study of these eminent individuals made it difficult to identify the specific innate characteristics that mediated their superiority, encouraging Galton to develop compelling arguments to indirectly prove their existence. Galton's original arguments are still consistent with more recent theoretical approaches, and I have attempted to capture his fundamental assumptions about the nature of individual differences in abilities and capacities. These fundamental assumptions are discussed, along with a review of recent studies on expert and exceptional performance. The final portion of the chapter demonstrates how the theoretical framework of expert performance offers alternative perspectives on the structure and acquisition of ability, especially high levels of ability.

HISTORICAL BACKGROUND TO THE APPROACHES STUDYING, ABILITIES AND CAPACITIES

The search for stable attributes of individuals to explain individual differences in behavior is a relatively recent endeavor. During the Middle Ages it was generally believed that God controlled the outcome of all events and actively guided the destiny of people and their actions. During this period, the desire to search for causes of behavior in the physical and biological attributes of individuals was considered blasphemous. In successive centuries, scientific advances revealed that our natural environment was governed by stable regularities, and that God influenced events, not with moment-to-moment interventions, but by the creation of natural laws. This "realization" permitted scientists the opportunity for careful observation and experimental analysis by which they were able to uncover these laws, and use such laws to accurately predict the "behavior" of objects.

Scientists and philosophers eventually applied these same types of analyses to human behavior in an attempt to discover the stable attributes of human beings. However, the everyday behavior of human adults, unlike the behavior of physical objects, varies considerably
situations as a function of motivation, and thus makes stable its of
abilities difficult and controversial. It was therefore natural for the early
investigators to seek out individuals with extraordinary abilities where
the exceptional achievements were not questioned, therefore producing
less controversial assessments of stable attributes of human beings.

Franz Joseph Gall and Phrenology

In the eighteenth century, Gall made the revolutionary claim that the
size and shape of the brain determined individuals' personality and
abilities. This theory is often described as the first major step toward a
science of the brain (Young, 1970). Gall also proposed that the brain areas
associated with certain abilities could be found by looking for "bumps" on
the skulls of individuals with extreme manifestations of a certain
attribute. According to Young (1970, p. 33, original italics but underlining
added): "The main criterion was that it be manifested independent of
other characteristics of the individual or the species. When he found men
or animals with an eminent talent or propensity he examined the form of
the head for a cranial prominence. He collected and compared as many such
correlations as he could find." Gall's method was thus based on the
assumption that when "some particular quality is manifested in a much
higher degree of activity than the others, it is fundamental" (Gall, quoted by
Young, 1970, p. 36).

Gall's initial efforts into examination of his theory provided cases
that established new information about the structure of the brain,
but as the number of cases kept coming in, a growing number of
counterexamples began to arise as well (Young, 1970) even as they were
argued away. One example of such a "counterexample" included the
head shapes of statues of famous people with dear traits and abilities,
which presented in the statue no obvious head bumps or cranial
protrusions as predicted by Gall's theory. These cases were simply
rejected, however, as incorrect renderings of the head by the sculptors.
Other inconsistencies were explained away by arguing that the
expected talent might have been lost to excesses or diseases.
Eventually, more challenging counterexamples emerged. For example, "a
young boy was found with remarkable calculating ability and a de-
pression where the prominence for numbers should have been" (p. 43),
and Descartes' skull was found to be very small in the regions where
the rational faculties were predicted to be located. Although complex
explanations could be generated to explain these counterexamples, it was becoming increasingly clear that the theoretical framework's ability to make precise predictions was flawed, and the approach eventually lost favor.

Sir Francis Galton and "Heritable Genius"

If Gall pioneered the search for biological markers of ability, then Sir Francis Galton provided the theoretical rationale and methodology to find the innate biological attributes and mechanisms that would explain eminent achievement and ability. In his famous book, Heritable Genius, Galton presented evidence suggesting the heritable influence on height and body size, and more important, an argument that similar innate mechanisms must determine mental capacities. Galton (1869/1979, pp. 31-32, underlining added) argues, "Now, if this be the case with stature, then it will be true as regard to every other physical feature -as circumference of head, size of brain, weight of grey matter, number of brain fibres, etc., and thence, a step on which no physiologist will hesitate, as regards mental capacity."

Galton (1869/1979) clearly acknowledged the need for training to reach high levels of performance in any domain. He argued, however, that improvements are rapid only in the beginning of training and that subsequent increases become increasingly smaller, until "maximal performance becomes a rigidly determinate quantity" (p. 15). According to Galton, the relevant heritable capacities set the upper bound for the attainable level in physical and mental activities. Once the training benefits have been attained through sufficient practice, then the immutable limit for performance is attained, "where he cannot by any education or exertion overpass" (p. 15), and the maximal performance is achieved that "his nature has rendered him capable of performing" (p. 16). Gallon's immutable characteristics limiting performance must, by definition, have had an origin different from training, and thus, by inference, must have been innately endowed. Gallon's argument for the importance of innate factors in elite performance is highly compelling, and thus has had a lasting impact on researchers. I critically review this argument's fundamental assumptions later in this chapter.

It is important to note that Galton never was able to pinpoint which specific attributes or biological mechanisms determined "heritable" differences in various capacities. Nevertheless, he pioneered the methodology of measuring individual differences in mental performance. He
also developed the correlation coefficient as a measure of how closely related different variables and factors are for a given sample of subjects.

The Inductive Search for Mental Abilities and Capacities

Toward the beginning of the twentieth century, numerous investigators collected data on the relation between performance and mental tests measuring basic cognitive functions of memory, attention, and perception. However, the patterns of correlation between tests measuring similar basic functions were not consistent across studies, and gave the appearance of being spurious (Anastasi, 1988; Brown and Thomson, 1921; Spearman, 1904). Much of the large variability could be attributed to the testing of school children who differed greatly in age, or the use of small samples of adults. However, when Wissler (1901) tested basic mental processes on over 150 college students, the correlations were low, and most not reliably different from zero. The correlation between these mental tests and the students' grades in different academic subjects were in the 0.0 to 0.3 range, even though the correlation between grades was mostly in the 0.5 to 0.7 range. Successful replications of Wissler's findings led Aikens, Thorndike, and Hubbell (1902) to argue that the tests measuring "speed of association" were not reliably correlated, and ability differences in the quickness of association of ideas was a myth. Other studies showed that performance on these types of tests could be improved with practice, but that these improvements were remarkably specific and did not transfer to other tests and types of stimulus materials (see Woodworm and Thorndike, 1901, for a pioneering study).

In a very influential paper, Charles Spearman (1904) proposed how one could use statistical techniques for controlling for factors contaminating the influence of intelligence, such as participants' age and relevant experience, and to correct for observational errors and lack of test reliability. Spearman initiated a research tradition that developed methods for analyzing the full matrix of correlations between a large number of psychometric tests to identify latent factors that could account for the pattern of covariance. He found evidence for clusters of correlated tests in the same domain that could be explained by relevant experience and basic domain-specific abilities. Most important, he found evidence for a general factor, referred to by the simple letter g, that "explains the correlations that exist between even the most diverse sorts of cognitive performance" (Spearman, 1923, p. 5). Spearman found it difficult to
conceive what such a general mechanism might be, and speculated: "the factor was taken, pending further information, to consist in something of the nature of an 'energy' or 'power' which serves in common the whole cortex (or possibly, even the whole nervous system)" (p. 5). In later books, Spearman (1937) argued that $g$ should "supplant all current determinations of 'mental age' or 'general intelligence'" (p. 241) and that its suggested innate nature would revolutionize the social sciences.

The complex statistical procedures used by Spearman and others to extract general latent variables such as $g$ from the massive bodies of data and patterns of correlations across large populations of individuals made it impossible to study and capture these phenomena in individual subjects. Most investigators, however, accepted Spearman's proposed procedures to separate general capacities from domain-specific cognitive skills and knowledge, and the idea of neural hardware (discussed later) had an important influence on subsequent research on individual differences.

**From Associative Learning to Information Processing Models of Human Cognition**

During the reign of behaviorism (c. 1920 through c. 1950), the focus of research in general psychology was on mechanisms mediating learning of simple associations in long-term memory (LTM). Consequently, the research of learning never encountered the need to propose limits on processing capacity and associated interindividual differences. It was only when researchers became interested in contrasting the speed of human performance to that of machines and computers that investigators found it appropriate to describe human performance as limited by channel capacities. When scientists in the 1950s started to address complex cognitive processes such as concept formation, problem solving, and decision, they saw important parallels between computers and humans in that both could be viewed as instances of information-processing systems. Newell and Simon (1972) proposed a theory explicating a set of specified information-processing constraints for humans and described how human information-processing models could be designed for a wide range of cognitive tasks. These models could be implemented as completely specified models in the form of computer programs that could produce performance on laboratory tasks that matched the observable behavior and performance of humans.
The computer as metaphor for human cognition suggests a distinction between software and hardware. Humans can typically easily acquire new knowledge and skills, which is roughly comparable to the ease of exchanging and revising software (that is, computer programs and an operating system) on a computer. In fact, the observable behavior and performance of humans on a wide range of laboratory tasks can be reproduced by information-processing models implemented as computer programs. On the other hand, the hardware of the computer with its central processor and internal and external memories is fixed, and such hardware components determine the available memory capacity and overall processing speed. In a similar manner, the basic parameters of the nervous system and the brain in adult humans were typically believed to be fixed and thus not modifiable by experience and training. Hence, the neural "hardware" would seem a very plausible locus for innate differences between individuals in basic memory capacity and speed of elementary processes that would influence the performance in most tasks in differing degrees. Ever since George Miller's (1956) classical paper on the magical number of seven, the limits of short-term memory (STM) have been seen as quantifiable capacity of human cognition and a critical bottleneck for processing a possible source of individual differences. Newell and Simon (1972, p. 865) write that "Differences in the capacity of STM, for example, probably play a large role in the functional difference between the very young and the mature, and between those we consider intellectually sub-normal and those we consider normal." In the subsequent three decades, investigators have become interested in the related ideas of limits of working memory and/or attention as likely sources of individual differences in processing capacity and general ability (Miyake and Shah, 1999).

Some Fundamental Assumptions in the Search of Basic Capacities and General Abilities

My historical sketch shows that eminent psychologists have taken for granted that individual differences - especially those of outstanding individuals - can be explained by some measurable underlying mechanism that has a biological and innate basis, much as we know that the length of bones determine height and body size in a very heritable manner (compare Gallon's suggestive analogy). If the neurological mechanisms have innately determined limits (like the length of most
bones in our bodies), these limits cannot be improved by training and, by inference, individual differences in maximal performance are inherently fixed.

Rather than simply accepting this inference, I review the empirical evidence on the modifiability of performance and its mediating biological mechanisms as a result of extended practice. My review will show that the mediating biological mechanisms and the observable performance can be improved substantially even when individuals are highly experienced. I also reject Gallon's hypothesis that performance after practice has removed all trainable aspects, and thus becomes rigidly constrained by fixed innate capacities. Drawing on the research on expert performance, I will review evidence demonstrating that expert performance is mediated by complex modifiable representations that allow experts to exhibit faster speed, superior selection of actions, and more precise motor execution.

In the third and final section, I discuss the major challenges to any account of individual differences based primarily on acquisition. What are the processes that mediate the construction of complex mechanisms, and why do only a small fraction of individuals in a domain reach the highest levels? My conclusion will discuss the theoretical implications of the structure of an expert's acquired superior performance for the current practice of "quantifying" latent variables - such as capacities and abilities - that are hypothesized to determine individual differences in performance.

THE MODIFIABILITY OF PERFORMANCE AND ITS MEDIATING MECHANISMS

If psychometric tests measure basic nonmodifiable capacities and processes, then one would predict that this performance should be highly reliable across multiple test occasions. In particular, Gallon's hypothesis would predict increased stability of performance and greater range of individual differences with opportunities for practice.

In my introductory review, I remark that investigators in the beginning of the twentieth century found substantial practice effects with laboratory tasks designed to measure simple mental functions. Even psychometric tests were shown to have a similar problem with practice effects. Greene (1937) found that college students' performances on a large number of psychometric tests improved substantially after they had taken the tests several times. Some psychometric tests, such as Kohl's cube design and Minnesota space relation tests, showed between
50 percent and 100 percent improvement. Other tests, such as auditory digit span, showed intermediate improvement in a range around 10 percent. Some tests measuring speed of movement and sensory discriminations showed negligible gains. However, one should not infer from Greene's study that sensory judgments could not be improved by practice. In an extensive review Gibson (1969) showed that when the amount of practice with feedback increased, improvements on sensory discrimination and other types of perceptual tasks were large.

Large Practice Effects after Extended Practice

One of the most striking and reproducible processing constraints for humans concerns the limited capacity of their STM (Miller, 1956). In the 1960s and 1970s, investigators repeatedly demonstrated college students' inability to repeat correctly more than around nine presented digits - roughly a phone number with an unfamiliar area code. Would it be possible to increase the capacity of STM, commonly believed to be the primary constraint on information processing?

Bill Chase and I (Chase and Ericsson, 1982; Ericsson, 1988; Ericsson, Chase, and Faloon, 1980) recruited college students to be repeatedly tested on the standard test of STM - the digit span - for an hour every other day for many weeks and months. When we tested their STM before the start of the training, their recall performance was normal and limited to around seven digits. All the trained students increased their memory performance by 200 percent to over twenty digits after around fifty hours of practice on this task. After two hundred to four hundred hours, two of them improved their recall by more than 1000 percent (over eighty digits). Experimental analyses showed that the students had acquired a memory skill for rapid retrievable storage in LTM, and Ericsson and Kintsch (1995) showed that the same mechanisms of long-term working memory (LTWM) mediate reading and comprehension - skills attained by all educated adults. Furthermore, memory experts and expert performers are shown to acquire related LTWM mechanisms to improve their ability to expand their functional working memory (Ericsson and Lehmann, 1996). For example, these LTWM mechanisms allow chess masters to plan out possible move sequences mentally while selecting moves to a degree that they are able to play blindfold chess, that is, to play chess without a visible chess board.

The effects of specialized training are by no means limited to memory and other cognitive capacities. With specific practice, speed of
performance increases considerably, and even physiological capacities can be markedly improved (Ericsson, Krampe, and Tesch-Romer, 1993). For example, Astrand and Roehdahl (1977) reported that the ability to sustain powerful activity could increase by over 5000 percent in some group studies. Let me also give one striking example of the effects of practice for a familiar activity often used to assess physical fitness where the improvements are far greater than most people believe possible. Physically fit adults, such as college students in a physical education class can make around twenty push-ups in a row, with a range from eight to thirty-two. However, in 1966 one individual was able, after extended practice, to achieve a new record for consecutive push-ups and completed over six thousand in a row. This record did not last long and has been broken again and again. The current record is over twenty-six thousand and is limited to the number of push-ups completed within twenty-four hours. This amounts to an improvement of push-up performance of 100,000 percent or an average of a completed push-up every three seconds for twenty-four hours straight. The possibility of changes in performance on tasks originally designed to measure stable capacities, such as anaerobic fitness, boggles the mind.

The Applicability of the Hardware versus Software Distinction for Biological Systems

When extended practice is permitted, the modifiability of the human body and its nervous system differs greatly from that of computers and other types of machines. Humans and other biological systems are able to change their "hardware," that is, their cells and organs. In contrast to machines, humans are able to heal wounds and broken bones, as well as build their organs to assist the body in adapting to repeated strain induced by practice and performance. Humans do not wear out from performing repetitive action (as long as the actions do not seriously injure tissue, and sufficient recuperation periods are allowed to avoid repeated stress injuries). Animals and humans are able to adapt over time, and will increase efficiency of repetitive actions (Bernstein, 1996). For example, it is well documented that adults have to engage in intense aerobic exercise to improve aerobic fitness. Specifically, young adults have to exercise at least a couple of times each week for at least thirty minutes per session with a sustained heart rate that is 70 percent of their maximal level (around 140 beats per minute for a maximal heart rate of 200). Similarly, improvements of strength and endurance require
that individuals strain themselves on a weekly basis and each training session push the associated physiological systems outside the comfort zone, stimulating physiological growth and adaptation (Ericsson, 2001a, 2001b).

When the human body is put under exceptional strain, a whole range of extraordinary physiological processes are activated. For example, when an adult donates a kidney, the remaining kidney is insufficient to perform the clearance of waste products from the body. This insufficiency leads to a chemical reaction that signals the remaining kidney to grow in size to make up for the lost functioning of the missing kidney. During a period of a few weeks, the remaining kidney grows by around 70 percent to handle the increased load. Similar adaptations occur when individuals start training for long-distance running. Sustained running causes an oxygen deficiency in the affected muscles, which results in physiological strain that causes capillaries to grow and develop around the muscles within the first few weeks of regular training to permit muscle growth and development. Drawing on similar types of mechanisms, specific changes in various areas of the brains of animals have been induced by different types of physical activity (Black, Isaacs, Anderson, Alcantara, and Greenough, 1990). In fact, recent reviews (Buonomano and Merzenich, 1998; Kolb and Whishaw, 1998) show that the function and structure of the brain is far more adaptable to experience, especially early and extended experience, such as the effects of early practice by expert musicians (Elbert, Pantev, Wienbruch, Rockstoh, and Taub, 1995; Schlaug, Jancke, Huang, Staiger, and Steinmetz, 1995).

Adults are able to generate demanding, exceptional situations for their bodies by engaging in vigorous practice with a regular frequency and gradually increased intensity over extended time. The long-term responses to these physiological challenges allow elite athletes to transcend the typical physiological capacities necessary for everyday life. When we include all the evidence for training-related changes in the size of hearts, thickness of bones, and allocation of cortical areas in the brain, we see that virtually all aspects of humans' bodies and nervous systems are modifiable, with the exception of height and body size (Ericsson, 2002a, 2002b).

These and other examples raise doubt that fixed innate capacities limit an individual's ability to reach the highest levels of performance. Reviews of expert performance (Ericsson, 1996; Ericsson and Lehmann, 1996) have uncovered no evidence of characteristics that are critical to
expert performance that cannot also be altered or circumvented with extended practice. There are some well-documented exceptions to this general principle, such as physical height and body size. (There is an obvious advantage to being a taller player in basketball and a shorter participant in gymnastics, and there is no known practice activity that can increase the length of bones and the associated height of humans.) When one excludes height-related characteristics, however, recent reviews (Ericsson and Lehmann, 1996; Howe, Davidson, and Sloboda, 1998) have not found any accepted evidence that innate characteristics are required for healthy adults to attain elite performance. When appropriately designed training is maintained with full concentration on a regular basis for weeks, months, or years, there appears to be no firm empirical evidence for innate capacities besides physical size that limits the attainment of high level performance. Consequently, height and body size appear to be qualitatively different from other anatomical and physiological characteristics, and rather than being typical examples of a general rule, as Sir Francis Galton suggested, the characteristics appear to be rare exceptions.

Perhaps the best evidence against a well-defined upper bound for individuals' capacity to perform is found in professional domains, where experienced individuals have repeatedly shown that they are able to increase their attained stable performance when they are sufficiently motivated (Ericsson et al., 1993). Similar increases in performance at the highest levels can be inferred from the improvements of performance across long periods of time. The best evidence for the value of current training methods and practice schedules comes from historical comparisons (Ericsson et al., 1993; Lehmann and Ericsson, 1998). Historically, very dramatic improvements in the level of performance are found in the sports domain. In competitions such as the marathon and swimming events, many serious amateurs of today could easily beat the gold medal winners of the early Olympic Games. For example, after the fourth Olympic Games in 1908, the Olympic committee almost prohibited double somersault dives because these dives were thought to be dangerous and could not be controlled. Today, divers have not only mastered double somersaults, but dives of far greater complexity.

This remarkable adaptability at the level of physiological, behavioral, and cognitive systems presents a major challenge to the view that nonmodifiable capacities and characteristics limit the attainable performance of individuals. On the other hand, these findings raise new
questions, such as what is the structure of skilled performance that allows it to be gradually changed and improved?

THE COMPLEXITY OF THE MECHANISMS MEDIATING THE SUPERIOR PERFORMANCE OF EXPERTS

In my historical sketch, I describe Gallon's compelling argument for why superior performance after sufficient experience would be constrained by general capacities that could not be modified. In light of the demonstrated modifiability of human performance after extended practice, however, we now face the challenge of identifying the detailed mechanisms that allow individual experts to keep improving and eventually attain and exhibit vastly superior performance.

Ericsson and Smith (1991) proposed that, in order to describe these mechanisms, we need to identify and examine individuals who are able to perform repeatedly at a higher level than others. It would be reasonable, too, to identify experts within a wide variety of domains and study their superior performance in these differing areas. Finding individuals with superior performance turned out to be surprisingly challenging, because experts in many domains, such as investing, auditing, and clinical therapy, have not been found to perform at a level superior to other experienced individuals on representative tasks in their domains (see Ericsson and Lehmann, 1996, for a review). For example, highly experienced psychotherapists are not more successful in treatment of patients than novice therapists (Dawes, 1994) and stock market experts and bankers are not able to forecast stock prices reliably better than university teachers and students (Stael von Holstein, 1972). Consequently, Ericsson and Smith (1991) argued that the scientific study of expert and exceptional performance must be restricted to individuals with reliably superior performance characteristics. Once we have found individuals who can repeatedly perform at an exceptional level, then we should attempt to capture and reproduce their performance in the laboratory so we can use standard process tracing and experimental techniques to assess the structure of the mechanisms mediating their exceptional performance.

In many domains there have evolved procedures for fair measurement of superior performance. Over time, methods of measuring performance have become extremely precise, and a tenth or a hundredth of a second may distinguish the winner in swimming and sprinting events. In many sports, the conditions of competition are highly standardized
so that it is common to use an individual's best performance at local and regional competitions to assess his or her qualifications to participate in national and international competitions.

Competitions in music, dance, and chess have a similar long history of attempting to design standardized situations that allow fair competition between individuals. In all these domains, elite individuals reliably outperform less accomplished individuals. Expert performers can reliably demonstrate their performance any time when required during competitions and training, and are thus also capable of reproducing their superior performance under controlled laboratory conditions.

Recent reviews (Ericsson, 2001; 2001; Ericsson and Lehmann, 1996) have shown that the performances of experts have been successfully reproduced in the laboratory, where methods of process tracing, such as analysis of think-aloud protocols and eye movements have been applied to assessing mechanisms that mediate experts’ superior performances. In this chapter I briefly discuss three general characteristics of distinguishing expert performance: the ability to select superior actions, the ability to generate rapid reactions, and the ability to control movement production.

The Ability to Select Superior Actions

Most of us have had the experience of facing a superior opponent in chess or other competitive games. Whatever move we select, the expert has already anticipated the move, seemingly remaining several steps ahead of our strategy. In his pioneering work on chess expertise, de Groot (1946/1978) was the first to repeatedly reproduce this type of superior performance in the laboratory. He instructed good and world-class chess players to think aloud while they selected the best move in a set of unfamiliar chess positions taken from games of chess masters. The superior quality of the moves that the world-class chess players selected were closely associated with their higher chess skill, and later research validated the move-selection task as the best available assessment of chess skill (Ericsson and Lehmann, 1996; Ericsson, Patel, and Kintsch, 2000). Verbal report evidence revealed that all of the chess players first perceived, then interpreted, the chess position in order to retrieve potential moves from memory. Promising moves were then evaluated by mentally planning out the consequences of sequences of move exchanges. During this evaluation, even world-class players were able to discover better moves. Hence, the performance of experts is mediated by increasingly
complex control processes. Although chess experts can rapidly retrieve appropriate actions for a new chess position (compare Calderwood et al., 1988 and Gobet and Simon, 1996), their move selection can be further improved by planning, reasoning, and evaluation (Ericsson et al., 2000). The superior ability of highly skilled players to plan out consequences of move sequences is well documented. In fact, chess masters are able to play blindfold, without a visible board showing the current position, at a relatively high level (Karpov, 1995; Koltanowski, 1985). Experiments show that chess masters are able to follow chess games in their head when the experimenter reads a sequence of moves from a chess game, and are also able to retrieve any aspect of the position when probed by the experimenter (see Ericsson and Oliver's studies described in Ericsson and Staszewski, 1989). Highly skilled players can even play several simultaneous games mentally, thus maintaining multiple chess positions in memory (Saariluoma, 1991).

The same paradigm has been adapted to study other types of expertise where experts have been presented with representative situations, such as simulated game situations, and asked to respond as rapidly and accurately as possible. Recent reviews (Ericsson, 1996; Ericsson and Kintsch, 1995) show that expert performers have acquired refined mental representations to maintain access to relevant information and to support flexible reasoning about an encountered task or situation. In most domains better performers are able to rapidly encode and store relevant information for representative tasks in memory so that they can efficiently manipulate the information mentally. For example, with increased chess skill, chess players are able to plan more deeply, generate longer mental sequences of chess moves, and evaluate the associated consequences. Similar evidence for mental representations has been shown for motor-skill experts such as snooker players and musicians (Ericsson and Lehmann, 1996).

The Ability to Generate Rapid Reactions

It is a common belief that athletes are able to hit fast balls or pucks because they can see better (superior vision) and exhibit greater quickness (faster reactions). However, expert athletes cannot be distinguished from their less skilled peers by superior basic abilities or faster speed on simple RT tasks. The superior performance of such athletes has been shown to reflect specialized perceptual skills, and not superiority on standard tests of visual ability (Williams, David, and Williams, 1999).
The rapid reactions of athletes, such as hockey goalies and tennis players, have been found to reflect acquired skills involving the anticipation of future events. For example, when highly skilled tennis players are preparing to return a serve, they study the movements of the opponent leading up to contact between the ball and the racquet to identify the type of spin and general direction of the ball. Given the ballistic and biomechanical nature of a serve, it is often possible for skilled players to anticipate outcomes far better than chance can explain. Thus, the advantage of expert athletes reflects primarily anticipatory skills rather than an innate neural speed advantage over their less accomplished peers (Abernethy, 1991).

Mediating cognitive representations can similarly account for the superior speed of expert typists and the faster rate of their typing movements. The key to the expert typists' advantage involves the ability to look beyond the word they are currently typing (Salthouse, 1984). By looking further ahead they are able to acquire skills to prepare future keystrokes in advance, moving relevant fingers toward their desired locations on the keyboard. This finding has been confirmed by analysis of high-speed films of expert typists and experimental studies in which expert typists have been prevented from looking ahead. It is important to note that novice typists use an entirely different strategy and usually type only a small group of letters at a time in a piecemeal fashion. The perceptual skill to prepare sequences of typing movements in advance to allow continuous typing at a high speed must have been acquired later at a more advanced level of skill.

The Ability to Control Movement Production

Expert performers often confront unfamiliar situations where they have to generate complex sequences of movements. For example, when expert musicians perform unfamiliar music, a technique called sight-reading, such experts demonstrate their ability to mentally plan how their fingers will strike the keys to retain control and minimize interference between fingers (Drake and Palmer, 2000; Lehmman and Ericsson, 1993, 1996; Sloboda, 1984; Sloboda, Clarke, Parncutt, and Raekallio, 1998). Evidence for the mental representation of pieces of music comes from studies showing that expert pianists retain control over their motor performance even after a piece of music has been memorized. In laboratory studies expert pianists have been able to perform music without additional practice under changed conditions,
such as a different key or a slower tempo (Lehmann and Ericsson, 1995, 1997).

At a higher level of expertise, musicians attain a higher level of control than novices and can repeatedly reproduce a given musical performance with its subtle variations in tempo and volume (Ericsson et al., 1993). Similarly, elite athletes, such as highly skilled golfers, are able to perform the same action, such as putt or drive, several times more consistently than less skilled athletes (Ericsson, 2001). More generally, empirical studies show that experts acquire mental representations that allow them to internally monitor and compare their concurrent performance with their desired goal, such as the intended musical sound or desired motor action, and thereby continue to improve their control over their performance.

Summary and Comments
When expert performance is studied with representative tasks, we find that the mechanisms that mediate the superior performance are not nonmodifiable basic capacities, but surprisingly complex mechanisms highly specific to the task domain. These experts have acquired mechanisms that transcend the limiting factors constraining a novice's performance. The novices' working memory problems are no longer relevant for experts who rely on acquired memory skills and LTWM to support their extensive working memory needs for planning, reasoning, and evaluation. The novices' problems with slow speed of cognitive and motor processes are made irrelevant with experts' acquired mechanisms mediating superior anticipation. The experts' need for higher consistency and control of motor actions is met with the development of more refined techniques tailored to the specific demands of the superior performance in the respective domain of expertise. As the principal mechanisms mediating experts' performance have not yet been acquired by novices, it is not surprising that the prediction by psychometric tests of individuals' ultimate expert performance has been so disappointingly poor (Ericsson et al., 1993; Ericsson and Lehmann, 1996).

EXPLANATION OF INTER- AND INTRA-INDIVIDUAL DIFFERENCES IN SKILLED PERFORMANCE
Expert performance was shown in the previous section to be mediated by complex mechanisms that allow the performers to increase speed,
consistency, and memory capacity only for activities in a given domain of expertise. These findings strongly suggest that expert performance is primarily acquired, and that learning mechanisms account for vast improvements in the performance of each individual, because there is no possibility to change a given individual's genetic endowment and associated innate potential.

If skill acquisition can explain striking differences between the performances of the same individual at the introduction to the domain and as a mature elite performer (intra-individual differences), then one is faced with the challenge of accounting for how the same mechanisms could explain large differences in the final performances of adults (inter-individual differences). Traditional theories of skill acquisition in psychology (Fitts and Posner, 1967; Anderson, 1982) do not propose explanations for how expert performance is acquired. They propose mechanisms for how adults reach an acceptable level of performance in everyday and recreational activities, such as typing and playing golf. I will first describe these accounts for typical performance, and then discuss how the acquisition of expert performance differs from the typical.

THE ACQUISITION OF AMATEUR AND TYPICAL LEVELS OF PERFORMANCE

When individuals are first introduced to an activity such as driving a car or typing or playing golf, their primary goal is to reach a level of mastery that will allow them to perform everyday tasks or engage in recreational activities with their friends. During the first phase of learning (Fitts and Posner, 1967), novices try to understand the activity and concentrate on avoiding mistakes, as illustrated in the first part of the lowest curve in Figure 4.1. With more experience in the middle phase of learning, gross mistakes become increasingly rare, performance appears smoother, and learners no longer need to concentrate as hard to perform at an acceptable level. After a limited period of training and experience - frequently less than 50 hours for most ordinary activities, such as typing, playing tennis, and driving a car - an acceptable standard of performance is typically attained. As individuals adapt to a domain and their performance skills become automated, they may lose conscious control over execution of those skills and it may become difficult to intentionally modify the skills. Once the automated phase of learning has been attained, further experience will not markedly improve performance. Consequently, the correlation between amount of experience and performance will be low,
FIGURE 4.1. The acquisition of levels of performance.
and it is common to find recreational golfers, tennis players, and skiers who have not improved their performance after years, or even decades, of regular experience. Similarly, there is a weak relation between performance and length of experience after individuals have gained their initial experience during the first year (Ericsson and Lehmann, 1996). However, these stable levels of attained performance do not reflect a firm upper bound and when individuals are motivated to improve their current level of performance by training they are able to do so, and their performance can gradually be improved, often in a consistent manner (Ericsson et al., 1993).

The Acquisition of Expert Performance and Its Mediating Mechanisms

In contrast to the rapid stabilization of the performance in everyday and recreational activities, performance of future experts continues to improve with more experience for years and decades (Ericsson and Lehmann, 1996). The long preparation time is not an artifact due to the fact that the best performers start in their domains at early ages. Outstanding swimmers, tennis players, musicians, and chess players frequently start at very young ages. The average starting age for elite performers is around six years in many of the major domains (Ericsson et al., 1993). However, experts in most domains continue to improve even after full maturation of the body and brain, which typically happens around the late teens in industrialized countries. The expert performers typically reach their highest level of performance many years, or even decades, later. For example, in many vigorous sports, athletes attain top performance in their mid- to late twenties; for fine-motor athletic activities and the arts and sciences, it is a decade later, in the thirties and forties (Lehman, 1953; Schulz and Cumow, 1988). Furthermore, the most compelling evidence for the role of vast experience in expertise is that even the most "talented" individuals require around ten years of intense involvement before they reach an international level, and for most individuals it takes considerably longer. Simon and Chase (1973) originally proposed the Ten-Year Rule, showing that no modern chess master had reached the international level in less than approximately ten years of playing. Subsequent reviews show that the Ten-Year Rule extends to music composition, as well as to sports, science, and the arts (Ericsson et al., 1993). The striking difference between the development of elite and average performance appears unrelated to the overall duration of
individuals' experience in the domain, but is rather reflected in the particular types of domain-related activities in which the future experts choose to engage.

The key challenge for aspiring expert performers is to avoid the arrested development associated with automaticity that is seen with everyday activities and instead acquire cognitive skills to support continued learning and improvement. The future expert performer actively counteracts the tendency toward automating performance by engaging in training activities. These training activities are specifically designed, typically with the help of teachers and coaches, to go just beyond the future experts' current reliable level of performance, referred to by Ericsson et al. (1993) as deliberate practice. These discrepancies between their actual and desired performance force the future expert performers to exert full concentration during practice, and "stretch" their performance by repeated attempts at higher performance levels. In addition, the raised performance standards cause experts to make mistakes. These failures force future expert performers to continuously refine their task representations so they continue regenerating the initial cognitive phase, as shown by the top curve in Figure 4.1. Experts continue to acquire and refine cognitive mechanisms that mediate continued learning and improvement. These mechanisms are designed to increase the experts' ability to monitor and control these processes (Ericsson, 1996, 1998, 2001a, 2001b). Most significantly, improvement in individuals' reproducible performance requires continued, often increased, levels of deliberate practice to change the mediating mechanisms. Without deliberate practice, the performer is likely to stagnate and prematurely automate his or her performance, as shown in the middle arm of Figure 4.1.

The acquisition of expert performance in most domains of expertise depends critically on access to training resources and follows a predictable course for most individuals. Many types of domains of expertise, such as music, figure skating, and ballet, involve mastering increasingly complex and challenging sequences of motor actions. In all these domains, guidance and instruction are crucial, and no performer reaches the elite levels without the help of coaches and teachers. International level performers start practice at very young ages, as young as three or four years of age, are given instruction by teachers, and are helped to engage in practice by their parents for their entire development cycle until adulthood (Bloom, 1985; Ericsson et al. 1993; Ericsson and Lehmann, 1996). The types of training activities (deliberate practice) that are necessary for development of mechanisms mediating expert
performance differ for different domains and the experts' level of current mastery.

The Acquisition of Highly Technical Skills
In domains with long traditions of successfully trained expert performers (such as music and ballet), teachers over centuries have developed a consensus about how to present the techniques and knowledge of the domain in an organized sequence. Let me illustrate this in the domain of music. In the training of music students, the focus is on a gradual development of the skill of performing music in public. Students start by mastering simple pieces of music with a focus on accuracy of keystrokes, but as they increase in mastery the teachers select more challenging pieces and have expectations for musical expression. When students repeatedly practice new and challenging pieces, their difficulties in mastering the pieces reveal weaknesses in their representations and technical skills. Depending on the type of problems, the teacher will recommend a specific type of deliberate practice to improve that aspect of the student's performance. Over the years many effective training methods have been devised to help musicians change their processes and representations. However, only the students themselves are able to address their own specific performance problems. Eventually, through problem solving, students can generate the specific modifications that, with extended practice, can be fully integrated with the complex representations that mediate their performance of complete pieces of music. The importance of solitary practice to master new pieces and techniques (deliberate practice) has been demonstrated by showing a close relation between the amount of deliberate practice accumulated during musicians' development and the level of attained music performance - even within groups of expert musicians (Ericsson, 2001b, for a review). The musicians in the most elite group were estimated to have spent over ten thousand hours in solitary practice by the age of twenty (Ericsson et al., 1993). Later studies have replicated the relation between attained level of skill and the amount of deliberate practice accumulated during the musicians' development (Krampe and Ericsson, 1996; Lehmann and Ericsson, 1996; Sloboda, 1996; Sloboda, Davidson, Howe, and Moore, 1996).

In other performance domains such as ballet, gymnastics, figure skating, and platform diving, there is a similar progression through increasingly difficult tasks, in which the guidance of a teacher is critical for success. Studies find that even in these domains, the level of attained
performance is related to the accumulated amount of deliberate practice (Starkes, Deakin, Allard, Hodges, and Hayes, 1996). However, there are domains where large improvements in performance are regularly attained without teachers, where individuals can increase the level of difficulty by seeking out more challenging situations, such as skiing more difficult slopes, or playing with older or better players in tennis and soccer.

The Acquisition of Increased Performance Speed The best insights into how speed of performance can be increased through deliberate practice are provided by extensive research on typing. The key finding is that individuals' typing speed is not completely fixed. It is possible for all typists to increase their typing speed by pushing themselves as long as they can sustain full concentration, which is typically about fifteen to thirty minutes per day for untrained typists. While straining to type at a faster speed - typically around 10 to 20 percent faster than their normal speed - typists seem to strive to anticipate better, possibly by extending their gaze ahead further. The faster tempo also serves to uncover keystroke combinations that are comparatively slow and poorly executed. By successively eliminating weaknesses, typists can increase their average speed and practice at a rate that is still 10 to 20 percent faster than the new average typing speed. In domains where speed and efficiency of performance present the primary challenge to expert levels, it is possible to attain high levels of performance with less instruction than in the highly technical domains. Even in domains focusing on speed, there is evidence for the role of deliberate practice in attaining the highest levels of performance. Elite athletes are shown to spend more time in solitary practice and/or practice with their teammates (Helsen, Starkes, and Hodges, 1998; Hodges and Starkes, 1996; Starkes et al., 1996). An important aspect of expert performance in team sports, such as soccer and land hockey, concerns the selection of the correct actions in game situations.

The Acquisition of Superior Skills to Select Actions The best insights into how it is possible to improve one's ability to generate superior plans and actions come from the study of chess expertise. Future chess experts spend as much as four hours a day studying games between chess masters (Ericsson et al., 1993). They play through the games one move at a time to see if their selected moves match the moves originally selected by the masters. If a chess master's move differed from
their own selection, it would imply that their planning and evaluation must have overlooked some aspect of the position. Through careful, extended analysis, the chess expert is generally able to discover the reasons for the chess master's move. By spending a longer time analyzing the consequences of moves for a chess position, players can improve the quality of their future move selections. The amount of accumulated solitary study in chess is the best predictor of current chess performance. International chess masters accumulate around six thousand hours of solitary study during the first ten years of chess playing (Charness, Krampe, and Mayr, 1996).

Deliberate Practice and Expert Performance: General Comments

The acquisition of expert performance extends over years and even decades, but improvement of performance is not an automatic consequence of additional experience. Merely performing the same activities repeatedly on a regular daily schedule will not lead to further change once a physiological and cognitive adaptation to the current demands has been achieved. The principal challenge for attaining expert performance is that further improvements require continuously increased challenges that raise the performance beyond its current level. The engagement in these selected activities designed to improve one's current performance is referred to as deliberate practice. Given that these practice activities are designed to be outside the aspiring experts' current performance, these activities create mistakes and failures in spite of the performers' full concentration and effort - at least when practice on a new training task is initiated. Failing in spite of full concentration is not viewed as enjoyable and creates a motivational challenge (Ericsson et al., 1993). For example, it is understandable that musicians are reluctant to take on a difficult piece they cannot give musical expression to or that ice skaters hesitate to attempt new jumps that are likely to make them fall repeatedly on the hard ice. Recent observational studies (Deakin, 2001) show that sub-elite ice skaters spend more time on jumps that they have already mastered, whereas elite ice skaters allocate more time to the more difficult jumps, where failure rate is higher and the likelihood of improvement greater. Once we conceive of expert performance as mediated by complex integrated systems of representations for the execution, monitoring, planning, and analyses of performance, it becomes clear that its acquisition requires an orderly and deliberate approach. Different forms of deliberate practice focus on improving specific aspects of performance while
assuring that attained changes can be successfully integrated into representative performance. Hence, practice aimed at improving integrated performance cannot be performed mindlessly nor independent of the representative context for the target performance.

The early research on deliberate practice in music (Ericsson et al., 1993) showed that the engagement in deliberate practice is constrained. When music students start practicing, they average one hour per week, often split into fifteen to twenty minute sessions. The weekly amount of solitary practice increases over the next ten to fifteen years to around twenty-five to thirty hours per week for full-time students at the academy. The constraint on deliberate practice doesn't seem determined completely by developmental factors due to the young starting ages of future expert musicians, because a very similar gradual increase in practice has been seen for athletes who start practice in adolescence (Starkes et al., 1996). When expert performers engage in deliberate practice, they report that full concentration is necessary for improving their performance and that when concentration waned they stopped their practice (Ericsson, 2001, 2002b; Ericsson et al., 1993). To maximize the time of full concentration, they tend to limit the duration of a single practice session and take short breaks after around an hour. They also tend to start early in the morning and frequently take a nap before resuming their demanding activity in the afternoon. When expert performers engage in deliberate practice on a daily basis, the available daily time with full concentration seems to limit the amount of deliberate practice for expert performers in all domains to around four to five hours. For example, world-class novelists work virtually exclusively in the morning and spend the rest of day recuperating, in order to prepare for the following day's writing session (Cowley, 1959; Plimpton, 1977).

In sum, the study of expert performance has uncovered a large number of factors associated with the acquisition of expert performance, such as an early start of involvement in domain-related activity, early start of training, and amount of relevant experience. More important, there is also an emerging body of necessary constraints for attaining expert levels of performance even among individuals regularly engaged in the activity, such as guidance and instruction by teachers and the regular engagement in deliberate practice. Even the most "talented" individuals need to engage in extended deliberate practice for many years to acquire the prerequisite mechanisms. Hence, the old assumption that expert performance is acquired virtually automatically by "talented" individuals has been replaced by the recognition of the complex structure
of expert performance and the complexity of the necessary learning activities that build the required mediating mechanisms to support expert performance. Whether any healthy individual with appropriate body size who engages in the appropriate prerequisite deliberate practice will necessarily attain expert levels of performance in the associated domain is not currently known. So far, I am not aware of any confirmed exceptions to this notion. Regardless, the overwhelming importance of factors other than innate talent to reach an expert level of performance is likely to remain uncontested.

CONCLUDING REMARKS

Contemporary theoretical frameworks of human ability focus primarily on the relatively narrow range of achievement of school children and college students, where large samples of participants and sophisticated statistical models are necessary to analyze the pattern of correlations, often with small to medium statistical strength. These methods of analysis and the associated theoretical interpretations are motivated by several fundamental assumptions. My introductory historical sketch attempted to identify some of these assumptions. When these theories were originally proposed in the eighteenth and nineteenth centuries, they were empirically evaluated with analyses of exceptional and expert performers. To continue this tradition, my chapter has attempted to assess the validity of these assumptions by reviewing recent relevant research on expert levels of performance as well as the effects of extended training on expert performance.

Psychological scientists have always been inspired by the success of the natural sciences in uncovering general laws explaining the "behavior" of objects based on stable characteristics of uniform materials, such as hardness, volume, and weight, which can be quantified by objective measurement procedures. It is therefore reasonable for scientists working within the social sciences to attempt to explain the large individual differences in human performance in a similar fashion by attributing these performance differences to stable characteristics and mental capacities. As scientists should always look for the most general and parsimonious mechanism to explain observable patterns of results, it would seem reasonable to attempt to use individual differences in general basic capacities to explain consistent differences in ability and performance. However, the complex structure of human skills and performance raises questions about the stability and uniformity of any
inferred capacities and characteristics. Mature human adults are *biological systems* that have developed from a single fertilized cell during a time period of around two decades. These developing systems are capable of remarkable changes and adaptations from large organic changes (such as increased kidney function) down to the individual cell level. From the perspective of developmental biology, the theoretical notion of basic general capacities that rigidly constrain the performance of adults is not simple, but requires explication in terms of specific genes and their timely expression to invariably influence the targeted anatomical structures. Until scientists have found the anatomical and physiological systems that implement these invariant basic capacities, along with plausible models for the specific genetic control of their differential development, these hypothesized capacities should not have priority among competing explanations of differences in human ability.

Because human characteristics are shown to be so modifiable after appropriate extended practice (with the exception of body size), scientists interested in performance limits need to search for a stable reproducible performance attained only after many years of deliberate practice designed to reach the highest levels. In the second section of this chapter, I outlined the compelling evidence that expert performance is mediated by complex mechanisms that anticipate, prepare, monitor, and evaluate its execution of actions. The highly reproducible performance of experts allows investigators to assess and validate the complex mechanisms at the level of each individual expert (Ericsson, in press). These complex mechanisms are not restricted to elite performers, and there is compelling evidence that the same types of mechanisms mediate skilled activities in all educated adults. [For example, there is a similar finding of advance anticipation of motor actions when adults read aloud: more skilled readers have a longer span between the words on which their eyes fixate and the words they concurrently vocalize (eye-voice span). Similarly, individuals who comprehend texts better also exhibit a larger functional working memory (LTWM) for the associated type of material (Ericsson and Kintsch, 1995; Kintsch, 1998).]

The complexity of the mechanisms that mediate skilled and expert performance presents a challenge to traditional theories of learning and skill acquisition. Ever since the seventeenth and eighteenth centuries, when associative learning was developed as an alternative account to the complex innate structure of the soul, the complexity of learning processes has been minimized by scientists. Learning based on simple processes, such as strengthening of associations, was preferred to avoid
the introduction of the complexities associated with learning processes. In
the third section of my chapter, I argue for the need for complex learning
mechanisms and highly structured activities of practice (deliberate
practice) to explain the extended acquisition of complex mechanisms that
mediate expert levels of performance. Experts were shown to avoid the
path taken by most novices where initial representations for performing
the tasks were rapidly automated. Instead, experts were shown to keep
building and refining their representations and the supporting working
memory (LTWM) that supports anticipation, planning, and decision-making.
I have also demonstrated how deliberate practice can develop and refine
the mediating mechanisms to allow aspiring experts to monitor and
evaluate their performance to identify potential weaknesses that can be
eliminated through problem solving and repetition (Ericsson, 2001b; in
press).

The gradual development of complex mechanisms on the path to-
ward high levels of performance has major implications for our current
conceptions of ability. Although it is possible to assign quantitative metrics
to a person's ability to play music, chess, or tennis, these numbers do not
quantify any uniform capacity or ability to perform in the respective
domains (see Mitchell, 1999, for a thorough critique of efforts to
quantify individual differences in ability and capacity). For example, an
international-level chess master does not simply have "two" times the
units of chess ability of a strong club-level player, nor can we describe
the difference as "one hundred" units of some uniform chess ability.
The analyses of expert performers in domains such as chess, music,
and tennis show a qualitative difference in the structure and complexity
of the mediating mechanisms that such individuals use to progress to
higher levels of performance. The steady development of the mediating
mechanisms and the associated performance by aspiring expert
performers makes it reasonable to describe successive levels of such
performance by an ordinal, or rank-order, scale. More generally, similar
rank-orders should be able to describe the stability of rank-orders across
competitions for performers in a given domain.

In this chapter I try to raise doubts about the validity of the long-
standing belief in stable innate capacities and any restraint such sup-
posed innate capacities have on an individual's ultimate performance
potential. The reviewed empirical evidence from the acquisition of expert
performance contradicts this theory, and demonstrates that individuals
gradually acquire increasingly complex mechanisms roughly ordered
along an ordinal path leading to elite levels of performance.
These ordinal paths of development are far more consistent with Binet and Simon's (1915) descriptions of normal cognitive development along a defined path of discrete milestones of mastery for each age. Only future research will speak to the matter of how research on human ability can best be reconciled with the rapidly developing body of evidence on the structure and acquisition of expert and exceptional performance.

References

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